Exxon Valdez Oil Spill
Restoration Project Annual Report

Sound Ecosystem Assessment (SEA): An Integrated Science Plan for the Restoration of Injured Species in Prince William Sound, Alaska

Restoration Project 96320
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Robert T. Cooney

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska 99775-7220

for:

Alaska Department of Fish and Game
Habitat and Restoration Division
333 Raspberry Road
Anchorage, Alaska 99518

April 1997

Chapter 1.

A SEA 1996 Synthesis

Sound Ecosystem Assessment (SEA): An Integrated Science Plan for the Restoration of Injured Species in Prince William Sound, Alaska

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Study History: The SEA program was initiated in April 1994, as an integrated, interdisciplinary, multi-project study of processes influencing the recovery of damaged pink salmon and herring populations in Prince William Sound. An annual report was submitted by Cooney, R.T. in April 1996, under the title SEA95, Sound Ecosystem Assessment (SEA): An Integrated Science Plan for the Restoration of Injured Species in Prince William Sound. This report contained 14 chapters contributed by the principal investigators and lead scientist. The FY96 annual report submitted as this document reports progress toward SEA goals and objectives during the third year of the five year study. FY98 is the last fully funded year for SEA. Close-out funds in FY99 will provide a final report for the project and include a synthesis across all contributing projects addressing the programs major hypotheses and goals.

Abstract: The compiled annual reports provided here describe work completed in FY96. Field work included the first fully coordinated studies driven by the needs of the ocean state, plankton, pink salmon and herring modeling subgroups. Physical oceanographic field studies involved measurements of inflow at Hinchinbrook Entrance as part of the model validation work. Complex circulation patterns continue to be described for the major oceanographic seasons in the region. Work on simulating the coupling between physical forcing and biological response in the plankton communities discovered that two dominant production scenarios seem to represent the system. Fisheries work was driven by continuing uncertainties that constrain modeling of prey-predator relationships defining survival of juvenile pink salmon, and the bioenergetics of herring overwintering survival. Juvenile pink salmon predator studies focused on critical nearshore refuges and included continuous video surveillance techniques. Juvenile herring studies focused on defining nursery areas and measuring seasonal changes in the growth and somatic energy content of juveniles. There are growing indications that juvenile herring feeding habitat may be isolated from the general pelagic production cycle, and isotope measurements suggest crucial interactions between summer and early fall feeding areas and seeded populations entering the Sound from the adjacent Gulf of Alaska.

Key Words: Biophysical models, circulation, energetics, experimental fry release, food-web, marine acoustics, modeling, numerical models, nutrients, oceanography, Pacific herring, phytoplankton, pink salmon, Prince William Sound, stable isotopes, zooplankton.

Project Data: (will be addressed in the final report)

Citation:

Cooney, Robert T. 1997. Sound Ecosystem Assessment (SEA): An integrated science plan for the restoration of injured species in Prince William Sound, Alaska, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 96320), Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.

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Preface

Each of the SEA individual Annual Reports compiled here as separate chapters has been written as a stand-alone document. Bundling the reports together under one cover with synthesis has been accomplished to address the integrative nature of the overall SEA approach, and to provide the Trustee Council and its agencies access to FY96 results in a convenient form. It must be understood that SEA is a work in progress, and that results presented in this report are not the result of an exhaustive analysis. The Synthesis chapter is intended as a executive summary for the overall program and has been prepared at the request of the EVOS Chief Scientist.

SEA was designed in the fall of 1993 to test hypotheses describing the mechanisms believed at that time to control survival in juvenile populations of pink salmon and Pacific herring in Prince William Sound. Refinements to these conjectures continue to guide the integrated research efforts:

a. The survival of juvenile pink salmon and post-larval herring populations in Prince William Sound and adjacent waters is determined primarily by losses to bird, fish and mammal predators.

b. For juvenile herring, the energetic condition prior to winter, and the winter environment (temperature and food) also establish the survival potential during periods of food deprivation. Under certain conditions, starvation may account for significant brood-year losses during this critical period.

c. Predation losses are related, in part, to the energetic condition and size of juvenile pink salmon and herring. Condition and size are established by growth rates that vary within and between years.

d. Predation losses are modified by the numbers and kinds of predators, and by the numbers, kinds and time/space distributions of alternative prey for these predators. Macrozooplankton serves as alternative prey during some seasons and years.

e. Macrozooplankton populations are established by local reproduction, and are modified by phytoplankton productivity and timing and by currents that both flush the region and seed the Sound from adjacent shelf and ocean populations.

These hypotheses continue to focus SEA field and modeling efforts as the program enters Phase II, the 1997-98 period of decrementing funds. During this remaining time, much of the energy in the overall program will be expended on data analysis, interpretation, and application to the numerical tools defined by SEA as the principal products of the research. Restructuring the program around model subgroups with responsibility for the areas of ocean state and plankton dynamics, pink salmon recruitment dynamics and Pacific herring recruitment dynamics provided the crucial linkages between investigators in the field and those constructing the models.

A Sound Ecosystem Assessment (SEA) Synthesis with Emphasis on Results Reported for the FY 96 Funding Period

Robert T. Cooney, Sea Lead Scientist
Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska 99775-1080

Completion of SEA's third and last fully-funded year brought with it additional refinements to the structural elements of the now fully integrated scientific program. The modeling subgroups that were initiated in the fall of 1995 became fully functional in 1996 and were primarily responsible for driving and guiding the field work. These programmatic results signal the maturity of SEA at a time when much of the continuing effort will, of necessity, be expended on data analysis, interpretation, and application to the numerical products being created as the principal deliverables of the science. With this in mind, the program extended a formal invitation to Alaska Department of Fish and Game to begin assisting SEA with the development of a management interface to project the modeling contributions into future decision making arenas. The translation of restoration science into management procedures is expected to be one of the greatest challenges facing SEA in the final years of the project. Willingness by the State of Alaska to join with SEA at this juncture represents the first substantial step toward establishing a working partnership for the future management of pink salmon and herring populations in Prince William Sound.

Ocean State and Plankton Dynamics

This subset of SEA projects is modeling Prince William Sound's responses to external forcing by winds, freshwater and tidal energy to simulate seasonal and spatial patterns in hydrography, deep and shallow currents, and lower trophic level production. In the vernacular of the original study plan, the OP group is describing "lake/river" attributes of the system reflected in both the physics and the biology. Our approach is similar to that being supported by the U.S. GLOBEC study of cod production on Georges Bank, and NOAA FOCI studies of walleye pollock in Shelikof Strait and the eastern Bering Sea (Kendall, et al., 1996). All of these studies emphasize process queries designed to elucidate major mechanisms of mortality in the larval and juvenile stages. The mechanisms are then captured in numerical simulations that have robust predictive properties. Once created, the models also provide the means to examine a variety of management "what if" scenarios from which appropriate agency actions can be selected. In the case of the recently completed Shelikof study, stochastic mathematical formulations and coupled bio-physical models have demonstrated strong applied predictive capabilities (Megrey, et al., 1996; Hermann et al., 1966). We expect the results of SEA modeling to make similar contributions to the future management of pink salmon and herring in Prince William Sound.

Work in 1996 emphasized validation of the 1.2 km, 3-dimensional, eddy resolving model of the circulation of Prince William Sound developed in 1995. Although yet to be fully tuned to freshwater and tidal forcing, the model presently simulates most of the features observed in direct measurements of current flow and hydrography. From reasonable northward transport values impressed at Hinchinbrook Entrance, the model reproduces the dominant flow regimes in the Sound, including a lake-like northern region and river-like southern extension of the Alaska Coastal Current (ACC). The completion of a hydrological model of seasonal freshwater input in FY97 is expected to significantly improve these simulations, and provide some of the first experimental opportunities for testing SEA hypotheses about the physical and biological effects of local flushing or the intrusion of shelf water into the Sound.

Regional-scale physical oceanographic studies continued to focus on understanding seasonality in upper and deeper water density structure and transport processes, variables that influence the timing, distribution and duration of seasonal plankton production. Analyses of this data portray considerable seasonal and year-to-year differences. For example, the spring and summer of 1996 was considerably warmer and saltier than 1995. Some of the first measurements of current flow in Hinchinbrook Entrance in December documented inflow in the upper 150 m, but outflow below that depth. These continuing observations are bringing refinements to previous understandings of seasonal transport in Prince William Sound (Neibauer et al., 1994).

Seasonal changes in temperature, salinity and density being measured by SEA agree well with historical records from the Sound (Schmidt, 1977). March and early April are generally the coldest and most saline periods for waters in the upper layers of the region. Seasonal warming and freshening begins in April and May promoting weak stratification and with it, annual plankton blooms. By late spring and early summer, the upper 50 m exhibits seasonal stability that generally carries forward into September. However, we now believe that certain wind conditions during the summer may be capable of injecting new nutrients into the surface waters forcing resumptions of enhanced levels of primary productivity. *In situ* measurements of fluorescence from the C-LAB mooring hint that late summer and early fall blooms are probably occurring in some (but not all) years. This part of the local production cycle has never been documented well for Prince William Sound. Late summer and early fall blooms might prove important in the growth cycle for age 0 herring. Continuing analyses of upper layer physical structure will include mapping the mixed-layer depth in March and April to help assess regional-scale differences in the timing of the phytoplankton blooms, and following wind events in late summer. Napp, et al., (1996) compare and contrast the timing of phytoplankton blooms occurring over deep and shallow water in Shelikof Strait and conclude that phytoplankton production is initiated annually in the more stable deeper water in the central portion of the Strait. Local knowledge (charter air services) indicates in most years the production cycle begins in the shallow eastern part of the region, then spreads to deeper water.

Upper-layer currents (20-100 m) obtained from a towed ADCP support a growing contention (and numerical model result) that flow fields in the eastern, northern and western Sound regions are generally weak and variable relative to south Sound flow - the so-called river region. Plots of potential density also reveal physical structure which in some cases persists for weeks and months. A cyclonic gyre appeared in the record north of Hinchinbrook Entrance during May, June and September, 1995. This structure is not apparent in the preliminary numerical simulations of upper-layer currents in the region, perhaps because the model has yet to be tuned to seasonal changes in density. However, these gyre structures were also apparent in the 1996 field observations.

SEA biophysical modeling draws on simulations that track field observations of the timing and magnitude of phyto and zooplankton blooms each spring. That timing was recognized by SEA as potentially establishing the matches and mismatches between predators and their prey. Since zooplankton require food to fuel their growth and reproductive cycles, peaks in the biomass of these two components are generally phased sequentially and occur about 15-30 days apart. Observations in 1996 demonstrate that the conditions setting limits on the timing and duration of the phytoplankton bloom manifest over a relatively short "critical" period in early spring. How year-to-year differences are related to problems with juvenile fish survival is presently unknown, but we suspect they can be substantial. Census of wild fry outmigrations from index streams in southwestern Prince William Sound in 1990 and 1991 demonstrated that entry into the near-shore zone from adjacent natal areas began in early April each year despite a 2 degree C difference in temperature between years (Cooney et al., 1995). If juvenile salmon begin entering the marine system at about the same time each year (regardless of environmental cues), shifts in the timing of the zooplankton bloom might afford more food (for fry), and better sheltering from predators in some years, but not in others.

Unlike the oceanic Gulf of Alaska, an early spring large diatom bloom is characteristic of Sound waters in late March and April. We have previously reported that the timing of this event is modelled accurately using the Sverdrup critical depth theory which identifies light levels (relative to photosynthesis) and the mixed layer depth relationships as principal criteria for triggering" the bloom. April and May are transition months for the Gulf of Alaska, separating the fall/winter downwelling regime from the spring/summer period of relaxation or weak upwelling. Our observations indicate the bloom quickly becomes nutrient limited (nitrogen or silicon), falling to low standing stocks by early May. C-LAB records often depict one or more weak secondary blooms during the summer, and in some years what appear to be substantial summer and early fall events.

Plankton modeling studies in 1996 demonstrated that there are two general scenarios for springtime ocean dynamics supporting the onset and continuation of phytoplankton productivity in the Sound. Warm, less-windy conditions lead to an early, intense period of plant production, much of which is poorly coupled to zooplankton grazing and settles out of the water column. In contrast, cool, windy conditions delay the bloom and extend its duration. Under this scenario, peaks in productivity are lower, but the extension in time provides closer coupling with zooplankton and the incorporation of more energy into the pelagic food web. These intriguing results are apparently at variance with relationships between spring stocks of south-Sound zooplankton and wind-forced downwelling over the adjacent shelf. There, zooplankton biomass tends to be substantially higher in the region when onshore wind forcing is weakest, and *visa versa.* Because the computed wind-forcing establishing the Bakun Upwelling Index is resolved into the eastward component only for the adjacent shelf, a reduction in the strength of the downwelling may not correspond to weakened overall winds, only the eastward vectors. The apparent discrepancy between observation and model results is providing fertile ground for increasing collaborative work in the plankton dynamics working group as we continue to seek resolution of the lake/river hypothesis.

A spring cruise in May investigated vertical and horizontal distributions of macrozooplankton at the peak of the annual wild and hatchery fry outmigration into near-shore nursery areas. Joint physical, biological (MOCNESS samples), acoustic and optical methods were used at locations inside and outside the Sound to describe the vertical structure of copepod-dominated communities in the upper 50 m, and their continuity along transects between stations. Cluster analyses of species composition based on abundance and biomass differentiated between two major grouping of stations. One group included all stations from south of the Sound over the continental shelf and locations in the south, central, eastern and northeastern regions of the Sound. The other group clustered stations from the western and northwestern regions. These results, coupled with information on nutrient and chlorophyll distributions (same cruise), provide additional evidence that Knight Island Passage and the deeper northern and northwestern areas are at least partially isolated from the intrusion of the Alaska Coastal Current and the biota it brings into the region.

SEA is actively pursuing an independent test of this possibility using differences in the stable isotopes of carbon to identify different plankton source populations - inside and outside Prince William Sound. Our work to date on a congeneric, *Neocalanus cristatus*, supports the idea that shelf populations of large calanoids do invade the region with the coastal water inflow at Hinchinbrook Entrance. *Neocalanus plumchrus* is the more oceanic form, and thus a natural marker for the inflow population (Miller and Clemons, 1988). Isotope ratios of *N. plumchrus* and *N. flemingeri*, obtained on the May, 1996 cruise, is expected to shed further light on the sources of large calanoids clustering with the two major geographic groupings. These two species occurred together in the upper portions of the near-surface layer in the western and northwestern areas suggesting that there is either some weak coupling between this region and the coastal flow to the south, or that both species overwinter in the deep water and contribute to local reproduction in the northern and western areas as separate populations. Incze, et al. (1997) provide direct evidence for oceanic influences on the composition of zooplankton collections from Shelikof Strait, demonstrating that cross-shelf flow does seed the coastal zone to the west of Prince William Sound.

Pink Salmon Recruitment Dynamics

Wild juvenile pink salmon enter the coastal zone in the Gulf of Alaska from April to early June each year (Taylor, 1988). Cooney et al. (1995) note that this timing corresponds closely with the macrozooplankton bloom in Prince William Sound. We now believe that this outmigration timing maximizes the potential for survival by matching the fry with their food at a time of increasing water temperature, and also by providing a partial refuge from predation by adult fishes that are drawn to plankton rather than fry at this same time.

Much was known about juvenile pink salmon during early marine residence from studies conducted prior to, and following the EVOS (Willette, 1996). Some of this work pointed to the importance of near-shore fry nurseries where juveniles feed and grow before leaving for open shelf and open ocean feeding grounds. The juvenile salmon literature has long suggested that losses of juveniles to predation is growth-rate dependent, the slowest growing fry being exposed in the smallest, presumably weakest stages for longer periods of time. Since both temperature and food influence growth rate, it seems reasonable to assume that the fry will always attempt to optimize their growth by exploiting gradients in food and temperature. Pink fry feed immediately on pelagic resources in the deep waters of Prince William Sound (Urquhart, 1979). During the period of early marine residence (April and May) waters of the region are generally warming and stabilizing. However, in the near-shore tidally-mixed zone, temperatures may actually be cooler than in adjacent stratified waters, and zooplankton concentrations diluted by mixing. Under these conditions, it seems odd the fry would remain in water that is less than optimal (food and temperature) for growth unless there are other factors dictating these distributions. Given the results of the SEA research on juvenile pink salmon predators, it now seems reasonable to assume the near-shore "nurseries" are actually only marginal predation refuges where fry are pinned between birds feeding from above and larger fish from below. In response to these threats, the young fish probably remain in the shallows until they have achieved a swimming ability (size) that tips the balance away from predation loss toward more optimal foraging opportunities (offshore). Another factor, the genetic clock driving an obligatory migration from coastal to open ocean feeding areas, must also play a role in dictating when fry are obligated to leave the shelter of the near-shore and begin swimming to offshore feeding areas. Because of this "clock", fry may be smaller-than-average in cold years when they begin migrating south to open coastal waters. Temperature-modulated size-dependent mortality could be contributing to the general relationship between fry-spring water temperatures and regional adult returns (Cooney et al., 1995).

Prince William Sound Aquaculture Corporation released 11.4 million hatchery pink salmon fry in 1996 from the Walley Noerenberg Hatchery on Esther Island at about 1.1 g live weight each. Additionally, 12.5 million smaller fry (0.7 g) were released from the Armin F. Koernig Hatchery on Evans Island. Although the releases in 1996 were about the same magnitude as those in 1995, the fish were smaller and generally released earlier.

Previous SEA studies of salmon fry predators focused primarily on offshore midwater collections of fishes and squids, and hatchery-based observations of losses to birds. An assessment of bird predation following the release of fry from pens in 1995 implicated black-legged kittiwakes and marbled murrelets as species targeting fry. Energy models of bird food demands provided a means to evaluate the impact of observed bird numbers on local fry survival. Field work in 1996 focused more intensely on fish predation in the near-shore zone. Prior observations also suggest that predation in this important transitions habitat was probably being underestimated for a variety of reasons. In this regard, studies in the spring and summer of 1996 were designed to expand our knowledge of predation processes in the edge-zone where most of the losses were believed to be occurring. Upward looking fixed video cameras and a higher frequency of direct sampling were designed to search for evidence that more predation than previously estimated was occurring. Dolly varden trout, age 1 and 2 pollock, Pacific cod and tomcod, and adult herring were observed feeding on fry in 1996. Camera results indicate a strong "shoreward compression" of fry at night, presumably as a predator avoidance response. Off-shore collections of adult pollock were lower than catches in 1994 and 95. The application of sonic tagging for tracking adult pollock diel feeding migrations was confirmed as part of a successful field experiment that involved tracking a tagged adult for 2 days. A second adult was tracked for a day.

SEA studies of fry predation losses are supported by acoustic surveys of nekton and plankton. This methodology is providing estimates of fry predators in relatively shallow water near some hatcheries (AFK), and of off-shore adult pollock and herring stocks (spawning and feeding populations). Problems associated with separating pollock and plankton acoustic signals have been solved using a counting rather than echo integration technique to estimate fish abundance. This "problem" confirmed the ecological co-occurrence of macrozooplankton and pollock, the latter probably filter-feeding in layers of high plankton biomass. Studies to interpret acoustic information relative to plankton species composition, size and densities were pursued in 1996 using a MOCNESS system to provide discrete-depth samples of layers and zooplankton swarms in conjunction with optical and acoustic plankton observations. This work demonstrated that *Neocalanus fleminger*, *N. plumchrus, N. cristatus* and *Calanus marshallae* all occurred in layers or near-surface swarms at many locations inside and outside Prince William Sound. Within-layer densities between 500 and 1000 individuals m-3 indicate suitable resources for filter or gulp-feeding by pollock and cod selecting these patches.

Much of the future survey work for zooplankton and pelagic fish distributions will be undertaken by quantitative acoustic and optical means. Work completed in 1996 by the acoustics component of SEA continued to resolve problems of interpreting signals from fish and plankton sources. Studies accompanying the MOCNESS survey in early May provide the strongest evidence to date linking zooplankton distributions to acoustic and optical signals. Because of these and other results, we are becoming increasingly confident in acoustic surveys of juvenile and adult pollock and herring in the region and their pelagic forage resources.

Modelling prey predator relationships in the "salmon fry ecosystem" is one of the most ambitious undertakings of the entire SEA program. The multi-dimensional approach is centered on the bioenergetics of the fry and their predators - the behaviors of both being driven by gradients in food and predation which in turn are modified by the oceanography - currents, mixing and temperature. This effort focuses SEA field investigations on "mechanisms of loss" for juvenile pink salmon and herring as the principal means for creating representative numerical simulations of these processes. The approach also draws from the literature to create bioenergetics models for the principal environmental components of the system. In 1996, an onshore-offshore model of fry, adult pollock, large copepods and euphausiids was further refined and used to test continuing ideas about prey switching and the time/space overlaps of fry, their food and their predators. Because we were unable to detect tidal influences on zooplankton populations (MOCNESS cruise), it seems likely that statistical relationships between fry survival and the state of the tide (Spring or Neap series) may be related to effects on fry predators, not fry food resources. Periods of intense tidal exchange during the height of a spring cycle might be causing enough current velocity in the shallow edge-zone to drive larger fishes deeper in the water column. A so-called "tidal shuffle" effect is well know to sports fishermen who adjust their fishing times to the state of the tide, both daily and monthly.

Herring Recruitment Dynamics

SEA sponsored herring studies began in 1994 with an investigation of the influence of avian predation on herring embryo mortalities in intertidal spawning areas. That research demonstrated that glaucous-wing gulls, mew gulls, surf scoters, surfbirds and black turnstones obtained all or a very large percentage of their daily rations from herring eggs while eggs were present in the natal areas. The application of a bioenergetics model predicted that in 1994, this assemblage of birds could account for an average loss of 2.5 % of the eggs per day for a spawning location on Montague Island. Depending on the numbers of birds, and their arrival times, bird predation can account for measurable losses during some years.

In 1995, an internal reorganization of SEA budgets was undertaken to accommodate the inclusion of studies designed to describe juvenile herring growth and habitats, and their energetic condition as a means to investigate how overwintering survivals might determine cohort recruitment strength to adult populations each year. Laboratory studies indicate that fasting herring use substantial energy, enough to result in starvation under some conditions. Herring store energy during the growth cycle each year, apparently drawing on that energy reserve to bridge seasonal reductions in plankton and other forage. If these reserves are exceeded during the winter, the fish may starve.

SEA investigators entered the herring picture with little previous local information available about juvenile growth or habitat preferences. Some observations indicated that larvae begin drifting seaward from natal areas in mid May, and that depending on water temperatures, the larval forms could drift from 30-60 days before metamorphosis to post-larvae and eventual re-invasion of the near-shore zones. It was reasoned that during the drift, some unknown percentage of larvae might be swept from the Sound via the Alaska Coastal Current.

In 1996, four broadscale surveys for juvenile Pacific herring were completed and four regions in the Sound designated for monitoring size and growth, physical oceanography (temperature and currents) and prey fields. Zaikof Bay on northern Montague Island, Eaglek Bay near Esther Island, Whale Bay in the southwestern region, and Simpson Bay near Cordova were selected for finescale studies and were sampled 4 times during 1996. In addition, four primarily "winter" cruises were undertaken to monitor the somatic energy content of juveniles transiting periods of food deprivation and to determine if winter feeding was occurring, and if so, on what prey resources.

We now have evidence that juvenile and adult herring populations are generally separated in the Sound except prior to spawning, when large schools of adults begin assembling near shore. In contrast, juveniles are generally found in the edge zone during all seasons. While there remains some question about the degree of site fidelity that juveniles exhibit for specific locations, it does seem apparent that once the young-of-the-year appear in bays and inlets, they become creatures of the shallow near-shore environment. Samples taken in March, 1996, (prior to adult spawning) exhibited three distinct length modes representing the overwintering 0-age juveniles (first winter), 1+ age juveniles surviving their second winter, and adults. Samples taken later in the summer (July/August) exhibited only two length modes. Surviving young-of -the-year as the smallest fish, and surviving age 2 juveniles. Adults were missing from these samples although thousands of fish were measured. This observation strengthens our contention that adults are using other feeding habitats at this time.

We now believe that following the period of adult spawning in early to mid-April, incubating demersal eggs in shallow water begin hatching and the larvae begin drifting into deeper water by mid May. Depending on water temperatures during the larval drift, a metamorphosis to the post-larval juvenile form can take from 4 to 10 weeks. SEA sampling in bays and inlets in late July and early August, 1996, discovered juveniles at many locations. The degree to which the "re-invasion" of near-shore natal areas represents the trajectories of surviving larvae or remnants of larval stocks that are retained in the near-shore (or both) remains to be investigated. Aerial surveys in the region during the summer document juvenile herring and sandlance schools in many near-shore environments.

Preliminary studies of the diet composition of juvenile herring are presenting surprises. Large, medium and small calanoids are major contributors, but a series of additional near-shore taxa including meroplankton (larval barnacles, polychaeta), insects, harpacticoid copepods, and cladocerns were also important at some sites. The most unusual result is the lack of *Neocalanus plumchrus* and *N. flemingeri* in stomachs. This would not be expected for 0 age juveniles in the late summer (*Neocalanus* mostly in deep, diapausing populations at that time), but unusual for spring populations of overwintering survivors feeding in April and May when 90 percent or more of macrozooplankton stocks are composed of *N. flemingeri* and *N. plumchrus* . Instead, the much less abundant and larger *N. cristatus* is listed as a diet item. This totally unexpected result is being carefully examined by repeated sampling in the spring of 1997 when both offshore and near-shore zooplankton stocks will be censused.

Summary and Related Matters

An increasingly refined view of processes constraining the production of pink salmon and herring in Prince William Sound is emerging as the result of new findings and growing collaborations between SEA investigators. The modeling subgroup structure has matured to the stage where the remaining effort is now closely coupled between diminishing field activities and growing data analysis, interpretation, and the application of results to the ocean state, plankton dynamics and juvenile pink salmon and herring survival simulations. 1996 marked a year of significant contributions, particularly from coordinated herring studies. Questions about juvenile herring growth and overwintering energetics, about preferred habitats, and about forage resources were addressed as the principal means for describing time/space aspects of critical early life stages previously unreported for Prince William Sound populations.

The resolution of hypotheses guiding SEA research is beginning in earnest, a procedure enhanced by increasing attention to data interpretation and cooperation between investigators working at all levels of the pink salmon and herring ecosystem. This report represents the first program-wide attempt to present results in manuscript form for most projects. SEA investigators agreed on this strategy at a 3-day workshop in Seward in September as one means for forcing greater peer review of details that will be needed later in the planned synthesis activities of 1998 and 1999.

SEA program investigators clearly understand that the final two years of the study pose the greatest challenges for everyone as data sets are applied to final model refinement, model validation and evaluations of hypotheses. For most, these important activities will be further complicated by needs to both plan and propose continuing research that takes advantage of the lessons learned by SEA. Opportunities afforded by the U.S. GLOBEC program in the North Pacific, by LTER/LMER (NSF) studies, and through new EVOS support will all be distractions that many will face at the same time SEA is undertaking its most important work.

Questions about the form of the SEA final report in 1999 are being actively explored so that plans can be made to aaccommodatethis exercise in a timely manner. The 1997 Annual Report (submitted in FY98) will represent the last contribution to a SEA annual report series (FY94-FY97). Current plans for the final report include summaries of all work completed through FY98 submitted as a bundling of published or in-press manuscripts by project as one or more volumes, supplemented by a another volume of collaborative manuscripts specifically addressing SEA hypotheses and synthesis. This volume will be prepared as a special scientific journal issue.

Literature Cited

Cooney, R. T., T. M. Willette, S. Sharr, D. Sharp and J. Olsen. 1995. The effect of climate on North Pacific pink (*Oncorhynchus gorbuscha*) populations: examining some details of a natural experiment. In R. J. Beamish (ed.) Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci., 121475-482.

Hermann, A. J., S. Hinckley, B. A. Megrey and P. J. Stabeno. 1996. Interannual variability of the early life history of walleye pollock near Shelikof Strait as inferred from a spatially explicit individual based model. Fish. Oceanogr. 5(Suppl. 1):39-57.

Incze, L. S., D. W. Siefert and J. M. Napp. 1997. Mesozooplankton of Shelikof Strait, Alaska: abundance and community composition. Prog. Oceanogr. 17(3):287-305.

Kendall, A. W., J. D. Schumacher, and S. Kim. 1996. Walleye pollock recruitment in Shelikof Strait. Fish. Oceanogr. 5(Suppl. 1):4-18.

Megrey, B. A., A. B. Hollowed, S. R. Harr, S. A. Macklin, and P. J. Stabeno. 1996. Contributions of FOCI research to forecasts of year-class strength of walleye pollock in Fish. Oceanogr. 5(Suppli 1):189-203.

Miller, C. B. and M. J. Clemons. 1988. Revised life history analysis for large grazing copepods in the Subarctic Pacific Ocean. Prog. Oceanogr., 20(4):293-313

Napp, J. M., L. S. Incze, P. B. Ortner, D. L. W. Siefert, and L. Britt. 1966. The plankton of Shelikof Strait, Alaska: standing stock, production, mesoscale variability, and their relevance to larval fish survival. Prog. Oceanogr. 5 (supplement 1):19-38.

Neibauer, H. G., T. C. Royer and T. J. Weingartner. 1994. Circulation of Prince William Sound, Alaska. J. Geophys. Res., 99 (14):113-126.

Schmidt, G. M. 1977. The exchange of water between Prince William Sound and the Gulf of Alaska. M. S. Thesis, University of Alaska, Fairbanks, AK, 116 p.

Taylor, S. G. 1988. Inter- and intra-annual survival of pink salmon (Oncorhynchus gorbuscha) returning to Auke Creek, Alaska in 1986 and 1987. APPRISE Annual Report 1987 Alaska Tech. Rep. 1: 547-571.

Urquhart, D. L. 1979. The feeding, movement and growth of pink salmon (Oncorhynchus gorbuscha) fry released from a hatchery in Prince William Sound. M.S. Thesis, University of Alaska, Fairbanks, AK., 111 p.

Willette, T. M. 1996. Impacts of the Exxon Valdez oil spill on the migration, growth, and survival of juvenile pink salmon in Prince William Sound, Alaska. Proc. EVOS Symp., Feb. 1993, Anchorage, Alaska (in press).

Chapter 2.

Juvenile Salmon Predation (96320E)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Sound Ecosystem Assessment: Juvenile Salmon Predation

Restoration Project 96320E
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil spill Trustee Council Restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

T. Mark Willette
Mark Clapsadl
Penny Saddler
Margaret Powell

Alaska Department of Fish and Game
401 Railroad Avenue
Cordova, Alaska 99574

April 1997

Sound Ecosystem Assessment: Juvenile Salmon Predation

Restoration Project 96320E
Annual Report

Study History: This project was initiated under Restoration project 94320E. An annual report was issued in 1994 by Willette, M., E. Debevec, Jay Johnson under the title Sound Ecosystem Assessment: Salmon Predation. The project effort was continued under Restoration Project 96320E, the subject of this annual report. In 1996, this project was merged with project 96320A. A final report will be prepared for both projects in FY98.

Abstract: This project is a component of the Sound Ecosystem Assessment (SEA) program. SEA is a multi-disciplinary effort designed to acquire an ecosystem-level understanding of the marine and freshwater processes that interact to constrain levels of pink salmon and herring production in Prince William Sound (PWS). This project collected data needed to test several hypotheses related to predator-prey interactions affecting the mortality of pink salmon (*Oncorhynchus gorbuscha*) in PWS. Our efforts in 1996 focused on estimation of predator abundance, as well as predator behavior and feeding rates in nearshore habitats. Results from the first two years of research suggest that predation in nearshore areas may have been underestimated. Studies were conducted at six nearshore sites during each of three time periods in northwest PWS during May and June. Otolith marked juvenile salmon were recovered at each site to estimate stock composition and test for differences in size and growth of wild and hatchery salmon fry. Dolly varden trout, age 1-2 pollock, Pacific cod and tomcod appeared to be the most important fish predators on juvenile salmon in nearshore habitats in 1996. However, abundances of age 3+ pollock in the upper 50 m of the water column were much lower than in previous years. Pacific herring appeared to switch to feeding on juvenile salmon after the decline of the zooplankton bloom. This behavior had not been observed in previous years. We also examined the feasibility of using fixed uplooking video cameras to study salmon fry and fish predator behavior and estimate fish abundances in nearshore habitats not easily surveyed using acoustic methods. Two cameras were operated at three sites during May and June. Results indicated a strong inshore movement of salmon fry at night. We also examined the feasibility of sonic tagging age 3+ walleye pollock to study diel feeding behavior. One fish was successfully tagged and tracked for two days. It exhibited a diel vertical migration, apparently moving inshore to feed at night and returning to the bottom during the day. A second fish was tracked for one day at which time it either regurgitated the tag or died. Net pen studies will be conducted to examine the mortality of fish tagged by various methods. Results from field studies conducted since 1994 will be used to construct the SEA pink salmon recruitment model and conduct tests of the SEA predator/prey hypotheses.

Key Words: *Clupea pallasi*, *Exxon Valdez* oil spill, food habits, *Microgadus proximus*, mortality, *Oncorhynchus gorbuscha*, Pacific herring, Pacific tomcod, pink salmon, predation, *Theragra chalcogramma*, walleye pollock.

Citation:

Willette, T.M., M.Clapsadl, P. Saddler, and M. Powell. 1996. Sound ecosystem assessment: salmon and herring integration. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 96320E), Alaska Department of Fish and Game, Cordova, Alaska.

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Executive Summary

This project is a component of the Sound Ecosystem Assessment (SEA) program. SEA is a multi-disciplinary effort to acquire an ecosystem-level understanding of the marine and freshwater processes that interact to constrain levels of pink salmon and herring production in Prince William Sound (PWS). Pink salmon runs to PWS failed in 1992 and 1993, and herring biomass dropped sharply in 1993. These run failures have drastically affected the economy of the PWS region which is largely based on the salmon and herring resources. This project collected data needed to test several hypotheses related to predator-prey interactions affecting the mortality of pink salmon (*Oncorhynchus gorbuscha*) in PWS. This project is a component of the Sound Ecosystem Assessment (SEA) program. SEA is a multi-disciplinary effort designed to acquire an ecosystem-level understanding of the marine and freshwater processes that interact to constrain levels of pink salmon and herring production in Prince William Sound (PWS). This project collected data needed to test several hypotheses related to predator-prey interactions affecting the mortality of pink salmon (*Oncorhynchus gorbuscha*) in PWS. These hypotheses include the following: (1) predation on juvenile salmon and other age-0 fish is inversely related to the abundance of large calanoid copepods, (2) predation risk is related to the daily foraging times of juvenile salmon, and (3) predation on wild salmon fry is greater when wild fry are mixed with larger hatchery-reared fish. This project was designed to achieve the following objectives: (1) estimate the juvenile salmon consumption rate of fish predators in western PWS, (2) estimate the species/size composition of fish predators, and (3) conduct preliminary tests of predator/prey hypotheses. This project also provided logistical support (personnel and equipment) to the SEA herring program.

Our efforts in 1996 focused on estimation of predator abundance, as well as predator behavior and feeding rates in nearshore habitats. Results from the first two years of research suggest that predation in nearshore areas may have been underestimated. Studies were conducted at six nearshore sites during each of three time periods in northwest PWS during May and June. Each nearshore study site consisted of an approximately 3000 m long segment of shoreline. Fish sampling was generally conducted at two stations every 3 hours throughout a 12-hour period spanning the night. Otolith marked juvenile salmon were recovered at each site to estimate stock composition and test for differences in size and growth of wild and hatchery salmon fry. Dolly varden trout, age 1-2 pollock, Pacific cod and tomcod appeared to be the most important fish predators on juvenile salmon in nearshore habitats in 1996. However, abundances of age 3+ pollock in the upper 50 m of the water column were much lower than in previous years. Pacific herring appeared to switch to feeding on juvenile salmon after the decline of the zooplankton bloom. This behavior had not been observed in previous years. We also examined the feasibility of using fixed uplooking video cameras to study salmon fry and fish predator behavior and estimate fish abundances in nearshore habitats not easily surveyed using acoustic methods. Two cameras were operated at three sites during May and June. Results indicated a strong inshore movement of salmon fry at night. We also examined the feasibility of sonic tagging age 3+ walleye pollock to study diel feeding behavior. One fish was successfully tagged and tracked for two days. It exhibited a diel vertical migration, apparently moving inshore to feed at night and returning to the bottom during the day. A second fish was tracked for one day at which time it either regurgitated the tag or died. Net pen studies will be conducted to examine the mortality of fish tagged by various methods. Results from field studies conducted since 1994 will be used to construct the SEA pink salmon recruitment model and conduct tests of the SEA predator/prey hypotheses.

Introduction:

This project is a component of the Sound Ecosystem Assessment (SEA) program. SEA is a multi-disciplinary effort to acquire an ecosystem-level understanding of the marine and freshwater processes that interact to constrain levels of pink salmon and herring production in Prince William Sound (PWS). Pink salmon runs to PWS failed in 1992 and 1993, and herring biomass dropped sharply in 1993. These run failures have drastically affected the economy of the PWS region which is largely based on the salmon and herring resources. In 1992, pink salmon returns were low in Kodiak, Lower Cook Inlet, and PWS, but pink salmon returns in 1993 were low only in PWS. Low returns of hatchery-produced salmon in both years indicates that the failures were likely caused by processes occurring during the juvenile lifestage. Damage assessment studies on juvenile pink salmon in PWS have demonstrated that growth during the juvenile lifestage is related to survival to adult (Willette et al. 1994). Growth rates of juvenile salmon were estimated in 1991 and 1992 after the fish were released from hatcheries. Juvenile growth and ocean temperatures were low in PWS during the early marine period in 1991. However, in 1992 juvenile growth and ocean temperatures were near average; although, zooplankton abundance was very low. The growth of juvenile fishes is believed to be related to survival, because slow-growing individuals are vulnerable to predators for a longer time (Parker 1971; Healey 1982; West and Larkin 1987). The growth and mortality rates of juvenile salmon released into PWS in 1992 suggests that a change in predation rate may have contributed to the observed run failures.

During phase I of SEA, pink salmon research focused on identification of the principal species preying on pink salmon and the processes affecting rates of predation. Phase I results indicate that predation by pelagic pollock (age 3+) and seabirds may account for only 15-25% of probable losses of juvenile salmon (Willette et al. 1995b). However, results from an experimental release of large juvenile pink salmon from Wally H. Noerenberg Hatchery suggests that high mortality likely occurred among an early release of small juvenile pink salmon during May, 1994 (Willette et al. 1995a). Age 3+ pollock and squid were the most abundant species in net catches during May, 1994 (Willette et al. 1994b). The following three hypotheses have been developed from our phase I results: (1) predation by age 3+ pollock in offshore habitats was underestimated in 1994, (2) age 3+ pollock that target juvenile salmon in nearshore habitats account for the majority of the predation losses and these predators were not sampled adequately in 1994, (3) other nearshore fish predators not sampled in 1994 account for the majority of the predation losses, and (4) high condition of the late release group resulted in differential mortality between early and late releases after early June.

Several factors may have resulted in underestimation of juvenile salmon consumption by pelagic age 3+ pollock. Pollock biomass may have been underestimated due to vessel avoidance, occurrence of pollock in the surface layer (0-5m) that was not surveyed, and occurrence of pollock below 125 m depth that was not surveyed. These questions are being addressed by project (96320N). In addition, pollock food consumption may have been underestimated if the fish are glut feeding in the surface layer then migrating to depth to rest. This project conducted studies in FY96 to determine the feasibility of sonic tagging pollock as a means of evaluating their vertical migratory behavior. Sonic telemetry has been used successfully to investigate the daily activity and movement patterns of juvenile Atlantic cod (Clark and Green 1990). During summer, these fish migrated between a warm surface layer to feed at night and a deep cold layer to rest during the day.

Much of our effort in FY96 focused on developing techniques for sampling predators in nearshore habitats that may not have been adequately sampled in previous years. This involved studies to determine the feasibility of using fixed-uplooking video cameras to estimate relative abundance and observe the behavior of juvenile salmon and their predators. This technology has been used successfully to estimate fish abundance and size (Irvine et al. 1991, DeMartini and Ellis 1995), identify fish species (DeMartini and Ellis 1995), and evaluate activity and feeding patterns (Collins et al. 1991). Night observations have been made using infrared lighting which cannot be detected by fish and invertebrates (Collins et al. 1991). Project 96320N examined the feasibility of using side-looking acoustics to estimate the relative abundance of predators in nearshore habitats. Variable mesh gillnets were used to obtain fish samples in nearshore habitats.

This project also collected samples to evaluate whether condition-dependent predation may lead to differential mortality of juveniles rearing in nearshore habitats. These samples are being analyzed by project 96320U. If condition-dependent predation occurs the presence of large numbers of enhanced salmon may adversely affect wild salmon during the early marine period. An inverse relationship between whole body energy content and fry density at three sites sampled in 1995 suggests that growth may be density-dependent (Paul and Willette 1996). All juvenile pink salmon released from PWS hatcheries will be otolith thermal marked in FY96 providing an essential tool for these investigations. This component of the pink salmon recruitment model will provide a useful tool to improve management of the Sound's wild and enhanced salmon stocks.

Objectives:

1. Refine estimates of juvenile salmon consumption by pelagic pollock.

2. Develop techniques for sampling coupled predators in the nearshore zone.

3. Collect samples needed to evaluate condition-dependent predation among wild and enhanced salmon.

Methods:

Objective 1:

A feasibility study was conducted to determine if the diel behaviour of pelagic pollock can be revealed by application of sonic tags. Two pollock were tagged and tracked for several days in July, 1996. The fish were caught with a hook and line, immediately placed in a holding tank, and observed for several minutes. A Vemco ™ V16 depth sensitive sonic tag was inserted into each fishes stomach via the esophagus, and each fish was observed for several minutes before release. An approximately 7 m vessel was used to track the fish. Depth and position readings were recorded periodically using the Vemco ™ V60 directional receiver. A global positioning system (GPS) was used to obtain position readings.

Objective 2:

Investigations of predator/prey coupling in the nearshore zone were initiated in FY96 as a feasibility study. Seven sites were sampled during three 9-day sampling trips in May and June (Figure 1, Table 1). Acoustic and net sampling were conducted every three hours from approximately 9 pm to 9 am each day. Project 96320N conducted acoustic surveys utilizing side-looking (420kHz) and downlooking echosounders (70kHz). Acoustic data was collected on one alongshore transect on each three hour cycle to estimate the abundance of predators and juvenile salmon in the nearshore zone. Acoustic data was also collected along five transects perpendicular to shore to relate nearshore and offshore predator abundances. An approximately 25 m trawl vessel sampled fish in offshore areas using a 40 m x 28 m mid-water wing trawl equipped with a net sounder. The cod end of the trawl was lined with 1.5 cm stretch-mesh web to retain small specimens. Each tow was made approximately 1 km offshore parallel to the shore in the upper 40 m of the water column. A purse seine vessel sampled fish in the upper 20 m of the water column in nearshore areas with bottom depths greater than 20 m. Each seiner fished a small-mesh purse seine (250 m x 30 m, 1.5 cm stretch mesh web) holding a hook with the seine open in the direction of the prevailing current for 20 minutes. In nearshore areas shallower than 20 m, variable mesh sinking and floating gill nets (150 m, 1.5 cm to 10 cm stretch mesh) were used to sample fish predators. These gear were deployed from an approximately 6 m aluminum skiff. Each gill net was attached to the beach and set perpendicular to shore. A hotel boat provided room and board for field sampling crews. All sample processing was conducted on board the hotel boat by a single processing crew.

Processing of fish samples from each net set occurred in two stages following procedures outlined by Livingston (1989) and Dwyer et al. (1987). If less than 300 fish were captured, all fish in the catch were enumerated by species. If a large number of fish were caught, species composition was estimated from a random sample of 300 individuals. Fish greater than 150 mm FL were processed differently than those less than 150 mm FL. Fish less than 150 mm FL were identified to the lowest possible taxonomic level. A sample of 30 individuals from each species was preserved in 10% buffered formaldehyde for later analysis of stomach contents under project 96163 (Forage Fish Influence on Recovery of Injured Species). The purpose of these studies is to examine diet overlap among forage fish.

For large fish (greater than 150 mm FL), a randomly selected sample (n=60) from each net set and each species was taken. The stomach was excised, placed in a cloth bag, and preserved in 10% buffered formaldehyde for later analysis of stomach contents. Fish showing evidence of regurgitation were not included in the sample. Fork length was measured to the nearest millimeter. Weight was measured to the nearest gram when conditions permitted. Sex and sexual maturity was recorded. Later in the laboratory, total stomach contents wet weight was measured to the nearest .01 gram. Invertebrate prey in the gut were generally identified to the family level. Fish in the gut were identified to the lowest possible taxonomic level, enumerated, and measured to the nearest millimeter. The proportion of total stomach contents in each taxonomic group was visually estimated. Stomach fullness was expressed as a proportion of fish body weight. In cases where distinct size classes occurred within species, stomach contents analysis was conducted for each size class as described above. Size related shifts in diet toward piscivory have been noted in several species of gadoid fishes, including Pacific cod (*Gadus macrocephalus*) (Livingston 1989), walleye pollock (*Theragra chalgogramma*) (Dwyer et al. 1987), Atlantic cod (*Gadus morhua*) (Daan 1973), Pacific whiting (*Merluccius productus*) (Livingston 1983), and silver hake (*Merluccius bilinearis*) (Langton 1982).

An analysis of variance was conducted to test for differences in the mean percent of predator diets comprised of juvenile salmon among three time periods in May and June. Data were arcsin square root transformed prior to conducting the test (Zar 1984). Several species of nearshore benthic fish (*Hemilepidotus hemilepidotus, Myxocephalus verrucosus, Hexagrammos decagrammus, Hexagrammos octogrammus, Blepsias bilobus*) were pooled in the analysis All specimens were included in the analysis to examine changes in diet for the population within each taxonomic group as a whole. An analysis of variance was conducted to test for changes in the natural-logarithm transformed mean catch per net set of juvenile salmon predators by date. Trawl data was expressed as natural-logarithm of catch per hour of tow. Analysis of variance was also conducted to test for differences in the mean proportion of the diet comprised of various taxonomic groups by date. Data were arcsin-square root transformed prior to conducting the test.

A study was conducted to determine the feasibility of using fixed-uplooking video cameras to estimate the abundance and feeding behavior of fry and predators in nearshore nursery habitats where side-scan acoustics are not feasible due to reflection from the bottom and sea surface. Two cameras were installed at locations where fry continuously reside due to current structures. The study sites were at Tipping point on Northwest Perry Island and at Fox Farm Harbor on the west end of Elrington Island. These sites differed in that Tipping Point is exposed in Perry Passage, while the Fox Farm Harbor site is located in a protected bay.

Underwater video cameras were held in an uplooking position approximately 2.5 m from the waters surface. This position was maintained by attaching the camera body to foam flotation. The foam flotation was in turn attached to a line running down through a pulley anchored to the bottom and back up to a fixed object on shore. Camera depth was adjusted by pulling in or letting out line as tides rose and fell. These adjustments were made every two hours when tapes were changed or more often when tides were changing rapidly. After the field season, all tapes were reviewed manually, potential predators enumerated, and the time in field of view recorded for each group of potential predators. The approximate density of predators (no. m^{-3}) was calculated from the product of abundance and time in view (no.· sec) divided by the product of the approximate volume of water in view and the total time the cameras were in operation ($m^3 \cdot$ sec). The occurrence of juvenile salmon in the field of view was enumerated for each hour of the day over all observations.

Objective 3:

Analyses of condition-dependent predation among wild and enhanced salmon was conducted at sites where sufficient numbers of juvenile salmon could be obtained from predator stomachs. All samples were taken from the stomachs of age 1-2 pollock, Pacific cod, tomcod or dolly varden trout. Processing of predator stomach samples was generally conducted as described in objective 2; however, any juvenile pink salmon with intact skin found in the stomachs were washed in freshwater and immediately frozen for later analysis of energetic content (Project 96320U). Each fry specimen was labelled to allow sample tracking in relation to the predator.

At each site, samples (n=20) of juvenile salmon were also obtained with a small mesh purse seine (10 m x 40 m, 2 mm mesh) deployed from an approximately 4 m skiff every three hours. All samples were frozen as soon as possible after collection. Several of these samples were pooled from each site for analysis of energetic content. In the laboratory, the otolith was extracted from each juvenile pink salmon, length and wet weight measured, and the whole body and head placed in a 20 ml vial and frozen for later analysis of energetic content. For samples not analyzed for energetic content, the otolith was extracted and length, wet weight and dry weight measured Otolith thermal marks will be used to identify the wild or hatchery-origin of these fish.

At each site, samples (n=20) of juvenile salmon were also for stomach contents analysis. All samples were preserved in 10% buffered formaldehyde solution. Later in the laboratory, length was measured to the nearest millimeter, wet weight to the nearest .01 g and stomach contents weight to the nearest milligram. The proportion of total stomach contents weight in three taxonomic groups (large calanoid copepod (>2.5 mm), small calanoid copepod (<2.5 mm), and 'other' prey) was visually estimated . At each site, CTD and zooplankton samples (20m vertical tow, 243 um mesh) were collected in association with each fry sample to evaluate environmental conditions at each site. Zooplankton samples were subsampled with a stimpel pipette and zooplankton enumerated into the following groups: large calanoid copepod (>2.5

mm), small calanoid copepod (<2.5 mm), and 'other' zooplankters.

Results:

Objective 1:

The first pollock was tagged on July 11 at 1715 hrs approximately 5 km from Cordova near Salmo Point. After release, the fish moved towards bottom where it remained until approximately 1845 hrs. With fading light, at 1945 hrs the pollock began a gradual ascent at the same time moving in an arc that took it closer to shore (Figure 2). By 2230 hrs the fish had moved very close to shore (less than 50 meters) and was now only 7 meters deep. Numerous small fish were observed jumping at the surface in the area of the tagged fish. The tagged fish moved in a westerly direction, remaining nearshore until approximately 0345 hrs on July 12. As light levels began to increase, the pollock began to descend, move away from shore and back towards the original capture point. Between 0420-0830 hrs the pollock had made vertical movements ranging its depth from 9.5 to 60 meters while moving east toward Nelson Bay. At one point, the sonic tag indicated a depth of 36 meters, while at the same time hydroacoustic equipment showed a group of targets at the same depth indicating that the tagged fish was moving with a group of other fish. By 1100 hrs on July 12, the tagged fish had slowly moved into Nelson Bay maintaining a depth of about 45 m. The fish appeared to be remaining within approximately 10 meters of bottom. Throughout July 13 the pollock moved sporadically about within Nelson Bay. Most of the time it remained within a few meters of the bottom. At 0100 hrs on July 14, the tagged fish made a short movement out to slightly deeper water. This was the last recorded movement.

The second pollock was tagged on July 18 at 1840 hrs approximately 5 km from Cordova near Salmo Point. The fish returned to the bottom after release. At about 2100 hrs, it moved up in the water column from 74 m to 16 m. By 0100 hrs it returned to the bottom and by 0400 hrs it stopped moving. It is not clear whether the tag was regurgitated or the fish died.

Objective 2:

Species composition and mean catch per net set of fishes in variable-mesh gillnets deployed in nearshore habitats were similar between 1995 and 1996 (Table 2). Various sculpins, gunnels, greenlings, and rockfish, as well as, Pacific cod, tomcod and pollock occurred commonly in the catches. Herring appeared to be more abundant in nearshore habitats in 1996 compared to 1995 (Table 2). Catches of age 3+ pollock in the mid-water trawl declined during a period of high tidal range (julian date 140) then increased again (Figure 3a). Mean catch per net set of herring, age 1-2 pollock and age-0 fishes in small-mesh purse seines increased from May to June (Figure 3).

The mean percent of the diet comprised of juvenile salmon was greatest for dolly varden trout followed by age 1-2 tomcod, Pacific cod and pollock (Table 3). The mean percent of the diet comprised of juvenile salmon increased significantly for herring ($P=.043$) and benthic fishes ($P=.057$) in early June (Table 3). During early May, large calanoid copepods comprised approximately 30% and less than 20% of the diets of age 3+ and age 1-2 pollock, respectively (Figure 4). The mean percent of the diet comprised of large calanoid copepods ranged from 20-60% for herring during this same time period (Figure 4). Euphausiids and amphipods comprised the majority of the diets of age 3+ pollock during late May and early June (Figure 4). Consumption of fish increased among age 1-2 pollock in early June (Figure 4b).

Video cameras were successfully operated in nearshore habitats for approximately 59 hours at Tipping Point and 32 hours at Fox Farm Harbor. Approximately 343 potential predators were seen on three occasions mostly after 2300 hrs. Species identification was difficult due to backlighting, but most of the fish appeared to be herring or juvenile gadids. The approximate density of potential predators calculated from these observations was .0015 m^{-3}. The frequency of occurrence of juvenile salmon in the field of view was relatively low from 0500 hrs to 1200 hrs increasing until nightfall at approximately 2300 hrs (Figure 5).

Objective 3:

Sixty-three juvenile pink salmon were obtained in relatively intact condition from predator stomachs at 7 sites in northwest PWS. An additional 100 juvenile pink salmon were randomly selected from samples ($n=20$) taken with a small mesh purse seine at these sites. All samples were frozen and sent to Seward for analysis under project 96320U. No data is yet available from analyses of juvenile salmon energy content or origin using otolith thermal marks.

Total zooplankton biomass in nearshore habitats ranged from approximately 0.2-0.7 g m^{-3} (Figure 6). The abundance of large calanoid copepods declined rapidly in early May while abundances of 'other' zooplankters increased from May to June (Figure 6). Juvenile salmon increased in size from approximately 35 mm and 0.3 g in early May to approximately 57 mm and 1.5 g in early June (Figure 7). Juvenile salmon stomach fullness generally declined from early May to June (Figure 8a). The percent of the diet comprised of large calanoid copepods declined during May while consumption of 'other' zooplankters increased from May to June (Figure 8).

Discussion:

Sampling with fixed gear in nearshore habitats revealed an assemblage of fish species that may be important predators on juvenile salmon. The species composition of this assemblage was generally similar between 1995 and 1996 (Willette et al. 1996b). Fixed gear sampling in 1996 consisted of sinking and floating variable-mesh gillnets deployed from the shore in nearshore habitats. These gear appeared to be very efficient for capturing potential predators in shallow nearshore habitats.

In general, consumption of juvenile salmon in nearshore habitats appeared to be greater in 1996 compared with 1995. As in previous years, dolly varden trout (*Salvelinus malma*) appeared to be an important predator on juvenile salmon in these areas (Willette et al. 1995b, 1996b). As in 1995 (Willette et al. 1996b), the percent of the diet comprised of juvenile salmon was also relatively high for age 1-2 Pacific cod (*Gadus macrocephalus*), Pacific tomcod (*Microgadus proximus*) and pollock (Table 3). However, age 3+ pollock, herring, and adult pink salmon appeared to be important predators on juvenile salmon in 1994 (Willette et al. 1995b). Bakshtanskiy (1964) concluded that juvenile pollack (*Pollachius virens*) and cod (*Melanogrammus morhua morhua*) were important predators on juvenile pink and chum salmon in the White Sea. He observed that juvenile pink and chum salmon were at times driven from nearshore nursery habitats by large schools of juvenile pollack and cod. Consumption of juvenile salmon by nearshore benthic fish and herring appeared to increase in early June (Table 3). We observed schools of herring targeting on juvenile salmon during night surveys of some study sites in early June. Bakshtanskiy (1964, 1965) concluded that predation by herring largely determined survival of juvenile pink and chum salmon in the Barents Sea and White Sea. Predation by herring and pollock on juvenile salmon has also been observed in Alaska (Thorsteinson 1962, Armstrong and Winslow 1968).

Mean catch per net set was relatively low for age 3+ pollock sampled in the upper 50 m of the water column in 1996 compared with the previous two years. In early May, the abundance of large calanoid copepods in vertical net tows was relatively high, yet the percent of pollock diets comprised of large calanoid copepods was only about 30% (Figure 4). In 1994, consumption of large copepods and pollock catches in the 0-50 m layer declined during June (Willette et al. 1995b). The decline in consumption of large copepods in June coincided with a decline in the biomass of late-stage *Neocalanus spp.* in the upper 50 m of the water column (Cooney 1995). It appears that age 3+ pollock filter feed on large calanoid copepods (Yoshida 1994). Shifts between particulate and filter feeding modes are likely related to the relative profitability of each strategy, which is largely determined by prey size and density (Crowder 1985). Pollock likely filter feed in relatively high density layers of large calanoid copepods. Perhaps the density of copepods in these layers was largely below the threshold at which filter feeding becomes profitable for age 3+ pollock. Further, analyses of these data are needed to explore the possible causes for these observations.

Mean catch per net set of herring and age 1-2 pollock tended to increase from May to June in 1996. Rogers et al. (1986) noted a substantial seasonal increase in fish species diversity and density in Prince William Sound. In winter, fish distributions shifted further offshore and deeper in the water column (Rogers et al. 1986). Seasonal migrations of fish into deeper water in winter and shallow water in summer are well known (Trout 1957, Alverson 1960, Jean 1964, Heeseen 1983). These seasonal shifts in distribution may be related to temperature, light or food abundance (Laevastu and Hela 1970). Seasonal changes in the vertical distribution and activity patterns of cod have been related to seasonal stratification of the water column (Clark and Green 1990). In the present study, a more detailed analysis of fish distribution and water column structure is needed.

Feasibility studies on sonic tagging of age 3+ pollock suggest that this technique may be used effectively for behavioral studies. However, few conclusions should be drawn about pollock behavior from this one experiment because of questions about tag effect. In the present study, tags were inserted into the fishes stomach. This method of tagging may have caused mortality or tag regurgitation. In FY97, net pen studies will be conducted prior to the field season to evaluate mortality and behavioral effects associated with placement of the tag in the stomach, external attachment of the tag and surgical placement in the body cavity. Results from this work should enable us to minimize mortality and behavioral effects of tagging in future field studies.

Feasibility studies on the use of underwater video cameras to estimate relative abundance of juvenile salmon and their predators provided mixed results. The technique provided useful information about diel changes in the relative abundance of juvenile salmon in nearshore habitats. Video observations clearly indicated that juvenile salmon moved inshore at night (Figure 5). Results from shoreline surveys conducted every three hours throughout the night indicated the same behavior. It seems likely that this behavior is related to avoidance of predators in offshore waters. Fixed-uplooking video cameras may not be a practical method for estimating the relative abundance of potential predators. In the present study, potential predators were within the field of view of the cameras only .01% of the time. In addition, species were difficult to identify due to back lighting of targets. In FY97, we will examine the feasibility of towing underwater cameras along fixed transects to examine relative abundance of potential predators and predator behavior.

Conclusions:

1. Dolly varden trout, age 1-2 pollock, Pacific cod, and tomcod appeared to be important predators on juvenile salmon in nearshore habitats in 1996.

2. Abundance of age 3+ pollock in the upper 50 m of the water column was relatively low in 1996 compared with the previous two years, and large calanoid copepods were not the most important component of the diet of age 3+ pollock during the spring bloom period.

3. Sonic tagging of age 3+ pollock appears to be an effective method for studying the behavior of these fish, but further evaluation of tagging methods is required.

4. Juvenile pink salmon migrated inshore at night apparently to avoid predators in offshore waters of the passages.

Acknowledgements:

We would like to thank the staff of the Alaska Department of Fish and Game, Prince William Sound Science Center, and University of Alaska Fairbanks who endured difficult field conditions to obtain the samples needed for this study. The staff of the Prince William Sound Aquaculture Corporation was always very helpful when we needed logistical support in the western sound. This project would not have been possible without the charter vessel captains and crew who provided their equipment, assistance, and expertise.

Literature Cited:

Alverson, D.L. 1960. A study of annual and seasonal bathymetric catch patterns for commercially important groundfishes of the Pacific Northwest coast of North America. Bull. Pacific Mar. Fish. Comm. Portland. 4, 66p.

Armstrong, R.H. and P.C. Winslow. 1968. An incidence of walleye pollock feeding on young salmon. Trans. Amer. Fish. Soc. 97(2): 202-203.

Bakshtanskiy, E.L. 1964. Effect of predators on the young of *Oncorhynchus gorbuscha* and *Oncorhynchus keta* in the White and Barents Seas. Voprosy Ikhtiologii 4(1): 136-141.

Bakshtanskiy, E.L. 1965. The impact of the environmental factors on survival of the far eastern young salmon during the acclimatization of the latter in the northwest part of the USSR. ICNAF Spec. Publ. 6: 477-479.

Clark, D.S. and J.M. Green. 1990. Activity and movement patterns of juvenile Atlantic cod, *Gadus morhua*, in Conception Bay, Newfoundland, as determined by sonic telemetry. Can. J. Zool. 68: 1434-1442.

Collins, N.C., S.G. Hinch, and K.A. Baia. 1991. Non-intrusive time-lapse video monitoring of shallow aquatic environments. Can. Tech. Rep. Fish. Aquat. Sci. No. 1821.

Cooney, R.T. 1995. The role of zooplankton in the Prince William Sound Ecosystem. In Sound Ecosystem Assessment 1994 Final Report to the *Exxon Valdez* Oil Spill Trustee Council, 13p.

Crowder, L.B. 1985. Optimal foraging and feeding mode shifts in fishes. Environ. Biol. Fish. 12(1): 57-62.

Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Neth. J. Sea Res. 6: 479-517.

DeMartini, E.E. and D.M. Ellis. 1995. Evaluation of a video camera technique for indexing abundances of juvenile pink snapper, (*Pristipomoides filamentosus*), and other Hawaiian insular shelf fishes. Fish. Bull. 93(1): 67.

Dwyer, D.A., K.M. Bailey, P.A. Livingston. 1987. Feeding habits and daily ration of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea, with special reference to cannibalism. Can. J. Fish. Aquat. Sci. 44: 1972-1984.

Healey, M.C. 1982. Timing and relative intensity of size-selective mortality of juvenile chum salmon during early sea life. Can. J. Fish. Aquat. Sci. 39: 952-957.

Heessen, H.J.L. 1983. Distribution and abundance of young cod and whiting in the southeastern North Sea in the period 1980-1982. Int. Coun. Expl. Sea., C.M. 1983/G: 30.

Irvine, J.R., B.R. Ward and P.A. Teti. 1991. Evaluation of a method to count and measure live salmonids in the field with a video camera and a computer. N. Amer. J. Fish. Mgmt. 11(1).

Jean, Y. 1964. Seasonal distribution of cod (*Gadus morhua L.*) along the Canadian Atlantic coast in relation to water temperature. J. Fish. Res. Board Can. 21: 429-460.

Laevastu, T. and I. Hela. 1970. Fisheries Oceanography. Fishing News Ltd., London, 238p.

Langton, R.W. 1982. Diet overlap between Atlantic cod, *Gadus morhua*, silver hake, *Merluccius bilinearis*, and fifteen other northwest Atlantic finfish. Fish. Bull. 80: 745-759.

Livingston, P.A. 1983. Food habits of Pacific whiting, *Merluccius productus*, off the west coast of North America, 1967 and 1980. Fish. Bull. 81: 629-636.

Livingston, P.A. 1989. Interannual trends in Pacific Cod, *Gadus macrocephalus*, predation on three commercially important crab species in the eastern Bering Sea. Fish. bull. 87: 807-827.

Parker, R.R. 1971. Size-selective predation among juvenile salmonid fishes in a British Columbia inlet. J. Fish. Res. Board Can. 28: 1503-1510.

Paul, A.J. and T.M. Willette. 1996. Geographical variation in somatic energy content of migrating pink salmon fry from Prince William Sound: a tool to measure nutritional status. *In* Proceedings of the Wakefield Forage Fish Symposium, Alaska Sea Grant Program, in press.

Rogers, D.E., B.J. Rogers and R.J. Rosenthal. 1986. The nearshore fish. pp. 399-416 *In* D.W. Hood and S.T. Zimmerman (eds.), The Gulf of Alaska: physical environment and biological resources. NOAA, Anchorage, Alaska.

Thorsteinson, F.V. 1962. Herring predation on pink salmon fry in a southeastern Alaska estuary. Trans. Am. Fish. Soc. 91(3): 321-323.

Trout, G.C. 1957. The bear Island cod: migrations and movements. Fish. Invest. London. Ser. 2(21): 51p.

West, C.J. and P.A. Larkin. 1987. Evidence of size-selective mortality of juvenile sockeye salmon (*Oncorhynchus nerka*) in Babine Lake, British Columbia. Can. J. Fish. Aquat. Sci. 44: 712-721.

Willette, T.M., G. Carpenter, P. Shields, S. Carlson. 1994. Early marine salmon injury assessment in Prince William Sound. *Exxon Valdez* Natural Resource Damage Assessment Program, Final Report, Alaska Department of Fish and Game, 64p.

Willette, T.M., G. Carpenter, E. Debevec. 1995a. Sound ecosystem assessment: salmon growth and mortality. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 94320A), Alaska Department of Fish and Game, Anchorage, Alaska.

Willette, T.M., E. Debevec. J. Johnson. 1995b. Sound ecosystem assessment: salmon predation. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 94320E), Alaska Department of Fish and Game, Anchorage, Alaska.

Willette, T.M., G. Carpenter, P. Saddler, M. Powell. 1996a. Sound ecosystem assessment: salmon growth and mortality. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 95320A), Alaska Department of Fish and Game, Anchorage, Alaska.

Willette, T.M., E. Debevec. J. Johnson. 1996b. Sound ecosystem assessment: salmon predation. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 95320E), Alaska Department of Fish and Game, Anchorage, Alaska.

Yoshida, H. 1994. Food and feeding habits of pelagic walleye pollock in the central Bering Sea in summer, 1976-1980. Sci. Rep. Hokkaido Fish. Exp. Stn. 45: 1-35.

Zar, J.H. 1984. Biostatistical Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Table 1: Dates and sites where sampling was conducted in nearshore habitats in northwestern Prince William Sound. See figure 1 for locations of sampling areas.

Year	Area	Dates Sampled
1995	501	May 3, May 11, May 30
	502	May 17, June 5
	504	June 9
	505	June 11
	506	May 5, May 15, June 8
	509	June 13
	525	May 8, May 13, June 3
	526	May 9
1996	501	May 3, May 6, June 5
	502	May 4, May 7, May 24, June 1
	525	May 5, May 8, May 19, May 23, June 2, June 8
	504	May 25, June 6
	506	May 20, June 7
	586	May 21, June 3
	587	May 22, June 4

Table 2: Mean catch per net set for various fish taxonomic groups in nearshore habitats in western Prince William Sound during May and June .

	1995			1996		
Species	n	Mean	SE	n	Mean	SE
Sculpins, gunnels, etc.	165	1.4	0.06	86	1.6	0.11
Pacific cod, tomcod	123	1.8	0.15	122	3.4	0.35
Flatfish	16	1.1	0.10	8	1.0	0.00
Greenlings	247	1.9	0.08	155	2.6	0.17
Rockfish	147	3.4	0.42			0.83
Herring	23	6.4	3.52	130	87.8	36.90
Pollock	77	14.4	5.58	63	5.7	1.44
Adult Salmon	9	1.5	0.29	30	2.5	0.58
Sandlance, capelin	9	6.6	3.21	1	1.0	-
Dolly Varden	43	1.9	0.25	48	4.2	0.76
Squid	1	1.0	-	15	1.6	0.36

Table 3: Mean percent of diet comprised of juvenile salmon for several fish taxonomic groups during three time periods in northwest Prince William Sound, 1996. Benthic fishes include various species of sculpin and greenlings. Statistical test for changes in the mean diet percentage comprised of juvenile salmon among time periods. All specimens included in the analysis.

Date	Pacific Herring	Pacific Cod	Pacific Tomcod	Pollock (age 1-2)	Pollock (age 3+)	Dolly Varden	Benthic Fishes
5/3 - 5/9	.19	14.68	25.00	20.33	1.21	-	.39
5/19-5/26	.60	15.16	25.54	11.56	1.61	65.69	0
6/1 - 6/9	8.31	24.12	14.52	9.42	1.50	28.59	5.70
P-value	.043	.634	.638	.556	.937	.027	.057

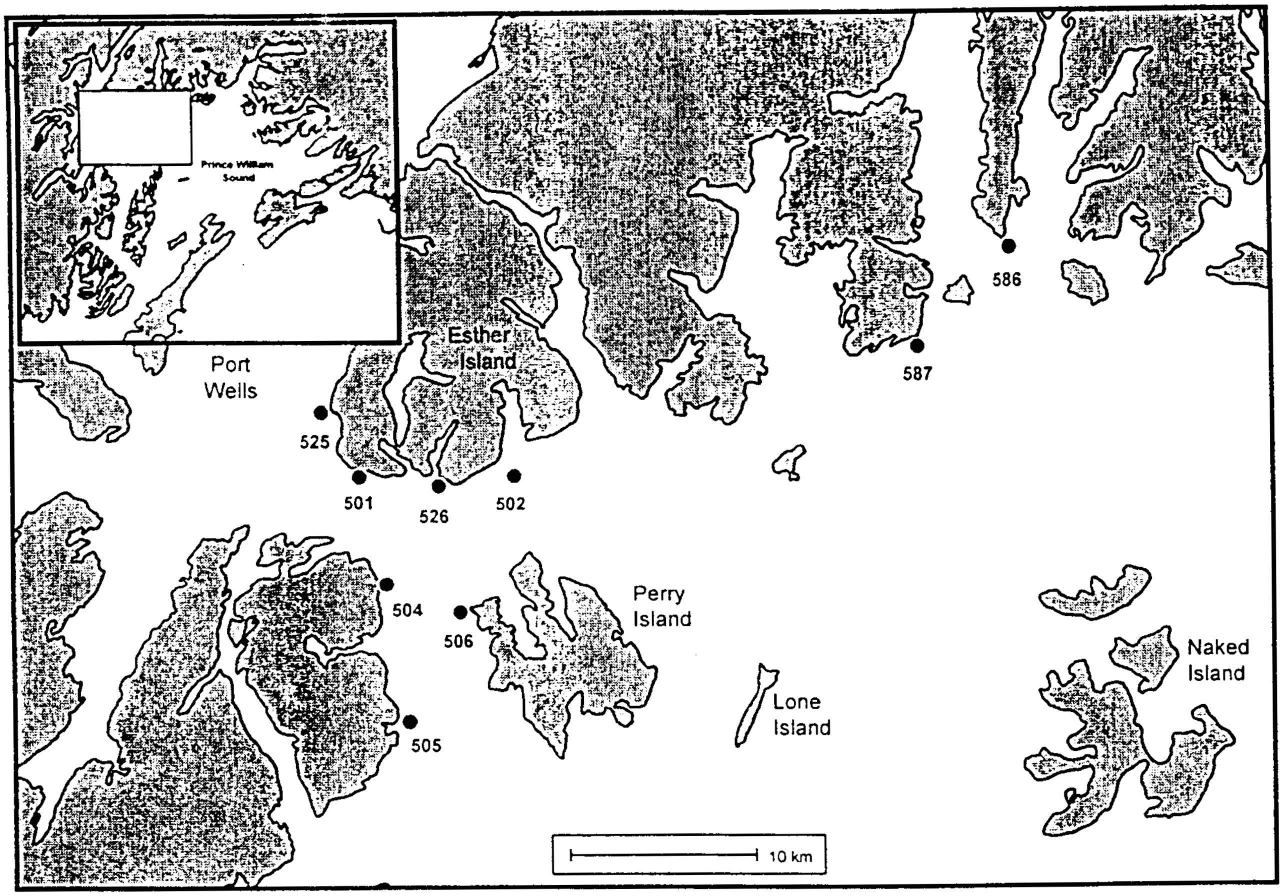

Figure 1: Study sites sampled in northwestern in Prince William Sound, 1996.

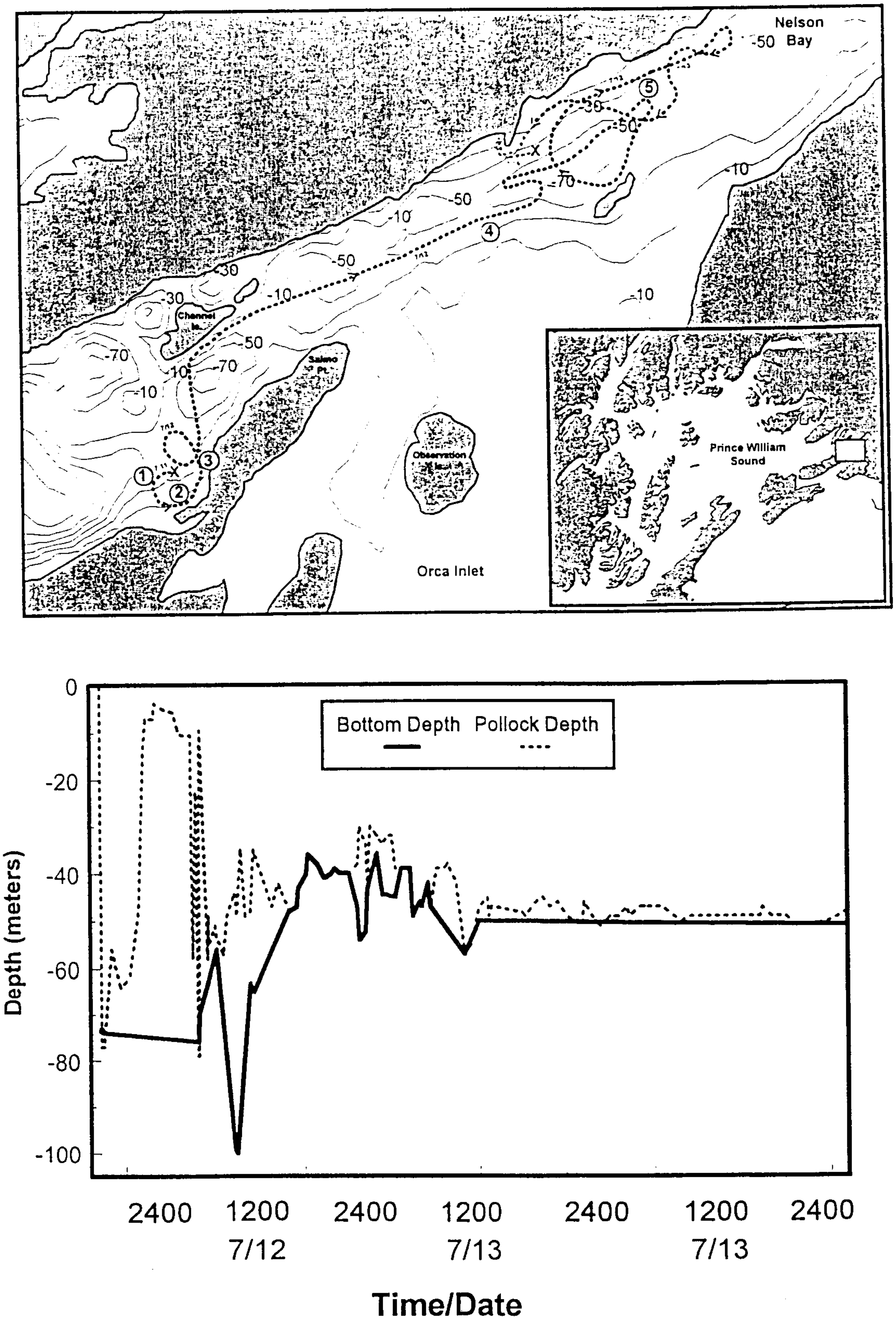

Figure 2: (a) Horizontal and (b) vertical movements of age 3+ walleye pollock sonic tagged in July, 1996.

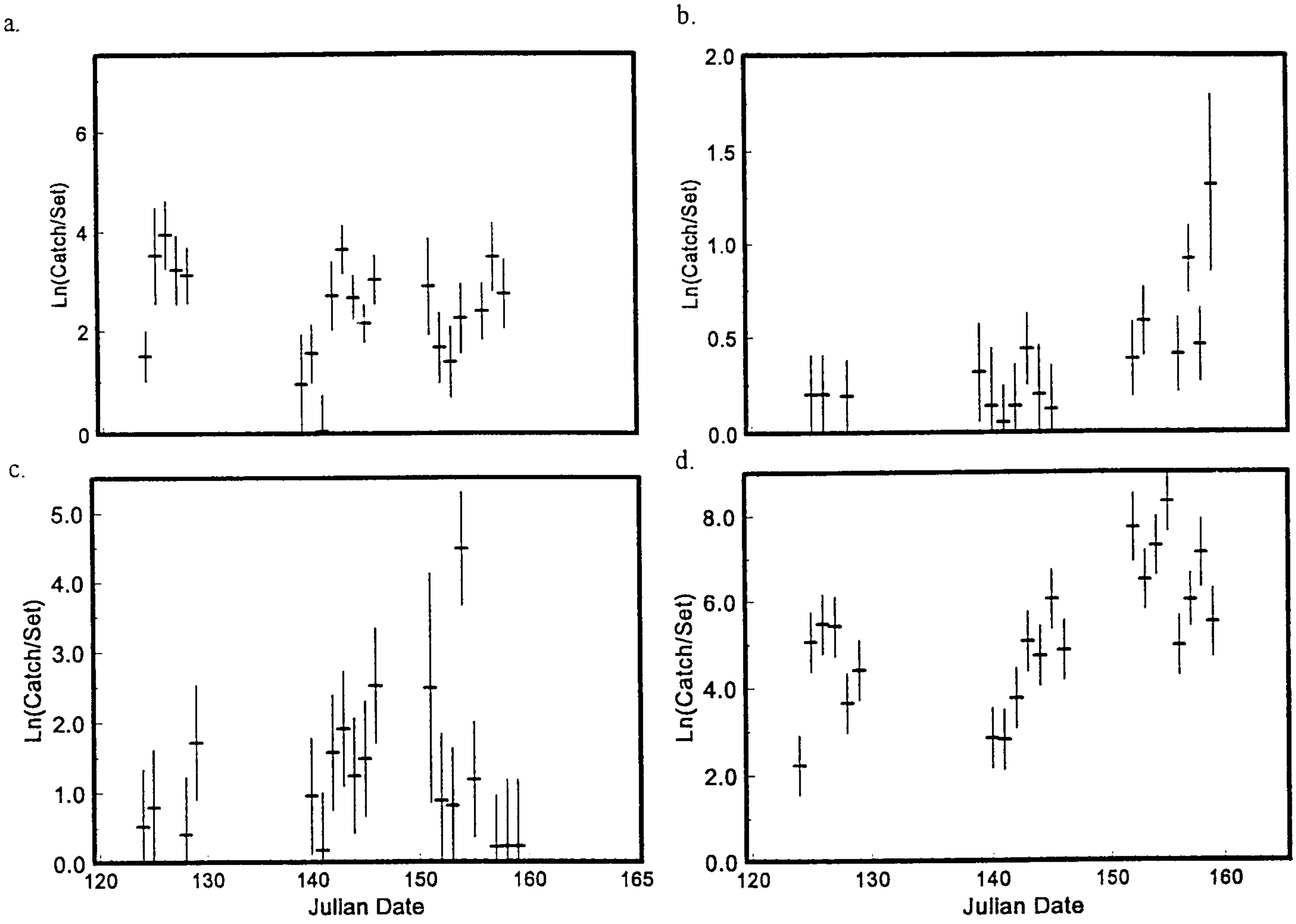

Figure 3: Mean catch per net set for (a) age 3+ pollock, (b) age 1-2 pollock, (c) herring and (d) all age-0 fishes in northwestern Prince William Sound, May-June 1996.

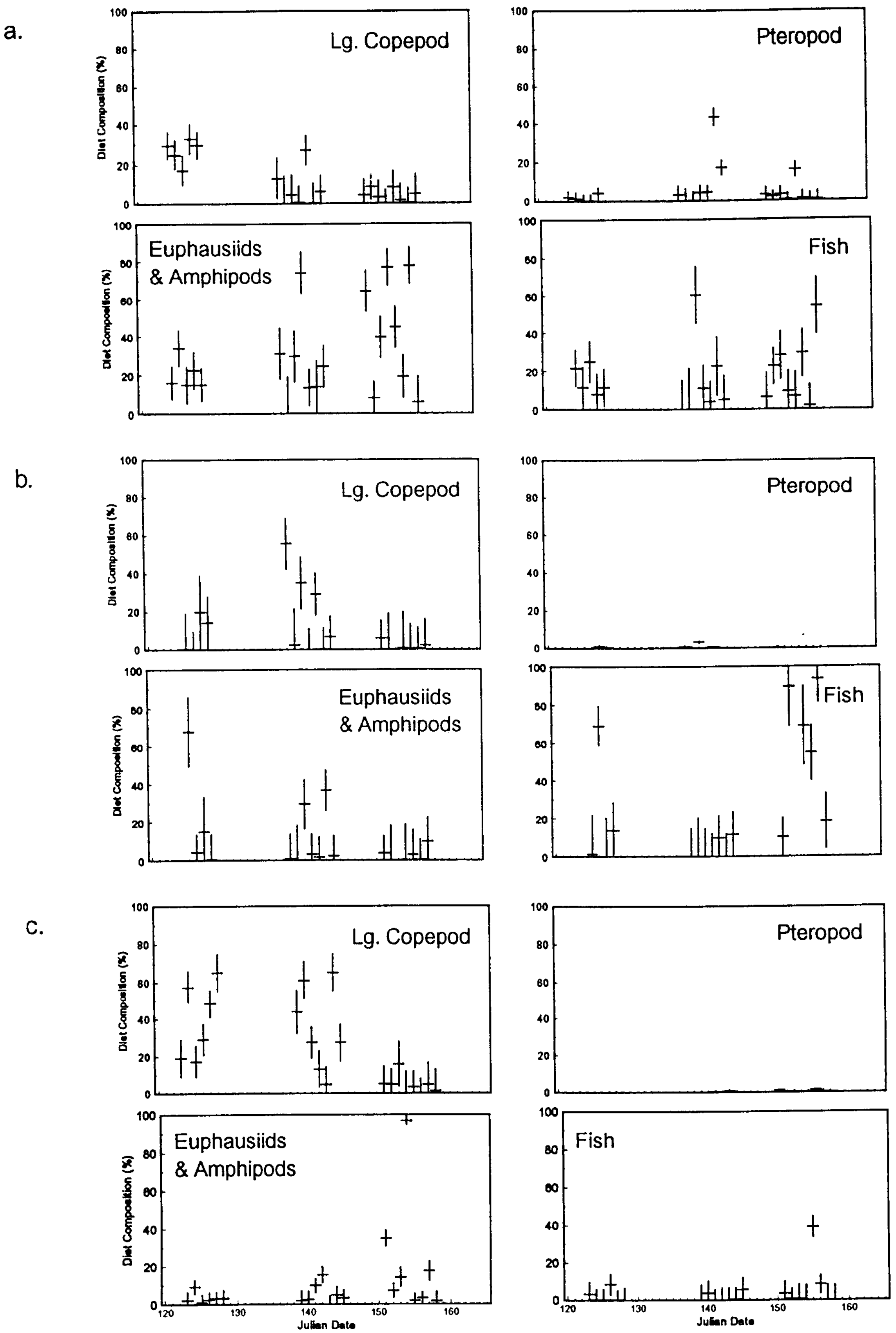

Figure 4: Diet composition of (a) age 3+ pollock, (b) age 1-2 pollock, (c) herring in northwestern Prince William Sound, May-June 1996.

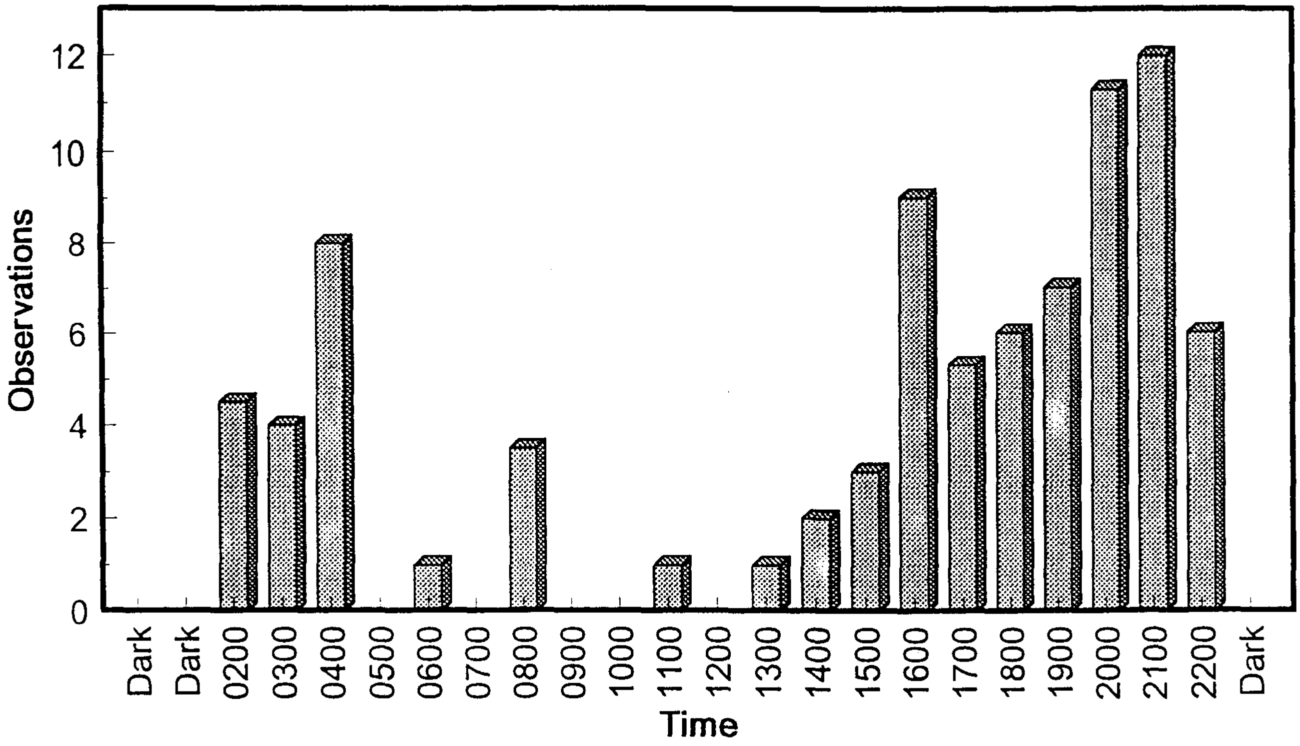

Figure 5: Estimates of relative abundance of juvenile salmon from fixed-uplooking video cameras in nearshore habitats of western in Prince William Sound, 1996.

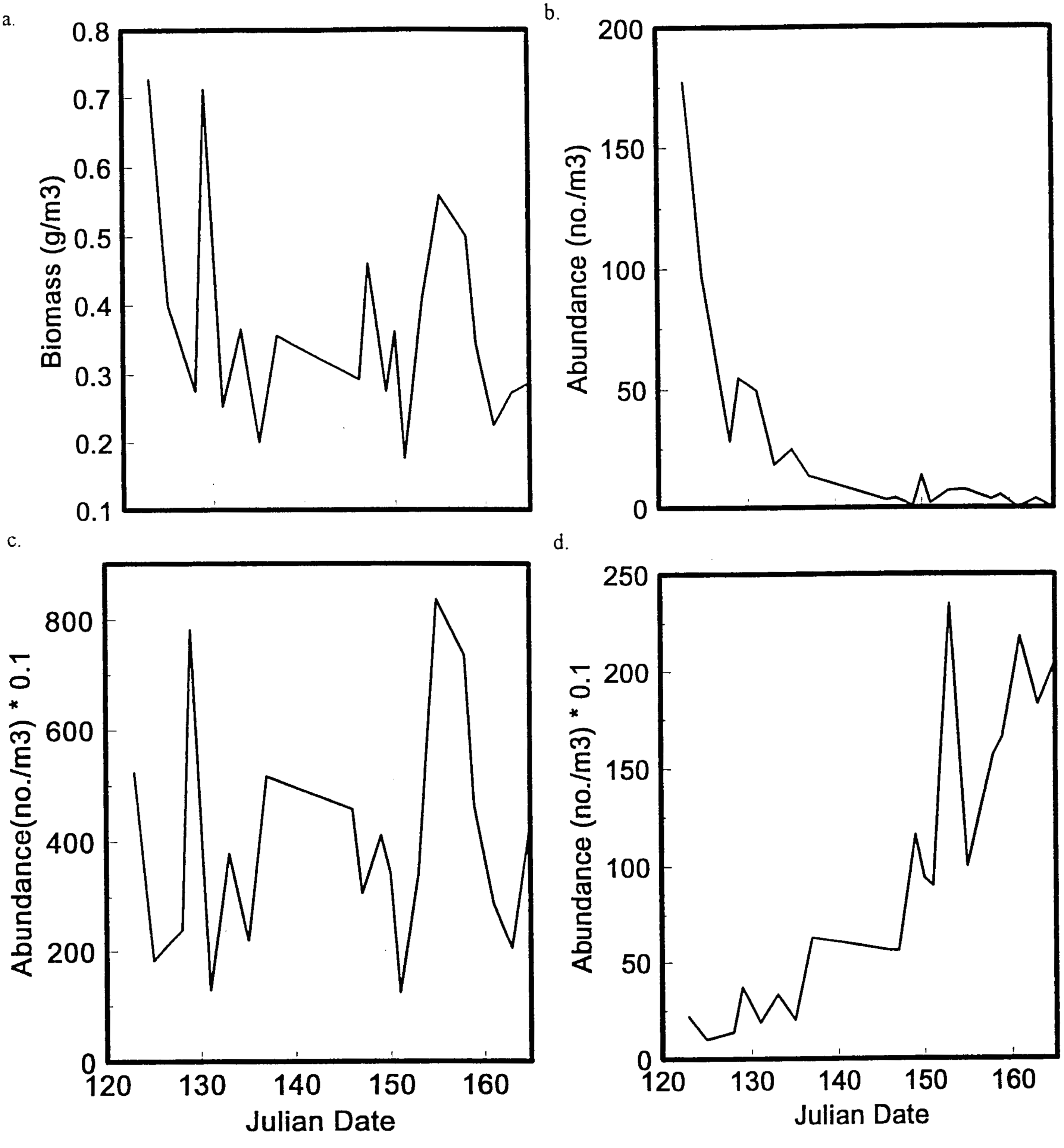

Figure 6: (a) Total zooplankton biomass and abundance (no./m3) of (b)large calanoid copepods, (c) small calanoid copepods, and (c) other zooplankters in nearshore habitats of northwestern Prince William Sound, May-June 1996.

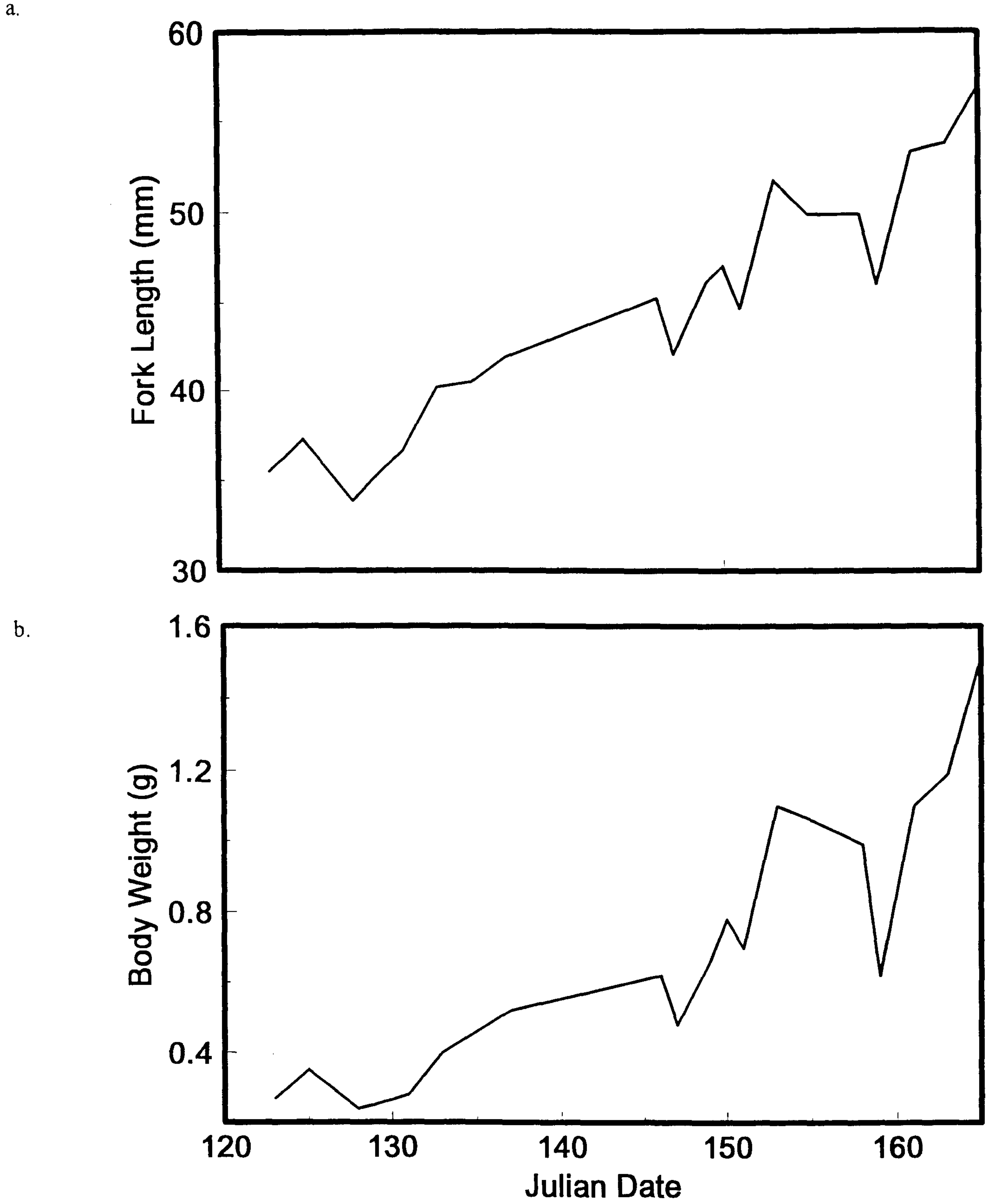

Figure 7: (a) Fork length and (b) body weight of juvenile pink salmon in nearshore habitats of northwestern Prince William Sound, May-June 1996.

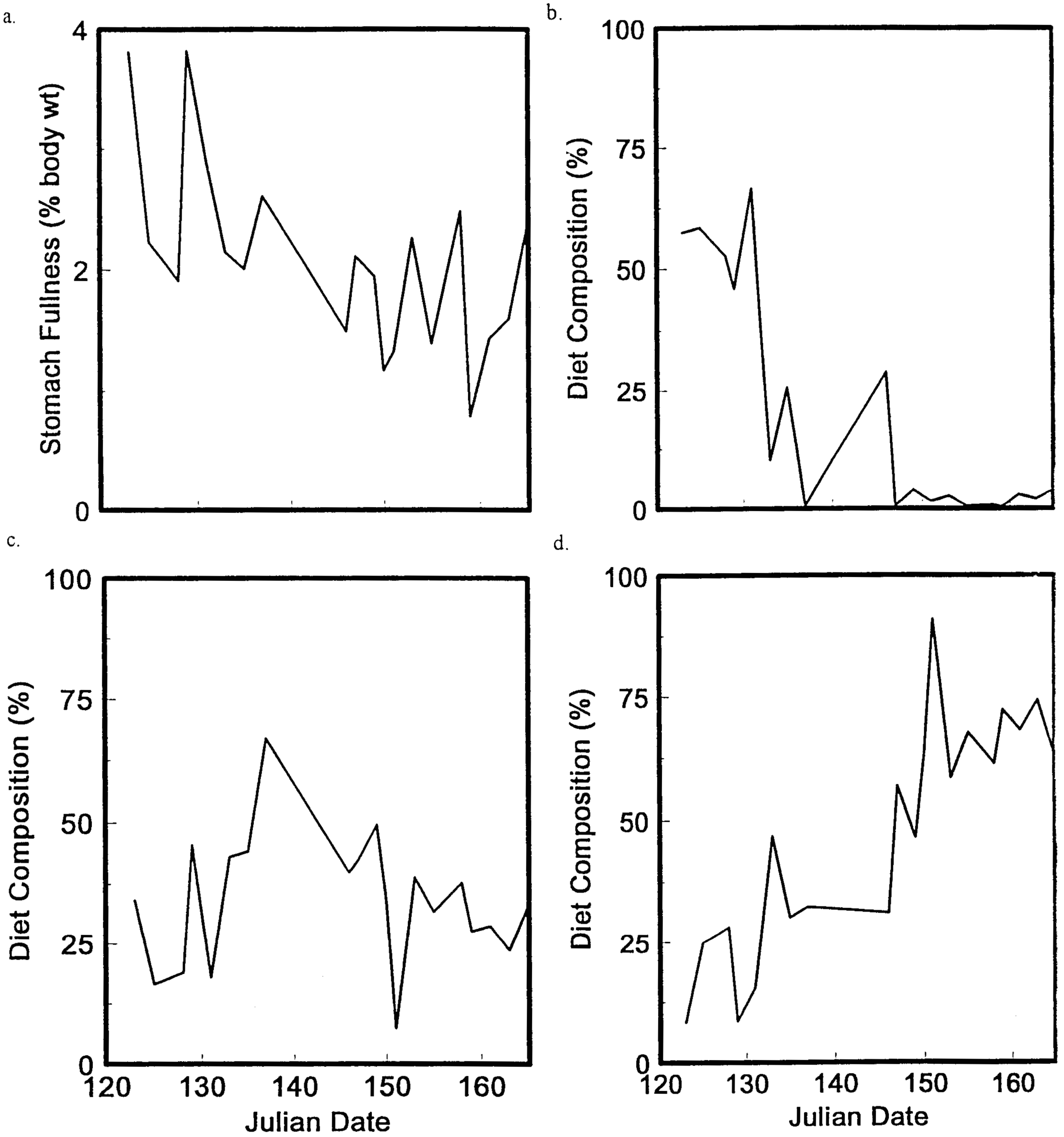

Figure 8: (a) Stomach fullness and the percent of total stomach contents weight comprised of (b) large calanoid copepods, (c) small calanoid copepods, and (d) other zooplankters for juvenile pink salmon in nearshore habitats of northwestern Prince William Sound, May-June 1996.

Chapter 3.

Phytoplankton and Nutrients (96320G)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Sound Ecosystem Analysis: Phytoplankton and Nutrients
Restoration Project 96320G

This annual report has been prepared for peer review as part of the Exxon Valdez Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

C. Peter McRoy
Alison Ward
E. Paul Simpson
Deena Clayton
Jill Cameron
Sue McCullough
Eric Suring

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks AK 99775

April 1997

Sound Ecosystem Analysis: Phytoplankton and Nutrients

Restoration Project 96320G
Annual Report

Study History: The project was initiated as Restoration Project 94320G. A "Draft Final Report" was produced as an annual report in 1995 and 1996 under the title "SOUND ECOSYSTEM ANALYSIS: Phytoplankton and Nutrients" and continues under the present grant number. Papers were presented at the AGU/ASLO Ocean Sciences meeting and The Oceanography Society meeting.

Abstract: In 1996 we collected 1110 samples from several platforms including 3 cruises (April, May and June) on chartered vessels and daily collections (April through June) from a station in Elrington Passage near AFK Hatchery. Measurements included chlorophyll, nutrients, particulate carbon and nitrogen, species composition, CTD, and dissolved oxygen from 6 depths in the upper water column. This is the second data set for phytoplankton and nutrients that fully includes the spring bloom. The spring phytoplankton increase is strongly influenced by light and mixing. The decline of phytoplankton biomass is a result of nutrient depletion and grazing. The spring phytoplankton cycle begins with a bloom dominated by diatoms, particularly *Skeletonema costatum*, followed by a low biomass of flagellates and succeeded by another low biomass of diatoms. The timing of the spring bloom is a signal to zooplankton. In the 4 years that we have data, the peak of zooplankton biomass occurs 3 weeks after the bloom. The data indicate a robust, healthy foundation for the pelagic ecosystem in Prince William Sound where variability is determined by weather, mixing processes and basin structure.

Key Words: Exxon Valdez, phytoplankton, nutrients, primary productivity, algae

Citation: McRoy, C.P., A. Ward, E.P. Simpson, D. Clayton, J. Cameron, S. McCullough and E. Suring. 1997. Sound Ecosystem Analysis: Phytoplankton and Nutrients, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 95320G), Institute of Marine Science, University of Alaska, Fairbanks, Alaska

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INTRODUCTION:

The project seeks to determine the driving force and variability of ecosystem production from a bottom-up point of view. It is our hypothesis in this component that the timing, quantity and species composition of the plant community, that is, the phytoplankton, is the major determinant of annual cycles. Ultimately, physical forces in the ocean play a major role in the dynamics of the phytoplankton community.

The Sound Ecosystem Assessment program (SEA) aims to understand and predict restoration of populations of pink salmon and herring in Prince William Sound. Fundamental to this goal is the understanding of controls of ecosystem processes that nourish the food web at its primary level. This is the goal of this component of SEA. Restoration of marine populations that have been damaged by human activity is usually limited to a few options that focus on controlling loss rate processes, i.e. harvest level, predator control, etc., or minor habitat modification. Pink salmon and herring offer a spectrum of strategies since a large portion of salmon are protected in hatcheries in their early life and herring are completely wild subject to the variance of nature. What then is the role of the annual cycle of primary production in the success of these upper trophic level species? Does the magnitude of the phytoplankton production determine the strength of a year class? Is the phytoplankton species composition an important determinant of the grazing zooplankton community? Does any of this matter or is there always enough food at the right time of the year so that predator populations are determined by the uppermost consumer on the food web? All are questions that are being examined in this study.

One central SEA hypothesis concerns the impact of circulation and physical conditions on the restoration of fish stocks (the Lake-River Hypothesis). This proposes that the circulation of Prince William Sound alternates irregularly between years of strong through-flow, river-like conditions, and relatively stagnant, lake-like conditions. The consequence is a high biomass of large zooplankton (copepods) in 'lake' years that are the major food for target fish (salmon, herring) and their predators (termed 'middle-out' food web control by Cooney and associates). In alternate 'river' years, the large zooplankton are sparse and predation on the target fish species predominates ("top-down" control).

While middle-out or top-down are principal hypotheses being tested by SEA research, the possibility of 'bottom-up' control, where the production of upper trophic level species is modulated by variations in light- and nutrient-driven phytoplankton production. In this hypothesis, the structure and composition of the zooplankton community are determined by variations in phytoplankton primary production and by the species composition of the phytoplankton community. For example, a phytoplankton community dominated by large diatoms can support a high biomass of large oceanic copepods, whereas a phytoplankton population dominated by smaller flagellates results in a reduced number of larger copepods, or in a shift to a zooplankton community dominated by smaller neritic copepod species. Variations in the timing of phytoplankton populations have been previously suggested to be a control of ecosystem events in Prince William Sound (McRoy 1988). A further complication in the interrelationship is that the large zooplankton are one year old when they become major prey for fishes (Cooney, personal communication) so their abundance must be determined by the events of the previous year and their specific biomass by the production cycle of the present year.

In this component, we provide the nutrient and phytoplankton data that are essential to evaluate the influence of phytoplankton dynamics on the food web and to test the bottom-up hypothesis. We will characterize the interannual spatial and temporal variation in nutrient and phytoplankton fields. We will evaluate the role of phytoplankton production in zooplankton recruitment and growth (especially for *Neocalanus* and *Pseudocalanus*). In a general sense we will provide an answer to the question “Is it food?”.

A central tenet of the Lake/River Hypothesis is the variable advection of Gulf of Alaska waters into Prince William Sound. This advection affects not only zooplankton populations, but also the Prince William Sound phytoplankton populations and production. Strong advection may confound the effects of in situ primary production in the Sound. To test the hypotheses further, we use satellite-derived sea-surface temperatures to examine the movement of Gulf of Alaska surface waters into Prince William Sound.

OBJECTIVES:

This study is designed to investigate the distribution, amount, and type of phytoplankton growth and the major inorganic nutrient fields associated with the growth processes. Our hypothesis is that variations in the phytoplankton production and populations are transferred to the zooplankton and that such variations are a function of oceanographic conditions that control the supply of inorganic nutrients and light. The objectives for 1995 were:

1. Analysis of phytoplankton community ecology in Prince William Sound.
2. Determination of basin-wide patterns of temperature, salinity nutrients and chlorophyll from ship-board observations.
3. Determination of temporal patterns of temperature, salinity, nutrients and chlorophyll in western Prince William Sound from a station near AFK Hatchery.
4. Determination of the linking between phytoplankton and upper trophic levels.

METHODS:

Phytoplankton Biomass, Spatial and Temporal Patterns

Phytoplankton biomass is measured using the standard chlorophyll techniques (Parsons et al., 1984) on a Turner Designs Fluorometer. Samples were collected at specific 309 time/space locations on cruises and at a shore-based station. Data allow mapping the areal pattern and description of the water column profile.

Phytoplankton Primary Production

The biomass pattern provides a picture of what is present, but it does not provide information on the phytoplankton dynamics. We can estimate production using dissolved oxygen and nutrient data. Productivity data are also available in our historical database (McRoy, unpublished data). Methods used involved uptake of ^{14}C by phytoplankton in containers under neutral density filters (Strickland and Parsons, 1972; Parsons et al., 1984).

Phytoplankton Community Composition

The composition of the phytoplankton community can be as important as the total primary production in determining zooplankton species and abundance. We collected 50 ml aliquots from water samples and preserved them in Lugol's solution for species identification. Identifications and cell counts were done using an inverted microscopy method (Sournia 1978). On low (20x) magnification, all visible cells in two transects are counted. On high (40x) magnification, fields are counted until a total of 300 cells is reached. For cell volume calculations and calculation of carbon content, cells identified to genus were grouped according to the maximum cell dimension. At least 20 cells of each species for size class were measured. The procedure is labor intensive and only a portion of the samples collected can be counted.

Nutrient Fields

Phytoplankton require the major inorganic nutrients (nitrogen, phosphorus and silica) for growth. General oceanographic circulation and land run-off supply nutrients. Since phytoplankton also require light, the problem is understanding how the nutrients are supplied to the illuminated zone of the sea. We routinely collected water samples for quantitative nutrient analysis. In the field, water samples were collected with Niskin Bottles at standard depths over the upper 100 m (deeper if necessary). A small aliquot (250 ml) was filtered and frozen for later chemical analysis. Chemical determination of the quantity of dissolved nitrogen (as nitrate, nitrite and ammonium), phosphate and silicate were measured using prescribed Continuous Flow Analysis methods with an Alpkem Auto-Analyzer in our laboratory in Fairbanks.

Personnel

The following people have contributed to sample and data collection and analysis:

P. Simpson	Graduate Student
A. Ward	Graduate Student
D. Clayton	Technician
J. Cameron	Technician
S. McCullough	Technician
E. Suring	Student

RESULTS:

Samples were collected to document the time series of events in the annual phytoplankton/nutrient cycle as well as to examine spatial variations in Prince William Sound. These data are collected in conjunction with other SEA projects and are supplied to the SEA data base after appropriate analysis and verification.

Sample Collection

We collected water samples for analysis from two types of platforms in Prince William Sound. Short, monthly SEA cruises on board chartered vessels from March to June permitted regional sampling from the standard SEA ocean stations. The second sample site is a station in Elrington Passage near the AFK Hatchery on Evans Island in the southwestern corner of the sound. We used this shore facility to collect daily samples from mid-April until late June. These data provide temporal continuity to the ship-board sampling.

The field season began in March and ended in June. In 1996 we collected 1110 samples from 3 cruises and a time series station. An decrease of 14% over 1995 (Tables 1 and 2). The chartered vessels provided areal coverage of the sound for oceanographic and biological parameters (Figure 1).

The Phytoplankton-Nutrient Component database includes dissolved nutrients (nitrate+nitrite, ammonia, phosphate, and silicate), dissolved oxygen, CTD (salinity, temperature, depth), chlorophyll a, and particulate carbon (PC) and nitrogen (PN) from all sampling platforms. In addition selected representative samples for phytoplankton identification and enumeration were processed.

Time Series Measurements

The best time series data in 1995 were collected from a station in Elrington Passage (60°01'N, 148°00'W) the southwest sound near the AFK Hatchery. The station was visited daily by skiff and all samples were collected from a 5 liter Niskin bottle lowered repeatedly to each sample depth with a hand winch. The data series begins on 06 April 96 and ends on 16 June 96. The phytoplankton bloom was already underway when sampling began (Day 97) and terminated by Day 126. The pattern is similar to that in 1995.

Hydrography

One CTD cast to 80 m was lowered daily to determine salinity, temperature and density of the sea water over the duration of the study. From a contour plot of σ_t vs. depth and time we were able to determine mixing events and the stability of the water column throughout the season.

The waters were cold and well mixed throughout the water column during the spring bloom in 1995 and 1996 (Figure 2). In 1995, from April through early May temperatures remained between 4 - 5 °C. Surface warming wasn't apparent until Day 121. Weak stratification occurred earlier around Day 112 due to freshening at the surface from precipitation. However this weak stability was disrupted two days later as waters continued to mix within the upper 75 m. That year the salinity averaged 31.17 (psu) at 5 m and density profiles mirrored salinity (Figure 2). The density remained between 24.2 - 25.2 σ_t. In 1996, temperatures were the same as 1995 and mixing extended down to 80 m prior to Day 113. Fresh water input was reduced in 1996 and salinity averaged 31.55 psu at 5 m. Stratification didn't occur as the density of the water remained between 24. 8 -25.2 σ_t.

During the post bloom, stronger stratification was achieved as solar gain and fresh water runoff increased (Figure 2). In 1995, the surface waters warmed to 6.75°C by Day 143. A strong pycnocline was formed in the upper water column due to heavy fresh water input. Below 30 m mixing occurred daily. Salinity fell to 29 psu at surface. In 1996, clear sunny skies enable water temperatures to warm to 7 °C by Day 144. Salinity ranged from 31.2 - 31.8. Salinity remained higher in 1996 due to reduced precipitation and increased evaporation. Due to decreased freshwater input, densities remained much higher than 1995. Frequent deep mixing to 80 m (Days 135-140) continued to occur throughout this period. A salty intrusion was detected on Day 138 between 20 and 60 meters and lasted for several days.

Following Day 145, waters gained their greatest stability and temperatures (Figure 2). In 1995, surface temperatures reached a maximum of 9 °C as the surface salinity dropped to 26.7 psu. Strong stratification and pycnocline caused by heating and fresh water remained throughout the month of June. Mixing was restricted to depths below 50 m. In 1996, surface temperatures rose to 10 °C by Day 163 and warm waters penetrated to 80 m. Freshening occurred in the surface waters after Day 150 but the minimum salinity in June reached only 30 psu. Due to the large number of clear days, insolation warmed the waters increasing stability but, at the same time, increasing evaporation and therefore salinity which overall controlled the waters stability. In June waters were less stable in 1996 than 1995 and weak stratification in the upper 25 m was interspersed with deep mixing events. Another high salinity intrusion at mid depths was seen on Day 158 and lasted two days.

Nutrients

Daily water samples were collected and later analyzed for inorganic nutrient concentrations. Concentrations of nitrate+nitrite (µM), silicate (µM) and phosphate (µM) were determined. Phosphate and nitrate were chosen because the assimilation of these two nutrients in the Redfield-Richards Ratio of 1:16 (Libes 1992) is required for photosynthesis and phytoplankton growth. Silicate was chosen because it is required for the formation of diatom tests and it can affect phytoplankton community structure in its presence and absence.

Nutrient concentrations were high preceding the spring bloom; then they decreased in surface waters as production increased (Figure 3). In 1995, concentrations of all nutrients were highest around Day 107 and a nutricline was apparent throughout the bloom. In the upper 75 m concentrations of N+N, SiO_4 and PO_4 ranged from 10 - 15 µM, 15 - 25 µM, and 1.0 - 1.5 µM, respectively. As the bloom progressed nutrients were depleted in the surface waters but remained high below 50 m. By Day 120 concentrations of N+N, SiO_4 and PO_4 had dropped to levels between 1.7 - 2.5 µM, 3 - 4.5 µM and 0.3 - 0.7 µM in the upper 10 m. Following Day 120 nutrient concentrations remained low but detectable in the surface waters. In 1996, a similar pattern emerged but nutrient levels were lower throughout the bloom especially at depth. At Day 97, N+N, SiO_4 and PO_4 in the upper 75 m ranged from 10.9 - 11.3 µM, 16 - 17 µM and 1.2 - 1.5 µM, respectively. As the month of April passed, all the nutrients deceased at the surface around Days 104 and 117. No nutrients were completely assimilated by plankton but ratios of N+N:SiO_4 were very low. Nutrients were replenished in-between the periods of low concentrations.

During the post bloom nutrients were replenished from depth and low nutrient concentrations did not exist below 25 m (Figure 3). In 1995, high concentrations of all nutrients were present. Only around Days 138 - 143 did all the nutrients show a decline in the upper 10 m. Nutrients remained highest below 50 m with maximum N+N, SiO_4 and PO_4 concentrations of 16 µM, 25 µM and 2 µM, respectively. In 1996, all nutrients were also replenished in the upper layers. Only two periods around Days 131 and 141 had decreased concentrations. Maximum values at depth, as well as surface, were much lower in 1996. Below 50 m maximum N+N, SiO_4 and PO_4 concentrations only reached 14 µM, 19 µM and 1.8 µM, respectively. Higher concentrations of phosphate existed at depths in 1996.

During the resurgence period, nutrients in the surface waters deceased again and concentrations at depth remained high. In 1995, nutrient concentrations remained low in surface waters and high below 25 m. The highest concentrations throughout the entire spring bloom of nitrate appeared in June at 75 m. In 1996, all surface nutrients were reduced in the upper 25 m throughout the recovery period. Concentrations were highest at depth but considerable lower than 1995.

Phytoplankton Biomass

Water samples were collected daily from the upper 75 m of the water column to determine the vertical distribution of phytoplankton from chlorophyll *a* (mg/m^3) fluorescence over three months. The bloom in 1996 was bimodal with peaks around Days 104 and 118. The timing of the bloom is an important signal to the zooplankton community which in previous years seem to follow the bloom by about 3 weeks. The 1996 bloom spans most of the range observed from all sources since 1993 (Figure 4).

During the spring bloom chlorophyll extended as far down as 75 m and the highest concentrations of chlorophyll were present at this time (Figure 4). In 1995, the highest chlorophyll levels were between 4 - 36 mg/m^3 in the upper 25 m dropping to 2 - 25 mg/m^3 at 50 m and 75 m. The peak biomass occurred in a short pulse between Days 111-114 in the upper 25 m. In 1996 chlorophyll levels were lower, variations with depth were less and the length of the bloom increased. High levels of chlorophyll were present between Days 97 - 121. In the upper 25 m the chlorophyll ranged from 2 -20 mg/m^3. At 50 m and below the levels decreased to 0.5 - 16 mg/m^3. There were two distinct periods of high biomass between Days 100 - 105 and 114 - 116. Both periods had high levels of chlorophyll at depth.

During the post bloom chlorophyll was at its' lowest concentrations and it was distributed uniformly throughout the water column (Figure 4). In 1995, chlorophyll ranged from 0.5 - 7 mg/m^3 throughout the water column. Small ephemeral blooms occurred in the upper 10 m on Days 125 - 127 and 138. Chlorophyll levels at 50 m and below remained ≤ 3 mg/m^3. In 1996, chlorophyll ranged from 0.2 - 3 mg/m^3. Unlike 1995, no small blooms occurred at this time.

Following Day 145, chlorophyll levels increased but almost all of the biomass remained above 25 m (Figure 4). The greatest resurgence was seen in 1995. Chlorophyll levels returned to as high as 12 mg/m^3 as stratification strengthened. Concentrations between 5 - 10 mg/m^3 remained until Day 170 in the upper 25 m. Small transitory increases in chlorophyll occurred in 1996 above 25 m. Chlorophyll biomass only increased to highs of approximately 5 mg/m^3 on Days 153 - 154, 160 - 163, 165 and 169. Levels remained low below 25 m except on Day 154 where 6.3 mg/m^3 was measured at 50 m. This anomaly may be due to downwelling of surface waters.

During the bloom phytoplankton growth strips the major nutrients from the water column and conditions of nutrient limitation develop. The close relationship of N+N to Silicate in the upper layers of the water column is a result of this activity (Figure 5). In 1996 the slope of the regression of silicate on N+N was 1.2 with a silicate intercept of 2.6. this relationship indicates that the bloom was terminated by nutrient limitation and that the concentration of silica was below that required by diatom cells. The species abundance reflect this fact (see Figure 8) since diatoms are absent from the water column for a time following the bloom. It is only after some additional nutrients are advected into the system that the diatoms reappear. This condition existed in 1994 and 1995. The average intercept for all 3 years of N+N vs. silicate is 2.5, a value just at the limiting threshold for diatoms.

Distribution and Abundance of Phytoplankton

In 1995 and 1996 during the spring bloom diatoms and flagellates were present at all depths (Figure 7 & 8; Table 3). Their population remained high throughout the bloom and started to decline by the end of the period at all depths. The distribution of cells revealed highest abundance within the uppermost 10 m, slightly lower populations at 25 m and lowest but still significant abundance at 50 m. In 1995, the diatom abundance ranged from 813 - 3,110 cells/ml within the top 50 m. Flagellates appeared in high abundance and ranged from 525 cells/ml at 50 m to 1,900 cells /ml at the surface. Flagellates were the most numerous phytoplankton with as great as 61 % of the total abundance and a mean of 45 % for all depths. In 1996, diatom abundance was approximately three times as great as 1995. Diatom abundance ranged from 1,872 - 13,500 cells/ml in the upper 50 m. However, flagellate abundance remained about the same in 1996 as 1995. Flagellates peaked at 2,021 cells/ml on Day 110 at 10 m. During the bloom their lowest abundance of 481 cells/ml occurred at 50 m on Day 106. At this time, they only accounted for ≤ 25 % of the total phytoplankton abundance. In both years, dinoflagellates (from the class *Dinophyceae*) and silicoflagellates, mainly *Distephanus speculum*, were less than 1 % of the cell abundance.

During the post bloom and recovery periods flagellates were more abundant than diatoms at all depths, interannual differences were less and abundance was low (Figure 7 & 8). In 1995, flagellates composed >90 % of the phytoplankton abundance and ranged from 283 - 880 cells/ml throughout the upper 50 m during periods of lowest chlorophyll. Populations increased slightly (250 - 1,088 cells/ml) during the recovery period and flagellates composed about 60% of the community. In 1996, >80 % of the post bloom phytoplankton was composed of flagellates. At this time the lowest flagellate abundance at 50 m as 300 cells/ml and the highest abundance (1,014 cells/ml) was at the surface. Day to day variations at all depths were slight. In June of 1996, populations increased but flagellates only composed an average of 53 % of the phytoplankton over 50 m. Flagellate abundance over the upper 50 m ranged from 494 - 1,689 cells/ml.

In both years, centric diatoms were the most common phytoplankton during the bloom at all depths but interannual differences in abundance were immense. In 1995 and 1996, *Chaetoceros spp.*, *Skeletonema costatum, Thalassiosira spp.*, *Leptocylindrus spp.* were present in highest abundance throughout the upper 50 m (Figure 7 & 8). Species composition remained the same over depth but diatom abundance decreased with depth below 10 m. In 1995, total diatom abundance ranged from lows of 813 cells/ml at 50 m on Day 109 to a maximum of 3,110 cells/ml at 10 m on Day 113. *Skeletonema costatum* and *Thalassiosira spp* averaged over 37 % and 30 %, respectively, of the total diatom abundance during the bloom at all depths (Figure 9). *Chaetoceros spp.* was always present at all depths and constituted between 5 - 31 % of the total diatoms. *Leptocylindrus spp.* appeared inconsistently composing only a small portion of the bloom. In 1996, the same species and genera reappeared in the sea-water but the smaller diatoms tripled in abundance while the larger species declined in abundance (Figure 8). *Skeletonema costatum* had greater than 72 % of the diatom abundance throughout the water column (Figure 10). Vertically its' abundance ranged from 1,150 - 12,072 cells/ml. The population of *Chaetoceros spp.* increased at all depths and reached a maximum of 2,311 cells/ml at the surface on Day 102. The same year had a lower abundance of *Thalassiosira spp.* and *Leptocylindrus spp.* than was present in 1995. These genera composed < 9 % and < 2 % , respectively, of the diatom population. For both years, other diatoms, in order of abundance, that were ≤ 5 % of the total diatom abundance were *Fragilariopsis spp.* , *Asterionella glacialis, Navicula spp., Eucampia spp., Stephanopyxis nipponica* and *Rhizosolenia stolterforthii* .

During the post bloom the lowest diatom abundance was present and 1995 and 1996 showed less dissimilarities in terms of abundance (Figure 7 & 8). In 1995, less than 100 cells/ml existed at all depths in mid May. Only small variations in cell abundance occurred with depth. The small diatoms, *Pseudo -nitzschia spp.* and *Chaetoceros spp.*, dominated the community and *Thalassiosira spp.* decreased in abundance (Figure 9). In 1996, at the same time, less than 150 cells/ml were observed and lowest abundance was at 50 m (Figure 8). *Chaetoceros spp.* dominated the abundance at all depths. *Pseudo -nitzschia spp.* and *Leptocylindus spp.*, present during the bloom in low abundance, were present still accounting for as high as 35 % of the diatom abundance (Figure 10). *Skeletonema costatum* abundance declined and was absent at several depths around Day 138. *Rhizosolenia fragilissima*, not present during the bloom, first appeared in low abundance at this time in 1996 but not 1995.

In June the diatom abundance recovered slightly and a shift in species composition occurred (Figure 7 & 8). In 1995, total diatom cells/ml increased to 1/3 of previous bloom abundance. This phytoplankton community was composed almost entirely of *Rhizosolenia fragilissima* at all depths (Figure 9). *Chaetoceros spp.* was the second most abundant diatom with < 10 % of the abundance. *Skeletonema costatum* was absent at this time. In June of 1996, diatoms resurged and ranged from 560 cells/ml at 50 m to 1,088 cells/ml at 5 m (Figure 8). *Rhizosolenia fragilissima* returned in 1996 but only accounted for 25 - 48 % of the diatom community and shared dominance with *Chaetoceros spp* (Figure 10). *Pseudo-nitzschia spp.* and *Leptocylindrus spp.* were the third most abundant diatoms. *Skeletonema costatum* was present but averaged only 6 % of the abundance in the upper 50 m.

Spatial Measurements:

The results from the April, May, and June cruises provided perspective of the areal patterns of phytoplankton and nutrients (Figures 9, 10, and 11). In April the integrated chlorophyll values are high everywhere except the along the northern-most coast and inlets including Port Valdez. A maximum value occurs around Green Island and this feature recurs annually. At this time the nutrient stocks are still high in most areas but large areas of low nitrate and silicate appear in the central sound. By June the transition from a spring to a summer sound is complete. Chlorophyll values are now 10% of the April quantities and nitrate and phosphate are 20 to 30 % of the earlier values. There is some evidence for a small addition of nutrients from the Gulf of Alaska through Hinchinbrook entrance.

Discussion

The general pattern of the time course of phytoplankton biomass is a rapid spring increase followed by an equally sharp decline after about 3 weeks. The increase begins in early April unless storm conditions are present, and the decline occurs by the beginning of May. Summer increases in phytoplankton biomass occur if oceanographic mixing events provide new nutrients to the surface euphotic zone. In both 1995 and 1996 the bloom occurred more than a month before that in the phytoplankton cycle reported for Port Valdez in 1987 (Alexander and Chapman, 1980; McRoy, 1988) indicating the effect of local control on the processes.

The timing of the spring bloom is apparently determined by the interaction of light and mixing in the classic relationship (Sverdrup, 1953). The interruption of the cycle by storms indicates the fragility of the relationship at this time of year and how the ocean conditions can impart an event signal to the food web. The zooplankton data that have been included here show that the delay in the phytoplankton bloom is translated to zooplankton and hence to upper trophic levels.

The pattern of the phytoplankton cycle indicates the classic response of increasing light and stratification in spring followed by nutrient limitation. This pattern has been reported for previous studies of Prince William Sound (Goering et al., 1973a, 1973b). The time series data indicate that nutrient limitation is a significant factor in terminating the bloom. The nutrient-nutrient plot of silicate vs. nitrate shows that the diatoms are able to utilize silicate below the threshold level required for growth (Paasche 1980). The condition must also be a powerful force in species succession. The end of the bloom period is also influenced by zooplankton grazing since the increase in zooplankton directly follows the decrease in phytoplankton. It is likely that both nutrient limitation and grazing lead to the decrease in phytoplankton biomass. These forces can also have a major impact on the composition of the phytoplankton community. Horner et al. (1973) report a detailed list of phytoplankton species for Port Valdez that can also be used for comparison

Alexander and Chapman (1980) report that the phytoplankton community consisted of 97% diatoms in April but by July it was 95 % microflagellates. We found that the diatom abundance in April 1995 and 1996 was over 55%, with remainder consisting of flagellates. The presence of abundant flagellates is indicative of a mechanism for channeling dissolved organic matter (DOM) that is excreted by phytoplankton through a microbial loop. Such a mechanism retains energy in the food web that might otherwise be lost through excreted DOM. The process is relatively inefficient since at least 3 trophic levels are probably involved (Azam et al. 1983).

The nutrient inventory presented by the sound-wide distributions for April, May and June (Figures 9, 10 and 11) permit an analysis of overall integrated production for the spring. The difference in the nitrate+nitrite inventory between April and June indicates a utilization of about 8.3 mmol $m^{-2}d^{-1}$ for nitrogen which based on a Redfield ratio of C/N of 6.6 converts to a carbon rate of 0.7 $gCm^{-2}d^{-1}$. This is a conservative estimate of new production. The total production is probably twice this value if the *f* ratio is less than 0.5 as would be expected for the region.

The diatoms present in April and May are expected to be prime food for the large zooplankton, and hence a major energy source for upper trophic level species. On the other hand the picoplankton are a poor food source for these zooplankton but contribute to a microbial food web that can eventually provide energy to the larger consumers. The close correlation of the phytoplankton and zooplankton increase in biomass in 1993, 1994, 1995 and 1996 indicates more bottom-up forcing than has generally been assumed in this system (refer to the SEA general overview documents).

Do phytoplankton drive the food web? Yes, but. Based on our evidence and that of past studies, the timing of the bloom is a critical event that sends a signal to all trophic levels. Actually, it is an oceanographic event that initiates the signal. The manifestation of such an event in the phytoplankton community could take several forms. It could lead to a different suite of species that may or may not be acceptable zooplankton food. It may simply be a quantitative event and the early zooplankton could be food limited. The translation of this could then be fewer progeny in the following year.

Finally, the picture that we now have is a robust foundation for the pelagic ecosystem that shows no continuing effects of the contamination from the 1989 oil spill. The species composition and primary production vary due to the vagaries of weather and mixing processes as further influenced by the characteristics of the basin.

Conclusions:

1. A well-defined spring bloom of phytoplankton occurs In Prince William Sound. The timing of the bloom depends on light and mixing conditions in a given year. Local conditions are important in determining the phytoplankton biomass. In 1996 the bloom began about Day 98 (7 Apr) and ended by Day 124 (1 May).
2. Phytoplankton bloom community consists of at least 55% diatoms in both '95 and '96, followed by a post-bloom period of 3 weeks consisting of more than 80% flagellates. A resurgence of diatoms occurred after the post-bloom period but attained only 33% of their former abundance.
3. Productivity in 1995 and 1996 was ultimately silica limited. New production (nitrate based) in spring is estimated to be about 0.7 gCm^{-2} d^{-1} which is likely to be half the total productivity rate for the period.
4. Phytoplankton and zooplankton are closely coupled in space and time. The timing of the spring phytoplankton bloom sets the timing of the appearance of the zooplankton.
5. The foundation of the pelagic ecosystem in Prince William Sound is robust and healthy.

Papers Presented

Ward, A. and C. P. McRoy. 1996. The spring phytoplankton bloom in Prince William Sound, Alaska. The Oceanography Society meeting, Seattle WA, April 1996.

Vaughan, S.L. and C. P. McRoy. 1996. Relating phytoplankton abundance to upper layer water mass variability in Prince William Sound, Alaska. The Oceanography Society meeting, Seattle WA, April 1996.

McRoy, C.P. R.T. Cooney, A. Ward, E.P. Simpson, D.L. Eslinger, T.C. Kline, S.L. Vaughn and J. Wang. 1996. THE architecture of the Prince William Sound ecosystem: nutrients, phytoplankton and zooplankton interactions. American Society of Limnology & Oceanography, Annual Meeting, Santa Fe, NM, February 1996.

Literature Cited

Alexander, V. and T. Chapman. 1980. Phytotoxicity. pp 125-142, in J.M. Colonell, ed., Port Valdez, Alaska: Environmental Studies 1976-1979. Institute of marine Science, University of Alaska, Fairbanks.

Azam, F., T. Fenchel, J.G. Field, J.S. Gray, L.A. Meyer-Reil, and F. Thingstad. 1983. The ecological role of water-column microbes in the sea. Marine Ecology Prog. Ser. 10:257-263.

Goering, J.J., C.J. Patton, and W.E. Shiels. 1973a. Nutrient cycles. Pp. 225-248, in D.W. Hood, W.E. Shiels and E.J. Kelley. Environmental studies of Port Valdez. Institute of Marine Science, University of Alaska, Fairbanks.

Goering, J.J., W.E. Shiels, and C.J. Patton. 1973b. Primary production. Pp. 225-248, in D.W. Hood, W.E. Shiels and E.J. Kelley. Environmental studies of Port Valdez. Institute of Marine Science, University of Alaska, Fairbanks.

Horner, R.A. L.S. Dick and W.E. Shiels. 1973a. Nutrient cycles. Pp. 283-294, in D.W. Hood, W.E. Shiels and E.J. Kelley. Environmental studies of Port Valdez. Institute of Marine Science, University of Alaska, Fairbanks.

Libes, S. M. 1992. An Introduction to Marine Biogeochemistry, John Wiley & Sons, Inc., New York.

McRoy, C.P. 1988. Natural and anthropogenic disturbances at the ecosystem level. Pp. 329-334, in D.G. Shaw and M.J. Hameedi, eds., Environmental Studies in Port Valdez, Alaska, Lecture Notes on Coastal and Estuarine Studies Vol. 24. Springer-Verlag. Berlin.

Napp, J.M., L.S. Incze, P.B. Ortner, D.L.W. Siefert, and L. Britt. 1996. The plankton of Shelikof Strait, Alaska: standing stock, production, mesoscale variability and their relevance to larval fish survival. Fisheries Ocean. 5(Suppl. 1):19-38.

Paasche, E. 1980. Silicon. Pp. 259-284 in I. Morris (ed.), The Physiological Ecology of Phytoplankton. Univ. California.

Parsons, T.R., Y. Maita, and C.M. Lalli. 1984. A Manual of Chemical and Biological Methods of Seawater Analysis, Pergamon Press, New York.

Sournia, A. 1978. Phytoplankton manual, UNESCO, Paris, 337 pp.

Strickland, J.D.H. and T.R. Parsons. 1972. A Practical Handbook of Seawater Analysis. Bulletin 167, Fisheries Research Board of Canada, Ottawa, 310 pp.

Sverdrup, H.U. 1953. On conditions for the vernal blooming of phytoplankton. Cons. perm intl. Expl. Mer 18(3):287-295.

Table 1. Summary of data collection, including number of samples collected, and sampling days for 1995 and 1996 at AFK Station SB2.

Data Collection	1995	1996
Sampling Dates (Julian)	107 - 170	97 - 169
Sampling Depths	0, 5, 10, 25, 50, 75	0, 5, 10, 25,50, 75
No. Sampling Days	64	73
CTD Casts	63	73
Secchi Depth Measurements	63	73
Chlorophyll a Concentration Measurements	372	437
Size Fractionation Measurements	0	68
Nitrate + Nitrite Concentration Measurements	372	438
Silicate Concentration Measurements	369	438
Phosphate Concentration Measurements	372	438
Species Composition and Abundance Measurements	73	80
Autotrophic Carbon Biomass Measurements	68	80

Table 2. Summary of data collection, including number of samples, for 1995 and 1996 from oceanographic cruises.

Data Collection	1995	1996
No. Cruises	5	3
No. Stations	153	112
Chlorophyll a Concentration Measurements	918	672
Size Fractionation Samples	329	0
Nitrate + Nitrite Concentration Measurements	918	672
Silicate Concentration Measurements	918	672
Phosphate Concentration Measurements	918	672
Species Composition and Abundance Samples	760	672

Table 3. Species list of diatoms and flagellates and their size ranges (μm) found in the upper 50 m during 1995 and1996 at AFK Station SB2.

DIATOMS	SIZE RANGE (lxw) μm	FLAGELLATES	SIZE RANGE (lxw) μm
Asterionella glacialis	10x5 -20x5	*Ceratium furca*	80x75
Biddulphia spp.	15x15	*Ceratium spp.*	20x12-90x90
Chaetoceros spp.	2.5x2.5 - 40x30	*Dinophysis spp.*	50x45
Chaetoceros deciprens	25x15 - 25x20	*Distephanus speculum*	20x20 - 25x25
Cocconeis spp.	40x20	*Ebria tripartita*	15x15-30x30
Coscinodiscus spp.	135 -190	*Oxytoxum sp.*	20x10 -40x15
Eucampia spp.	30x25 - 55x25	*Peridinium sp.*	20x15 - 65x50
Fragilariopsis sp.	10x2-15x2.5		
Grammatophora spp.	40x2.5-35x20	Unidentified flagellate	5 - 17.5
Leptocylindrus danicus	20x10- 85x10	Unidentified silicoflagellate	
Leptocylindrus minimus	20x2.5 - 35x2	Unidentified dinoflagellate	15x10- 60x20
Leptocylindrus spp.	35x5 - 40x7		
Licmophora glacialis			
Navicula spp.	20x5 - 80x5		
Pseudo-nitzschia spp.	30x2 -65x2		
Rhizosolenia fragilissima	15x5 - 35x5		
Rhizosolenia stolterforthii	45x8 - 60x10		
Rhizosolenia spp.	25x14 -500x15		
Skeletonema costatum	7.5x5 -17.5x5		
Stephanopyxis nipponica	30x20 - 60x20		
Thalassiosira spp.	10x7 - 55x15		
Thalassionema nitzschioides	25x5 -45x5		
Unidentified centric diatom	10x15-45x35		
Unidentified diatom	15x10 -130x15		
Unidentified pennate diatom	20x5 - 45x7		

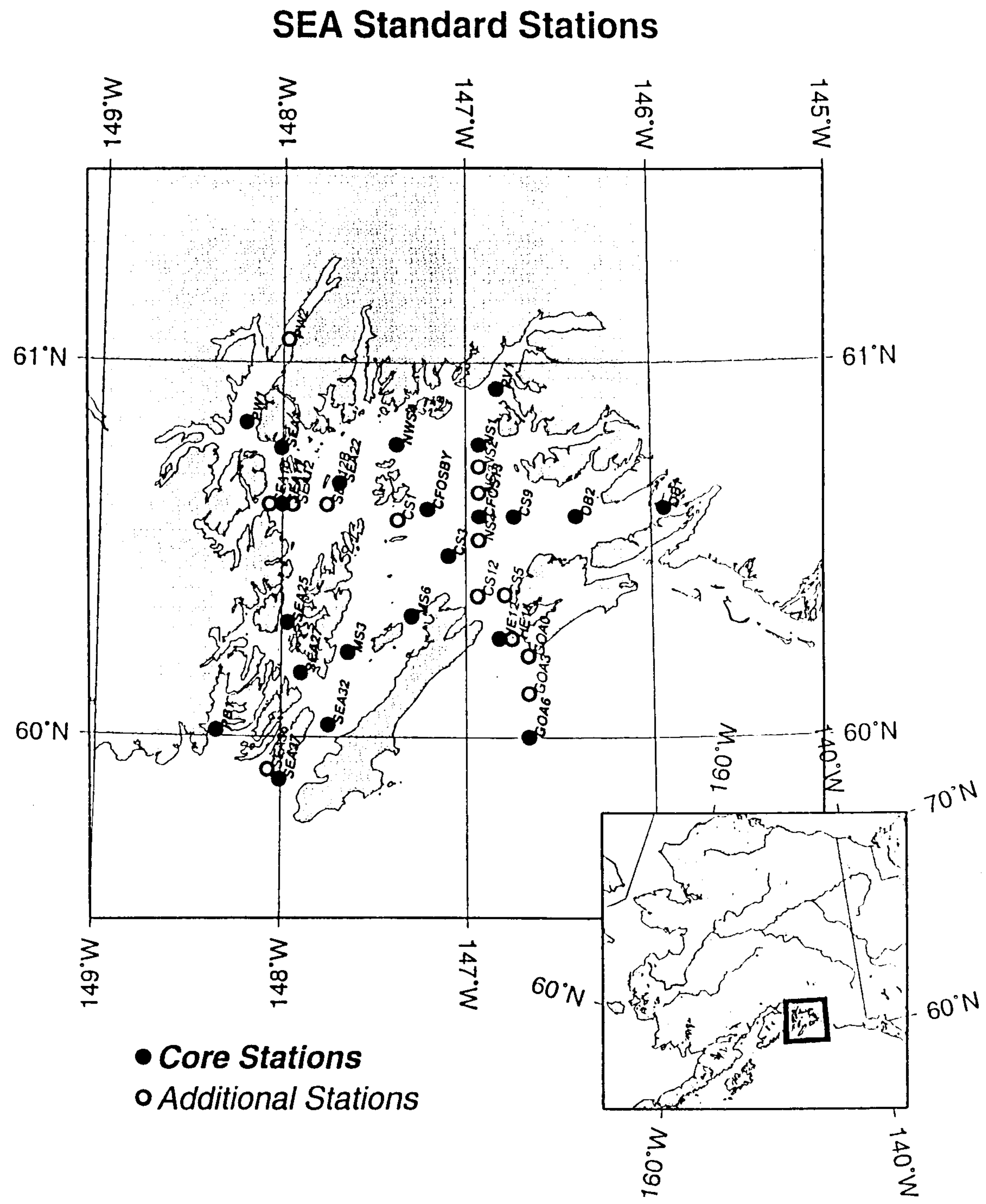

Figure 1. SEA 1996 station locations for phytoplankton and nutrient sample collection.

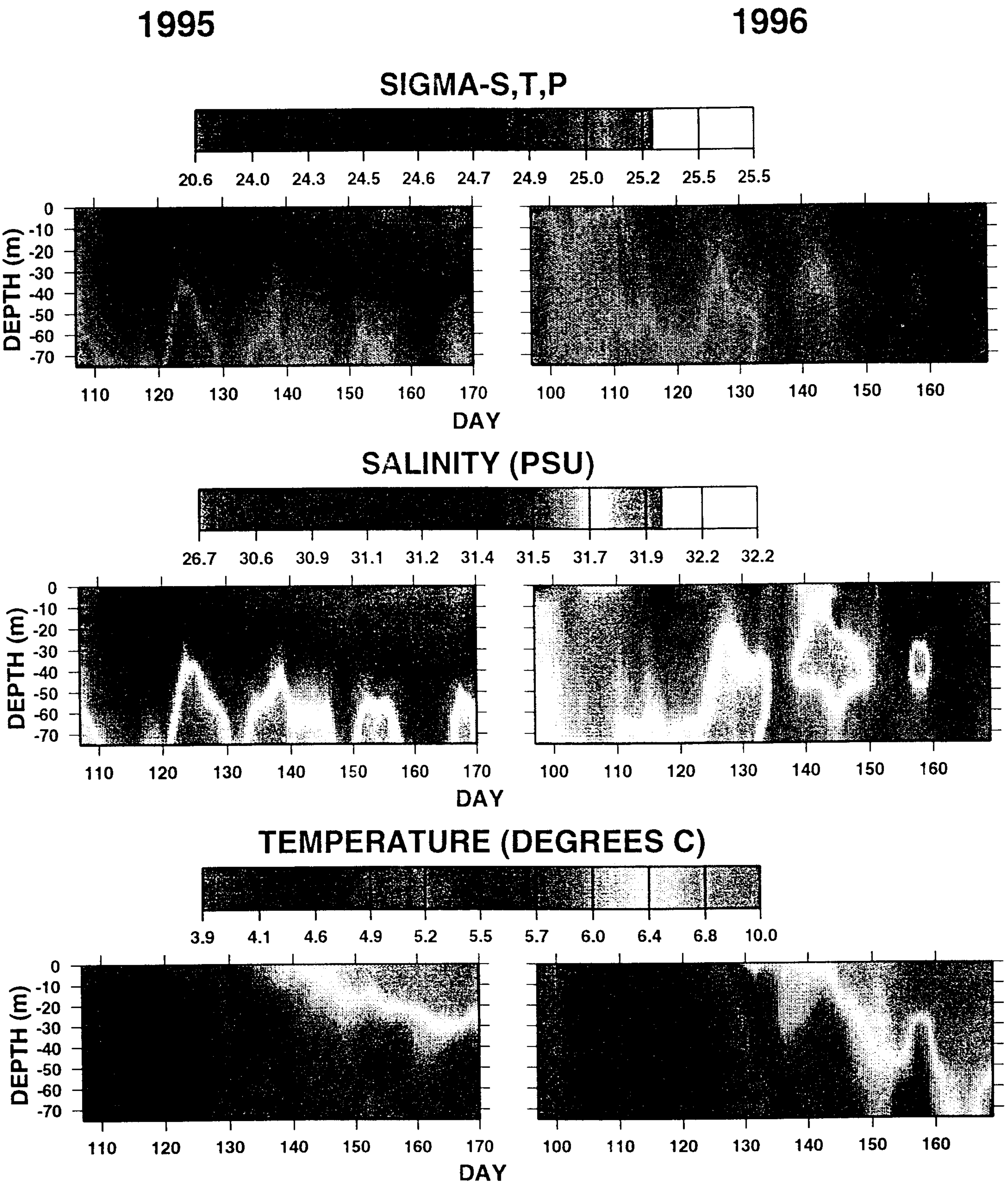

Figure 2. Time series of density (sigma-S,T,P), salinity (psu), and temperature (°C) for 07 Apr - 19 Jun 1995 (Days 97-170) and 06 Apr -17 Jun 1996 (Days 97-169) at Station AFK 96.2.

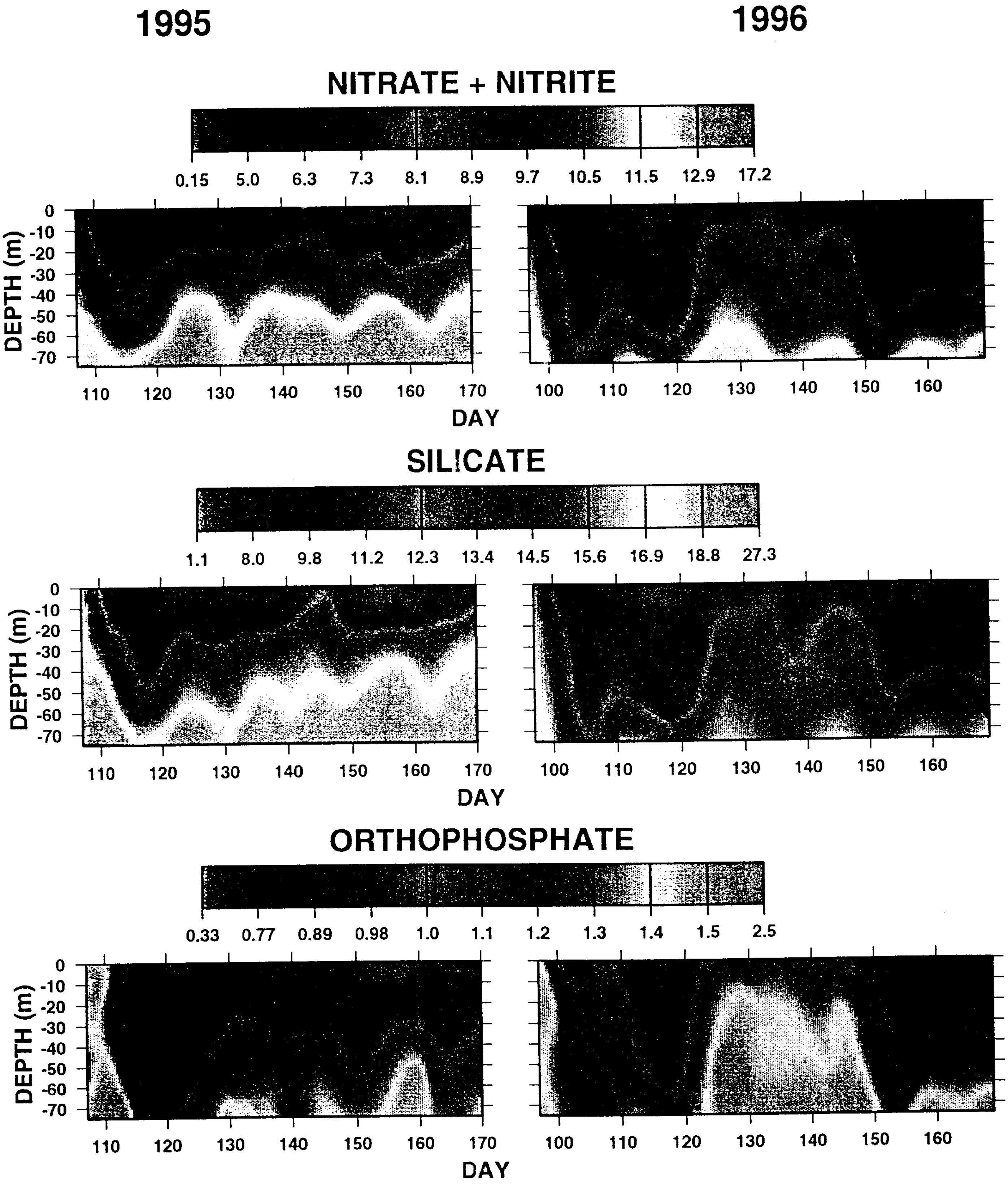

Figure 3. Time series of nutrients, Nitrate+Nitrite, Silicate and Orthophosphate (mmol m^{-2}) for 07 Apr - 19 Jun 1995 (Days 97-170) and 06 Apr -17 Jun 96 (Days 97-169) at Station AFK 96.2.

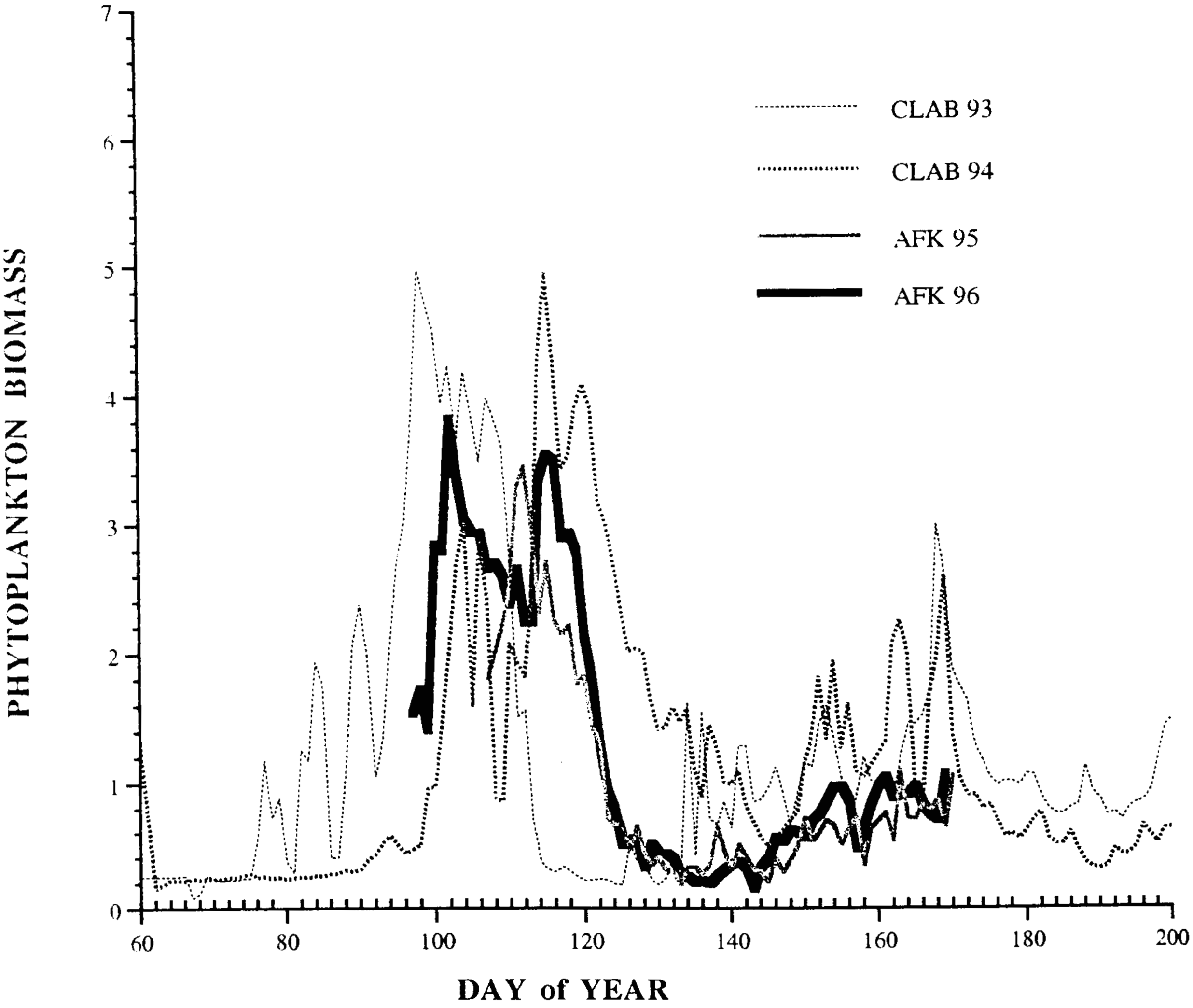

Figure 4. Comparison of phytoplankton time series for 1993 to 1996 in Prince William Sound (93 & 94 from CLAB buoy fluorometer; 95 & 96 from Station AFK96.2).

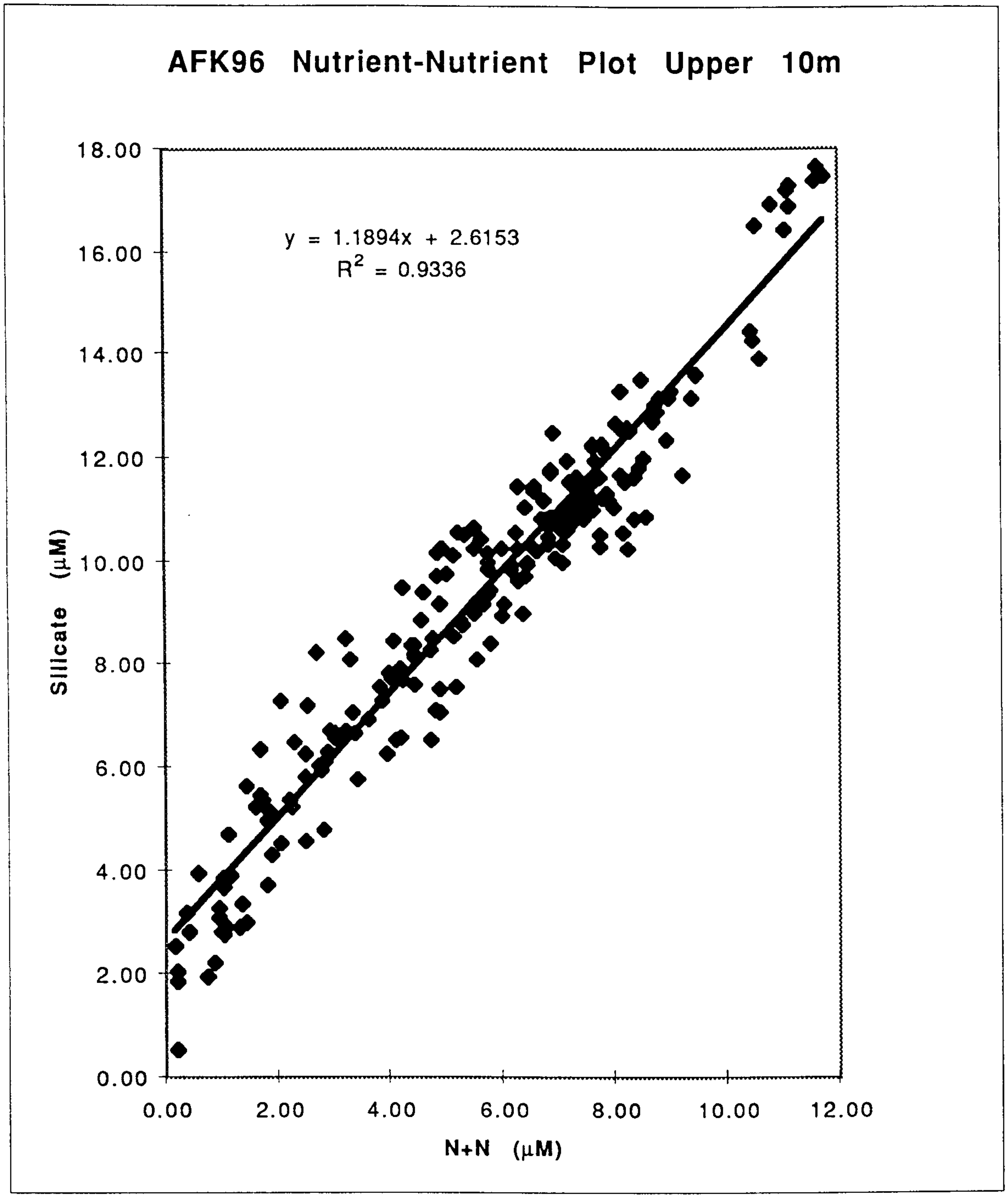

Figure 5. Nutrient-nutrient plot of N+N vs Silicate for the upper 10 m at Station AFK 96.2, 06 Apr -17 Jun 96 (Days 97-169).

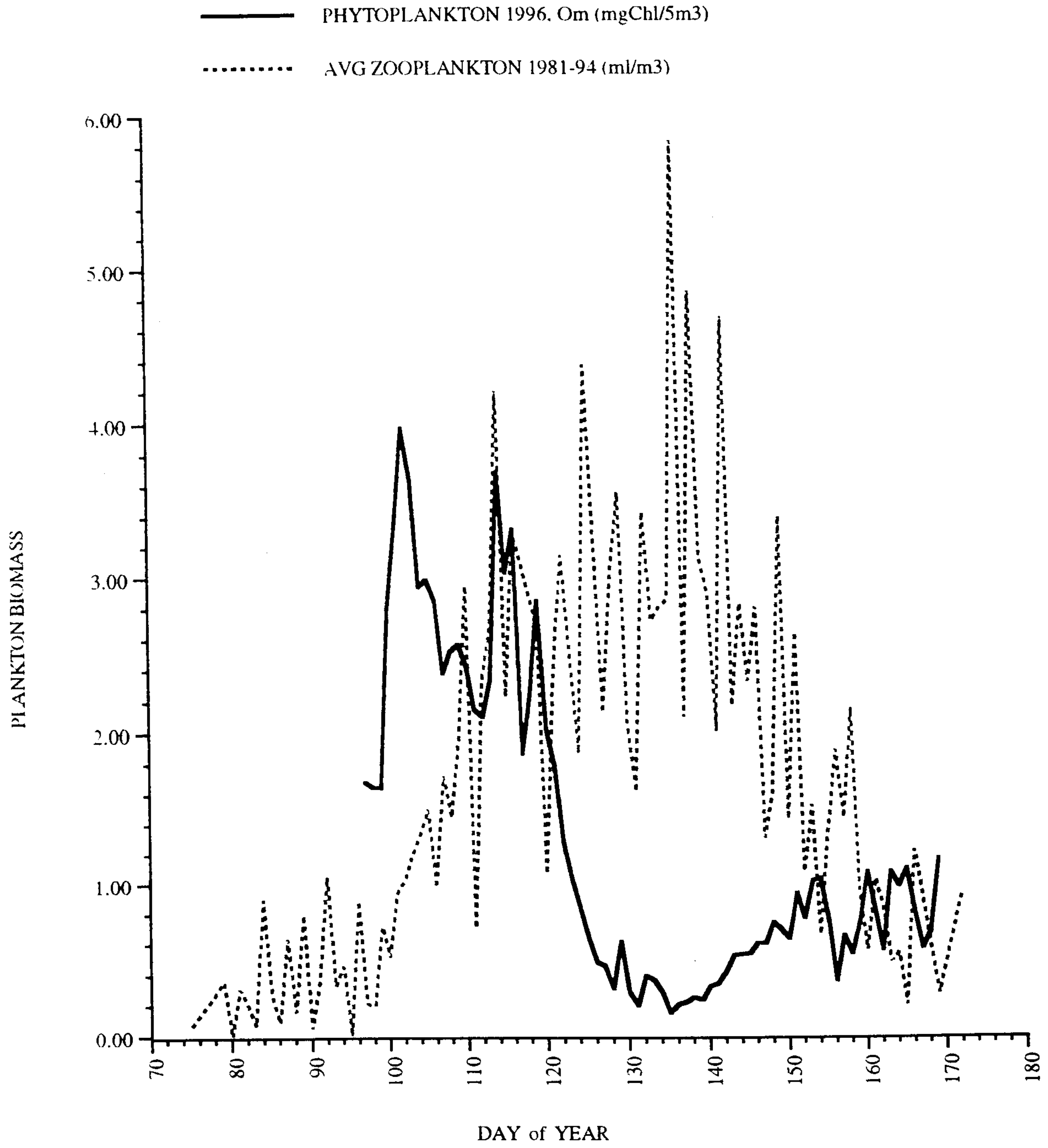

Figure 6. Time series of phytoplankton biomass (surface Chlorophyll a) from Station AFK96.2 and long-term average net zooplankton abundance near AFK hatchery.

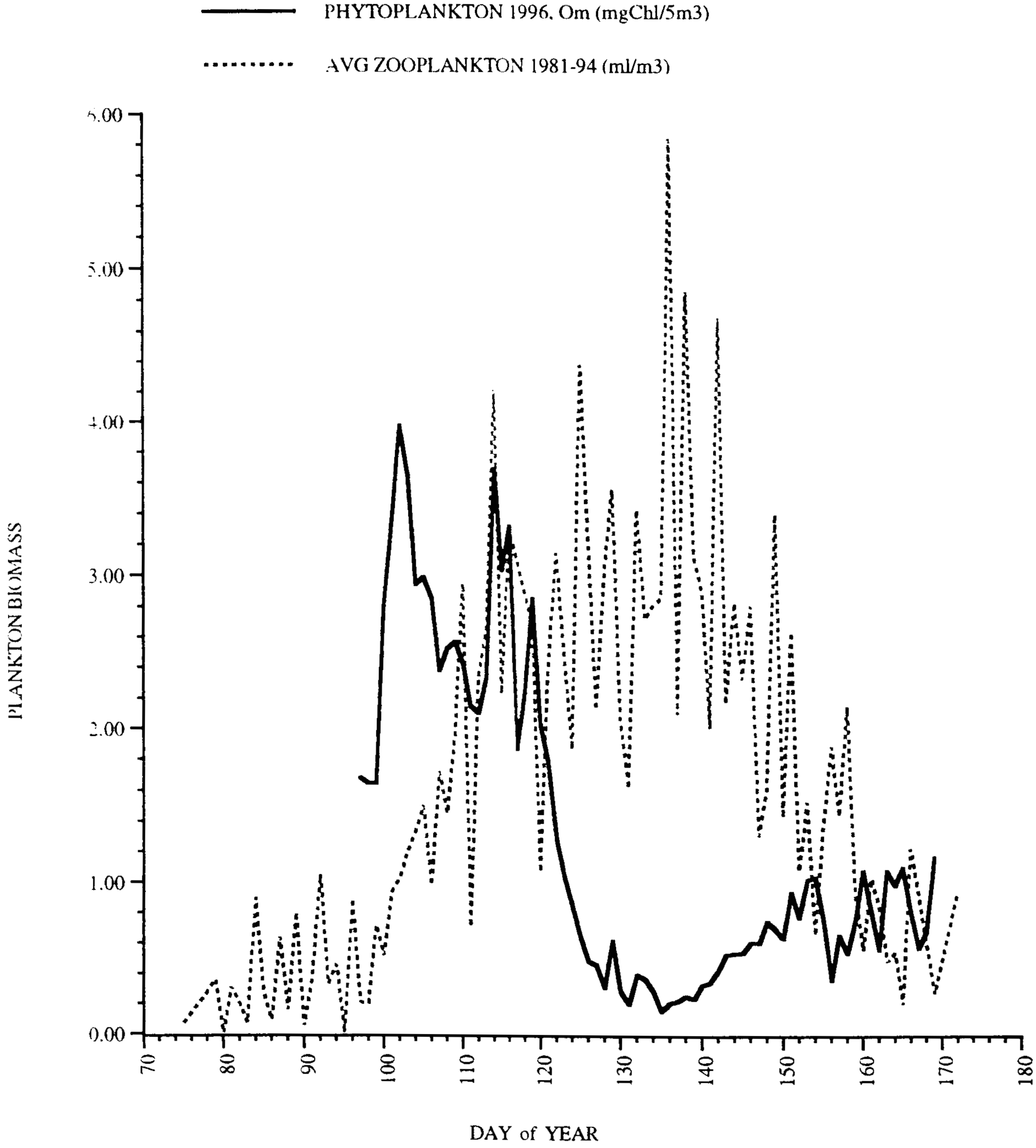

Figure 6. Time series of phytoplankton biomass (surface Chlorophyll a) from Station AFK96.2 and long-term average net zooplankton abundance near AFK hatchery.

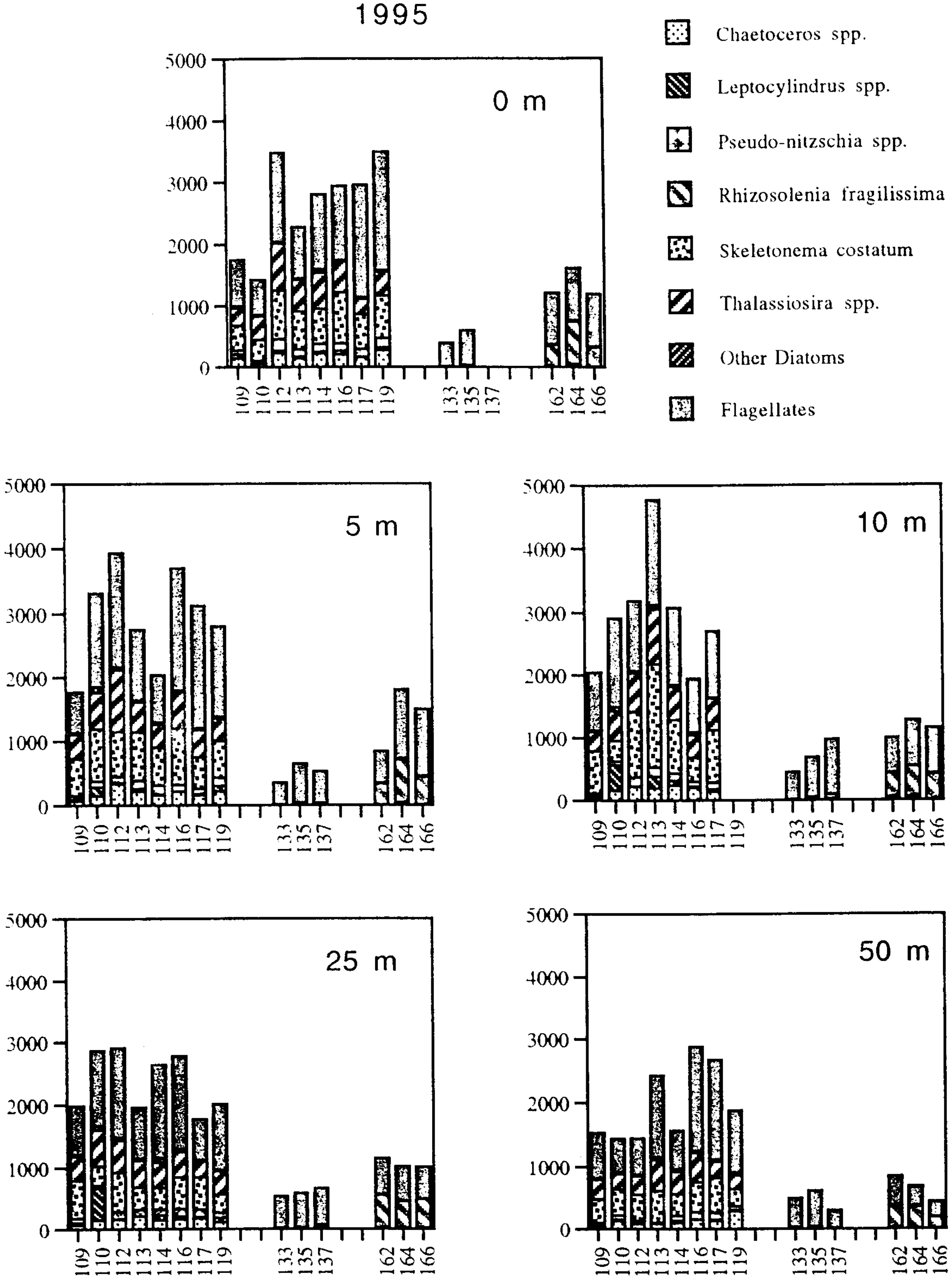

Figure 7. Abundance (cells/ml) of major diatoms and flagellates from 5 sample depths at Station AFK 95.2, during 19 Apr -15 Jun 95 (Days 110-167).

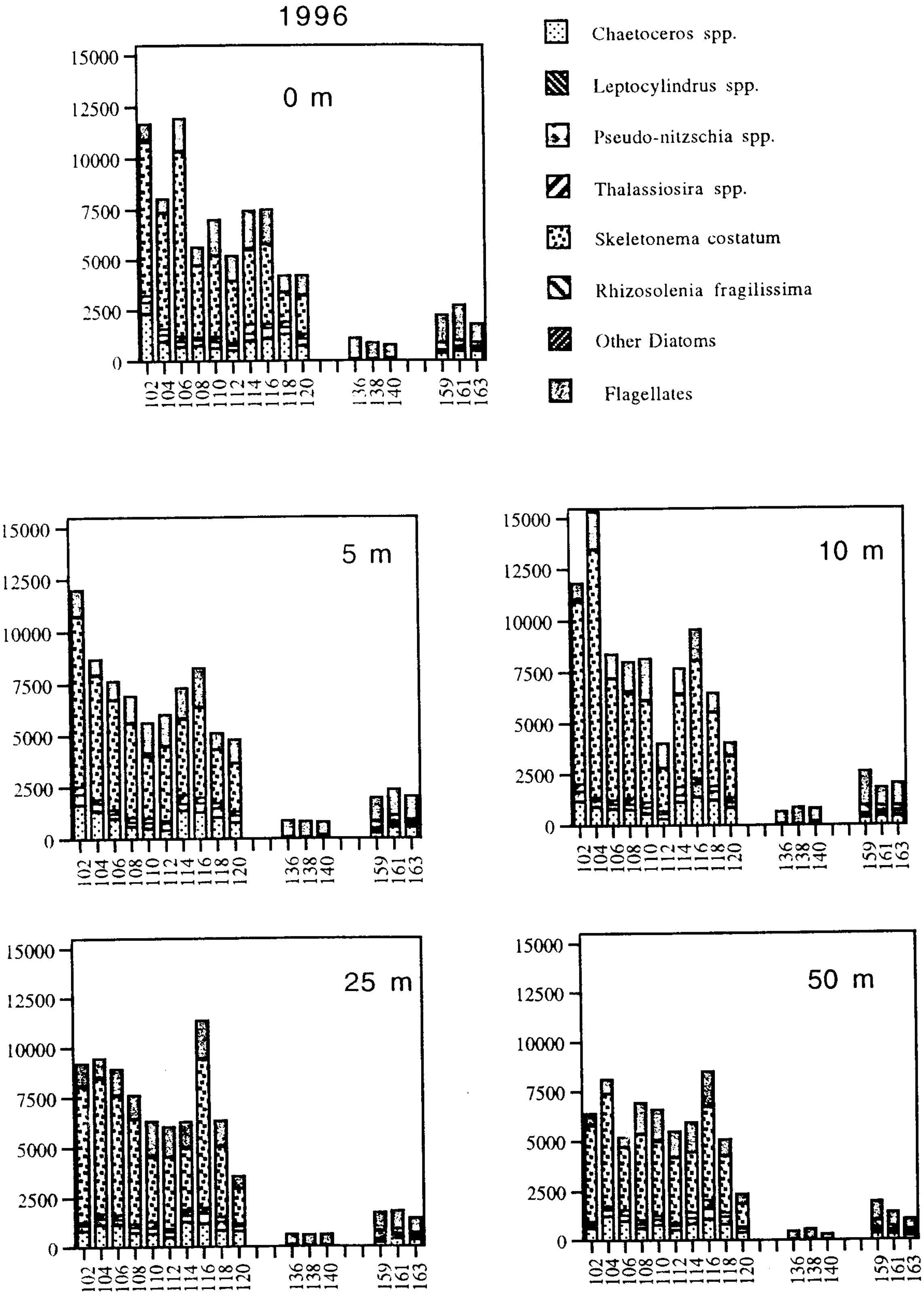

Figure 8. Abundance (cells/ml) of major diatoms and flagellates from 5 sample depths at Station AFK 96.2, during 11 Apr -11 Jun 96 (Days 102-163)

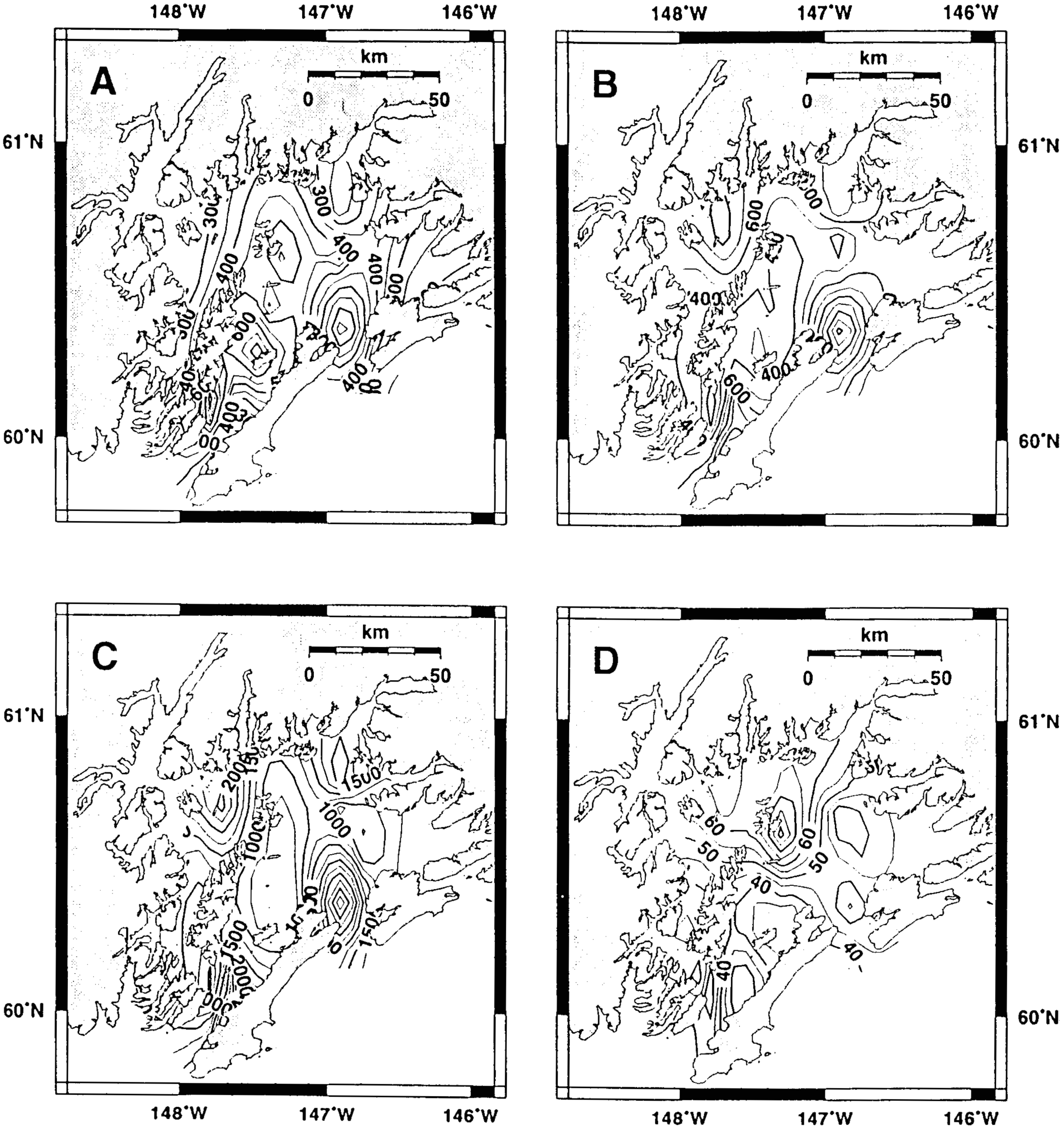

Figure 9. Distribution in Prince William Sound of integrated (upper 50 m) phytoplankton (mg/m^2) and nutrients (mmol/m^2) in April 1996: A. Chlorophyll a; B. N+N; C. Silicate; D. Orthophosphate.

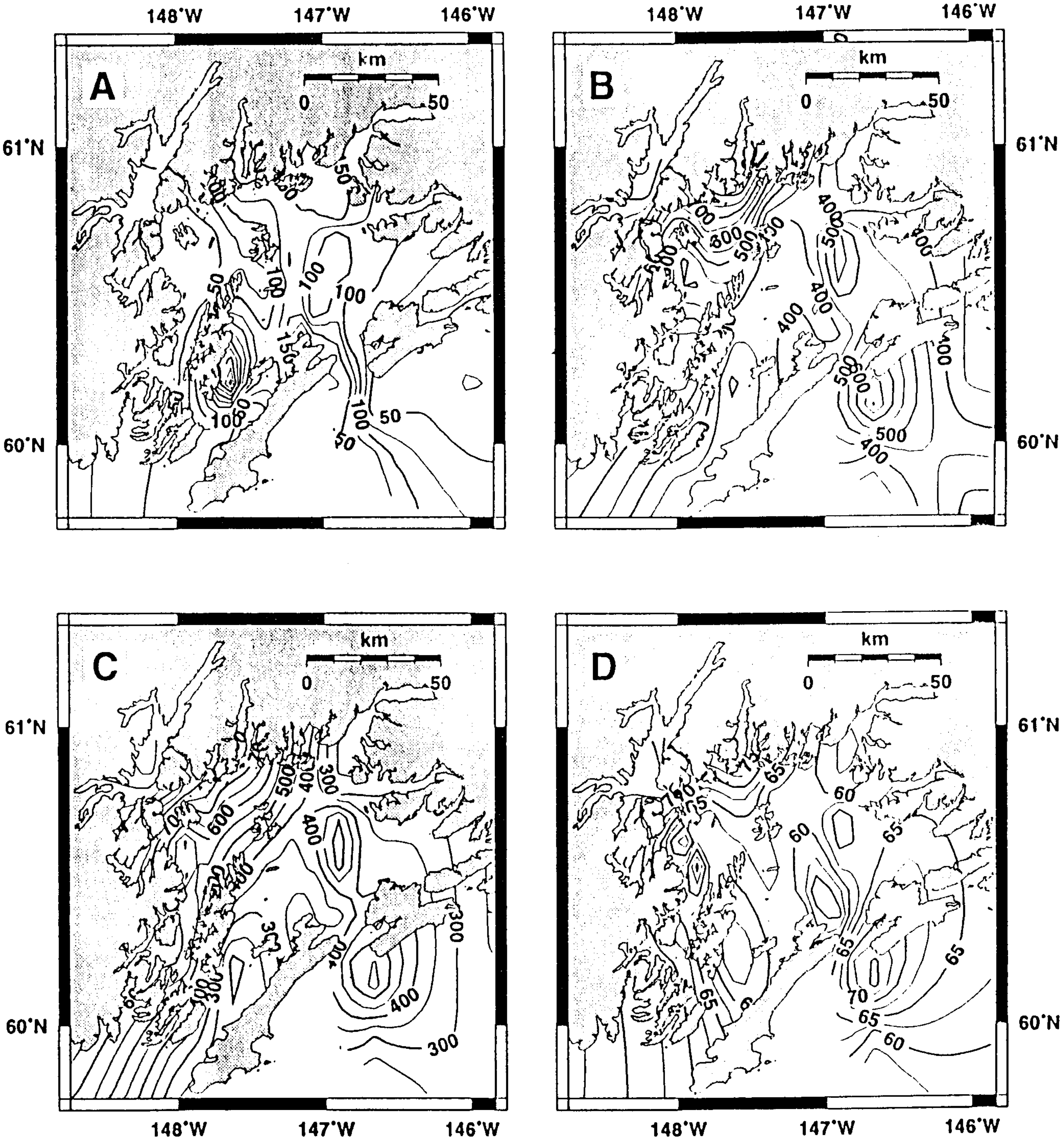

Figure 10. Distribution in Prince William Sound of integrated (upper 50 m) phytoplankton (mg/m^2) and nutrients (mmol/m^2) in May 1996: A. Chlorophyll a; B. N+N; C. Silicate; D. Orthophosphate.

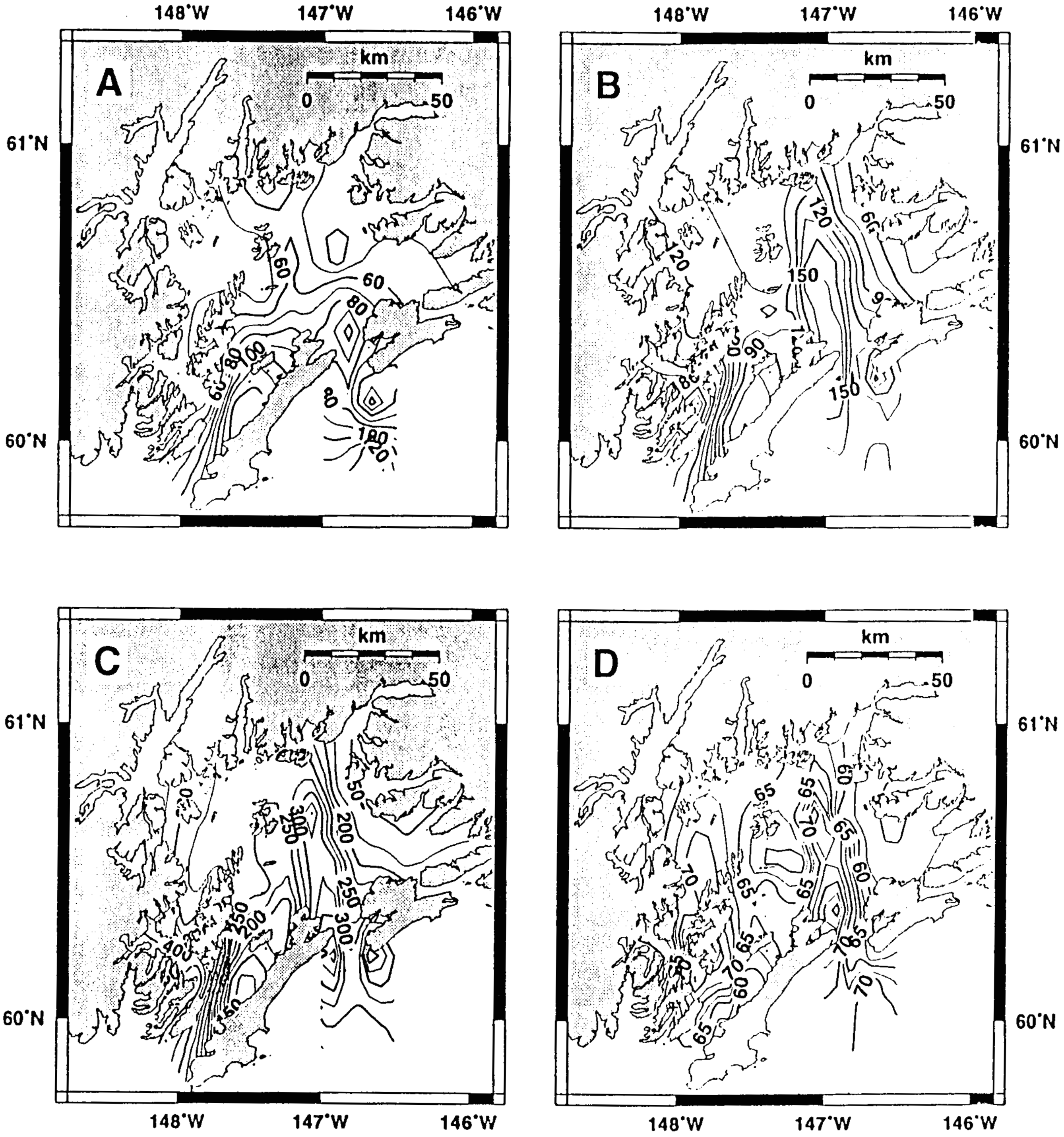

Figure 11. Distribution in Prince William Sound of integrated (upper 50 m) phytoplankton (mg/m^2) and nutrients (mmol/m^2) in June 1996: A. Chlorophyll a; B. N+N; C. Silicate; D. Orthophosphate.

Chapter 4.

The Role of Zooplankton (96320H)

Exxon Valdez Oil Spill
Restoration Project Annual Report

The Role of Zooplankton in the Prince William Sound Ecosystem

Restoration Project 96320-H
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Robert T. Cooney
Kenneth O. Coyle

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska 99775-7220

April 1997

The Role of Zooplankton in the Prince William Sound Ecosystem

Restoration Project 96320-H
Annual Report

Study History: Restoration Project 96320-H was continued in FY96 as part of the original integrated five-year Sound Ecosystem Assessment (SEA) program addressing injuries to pink salmon and herring populations in Prince William Sound initiated in April, 1994. Annual reports for this project have been submitted previously as part of single, integrated SEA program annual reports for FY94 and FY95. An invited paper (Cooney, R. T. and T. M. Willette. 1966. Factors influencing the marine survival of pink salmon (*Oncorhynchus gorbuscha*) in Prince William Sound, Alaska) was presented at the Estuarine and Ocean Survival of Northeastern Pacific Salmon conference in Newport, Oregon, March 20-22, 1996. The paper was subsequently accepted for publication in the proceedings of the conference - a joint NOAA/NMFS and OSU Hatfield Marine Center report (in press). A second invited paper (Cooney, R. T. and R. D. Brodeur. 1966. Carrying capacity and North Pacific salmon production: stock enhancement implications) was presented at the 1996 William R. and Lenore Mote Symposium on Marine Stock Enhancement held at the Mote Marine Laboratory, Sarasota, Florida, November 21-23, 1996. A manuscript is being reviewed for the *Bulletin of Marine Science* which will publish selected papers from the symposium. A final report of project 230-H will be prepared for the Trustee Council as part of the formal close out of the program in FY99.

Abstract: Our work in 1996 demonstrates that in early May, 1996, populations of *Neocalanus* spp. in Prince William Sound and in the waters over the adjacent continental shelf were molting rapidly to stage V. Differences in community composition detected by cluster analysis defined two major macrozooplankton assemblages. One group was associated with water intruding the region from the adjacent continental shelf, while the other may have been a remnant population arising from local reproduction in the deep western and northwestern areas. *Neocalanus* and *Calanus* formed discrete layers in the upper 50 m of the water column at locations inside and outside Prince William Sound. At most locations, *N. plumchrus* and *flemingeri* stage V occurred shallower than *N. cristatus* stages III-V. *C. marshallae* distributions exhibited little preference for depth in the upper 50 m; layers being shallow at some locations and deep at others. We found no convincing evidence that plant stocks focus these calanoids into thin layers, although we were unable to test whether the grazers found food in unlimited quantities at all depths or actively sought out the depth of maximum photosynthesis. Layering behavior by *Calanus* and *Neocalanus* likely provides strata in the water column where filter or gulp feeding pelagic fishes can forage efficiently on zooplankton.

Key Words: *Calanus*, *Exxon Valdez* oil spill, layers, Macrozooplankton, *Neocalanus*, Prince William Sound.

Project Data: Zooplankton abundance and biomass information is part of the SEA data base

(Project 96320-J Information Services and Modeling)

Citation:
Cooney, R.T., and K.O. Coyle. 1997. The role of zooplankton in the Prince William Sound ecosystem, Exxon Valdez Restoration Project Annual Report (Restoration Project 96320-H), Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, Alaska.

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Appendix 1. Vertical and horizontal distributions of macrozooplankton in Prince William Sound, Alaska, with emphasis on large calanoida (manuscript prepared for review by the *Journal of Plankton Research*).

Executive Summary

Previous 320-H studies of the role of zooplankton in Prince William Sound under the overall Sound Ecosystem Assessment (SEA) program have focused on describing seasonal and interannual variations in species composition and abundance, principally to support juvenile pink salmon growth and predation studies (320-E), but also to aid the broadscale numerical modeling of plankton fields in the region (320-J and 320-R). Work in FY96 focused attention on questions of *in situ* abundance and biomass, particularly the degree to which some macrozooplankters are capable of forming dense, near-surface layers that might prove to be efficient zones for the transfer of energy to higher trophic levels like adult walleye pollock. This collaborative work (high-frequency acoustics and optical plankton counting) was pursued on a joint cruise in early May aboard the University of Alaska vessel R/V *Alpha Helix*. Investigators from the University of Alaska and the Prince William Sound Science Center studied the layering phenomenon at a time when juvenile pink salmon were leaving natal streams and hatcheries for near-shore nursery areas, and populations of large calanoids were expected to be reaching seasonal biomass peaks.

This annual report presents results obtained by fishing a 1-m2 multiple opening-closing net environmental sensing system (MOCNESS) in the upper 50 m at locations inside and outside Prince William Sound. An appended draft manuscript describes patterns in broadscale horizontal and smallscale vertical distributions of selected macrozooplankters in the region. The work documents calanoid layers at many, but not all locations, zooplankton community affinities between the Sound and intruding water masses, and provides information about relationships between copepod layers or swarms and the vertical distribution of phytoplankton and mixing regimes in the water column. Results for other work in FY96 that were not met specifically by the field study in May are reported in the body of the report.

Introduction

The SEA program in Prince William Sound has undertaken an ecosystem approach to understanding the factors influencing pink salmon and herring production in the region. Study focus is on the early life stages of both species when most literature suggests that cohort strength is established. Juvenile pink salmon use Prince William Sound as a coastal nursery from late March through September before departing for oceanic feeding areas. In contrast, juvenile herring are resident in the Sound for 2+ years before recruiting to adult spawning populations. The juveniles of both species are dependent on zooplankton for food.

Previous studies of zooplankton in the subarctic Pacific Ocean demonstrate marked seasonality in upper-layer abundance and biomass (see Cooney, 1987 for a review). In coastal and nearshore waters, animal plankton populations respond to an early spring bloom of phytoplankton to build their populations. Cooney (1986) and Incze et al. (1997) provide evidence of the influence of ocean source populations on near-shore and coastal zooplankton assemblages. Oceanic stocks of large calanoid copepods invade the shelf each spring as part of the onshore transport of water in the northern Gulf of Alaska. These populations are believed to provide food for fishes, birds and marine mammals.

SEA studies of the role of zooplankton in Prince William Sound strive to understand how the species composition, distribution, abundance and biomass of this group influences the survival of juvenile pink salmon and herring rearing in Prince William Sound. SEA investigators hypothesize that while zooplankton serves as critical forage for rapidly growing immature stages, it may also serve as a predation refuge for juveniles whose losses to larger fishes, birds and mammals is probably related to the kinds and amounts of alternate prey. A clear match between the timing of the wild pink salmon fry outmigration from natal areas into nearshore marine waters with the timing and magnitude of the developing calanoid bloom observed in the Sound by a hatchery plankton watch program is probably not coincidental. We believe this relationship results from evolutionary pressure to match fry with appropriate food and quite possible shelter from predation from large fish like adult pollock that can also derive energy from plankton. Observations in 1995 at the peak of the salmon outmigration indicated that most adult pollock were consuming large quantities of maturing calanoid copepods at that time. SEA surmises that to be efficient, forage populations must occur in dense, near-surface layers providing efficient filter or gulp-feeding. Most of the field work in FY96 was designed to investigate this notion.

Objectives

The following objectives were stated in the approved FY96 DPD:

1. Measure collaboratively with other SEA components horizontal and vertical distributions of zooplankton in support of large and small-scale mapping activities, and determine the degree to which layers of zooplankton occur in Prince William Sound during the peak of the large calanoid bloom and juvenile salmon outmigration from natal streams and hatcheries.
2. Describe the time series of abundance and biomass for PWSAC plankton watches conducted at the AFK and WN hatcheries.
3. Work collaboratively with the three SEA modeling subgroups to make zooplankton data available for model construction and hypothesis testing.
4. Contribute information to investigators studying the somatic energy content of juvenile herring.

Methods

Methods used to pursue the documentation (or not) of calanoid copepod layers in Prince William Sound are described in the method section of the attached appendix 1. Samples from the plankton watches at the AFK and WN hatcheries were obtained by hatchery personnel fishing 1/2-m nets vertically by hand in the upper 20 m of the water column weekly from mid March through June. After settled volumes were determined by the hatchery, samples were saved and later processed in the Principal Investigator's laboratory.

Data were interpreted and made available to other collaborators in SEA via the SEA data base and by use of the SEA information network. In some cases, data exchange and application was facilitated by the Fall 1996 SEA workshop in Seward.

Results

Appendix 1 has been prepared for publication and describes the results of the MOCNESS survey work in Prince William Sound in early May, 1996. These results will join those collected by investigators sampling with high-frequency acoustic and optical plankton techniques to describe the structural properties of near-surface plankton layering and its implications for food web transfers to higher level consumers that also prey on juvenile pink salmon and herring. This broader, collaborative synthesis paper will probably be submitted in FY97.

Settled volume data for the AFK and WN hatcheries in southern and northern Prince William Sound respectively were examined for relationship with the Bakun upwelling index. However, the monthly index for May at location 60N 146W is missing from the time series, so I am unable to add the FY96 data to the regressions for AFK and WN hatcheries. Average settled volume at AFK in 1996 was somewhat lower (1.79 ml m-3) than the most recent high in 1995 (1.96 ml m-3). Samples are still being analyzed for species composition, abundance and biomass. These results will be reported in the FY97 annual report, and an attempt will be made to recover the May, 1996 upwelling observations from NOAA.

The principal investigator worked closely with project 320-R to assist with creating and testing a dynamic plankton 1-D model for Prince William Sound (see report of 320-R in this volume). The collaboration included providing data and data interpretation, and assisting with the preparation of a manuscript for publication that describes the preliminary results.

Information on the caloric content of several common zooplankters was made available to investigators studying and modeling the somatic energy content of juvenile herring. Previous work by Harris (1985) provided a starting point for initial evaluations of the energy input contributed by calanoid copepods, amphipods, pteropods and other dominant taxa. Data on zooplankton abundance and biomass continues to be posted in the SEA data base for use by all SEA (and other) investigators.

Discussion

Our field work continues to refine the role that zooplankton serves as a structuring element in food-webs influencing the survival of juvenile pink salmon and herring in Prince William Sound, Alaska. The suspicion that layering by large calanoids may be a common springtime phenomenon in the region was generally confirmed. Our preliminary results also add support to the idea that the northwestern and western parts of the Sound may be oceanographically isolated from other regions, at least in the spring and early summer. Cluster analyses on both abundance and biomass involving 30-40 major species and taxonomic categories demonstrated strong coherence between locations inside and outside the Sound. These observations further refine our view of lake (isolated) and river (intrusion) portions of the Sound, and challenge further work to understand the role that these biological and physical affinities play in influencing juvenile pink salmon and herring survival. The possibility that *Neocalanus* in the western and northwestern region may originate from local stocks will be evaluated when the isotope samples collected on the cruise become available. This new information will further assist in the validation of ocean state and plankton models.

Conclusions

The results of work completed in FY96 strengthen our collective understanding of the role that zooplankton plays in food-webs influencing the survival of juvenile pink salmon and herring in Prince William Sound. Our views on relationships between populations inside and outside the Sound have been enhanced. A case for partial isolation of some regions, and coherence between others with intruding shelf waters builds on the idea that the region is partitioned in ways that might also be apparent at higher trophic levels. As the result of the *Alpha Helix* cruise, we now know that zooplankters, principally the late stages of the *Neocalanus* and *Calanus* can occur in narrow layers at a time pink salmon are emerging from natal areas into coastal nurseries. Within-layer densities exceeding 1000 individuals m-3 at some locations probably provide efficient feeding opportunities for a variety of consumers, some capable of also feeding on fry. This information is critical to the process of modeling prey switching driven by the bioenergetics demands of predators and prey, and is finding immediate use in this regard.

Acknowledgments

This work was aided by investigators representing 320-N (Plankton and Nekton Acoustics), 320-M (Physical Oceanography), 320-I (Stable Isotopes) and 320-G (Phytoplankton and Nutrients). Hatchery managers at the WN and AFK PWSAC hatcheries are thanked for their continuing cooperation with the SEA Program. Bill Hauser is acknowledged for his participation on R/V *Alpha Helix* cruise HX-192.

Literature Cited

Cooney, R. T. 1986. The seasonal occurrence of *Neocalanus cristatus*, *Neocalanus plumchrus* and *Eucalanus bungii* over the shelf of the northern Gulf of Alaska. Continental Shelf Res. 5: 541-553.

Harris, R. K. 1985. Body composition (Carbon, Nitrogen, and calories) and energetics of immature Walleye pollock (Theragra chalcogramma) in the southeast Bering Sea. M. S. Thesis, University of Alaska Fairbanks, Faribanks, Alaska. 116 p.

Incze, L. S., D. W. Siefert and J. M. Napp. 1997. Mesozooplankton of Shelikof Strait, Alaska: abundance and commuity composition. Continental Shelf Res.36:287-305.

Appendix 1

Draft

(For Submission to the Journal of Plankton Research)

Vertical and Horizontal Distributions of Macrozooplankton in Prince William Sound, Alaska, with Emphasis on Large Calanoida

R. Ted Cooney, Kenneth O. Coyle and Elizabeth Stockmar

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska 99775

Abstract

Macrozooplankton populations in Prince William Sound were dominated by juvenile euphausiids and calanoid copepods in early May, 1996. Much of the abundance and biomass was associated with the large, older copepodite stages of *Neocalanus plumchrus* and *N. flemingeri*. Horizontal plankton distributions reflected affinities with Gulf of Alaska source populations except for collections in Knight Island Passage and the waters in the northwestern corner of the region which clustered as a separate group. These differences are probably related to water mass characteristics (temperature and salinity), and perhaps population remnants from local reproduction isolated in the deep northern and western areas of the Sound.

At many locations where *N. plumchrus* and *flemingeri* stage V dominated the abundance and biomass, these species occurred in well-defined layers 5 to 25 m in vertical extent. Within-layer densities exceeding 1000 individuals/m3 and 2-3 g/m3 (wet weight) demonstrate locally abundant forage resources for pelagic fishes and other consumers. Unlike the oceanic Gulf of Alaska, the surface mixed layer was very shallow at most locations over the shelf and inside Prince William Sound. *Neocalanus plumchrus*, N. *flemingeri* almost always occurred above and/or in the near-surface pycnocline, while *N. cristatus* was restricted to deeper water in the upper 50 m. *Calanus marshallae* exhibited layering behavior as well, but no clear preference for deep or shallow was observed. Layers of maximum copepod density co-occurred with surface or

subsurface fluorescence peaks at only 32% of the locations in the region.

Introduction

Mackas, et al. (1993) described vertical habitat partitioning by large calanoids in the open subarctic Pacific Ocean. Their study demonstrated close correlation between upper-layer mixing regimes and depth preferences for *Neocalanus plumchrus*, *N. flemingeri*, *N. cristatus*, and *Eucalanus bungii*. Annually developing copepodites of the former two species were consistently found above or in the weak seasonal thermocline, while the latter were generally restricted to the water column below the seasonal thermocline. This separation was interpreted to reflect feeding preferences for protozoans in the spring and summer surface mixed layer by *N. plumchrus* and *flemingeri*, and detrital feeding on aggregates settling from the surface zone by *N. cristatus* and *E. bungii*.

Cooney (1986) documented the presence of *Neocalanus plumchrus*, *N. cristatus* and *Eucalanus bungii* over the shelf of the northern Gulf of Alaska south of Prince William Sound. These distributions were attributed to strong cross-shelf transport forced by down-welling favorable winds interacting with source populations in the epipelagic layer of the adjacent deep ocean. These interzonal copepods have previously been reported overwintering in Prince William Sound by Damkaer (1977). Coupled with a growing understanding of coastal flow patterns and the intrusion of shelf water into Prince William Sound (Neibauer et al., 1994), a mechanism exists to infuse the coastal zone of the northern Gulf of Alaska oceanically-derived copepods each year, some of which are apparently capable of reproducing in the deep waters of sounds and fjords. This seeding phenomenon has most recently been demonstrated for the waters of Shelikof Strait, a portion of the shelf environment west of Prince William Sound near Kodiak Island (Incze et al., 1997).

Our study was designed to investigate similarities in upper-layer spring-time macrozooplankton populations inside and outside Prince William Sound when the older copepodite stages of *Neocalanus* were expected in the surface waters (0-50 m). Historical records from the plankton watch program of a regional aquaculture corporation (Prince William Sound Aquaculture Corporation; Cordova, Alaska) demonstrate that a peak in settled plankton volume occurs in early to mid-May each year. These same records indicate that average spring-time (March-June) settled volumes have varied in the southern part of Prince William Sound by about a factor of 5 since 1981. It is unclear to what extent year-to-year variability is the result of differences in local production or seeding/flushing from, or to the adjacent Gulf of Alaska. Because about 10 percent of the Sound is deeper than 400 m, deep overwintering habitat is available to accommodate *a Neocalanus* diapause and reproduction as described by Fulton (1973) for the Strait of Georgia.

Additionally, observations of adult pollock (*Theragra chalcogramma)* feeding behavior in late April and early May in Prince William Sound demonstrated selection for stage 4 and 5 *N. plumchrus* and *N. flemingeri* (Cooney, unpublished). This behavior raises questions about *in situ* concentrations required to sustain filter feeding by large pelagic fishes. We hypothesized that locally produced copepods and those intruding into the region with the coastal current could efficiently feed populations of adult pollock and other consumers if these plankters were restricted in their vertical distribution to narrow zones in the surface water (layers or swarms). Optical plankton records from a previous survey in Prince William Sound hinted at layers, although those observations were not accompanied by zooplankton collections. Our work sought resolution of the calanoid layer question with nets capable of resolving discrete depth distributions in strata as narrow as 5 m.

Methods

Zooplankton sampling was conducted in and adjacent to Prince William Sound, Alaska, a deep fjord-type estuary located at the northern-most reaches of the Gulf of Alaska (Figure 1). The region is deep (to 750 m), is bounded on to the west, north, and east by the Chugach Mountains, and communicates with the adjacent Gulf of Alaska via the Alaska Coastal Current (ACC) entering through Hinchinbrook Entrance and Montague Strait. The region occupies nearly 9000 km2 and exhibits 3200 km of shoreline. The adjacent shelf of the northern Gulf of Alaska is a wind-forced downwelling system for 8 months of each year. Stabilization or weak upwelling can occur in the summer months. Deep water in the Sound is renewed each year during the time of relaxed downwelling, late summer and early fall.

A MOCNESS sampler was employed at 24 stations inside and outside PWS to collect macrozooplankton in the upper 50 m (Figure 1). Sampling was undertaken at the peak of the early spring zooplankton bloom, early to mid-May, and about two weeks after the seasonal maximum in phytoplankton stocks judged by a moored fluorometer in the central region of the Sound. The MOCNESS fished nine,1-m2 Nitex nets of 0.505-mm mesh. Net one was lowered open from the surface to a depth below 50 m with the vessel steaming at about 1.5 m sec-1. The remaining nets were then opened and closed on a slow oblique retrieval. Sampling intervals were standardized at 50-40 m, 40-30 m, 30-25 m, 25-20 m, 20-15 m, 15-10 m, 10-5 m, and 5-0 m. Collections were carefully rinsed from nets and preserved in 10% seawater formalin for later processing. Processing included identification and enumeration of plankters and the various copepodite stages of the large calanoids. Representatives of species were weighed in size categories to convert numbers to estimated wet weight (Coyle, et al., 1990).

A SeaBird 911 CTD and *in situ* fluorometer were lowered at the beginning or end of each MOCNESS station to describe upper-layer hydrography and mixing, and the vertical distribution of phytoplankton. The fluorometer was not calibrated so only relative fluorescence was obtained from each cast. This was believed sufficient to examine the possibility that copepod layers might be strongly associated with vertical patchiness in plant stocks.

Results

Community composition

A cluster analysis was performed to determine similarities in the horizontal distribution of species composition among all stations. For each MOCNESS station, the top 5 ranked taxonomic categories (numbers or biomass) were selected from each of the 8 nets, and the overall listing of taxa used to differentiate between stations. Forty-three taxonomic categories contributed to the cluster analysis on abundance; 53 to clustering on biomass.

For abundance, the highest level of differentiation separated two groups that included 10 locations outside and from the central, northern and eastern regions of the Sound - Group 1, and 14 locations mostly in the northern and western part of the region - Group 2 (Figure 2). Only Station 15 in Group 2 clustered outside its geographic region (Figure 3). When biomass was used to cluster stations, the first level of differentiation separated two groups that were similar to those clustering on abundance. However, under the biomass ranking criteria three stations that previously clustered with Group 2 (Stations 6, 18 and 19), joined Group 1, while Station 9 shifted to the northwestern/western cluster (Figure 4). A t-test of differences between taxa and stages within groups for abundance and biomass demonstrated that for abundance, clustering was driven primarily by 8 different categories, while for biomass, the major differentiations were forced principally by only 2 categories ($p<0.05$; Table 1).

A ranking by numerical abundance within the major cluster groups was performed to describe the numerical dominants (Table 2). Group 1, the outer-shelf and central Sound assemblage was dominated by juvenile euphausiids (furcilia and calyptopis stages) and *Neocalanus flemingeri* stage V, while Group 2 was led by *N. plumchrus* and *N.flemingeri* stage V, with juvenile euphausiids playing a much lesser role. The top ten categories in Group 1 also contained the hydromedusan, *Aglantha digitale,* and the pterpod, *Limacina helicina.* These taxa were absent from the top ten ranking of Group 2.

Patterns of vertical distribution for large calanoids

Vertical profiles for the large calanoid species *Neocalanus plumchrus*, *N. flemingeri*, *N. cristatus*, and *Calanus marshallae* were examined for evidence of layering and association with the buoyancy frequency and fluorescence patterns in the upper 50 m at each location. We could only confidently distinguish between *N. flemingeri* and *N. plumchrus* at copepodite stage V, so restrict our accounts of those closely related copepods to that stage (Miller, 1988). A composite of *N.* spp. stage III and IV was examined separately. For *N. cristatus*, a composite of stages III-V is reported, and for *Calanus marshallae*, stages IV through adult were combined to search for patterns in vertical distribution. A distribution was considered "layered" in the upper 50 m when most of the abundance or biomass was restricted to 50% or less of the sampled domain.

Neocalanus flemingeri stage V ranked second in Group 1 and first in Group 2 by abundance, and *N. flemingeri* and *N. plumchrus* stage V ranked first and second respectively in both groups by biomass establishing their dominance throughout the region in early May, 1996. For outside waters and Prince William Sound Group 1, these species (stage V) co-occurred in 66% of the samples, while in Group 2 (western and northwestern stations and including station 15), co-occurrence was reduced to 37% of the samples. Also, in samples where they co-occurred, *N. plumchrus* was generally found at all depths in Group 1, but restricted to the upper portion of the sampling domain in Group 2, the exception being station 15 in which co-occurrence was present at all depths (Figure 5). The combined abundance and biomass of the stage Vs of these two species was greatest over the outer shelf near Middleton Island (station 9). Here, combined numbers and biomass exceeded 1500 individuals m-3 and 4 g m-3 respectively. For Group 1, 50% of the stations exhibited at least one depth for which the abundance of these combined species (stage V) exceeded 100 individuals m-3, while for group 2, 93 % of the stations exhibited at least one depth where the combined abundance exceeded 100 individuals m-

3. *Neocalanus plumchrus* and *N. flemingeri* stage V were found in dense layers at 50 % of the locations in Group 1, and 79% of the locations in Group 2 (Figure 6).

A composite of *Neocalanus plumchrus* and *N. flemingeri stages* III-IV exhibited vertical distributions similar to stage V. These copepodites occurred in dense layers at 50% of the locations in Group 1, and 79% of the locations in Group 2 (Table 3; Figure 7). Combined stages III and IV were more abundant than stage V at 4 locations (40%) in Group 1, but at only 1 location (7%) in Group 2. These stage differences suggest that the rate of development was more rapid in the western and northern regions of Prince William Sound, and that most IIIs and IVs had already molted to stage V across the region.

The large copepod *Neocalanus cristatus* stages III-V was much less abundant at all locations than *N. plumchrus* and *flemingeri*; at only 3 of 24 locations did the concentration of *N. cristatus* exceed 10 m-3. However, even at diminished numbers, this copepod occurred in layers at 50% of the locations in Group 1 and 93% of the locations in Group 2 (Table 3). In Group 1, the distribution of *N. flemingeri* and *N. plumchrus* stage V overlapped with *N. cristatus* at 70% of the locations, whereas in Group 2, there were only 2 locations of overlap (14%). Generally, maximum densities of *N. cristatus* occurred deeper in the water column than did *N. plumchrus* and *N. flemingeri* (Figure 9).

Calanus marshallae, stages IV-adult exhibited a lesser capacity to form dense layers. For Group 1, only 30% of the locations were represented by layering compared to 71% of the locations in Group 2 (Table 3). *C. marshallae* demonstrated no clear pattern of depth distribution (Figure 10).

Vertical patterns of florescence and copepod distributions

Subsurface maxima were apparent at 6 of 10 locations in Group 1 and at all locations in Group 2 (Figure 11). Surface florescence maxima occurred at the shelf-break location 9, and in the ACC at Station 11. Stations 13 and 14 in Montague Strait exhibited generally homogeneous patterns of fluorescence with depth. For the copepod species and stages examined in this study, maximum densities were closely aligned with florescence maxima at 40 % of the locations in Group 1, but at only 25% of the locations in Group 2. Overall, copepod layers co-occurred with subsurface fluorescence maxima at less than 32% of the locations (Figure 12).

Fluorescence levels varied throughout the region. Four Group 1, 4 of 10 locations exhibited depths where the fluorescence exceeded 1.0 volt. In Group 2, only 3 of 14 locations had fluorescence peaks exceeding 1.0 volt. These results indicate the spring phytoplankton bloom was probably over, except over the outer continental shelf south of the Sound and at spotty locations inside the Sound.

Vertical patterns in buoyancy frequency

Buoyancy frequency measures the degree of mixing with depth in the water column. Maxima correspond within regions of reduced vertical mixing. At most stations in this study, buoyancy frequency was maximum in the upper 20 m in response to seasonal freshwater input and thermal stabilization. Only at Station 9 at the self-break was there a well-defined subsurface maximum in buoyancy frequency at about 20 m (Figure 13). There was no consistent relationship between copepod distributions and the buoyancy frequency at any location. Since

Neocalanus cristatus generally occurred deeper in the water column than the other species and stages, it was most often (but not always) found below the near-surface maximum in buoyancy frequency.

Patterns in watercolumn temperature and salinity

Stations 9 and 10 at the edge and over the continental shelf were warm (8 C) and saline (>32 ppt). Station 11 in the ACC was also warm, but much less saline at the surface (30.5 ppt). In contrast, locations clustering with Group 2 (excluding Station 15) tended to be colder and less saline (6-7 C, ranging up to 30 ppt). The remaining locations in central and northern Prince William Sound were intermediate between these endpoints suggesting that a mixing process between intruding shelf and interior Sound waters was probably responsible for the observed gradients (Figure 14).

Discussion

We found that some macrozooplankton collections in Prince William Sound demonstrated statistical affinities with locations outside the region, while others grouped with an assemblage located primarily in Knight Island Passage and the northwestern part of the Sound. We have no explanation why one location (station 15) north of Hinchinbrook Entrance clustered with the other assemblage. We interpret the physical separation of these two groups as signaling strong continuity between northern, central, eastern and southern portions of Sound and waters intruding from the adjacent Gulf of Alaska, but isolation from this intrusion at locations in the west and northwest regions. Measured and modeled flow fields in the spring in Prince William Sound exhibit inflow at Hinchinbrook Entrance and outflow through Montague Strait (Neibauer et al., 1994; Mooers and Wang, submitted). This flow is generally believed to move northward and westward through the Sound. Our results seem to indicate the biological and physical influences of this flow are not as strongly demonstrated in the western and northern parts of the Sound as they are in other regions. Shelf waters intruding the Sound are generally warmer and more saline than those inside the region. As the intruding watermass spreads through the Sound, it cools and becomes less saline before exiting at Montague Strait. The western and northern waters in Knight Island Passage and in the northwestern regions appear more dominated by local processes; glacial meltwater probably forms a stable freshwater lens at the surface in much of that region.

Damkaer (1977) reported *Neocalanus* spp. in diapause in the deep waters of Prince William Sound in October. This is not surprising since Fulton (1973) described overwintering populations of *Calanus (Neocalanus) plumchrus* in the Strait of Georgia at depths of about 400 m. Prince William Sound is deeper than 400 m in the northern and western regions so should accommodate local reproduction, but only in these areas. Copepodites originating from deep-water stocks would presumably occur most abundantly in or near the location where spawning occurs. Because of this, we believe that some major portion, or all of the late stage *Neocalanus* spp. in Group 2 are remnants from local deep-water spawning in that region and exist there because of physical isolation from intruding shelf and ocean sources in the late winter and spring. If this is so, interannual variability in standing stocks of *Neocalanus* spp. at other locations in the Sound must be associated with year-to-year differences in source stocks over the shelf and/or differences in rates of seeding or flushing associated with late winter and spring intrusions of shelf water. Conversely, year-to-year variations in western and northwestern *Neocalanus* spp. stocks are probably related more to the reproductive success of adults spawning in the deep northwestern and western regions of Prince William Sound.

Prior to our study, limited information on adult pollock feeding ecology and some preliminary optical plankton counting observations (Prince William Sound Science Center; Cordova, Alaska) suggested that some zooplankton populations were probably occurring in layers or swarms in the upper 50 m in sufficient densities to support filter or gulp-feeding by large pelagic fishes and possibly other consumers. The ability to feed on plankton has been reported for pollock but not in the context of available food fields. Our results in May, 1996, demonstrate convincingly that layering by late-stage copepodites of *Neocalanus plumchrus* and *N. flemingeri* was occurring at within-layer densities up to 1000 individuals m-3 and 2-3 g m-3. The much larger *N. cristatus* also demonstrated layering behavior, but densities rarely exceeded 10 individuals m-3. A closely related large calanoid, *Calanus marshallae,* was abundant and formed layers as well. However, this medium-sized species exhibited no clear preference for deep or shallow parts of the upper 50 m, while *N. plumchrus* and *flemingeri* generally preferred the upper 30 m and *N. cristatus* was quite consistently found deeper. These patterns in *Neocalanus* vertical distribution generally agree with the findings of Mackas et al., (1993).

At most locations where physical stratification was apparent, there was a well-defined subsurface maximum in fluorescence. However maxima in copepod densities or biomass occurred in the subsurface peak in fluorescence at less than half the locations. *Neocalanus* spp. stage V should have been elaborating wax esters at this time (Miller, 1993), so might reasonably have been expected to co-occur with peaks food. In the absence of strong evidence that maxima in phytoplankton were focusing the vertical distributions of these large grazers, we conclude that either food was not limiting growth at most depths in the upper 50 m, or the copepods were targeting regions of high plant productivity, not standing stock. Unfortunately, our observations do not permit distinguishing between these possibilities.

In summary, our study demonstrates that in early May, 1996, populations of *Neocalanus* spp. in Prince William Sound and in the waters over the adjacent continental shelf were molting rapidly to stage V. Differences in community composition detected by cluster analysis defined two major macrozooplankton assemblages. One group was associated with water presumably intruding the region from the adjacent continental shelf, while the other could have been a remnant assemblage arising from local reproduction in the deep western and northwestern areas. *Neocalanus* and *Calanus* formed discrete layers in the upper 50 m of the water column at many locations inside and outside Prince William Sound. At most, *N. plumchrus* and *flemingeri* stage V occurred shallower than *N. cristatus* stages III-V. *C. marshallae* distributions exhibited little preference for depth in the upper 50 m, layers being shallow at some locations and deep at others. We found no convincing evidence that plant stocks focus these calanoids into thin layers, although we are unable to determine whether the grazers found food in unlimited quantities at all depths or actively sought out the depth of maximum photosynthesis. Layering behavior by *Calanus* and *Neocalanus* likely provides strata in the water column where filter or gulp feeding pelagic fishes can feed efficiently on plankton. This possibility is being pursued by other studies at this time.

Acknowledgements

This research was supported by the Exxon Valdez Oil Spill Trustee Council as project 320H. The Captain and crew of the R/V *Alpha Helix* are thanked for their cooperation and assistance with this work. Bill Hauser, Jay Kirsch, and Loren Tuttle assisted in the field. The taxonomy was undertaken by Chris Stark and Janet Ballek.

References

Cooney, R. T. 1986. The seasonal occurrence of *Neocalanus cristatus*, *Neocalanus plumchrus* and *Eucalanus bungii* over the shelf of the northern Gulf of Alaska. Continental Shelf Res. 5: 541-553.

Coyle, K. O., A. J. Paul and D. A. Ziemann. 1990. Copepod populations in the spring bloom in an Alaskan subarctic embayment. J. Plank. Res. 12(4):759-797.

Damkaer, D. M. 1977. Initial zooplantkton investigations in Prince William Sound, Gulf of Alaska and Lower Cook Inlet. Environmental Assessment of the Alaska Continental Shelf, Annual Reports of Principal Investigators for the year ending 1977. 10 (Receptors-fish, littoral and benthos): 137-274.

Fulton, J. D. 1973. Some aspects of the life history of *Calanus plumchrus* in the Strait of Georgia. J. Fish. Res. Bd. Can. 30:811.-815.

Incze, L. S., D. W. Siefert and J. M. Napp. 1997. Mesozooplankton of Shelikof Strait, Alaska: abundance and commuity composition. Continental Shelf Res.36:287-305.

Mackas, D. L., H. Sefton, C. B. Miller and A. Raich. 1993. Vertical Habitat partitioning by large calanoid copepods in the oceanic subarctic Pacific during Spring. Prog. Oceanog. 32: 259-294.

Miller, C. B. 1988. *Neocalanus flemingeri*, a new species of Calanidae (Copepoda:Calanoida) from the subarctic Pacific Ocean, with a comparative redescription of *Neocalanus plumchrus* (Marukawa) 1921. Prog. Oceanogr. 20:223-274.

Miller, C. B. 1993. Development of large copepods during spring in the Gulf of Alaska. Prog. Oceanog. 32:295-317.

Mooers, C. N. K. and J. Wang. (in review). On the development of a three-dimensional circulaton model for Prince William Sound, Alaska. Submitted to Continental Shelf Res., December, 1996.

Neibauer, H. J., T. C. Royer and T. J. Weingartner. 1994. Circulation of Prince William Sound, Alaska. J. Geophy. Res. 99(14):113-126.

Table 1. Significant statistical differences between groups clustering on number or biomass

Taxonomic Category	Group 1	Group 2	Probability
Clustering on number	Indiv. m-3*	Indiv. m-3*	P
Neocalanus flemingeri V	9.7	35.1	0.007
N. plumchrus V	3.8	9.5	0.031
Calanus marshallae adult	1.5	2.7	0.015
Euphausiid eggs	2.1	1	0.012
Euphausiid furcilia	13.2	4.5	0.046
Barnacle nauplii	4	1.6	0.007
Aglantha digitale	5.9	1.7	0.002
Limacina helicina	4.7	2.1	0.037
Clustering on biomass	g m-3*	g m-3*	P
Neocalanus spp. IV	0.019	0.038	0.038
Calanus marshallae IV	0.007	0.004	0.037

* = geometric mean

Table 2. Ranking taxa by abundance in groups identified by cluster analysis

Group I - Outside and central Sound	Group II - western and northwestern Sound
1 Euphausiid furcilia	1 *Neocalanus flemingeri* stage V
2 *Neocalanus flemingeri* stage V	2 *Neocalanus* spp. stage IV
3 *Neocalanus* spp. stage IV	3 *Neocalanus plumchrus* V
4 Euphausiid calyptopis	4 *Pseudocalanus* spp. V
5 *Aglantha digitale*	5 *Pseudocalanus* spp. adult female
6 *Pseudocalanus* spp. adult female	6 *Neocalanus* spp. stage III
7 *Calanus marshallae* stage IV	7 *Calanus marshallae* stage III
8 *Calanus marshallae* stage III	8 Euphausiid furcilia
9 *Limacina helicina*	9 *Calanus marshallae* stage IV
10 *Pseudocalanus* spp. stage V	10 Euphausiid calyptopis

Table 3. Tendencies for large calanoids to form layers in cluster groups 1 and 2

Taxonomic category	Group 1	Group 2	Overall
Layering by abundance	% locations	% locations	% locations
Neocalanus flemingeri and *N. plumchrus* stage V	50	79	67
N. spp. stages III-IV	50	79	67
N. cristatus stages III-IV	50	93	75
Calanus marshallae III-Adult	30	71	54

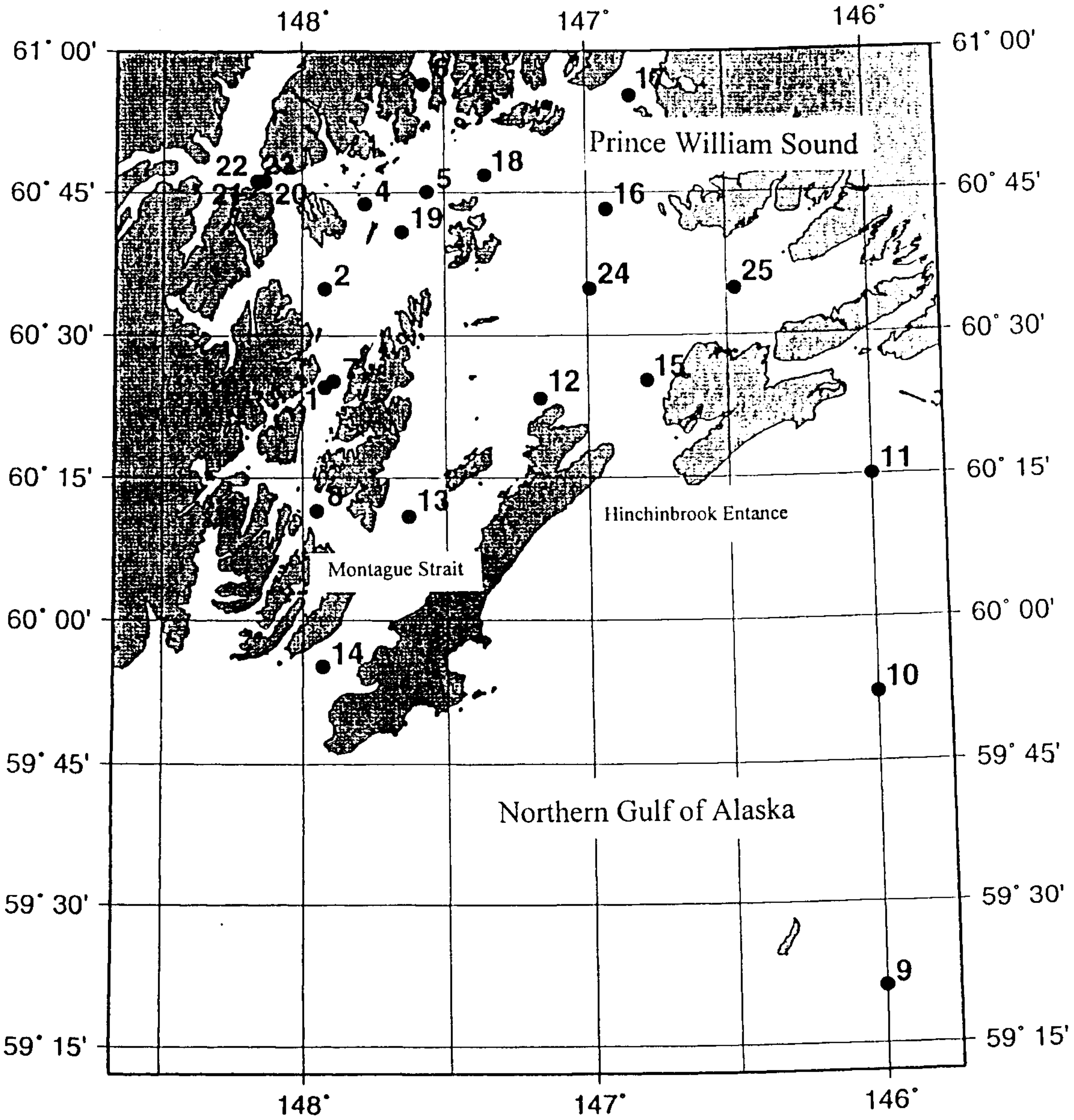

Figure 1. Prince William Sound, Alaska depicting geographic features and the location of MOCNESS stations occupied in May, 1996.

Clustering on Abundance

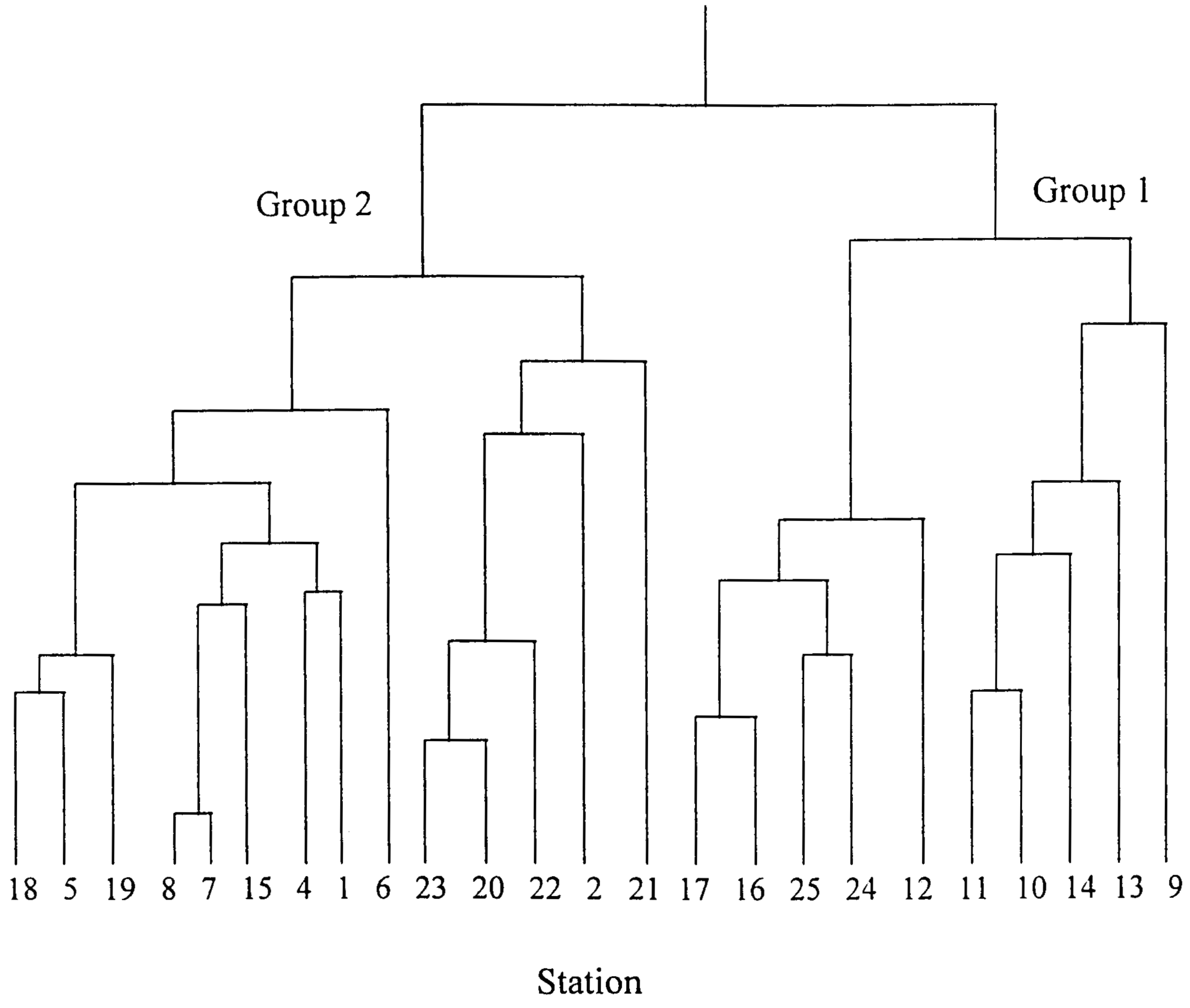

Figure 2. Results of clustering station locations by zooplankton abundance for samples collected in May, 1996

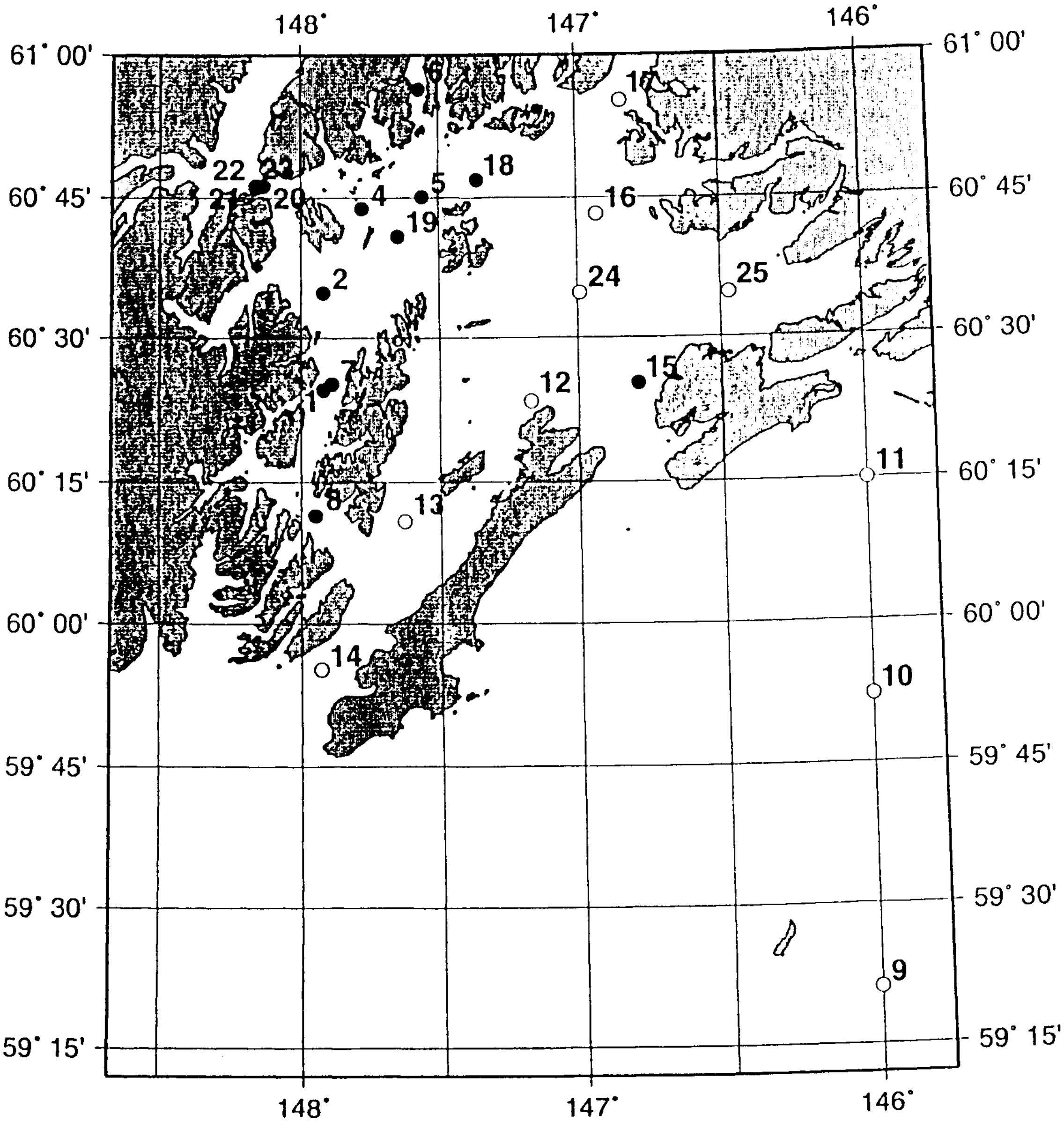

Figure 3. The locations of stations clustering by abundance in Group 1 (open circles) and Group 2 (closed circles).

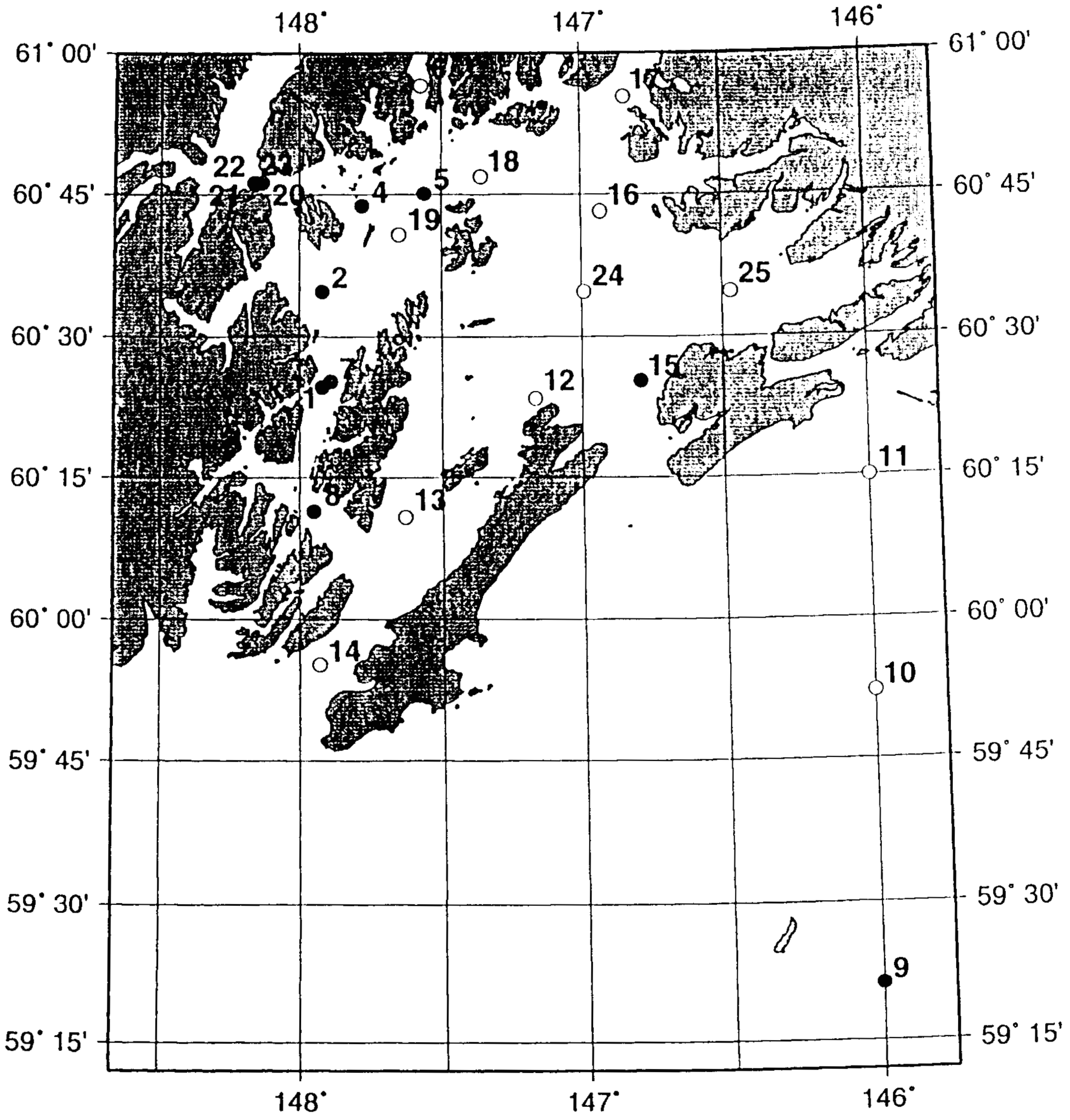

Figure 4. The location of stations clustering by biomass in Group 1 (open circles) and Group 2 (closed circles).

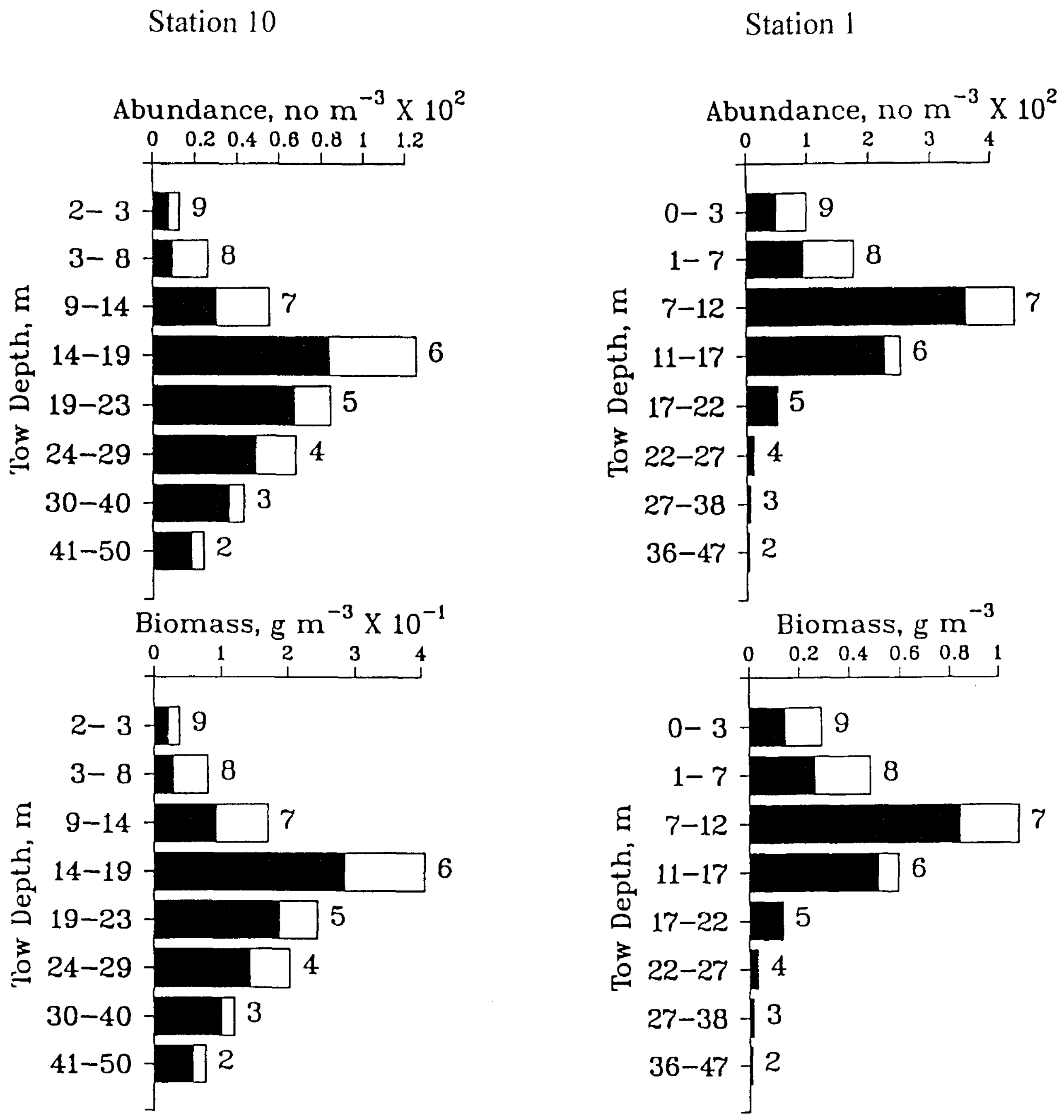

Figure 5. Co-occurrence of *Neocalanus flemingeri* and *N. plumchrus* stage V at Station 10 (Group 1) and Station 1 (Group 2). Open bars are *N. plumchrus*.

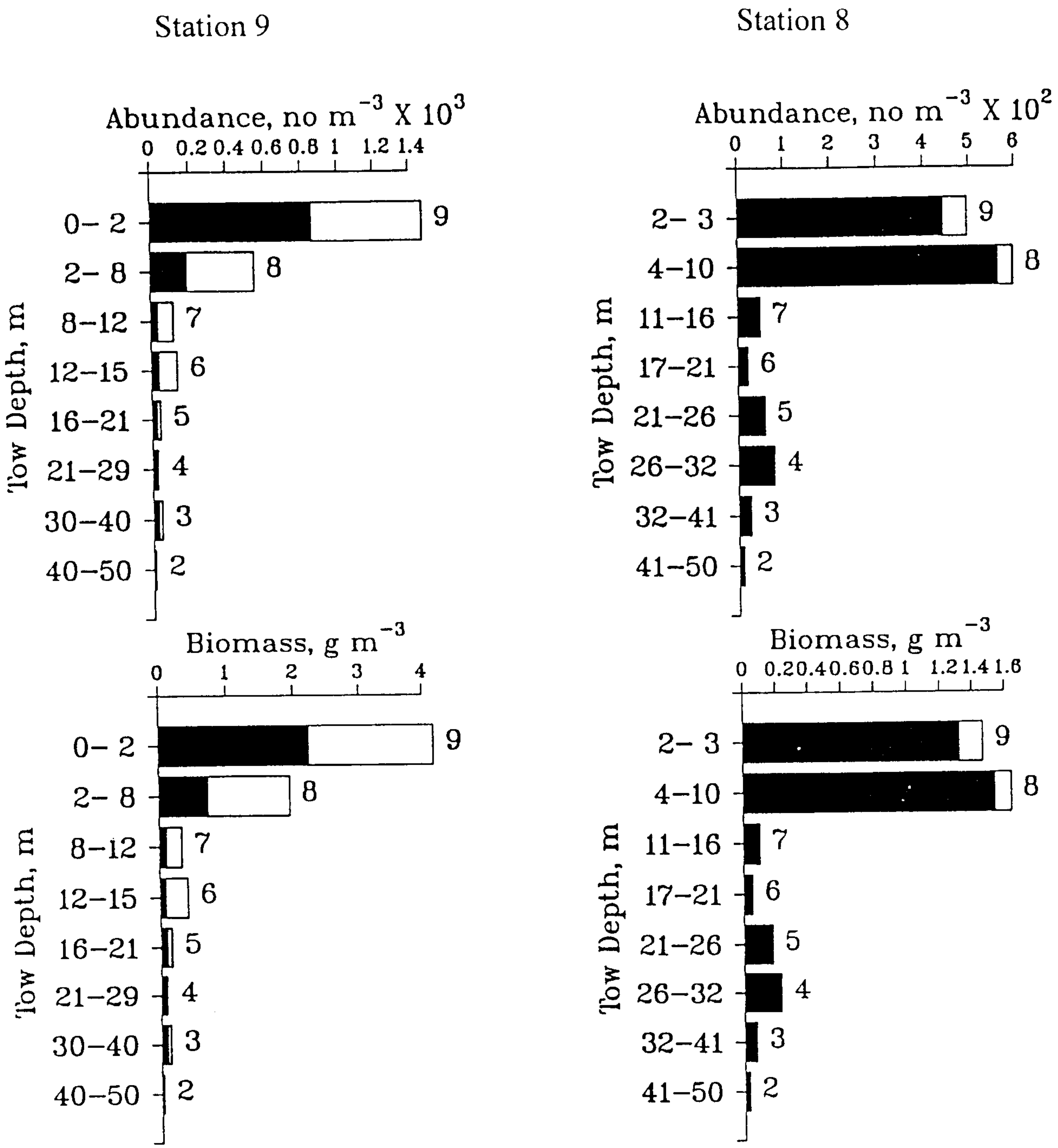

Figure 6. Examples of *Neocalanus flemingeri* and *N. plumchrus* stage V layering in Group 1 (Station 9) and Group 2 (Station 8).

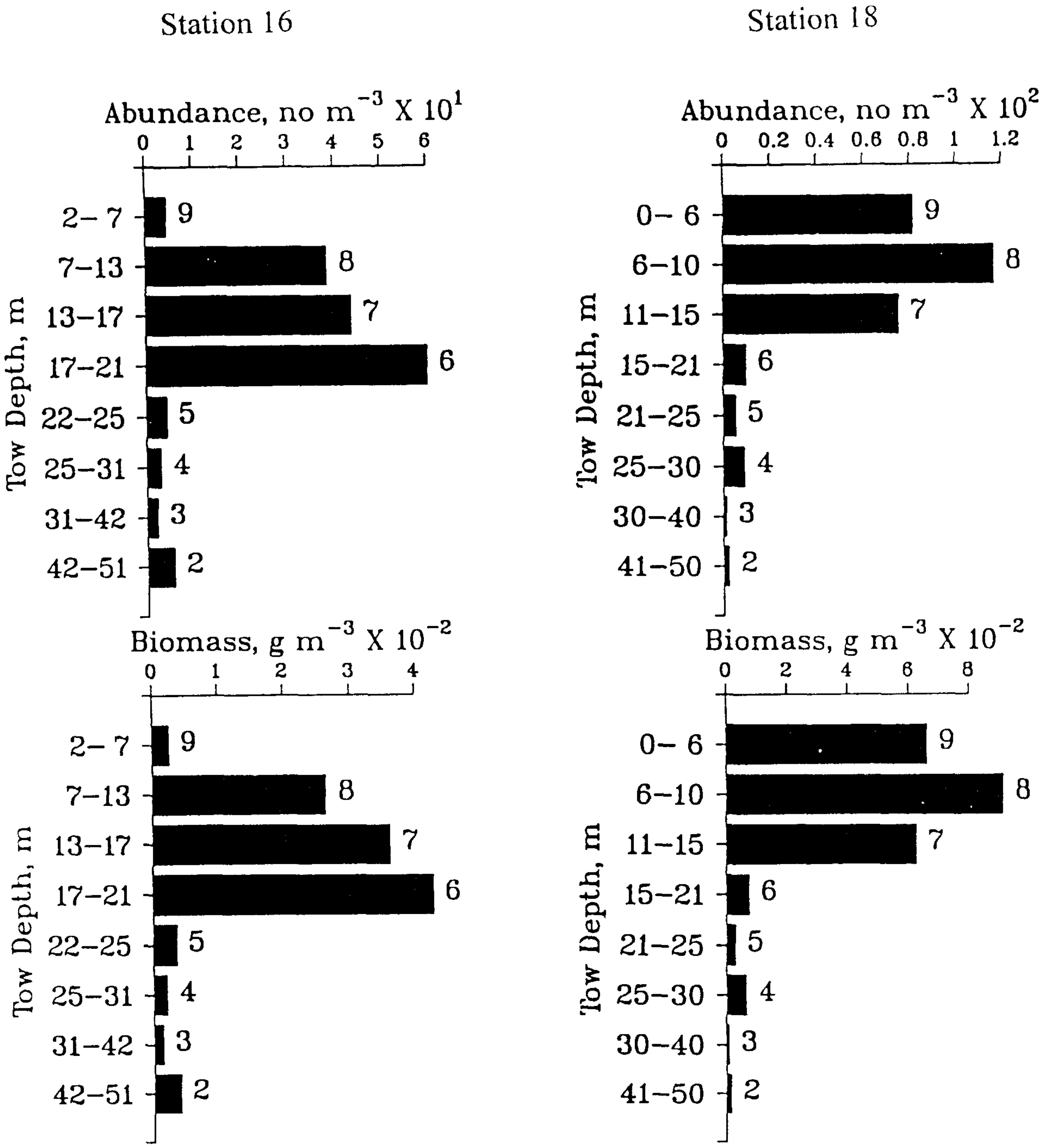

Figure 7. Examples of *Neocalanus* spp. stages III-IV layering in Group 1 (Station 16) and Group 2 (Station 18).

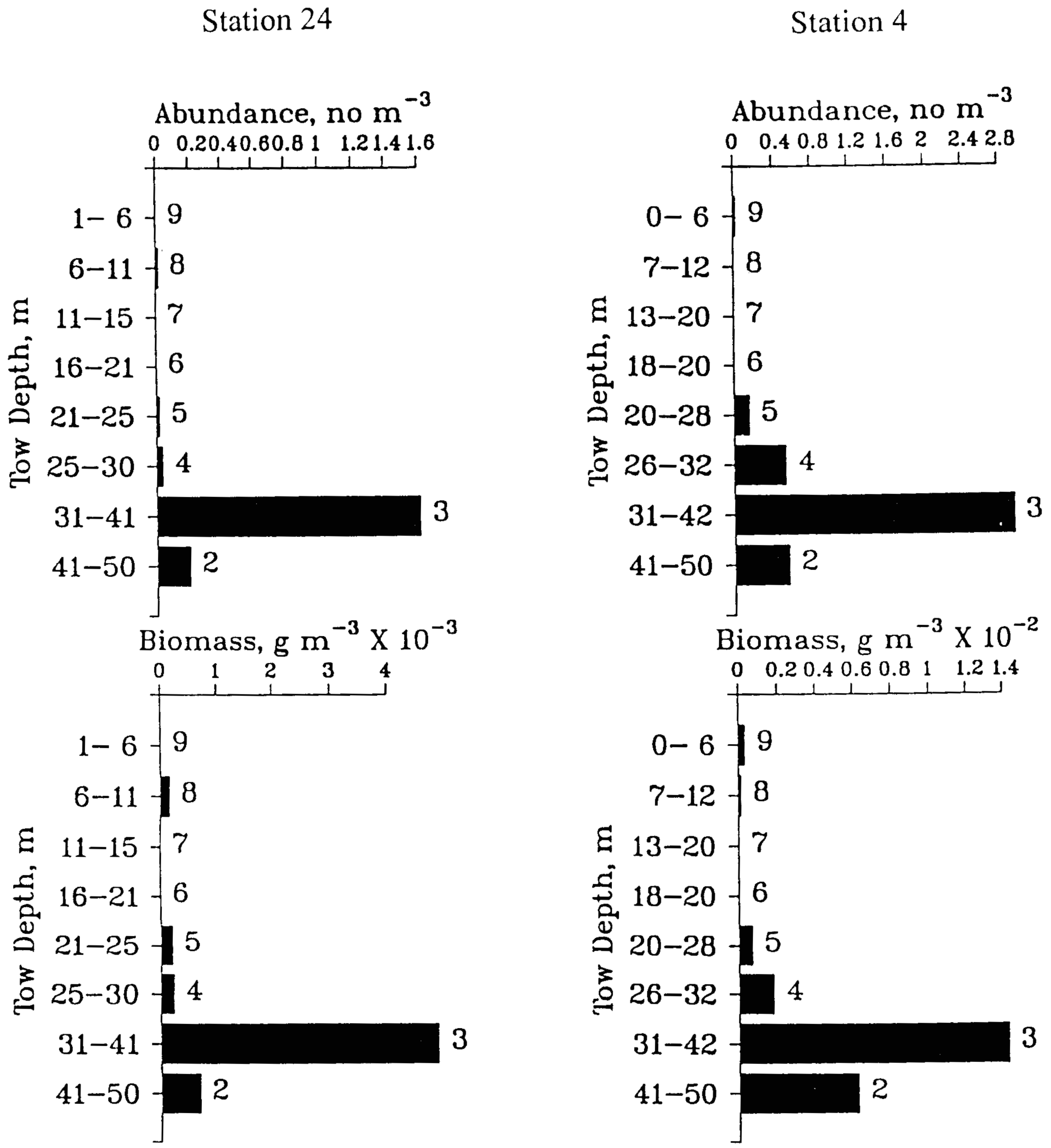

Figure 8. Examples of *Neocalanus cristatus* stages III-V layering in Group 1 (Station 24) and Group 1 (Station 4).

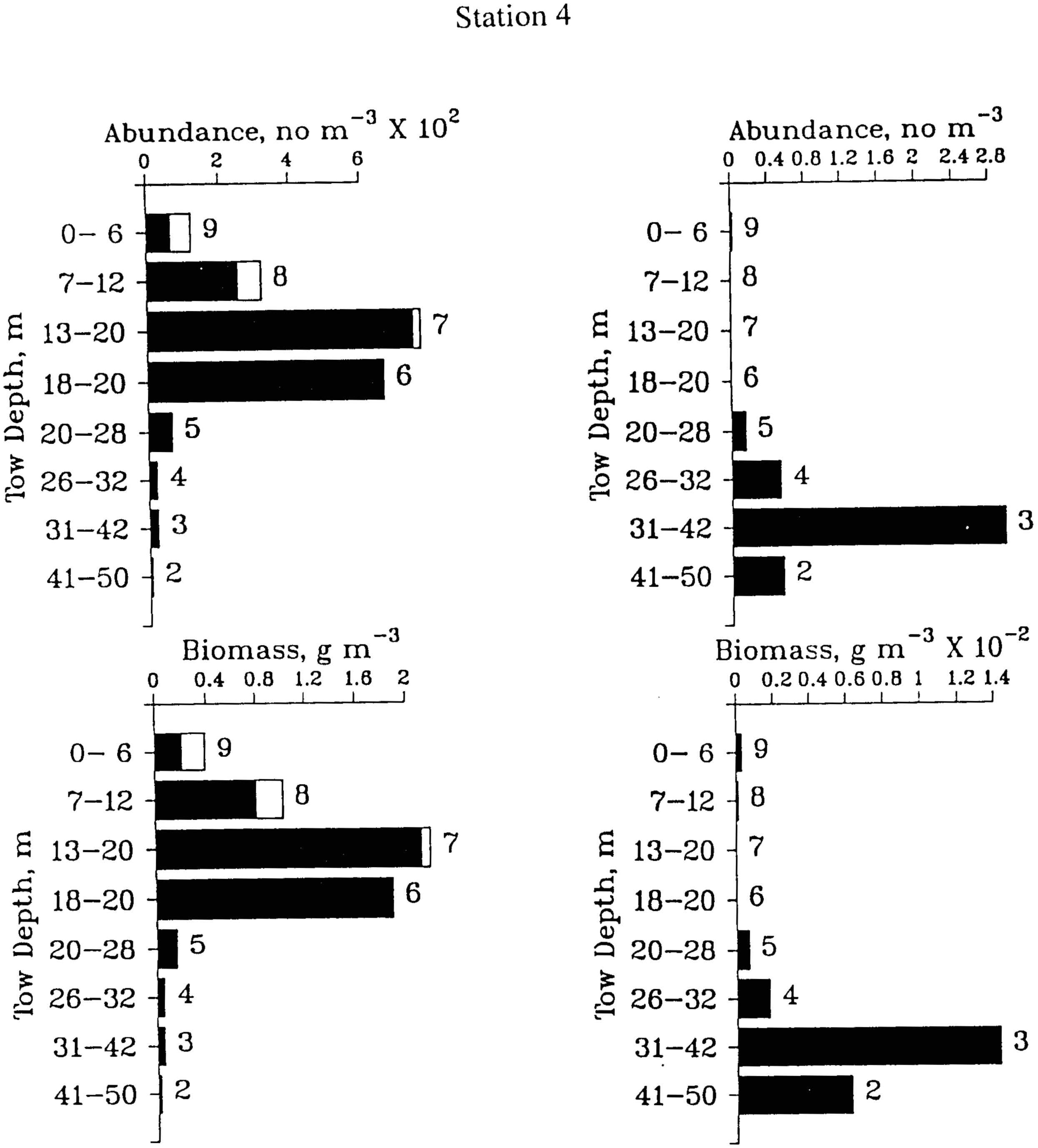

Figure 9. Comparing the vertical distributions of *Neocalanus flemingeri* and *N. plumchrus* stage V with *N. cristatus* stages III-V at Station 4.

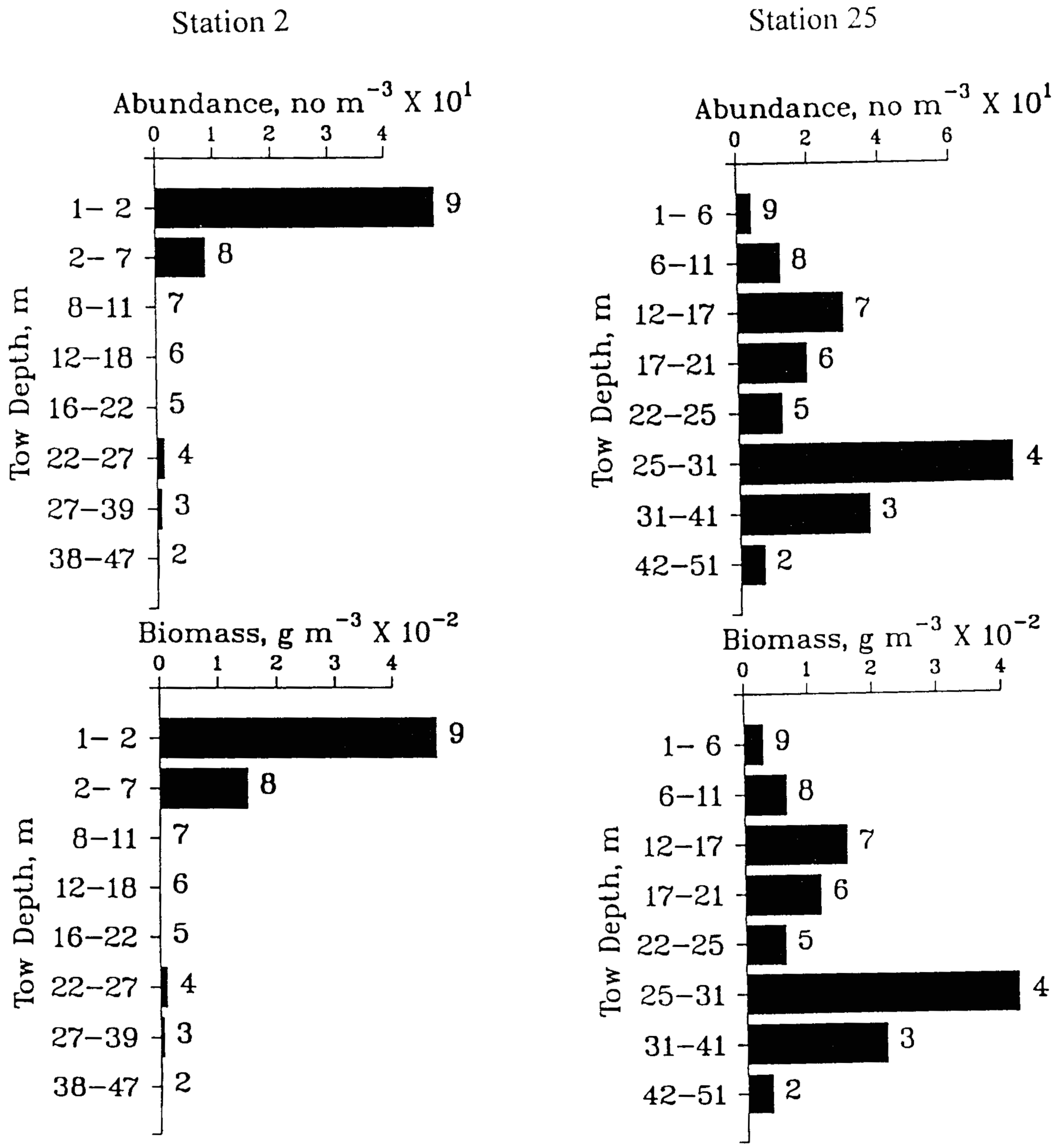

Figure 10. Comparing the depth of layering for *Calanus marshallae* stages IV-Adult at Stations 2 and 25.

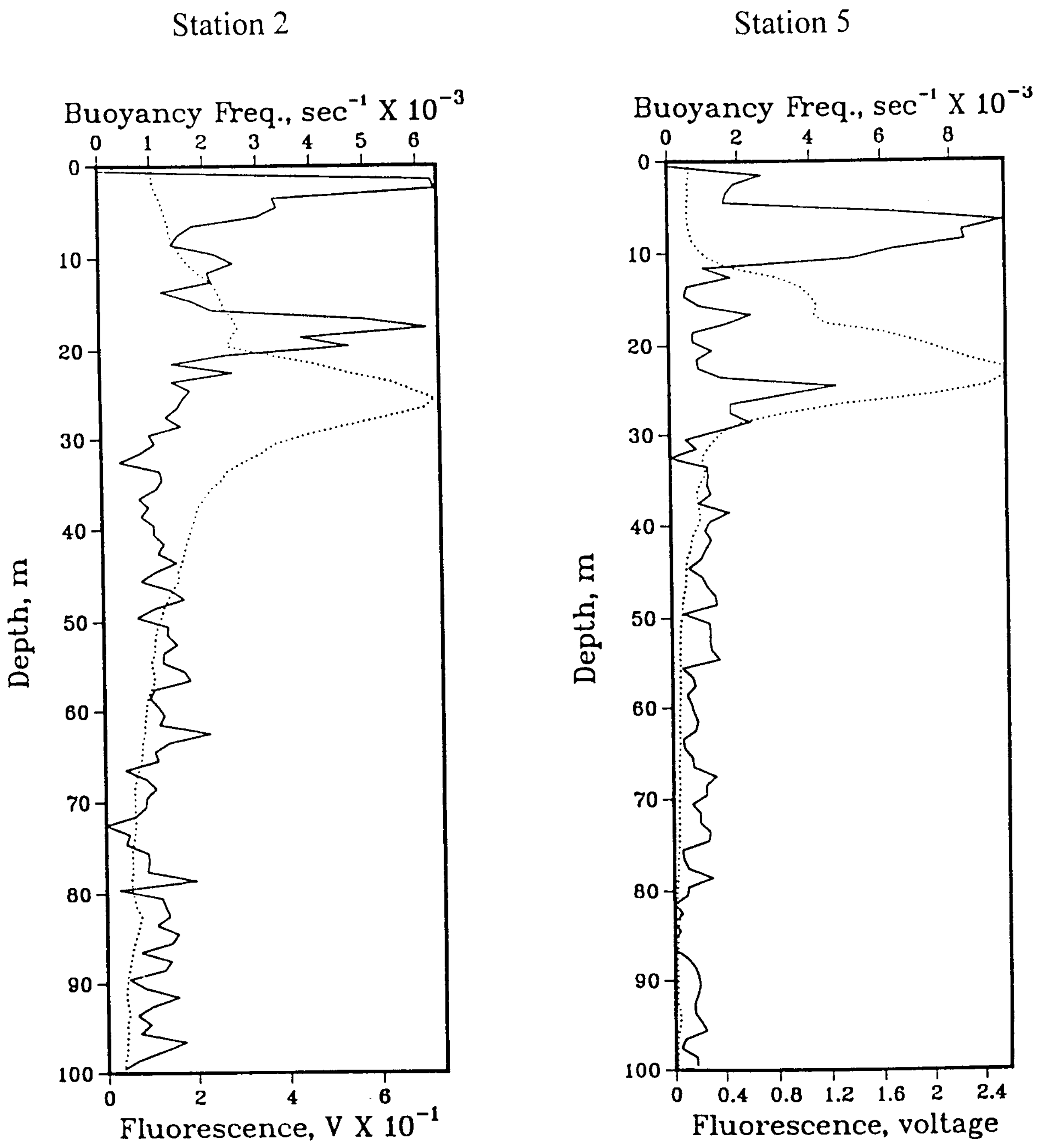

Figure 11. Examples of subsurface fluorescence maxima (dotted line) at Stations 2 and 5.

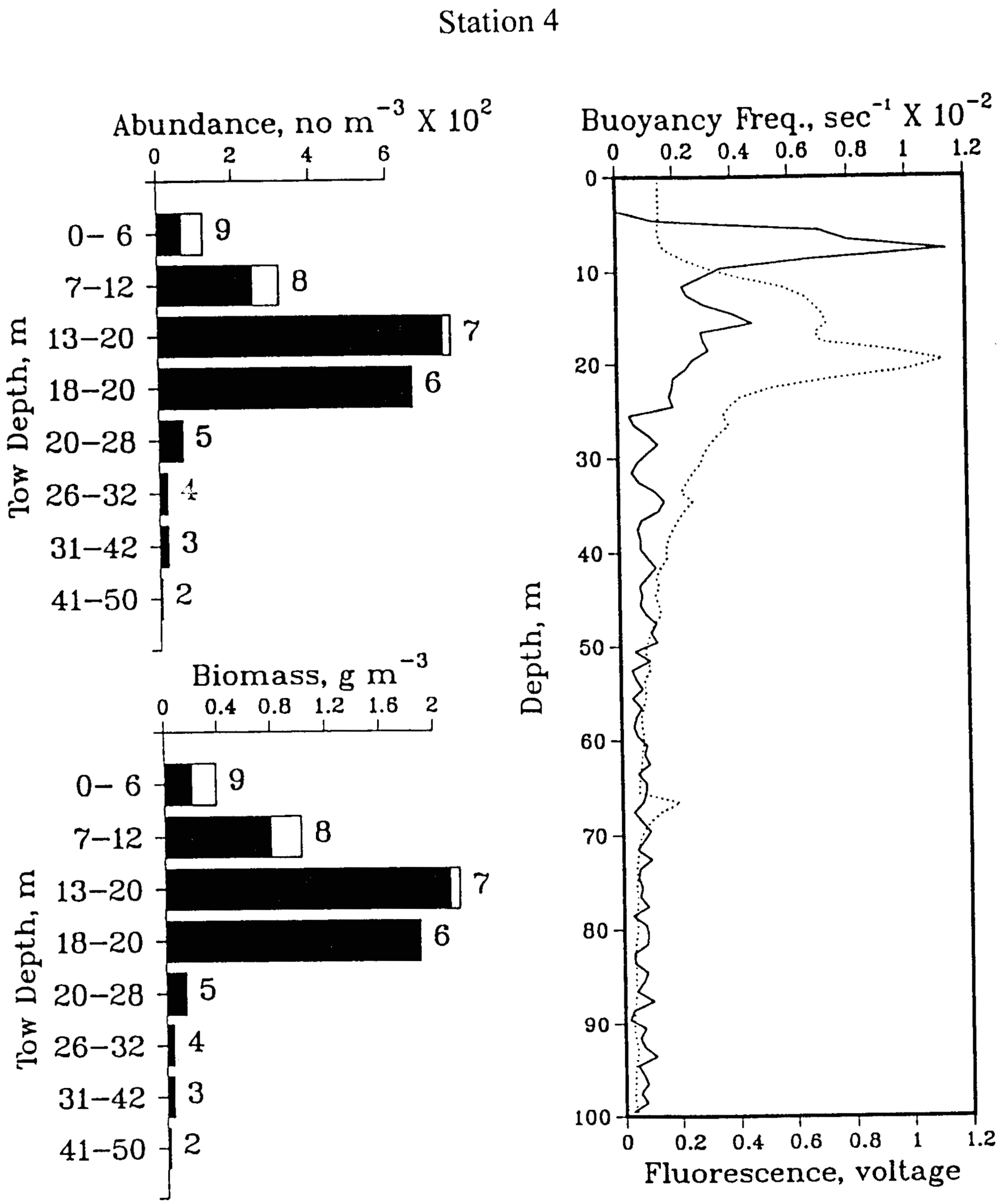

Figure 12. Example of a location where *Neocalanus flemingeri* and *N. plumchrus* stage V co-occurred with a fluorescence maximum (Stations 4).

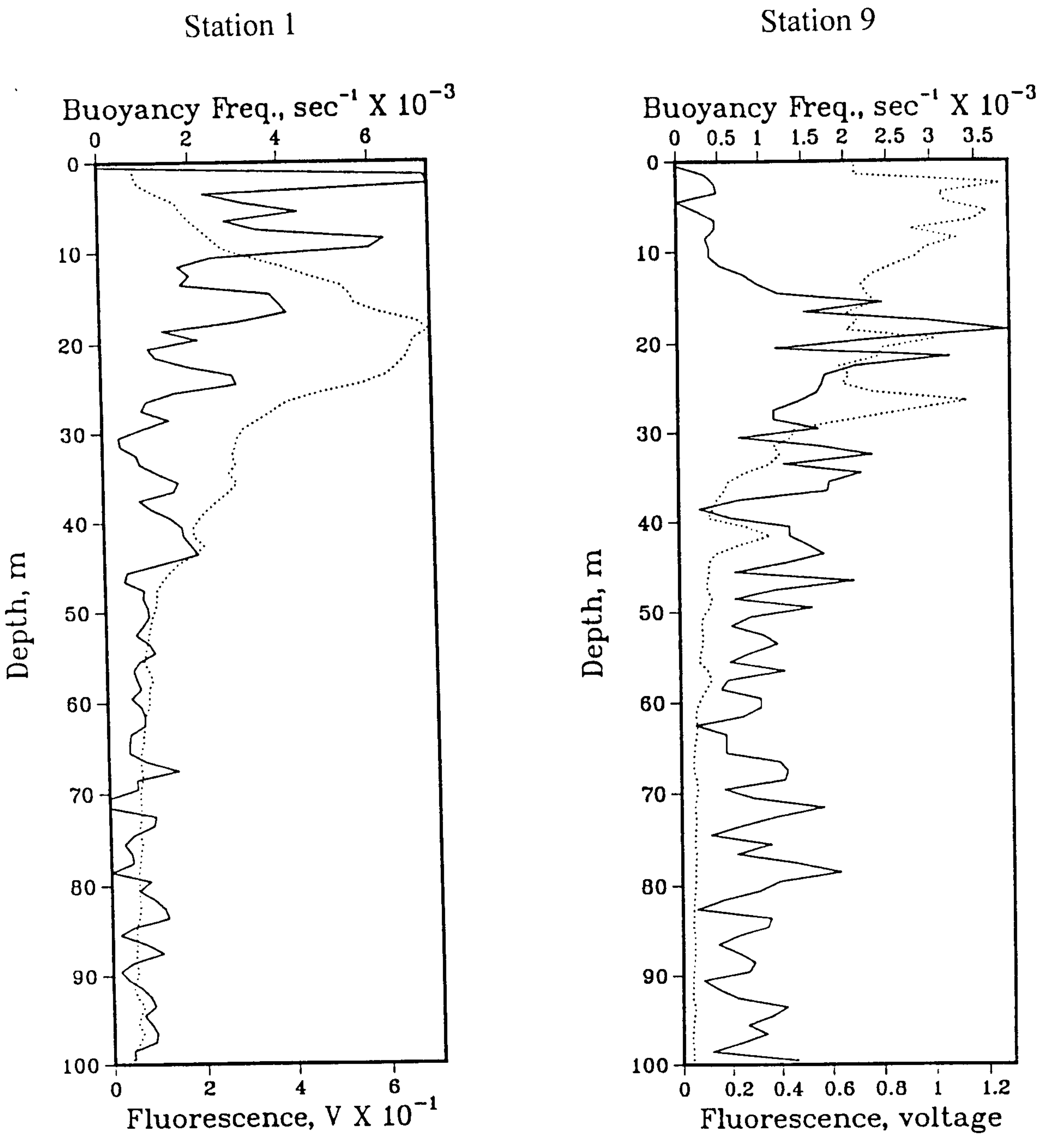

Figure 13. Examples of buoyancy frequency distributions (solid line) with depth illustrating maxima near the surface (Station 1) and below the surface (Station 9).

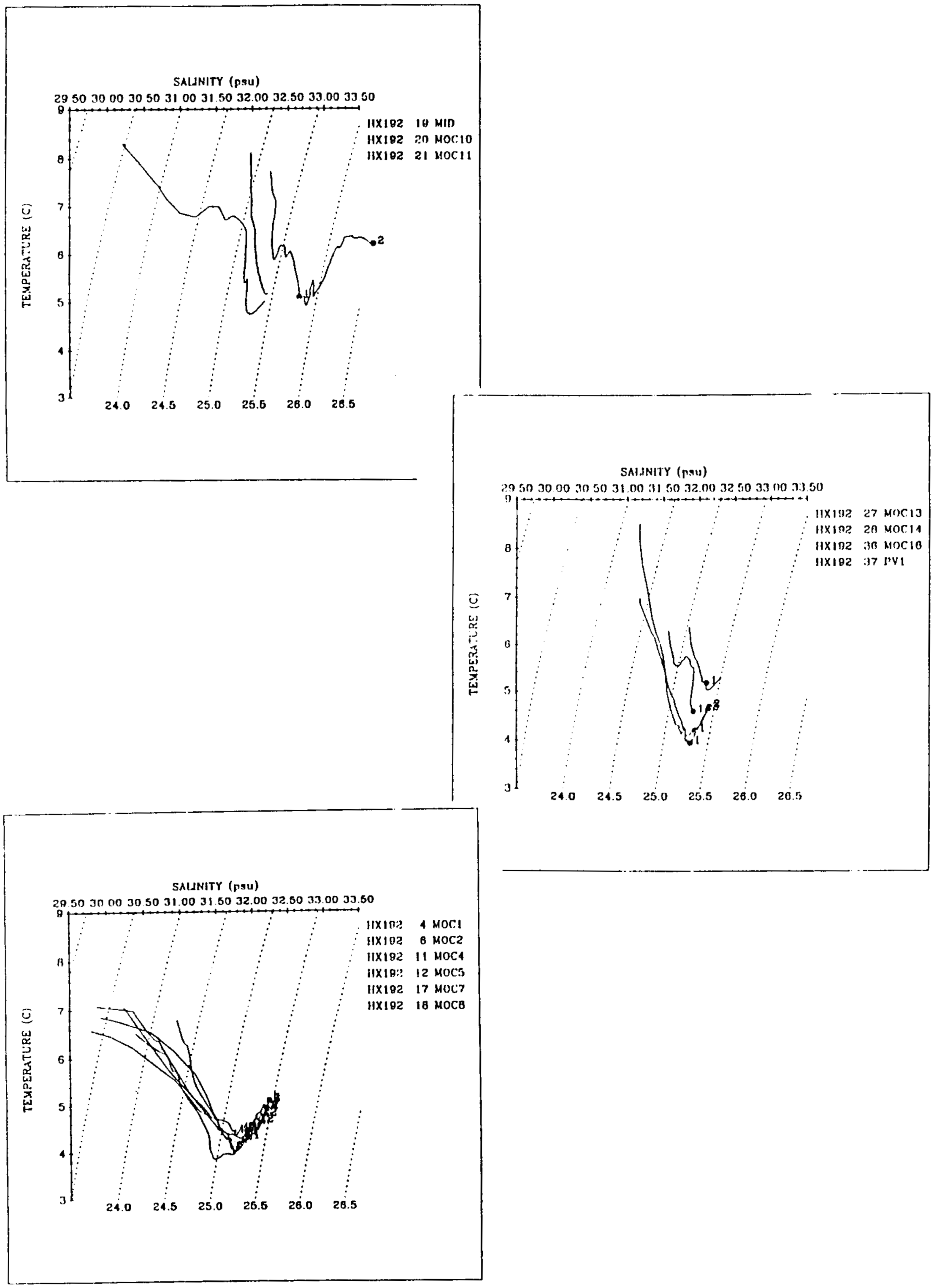

Figure 14. Temperature and salinity plots for locations in Group 1 outside the Sound (top panel), for Group 1 inside the Sound (middle panel) and Group 2 (lower panel).

Chapter 5.

Stable Isotopes as Food Web Tracers (96320I)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Sound Ecosystem Assessment: Confirming Fish Food Web Dependencies in the Prince William Sound Ecosystem Using Natural Stable Isotope Tracers (SEA-FOOD).

Restoration Project 97320I
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Thomas C. Kline, Jr., Ph. D.

Prince William Sound Science Center, P. O. Box 705, Cordova, Alaska 99574

April 1997

Isotopic Signature and Somatic Energy Content of Young of the Year Pacific Herring at Two Sites in Prince William Sound, Alaska: Implications for Trophic Studies

Thomas C. Kline, Jr.[1] and A. J. Paul[2]

[1]Prince William Sound Science Center, P. O. Box 705, Cordova, Alaska 99574 USA
email: tkline@grizzly.pwssc.gen.ak.us

[2]University of Alaska, Institute of Marine Science, Seward Marine Center, P. O. Box 730,
Seward, Alaska 99664 USA.

Revised draft resubmitted to:
Canadian Journal of Fisheries and Aquatic Sciences

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Thomas C. Kline, Jr.[1] and A. J. Paul[2]

[1]Prince William Sound Science Center, P. O. Box 705, Cordova, Alaska 99574 USA
email: tkline@grizzly.pwssc.gen.ak.us

[2]University of Alaska, Institute of Marine Science, Seward Marine Center, P. O. Box 730, Seward, Alaska 99664 USA.

Running head: Herring trophics

Key Words: Pacific herring, *Clupea*, somatic, energetics, stable N and C isotopes

Abstract

We compare the somatic energy content and natural stable isotopic signatures of young-of-the-year Pacific herring from 2 sites in Prince William Sound, Alaska, (PWS) in the fall of 1994. The fish at one site had an average standard length of 83 mm and 99 mm at the other. At the site with the smaller fish, the recruiting herring had an average of 5.5 kJg^{-1} dry wt for whole body samples vs. 8.9 kJg^{-1} at the other site. The isotopic signatures of the fish tissues were compared to that of terminal feeding stage (copepodite V) *Neocalanus cristatus* sampled throughout PWS. The copepods, which were collected during the period March through June, were relatively uniform and collectively dichotomus in their $^{13}C/^{12}C$ content compared to those collected at a station located on the continental shelf in the Gulf of Alaska (GOA) south of the entrance to PWS. The $^{15}N/^{14}N$ values of *N. cristatus,* which were relatively uniform throughout the region, were compared with herring to normalize the trophic enrichment of ^{13}C so that $^{13}C/^{12}C$ values from herring tissues could be compared with the copepods. The isotopic analysis showed that the herring with the most stored energy had lower $^{13}C/^{12}C$, which suggested they were utilizing carbon derived from GOA production rather than PWS. The study demonstrates that in Prince William Sound schools of young-of-the-year herring can have markedly different levels of somatic energy stores as they prepare to over-winter and that energy storage may depend on their nutritional sources, and the distribution of planktonic prey by physical processes.

Introduction

In Prince William Sound (PWS) the Pacific herring *Clupea pallasi* has supported important commercial and subsistence fisheries. Since 1993, herring have not been abundant enough to harvest. An ecosystem level study called Sound Ecosystem Assessment (SEA) is examining trophic interactions to see if the flow of energy through the food web is impeding recovery of herring stocks in PWS. The principal SEA hypothesis, known as the river-lake hypothesis, states that spatial and temporal variability in regional oceanographic conditions control production in PWS. Conditions are postulated to vary from lentic (lakelike) to lotic (riverlike) in relation to the strength and influence of the Alaska Coastal Current (Niebauer et al. 1994) on PWS.

Physical oceanographic processes are further hypothesized to affect both bottom-up and top-down biological processes that in turn affect recruitment of exploited fish stocks. Of concern here is the bottom-up effects on Pacific herring in PWS. Herring are seasonal feeders building up fat stores to sustain them when food is scarce during the winter months (Blaxter and Holiday 1963). In late autumn or winter, feeding either stops (Blaxter and Holiday 1963) or continues at low levels (Hay et al. 1988). Of concern here is the condition of herring prior to the long high-latitude winter. Since there is a wide range in the amount of fat stored for the winter season by individuals, even for similar sized fishes in same school (Blaxter and Holiday 1963), it is hypothesized in SEA that overwintering survival of herring may be dependent on body condition resulting from bottom-up effects. In this study, we began testing this hypothesis by comparing herring from two sites at the end of their first growing season for differences in somatic energy content and stable isotope composition as indicators of condition and bottom-up effects, respectively.

Stable Isotope chemistry is a powerful tool for use in ecological studies because of naturally existing isotope gradients and the fidelity of consumer isotope ratios with their diet (Fry and Sherr 1984, Wada et al. 1991, Michener and Schell 1994). In this study we compare the stable isotopic ratios of carbon and nitrogen in the bodies of young-of-the-year herring (i.e., 0-age) collected at 2 sites that had markedly different fall somatic energy and body size. The comparison was facilitated by using the large interzonal copepod *Neocalanus cristatus* as a proxy for carbon fixed during the spring bloom and as a trophic level reference. *N. cristatus* is one of three congeners which dominate herbivore plankton community of the north Pacific (Miller et al. 1984, 1993, Cooney 1986). Although *N. cristatus* is facultatively carnivorous on planktonic Protozoa, the species cannot be sustained on such a diet (Gifford 1993). *N cristatus* was the ideal low trophic reference organism for this study since they are a priori herbivores with a life history which makes them good integrators of the spring phytoplankton bloom when coupled with their large size (~ 2 mg dry weight), which enables isotopic measurement of individuals.

Methods

Neocalanus cristatus

Monthly oceanographic cruises, each one week in duration, were made from March to June, 1995 to capture conditions prior to, during, and following phyto- and zooplankton blooms in PWS on the *R/V Bering Explorer*. Twenty-two stations were sampled each cruise as conditions permitted. At these stations a 0.5 m-diameter 335μ-mesh ring net was lowered to 50 m and brought to the surface at 1 m^{-1}. The contents of the haul were processed immediately upon recovery. Individual life-history-stage copepodite V (C5) *Neocalanus cristatus* were forcepted out, species identity verified under a dissecting microscope (25X), placed into polyethlene vials (Wheaton Omni-vials), frozen (- 20 °C), and stored frozen (-20 °C) until freeze dried. Samples were freeze-dried (Labconco) in their vials and then sent to the University of Alaska Stable Isotope Facility where they were removed, weighed to the nearest µg and placed into combustion boats for mass spectrometric analysis.

Herring

In 1994 fine mesh purse seines were used to capture herring at one site in Windy Bay (60° 30.5' N and 146 ° 0.6' W), on the North side of Hawkins Island in eastern Prince William Sound, and another in Port Gravina Bay (60 ° 40.0' N and 146° 20.0' W), located about 10 km away in northern Prince William Sound (Fig. 1), for chemical analyses. The fish were collected on 26 and 29 October, respectively.

A subsample of the fish caught (Table 1) were immediately frozen in sea water aboard ship and kept frozen until processed. The length and weight of the remaining fish were determined by biologists from the Alaska Department of Fish and Game (Table 1). In the laboratory the fish were partially thawed, just enough to handle, but not enough so fluids were lost. All fish were measured for standard length (SL) to the nearest mm then weighed to the nearest 0.1 g using an electronic balance. Scales were removed from each fish for aging by the Alaska Department of Fish and Game. The scale-age data were used to select (randomly) only 0-age herring for this study.

Whole carcasses were freeze dried for 48 hours and then placed in a convection oven at 60°C until they reached a constant dry weight. The difference between individual wet and dry weight values were used to calculate the moisture content of each fish. Dried bodies were ground in a mill and somatic energy content (SEC) for each individual was estimated by bomb calorimetry. All calorimetric samples were weighed to the nearest mg. Somatic energy content is based on a single sample burned per fish and reported in kJ per g dry weight. A representative 88 fish from each site were used for energetic analysis (Table 1).

After bomb calorimetric analysis, 32 fish from Windy Bay and 28 fish from Port Gravina were randomly selected for natural stable isotopic analysis. The comparable size range of these fish with the calorimetric and field samples suggests that this was a representational sample (Table 1). The samples were ground to a fine powder with a dental amalgamator (Crescent Dental Wig-L-Bug). Ground freeze-dried samples stored in LSC vials were sent to the Stable Isotope Facility at the University of Alaska Fairbanks where replicate aliquots of ~2 mg were weighed to the nearest µg and loaded into combustion boats for mass spectrometric analysis.

Isotopic determination

A Europa Scientific model 20/20 stable isotope analyzer equipped with a Europa Scientific Roboprep sample preparation and purification unit was used. Analytical results include $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios in standard delta units, $\delta^{13}C$ and $\delta^{15}N$, respectively, and %C and %N.

The standard delta notation is used to express stable isotope ratios, which are reported relative to international standards (air for N and Vienna Peedee belemnite (VPDB) for C) and defined by the following expression:

$$(1) \qquad \delta^{15}N \text{ or } \delta^{13}C = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} -1 \right) \text{ x } 1000 \text{ per mil}$$

where R = $^{15}N/^{14}N$ or $^{13}C/^{12}C$ (after Craig 1957). The isotope standards have delta values of 0 by definition, i.e., $\delta^{15}N = 0$ for atmospheric N_2. Naturally occurring $\delta^{15}N$ and $\delta^{13}C$ values observed in biota, range from ~0 to ~ +20 and from ~ 0 to ~ -50, respectively. The negative $\delta^{13}C$ values reflect the relative enrichment of ^{13}C in the limestone standard compared with biota.

Samples were rerun when replication was poor (difference in delta units > 0.6). Typically, replication is < 0.2 delta units. The %C and %N data were used to calculate C/N. Mean of $\delta^{13}C$, $\delta^{15}N$ and C/N replicates were used for further analysis.

Lipid normalization

Normalization for lipid composition was by the method of McConnaughey and McRoy (1979) using the C/N ratios derived during mass spectrometry. The C/N atomic ratio (proxy for lipid, L):

$$(2) \qquad L = \frac{93}{\left(1 + \frac{1}{0.246C/N - 0.775}\right)}$$

was used to calculate lipid-normalized $\delta^{13}C$ (expressed as $\delta^{13}C'$):

$$(3) \qquad \delta^{13}C' = \delta^{13}C + 6 \left(\frac{3.9}{1 + \frac{287}{L}} - 1 \right)$$

Trophic level normalization for carbon source assessment

$\delta^{13}C'$ values were normalized for trophic level so that the residual values reflect carbon source isotopic effects (Fry and Sherr 1984). Normalization for trophic enrichment of ^{13}C was made using:

$$(6) \qquad \delta^{13}C'_{TL} = \delta^{13}C' - \varepsilon_C \Pi$$

where $\delta^{13}C'_{TL}$ is the trophic level normalized $^{13}C/^{12}C$ value of $\delta^{13}C'$, the trophic $\delta^{13}C$ enrichment factor, $\varepsilon_C = 1$ (DeNiro and Epstein 1978, Rau et al. 1983, Fry and Sherr 1984, McConnaughey and McRoy 1979), and Π is the trophic level difference with respect the reference organism (Cabana and Rasmussen 1994, 1996) and is calculated by:

$$(4) \qquad \Pi = \frac{\delta - \delta_F}{\varepsilon_N}$$

where δ is the $\delta^{15}N$ of the sample, δ_F is the $\delta^{15}N$ of the reference species, which here is *Neocalanus cristatus*, and the trophic $\delta^{15}N$ enrichment factor, $\varepsilon_N = 3.4$ (Minagawa and Wada 1984, Owens 1987).

Thus the expressions $\delta^{13}C$, $\delta^{13}C'$, $\delta^{13}C_{TL}$, or $\delta^{13}C'_{TL}$ are used to denote ^{13}C abundance with respect to the international standard, with normalization for lipid content, with normalization for trophic level, and with normalization for lipid content and trophic level, respectively. Whether or not lipid or trophic level normalization is used depends on the context of the data analysis. "^{13}C" is used to reflect generic $^{13}C/^{12}C$ isotopic trends irrespective of normalization.

Results and Discussion

Neocalanus cristatus

Neocalanus cristatus were found at least once in 16 of the zooplankton stations (Table 2). The peak occurrence in May corresponded to the peak in zooplankton biomass in PWS in 1995 (R. T. Cooney, University of Alaska, pers. comm.). The $\delta^{13}C$ of feeding stage C5 *N. cristatus*) in the northern GOA south of the entrance to PWS were found to be consistently dichotomous when compared to those from within PWS (Table 2). Feeding C5 *N. cristatus* from the GOA had $\delta^{13}C = -24.3$ (SD = 1.4, N = 33) and $\delta^{13}C' = -23.2$ (SD = 1.1, N = 33) whereas those from PWS had $\delta^{13}C = -20.2$ (SD = 1.1, N = 99) and $\delta^{13}C' = -19.7$ (SD = 0.9, N = 99). The relative uniformity of $\delta^{13}C'$ within PWS and strength of the $\delta^{13}C'$ gradient between PWS and the GOA is obvious when contours of the mean $\delta^{13}C'$ values observed for each station throughout the sampling period (Table 2) are potted (Fig. 2). Thus organic carbon in the form of this herbivorous zooplankter from the northern GOA is ^{13}C-depleted by ~ 4 per mil compared with PWS. This gradient is similar to the ~2.5 per mil gradient in $\delta^{13}C$ between the Bering Sea and the GOA at the Aleutian passes (Schell 1996) and the 7 per mil $\delta^{13}C$ gradient found across Drake Passage (Rau et al. 1991).

Herring

Somatic energy content (SEC)

The mean SEC for the young-of-the-year herring were 5.5 ± 1.0 (SD) and 8.9 ±1.3 (SD) kJg^{-1} dry wt at Windy Bay and Port Gravina, respectively (Fig. 3). The mean SL values for these two samples were 83 and 99 mm, respectively, very similar to the large collections made at the time of capture reported in Table 1. The SEC and SL values for the Windy Bay young-of-the-year herring were both significantly lower (Mann-Whitney Rank Sum test, $p < 0.0001$) than Port Gravina fish. The positive relationship between SEC to SL (Fig. 4), suggests accumulation of SEC with growth. Note, however, that where the size range of herring from the two sites overlapped with a fair number, i.e., from ~90 to 100 mm, there was a SL-independent difference in SEC of ~ 1 kJg g^{-1} dry wt (Fig. 4) suggesting site-specific effects on energy accumulation, thus inferring significant bottom-up effects.

Isotopic analysis

Windy Bay and Port Gravina young-of-the-year herring also differed in ^{13}C content (Fig. 5). The difference in $\delta^{13}C$ was partially due to lipid isotope effects (DeNiro and Epstein 1977) and thus related to energetic content. However, normalization for lipid effect reduced the ^{13}C difference between the two sites only slightly (Fig. 5). The difference in $\delta^{15}N$ between Windy Bay and Port Gravina young-of-the-year herring (Fig. 6) suggested a slight difference of ~ 0.1 trophic levels. Following normalization of $\delta^{13}C'$ for trophic level, the two sites continued to maintain a difference in ^{13}C (ANOVA, $p = 0.0001$, Fig. 5). Comparison of the copepod $\delta^{13}C'$ proxy for PWS and GOA production may explain the large range of herring $\delta^{13}C'_{TL}$ (Fig. 3). In comparison, the large ^{13}C range (Fig. 5) observed in PWS herring is >> the 1.2 per mil $\delta^{13}C$ gradient observed across the Georges Bank (Fry 1988). The mean $\delta^{13}C'$ of copepods sampled in PWS and GOA are denoted by the solid reference lines for PWS and GOA carbon in Figs. 7 and 8. A $\delta^{13}C'$ of -21.5 corresponded to half way between the distributions (Fig. 5) and is shown in Figs. 7 and 8 as a dashed reference line to suggest ~ 50 % from each carbon source.

The difference in $\delta^{15}N$ of ~0.3 per mil between the two sites is much less than the $\delta^{15}N$ trophic enrichment factor of 3.4 per mil (Minagawa and Wada 1984) and thus differ by no more than ~ 0.1 trophic levels. Given that $\delta^{15}N$ is a better indicator of trophic level than $\delta^{13}C$ (Fry 1988), the ~ 0.8 per mil difference in $\delta^{13}C'_{TL}$ means between the sites, which approximates the $\delta^{13}C$ trophic enrichment factor of 1 per mil (DeNiro and Epstein 1978, McConnaughey and McRoy 1979, Fry and Sherr 1984), most likely reflects differences in $\delta^{13}C'_{TL}$ of prey. Thus, herring from these two sites appear to have fed at a similar trophic level (number of trophic steps from primary producer) based on their $\delta^{15}N$ values (Cabana and Rasmussen 1994, 1996), but on different carbon sources based on their ^{13}C content.

Size

Comparison of the relation of herring ^{13}C to length suggests that the carbon source shift occurs relative to SL and is independent of site (Fig. 7). Collectively (both sites pooled), the regression of the $\delta^{13}C'_{TL}$ to SL had an $r^2 = 0.31$, $p = 0.0001$. Thus, the difference in ^{13}C between Windy Bay and Port Gravina reflects, in part, site-specific differences in fish size. The Port Gravina young-of-the-year herring had already shifted to the carbon source with less ^{13}C at the time the Windy Bay young-of-the-year herring were still feeding on the carbon with more ^{13}C. The shift to different carbon sources concomitant with growth is consistent with ontogenic shifts in diet of herring known since the work of Hardy (1924). The abundance of ^{13}C in consumers usually does not reflect specific taxa in the diet, but reflects isotopic signatures generated by primary producers which is passed conservatively (with a known trophic-step enrichment) on to higher trophic levels (Michener and Schell 1994). The observed shift in ^{13}C as a function of size (and indirectly, location) suggests ontogenic changes in the primary producer and thus, carbon source of herring food webs during their first summer in Prince William Sound.

The rapid growth rates of juvenile fishes result in isotopic composition change in proportion to addition of new tissue (Hesslein et al. 1993). Isotopic differences between individuals in groups of fast-growing fish changing diet to a different isotopic signature reflect different growth rates (Hesslein et al. 1993). Our observations are consistent with this notion. The change in $\delta^{13}C'_{TL}$ occurring with growth (Fig. 7) and the site-specific variability of $\delta^{13}C'_{TL}$ reflects the differences in fish size at the two sites and suggests that the faster growing Port Gravina herring had a better food source. Herring 90 - 100 mm at the two sites differed by ~ 1Kj/g dry weight (Fig. 2) inferring site-specific differences in available energy. The Port Gravina herring with SEC < ~7 kJ/g dry weight that overlaped the Windy Bay data distribution may have been recent immigrants to the area since some of them had $\delta^{13}C'_{TL}$ that was similar to Windy Bay (Fig. 8). SEC was generally proportional to a decrease in $\delta^{13}C'_{TL}$ ($r^2 = 0.37$, $p = 0.0001$, Fig. 8) suggesting a trend to a ^{13}C-depleted carbon source as energy is accumulated. The Fig. 8 plot demonstrates via the $\delta^{13}C'$ of *Neocalanus cristatus* a diet shift that results in a different SEC and shows the typical variation in these parameters encountered at different capture sites. Both the SEC and isotopic data represent an integration of carbon over time, unlike stomach samples that only reveal the most recent meal and cannot resolve effects of recent fish or plankton movement. Both SEC and isotopic values integrate a number of factors that affect assimilation of carbon and are difficult to assess in the wild, such as the effects of prey density, prey SEC, costs related to predator avoidance, and prey-density independent foraging costs.

Potential pelagic carbon source differentiation suggested by the $\delta^{13}C$ of *Neocalanus cristatus* sampled in PWS and the GOA south of Hinchinbrook Entrance, where the Alaska Coastal Current enters PWS (Niebauer et al. 1994) make it a good reference organism (Cabana and Rasmussen 1996) (Figs. 5, 7, and 8). The isotope gradient found in this zooplankter when used as a proxy inferred that PWS herbivores have $\delta^{13}C' > -21.5$ whereas those from the northern GOA are <-21.5. Larger young-of-the-year herring shift to more ^{13}C-depleted values (i.e., $\delta^{13}C'_{TL} < -21.5$) consistent with a shift toward oceanic carbon (Fig. 8). This shift of herring to more ^{13}C-depleted carbon and a higher SEC is consistent with the ontogenic shift of switching from neritic prey to eating larger oceanic calanoid copepods as they grow (Hardy 1924). Attainment of differential size and SEC levels at the end of the first summer's growth could have resulted from differences in growth rate or the timing of metamorphosis.

Typically there is a wide variety of lipid content seen within all age classes of herring (Blaxter and Holiday 1963. This survey suggests that food source plays a role in delimiting growth and energy storage in first-year herring. We have no way of knowing where our test fishes were foraging prior to capture, but clearly those captured at Windy Bay were not storing as much energy as those from Port Gravina. The measurements of natural stable isotopic ratios as energy supply tracers showed historical differences in prey type. The better fed fish in Port Gravina had a greater affinity for Gulf of Alaska carbon than the Windy Bay fish (Fig. 8) which increased as a function of size for both samples. This project has demonstrated the usefulness of combining energetic and isotopic techniques to measure nutritional status and looking back-wards at prey types consumed. Since the 0-age herring reflect the input of differing carbon sources, our combined tools could be the basis for surveys of herring in space and time to identify areas of prime habitat linking oceanographic factors to inshore pelagic habitat quality, providing a means to measure interannual offshore influences on the nearshore.

Acknowledgments: This project was funded by the Exxon Valdez Oil Spill Trustee Council through the Sound Ecosystem Assessment project. However the findings presented by the authors are their own and not necessarily the Trustee Council position. SEA colleagues collected the fish. Evelyn Brown of the Alaska Department of Fish and Game Cordova office oversaw aging of the fish. J. M. Paul and P. Shoemaker did the calorimetric analysis. Captain Mike Gaegel and crew of the *R/V Bering Explorer*, E. Stockmar, J. Murphy, B. Barnett, and T. Cooney assisted with *Neocalanus cristatus* sampling. Kim Antonucci did the laboratory processing of samples for stable isotope analysis. Bruce Barnett, University of Alaska Fairbanks Stable Isotope Facility performed the stable isotope analysis. John Williams made the contour plot (Fig. 2). Nancy Bird and three anonymous reviewers, through their constructive comments, aided the completion of this manuscript.

Literature cited

Blaxter J. H. and F. G. Holiday. 1963. The behavior and physiology of herring and other clupeids. Adv. Mar. Biol. 1: 261-393.

Cabana, G. and J.B. Rasmussen. 1996. Comparing aquatic food chains using nitrogen isotopes. Pro. Nat. Acad. Sci.

Craig, H. 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochim. Cosmochim. Acta 12:133-149.

Cooney, R.T. 1986. The seasonal occurrence of *Neocalanus cristatus*, *Neocalanus plumchrus*, and *Eucalanus bungii* over the shelf of the northern Gulf of Alaska. Cont. Shelf Res. 5:541-553.

DeNiro, M. J. and S. Epstein. 1977. Mechanism of carbon isotope fractionation associated with lipid synthesis. Science 197:261-263.

DeNiro, M. J. and S. Epstein. 1978. Influence of diet on the distribution of carbon isotopes in animals. Geochim. Cosmochim. Acta 42:495-506.

Fry, B. 1988. Food web structure on the Georges Bank from stable C, N, and S isotopic compositions. Limnol. Oceanogr. 33:1182-1190.

Fry, B. and E. B. Sherr. 1984. $\delta^{13}C$ measurements as indicators of carbon flow in marine and freshwater ecosystems. Contr. Mar. Sci. 27:13-47.

Gifford, D. J. 1993. Protozoa in the diets of Neocalanus spp. in the oceanic subarctic Pacific. Prog. Oceanog. 32:223-237.

Hardy, A.C. 1924. The herring in relation to its animate environment, part i, the food and feeding habits of the herring. Fish. Invest. Lond., Ser. II, 7, No. 3.

Hay D. E., J. R. Brett, E. Bilinski, D. T. Smith, E. M. Donaldson, G. A. Hunter and A. V. Solmie. 1988. Experimental impoundments of prespawning Pacific herring (*Clupea harengus pallasi*): effects of feeding and density on maturation, growth, and proximate analysis. Can. J. Fish. Aquat. Sci. 45: 388-398.

Hesslein, R. H., K. A. Hallard, and P. Ramlal. 1993. Replacement of sulfur, carbon, and nitrogen in tissue of growing broad whitefish (*Coregonus nasus*) in response to a change in diet traced by $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$. Can. J. Fish. Aquat. Sci. 50:2071-2076.

McConnaughey, T. and C. P. McRoy. 1979. Food-web structure and the fractionation of carbon isotopes in the Bering Sea. Mar. Biol. 53:257-262.

Michener, R.H. and D.M. Schell. 1994. Stable isotope ratios as tracers in marine aquatic food webs. *In*: Latjtha, K. and R.H. Michener (eds*) Stable Isotopes in Ecology and Environmental Science*. pp.138-157. Blackwell Scientific Publications, Oxford.

Miller, C.B., B. W. Frost, H.P. Batchelder, M.J. Clemons, and R.E. Conway. 1984. Life histories of large, grazing copepods in a subarctic ocean gyre: *Neocalanus plumchrus*, *Neocalanus cristatus*, and *Eucalanus bungii* in the northeast Pacific. Progr. Oceanog. 13:201-243.

Miller, C.B. 1993. Development of large copepods during spring in the Gulf of Alaska. Progr. Oceanog. 32:295-317.

Minagawa, M., and E. Wada. 1984. Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between $\delta^{15}N$ and animal age. Geochim. Cosmochim. Acta 48:1135-1140.

Niebauer, H.J., T.C. Royer, and T.J. Weingartner. 1994. Circulation of Prince William Sound, Alaska. J. Geophys. Res. 99:113-126.

Owens, N. J. P. 1987. Natural variations in ^{15}N in the marine environment. Advances in Marine Biology 24:389-451.
Rau, G.H., A.J. Mearns, D.R. Young, R.J. Olson. H.A. Schaffer, and I.R. Kaplan. 1983. Animal $^{13}C/^{12}C$ correlates with trophic level in pelagic food webs. Ecology 64:1314-1318.

Rau, G.H., T. Takahashi, D.J. Des Marais, C.W. Sullivan. 1991. Particulate organic matter $\delta^{13}C$ variations across the Drake Passage. J. Geophys. Res. 96:15131-15235.

Schell, D.M. 1996. Testing conceptual models of marine mammal trophic dynamics using carbon and nitrogen stable isotope ratios. OCS Study MMS 95-0057, U.S. Dept. Interior pp.86-96.

Wada, E., H. Mizutani, and M. Minagawa. 1991. The use of stable isotopes for food web analysis. Crit Rev Food Sci Nutr 30:361-371.

Figure captions (tables and figures follow)

1. Map of eastern Prince William Sound, Alaska indicating sampling sites at Port Gravina and Windy Bay.

2. Contoured $\delta^{13}C'$ data (from Table 2) of *Neocalanus cristatus* sampled as feeding stage copepodite V throughout Prince William Sound and adjacent Gulf of Alaska.

3. Box and whisker plots of young-of-the-year herring somatic energy content (SEC) in kJg^{-1}dry weight sampled from Windy Bay and Port Gravina in October, 1994. The upper, lower, and line through the middle of the box correspond to the 75th, 25th, and 50th percentiles, respectively. The "whiskers" indicate the 10th and 90th percentiles. The mean value is shown as a square symbol.

4. Relationship of young-of-the-year herring somatic energy content (SEC) in kJg^{-1} dry weight sampled from Windy Bay and Port Gravina in October, 1994 with standard length. Windy Bay $r^2 = 0.36$, $p = 0.0001$; Port Gravina $r^2 = 0.12$, $p = 0.0009$.

5. Box and whisker plots of young-of-the-year herring $\delta^{13}C$, $\delta^{13}C'$, and $\delta^{13}C'_{TL}$ sampled from Windy Bay and Port Gravina in October, 1994 (left three panels) compared with $\delta^{13}C'$ of the herbivorous copepod *Neocalanus cristatus* (data from Kline 1996, 1997) sampled in PWS and the Gulf of Alaska (GOA). The TL normalization makes the herring and copepods comparable (two right-hand panels). Box and whisker plots percentiles shown same as Fig. 2. The dashed lines correspond with the mean $\delta^{13}C'$ of copepods from PWS and GOA, and the midpoint between PWS and GOA.

6. Box and whisker plot of young-of-the-year herring $\delta^{15}N$ sampled from Windy Bay and Port

Gravina in October, 1994. Box and whisker plots percentiles shown same as Fig. 2.

7. $\delta^{13}C'_{TL}$ in young-of-the-year herring as a function of standard length. PWS and GOA reference lines as described in text. Data suggest ontogenic shift to more ^{13}C-depleted GOA-carbon based diet. Synoptic samples suggest heterogeneity in distribution of young-of-the-year herring with respect to this diet shift.

8. $\delta^{13}C_{TL}$ in young-of-the-year herring versus SEC in kJ/g dry weight sampled from Windy Bay and Port Gravina in October, 1994. PWS and GOA reference lines as described in text.

Table 1. Comparison of sizes and standard lengths of young-of-the-year herring samples used in this paper.

	All fish caught	Energetics sample	Isotope sample
<u>Windy Bay</u>			
Number of fish	99	88	32
Mean standard length	83.6 mm	82.9 mm	83.2 mm
Standard deviation	9.1	6.7	7.7
Mean wet weight	7.6 g		
Standard deviation	3.6		
<u>Port Gravina</u>			
Number of fish	381	88	28
Mean standard length	95.3 mm	98.6 mm	98.3 mm
Standard deviation	7.2	6.1	7.0
Mean wet weight	12.2 g		
Standard deviation	4.4		

Table 2. Number of copepodite V *Neocalanus cristatus* sampled from upper 50 m at indicated oceanographic stations in Prince William Sound and Gulf of Alaska where at least one individual was found in March to June, 1995. Zeros indicate that none were found and dashes indicate that station was not made. Mean $\delta^{13}C'$ and SD of total sample from each station given.

				Number Sampled				$\delta^{13}C'$	
Name	Latitude N	Longitude W	Depth (m)	March	April	May	June	Mean	SD
Prince William Sound stations									
CFOS13	60 35.1	146 55.7	441	0	0	1	0	-19.3	
CFOSBY	60 36.3	147 12.2	205	0	0	21	0	-19.7	0.4
CS3	60 28.7	147 05.5	300	-	0	11	0	-19.9	0.6
CS9	60 35.1	146 44.4	400	0	0	0	14	-20.3	0.6
HE12	60 15.7	146 49.4	254	0	0	2	0	-19.4	
NS1	60 46.8	146 55.8	289	0	1	2	0	-19.5	
NWS4	60 46.8	147 22.2	430	1	0	4	0	-19.1	1.1
OB1	60 36.6	145 55.8	180	-	1	0	0	-18.7	
OB2	60 35.2	146 24.6	120	0	1	0	8	-20.0	0.8
PV1	60 55.9	146 50.0	330	-	0	2	0	-18.9	
PW1	60 50.4	148 12.3	405	6	1	0	0	-19.8	1.5
SEA4	60 46.2	148 04.9	330	-	0	3	0	-19.4	
SEA11	60 37.0	148 00.0	496	0	0	9	0	-19.4	0.6
SEA22	60 40.5	147 41.0	753	-	3	0	0	-19.3	1.6
SEA25	60 18.1	147 58.0	558	0	8	0	0	-19.4	1.3
Gulf of Alaska station									
GOA6	60 00.0	146 40.0	100	0	-	20	13	-23.2	1.1

FIGURE 1

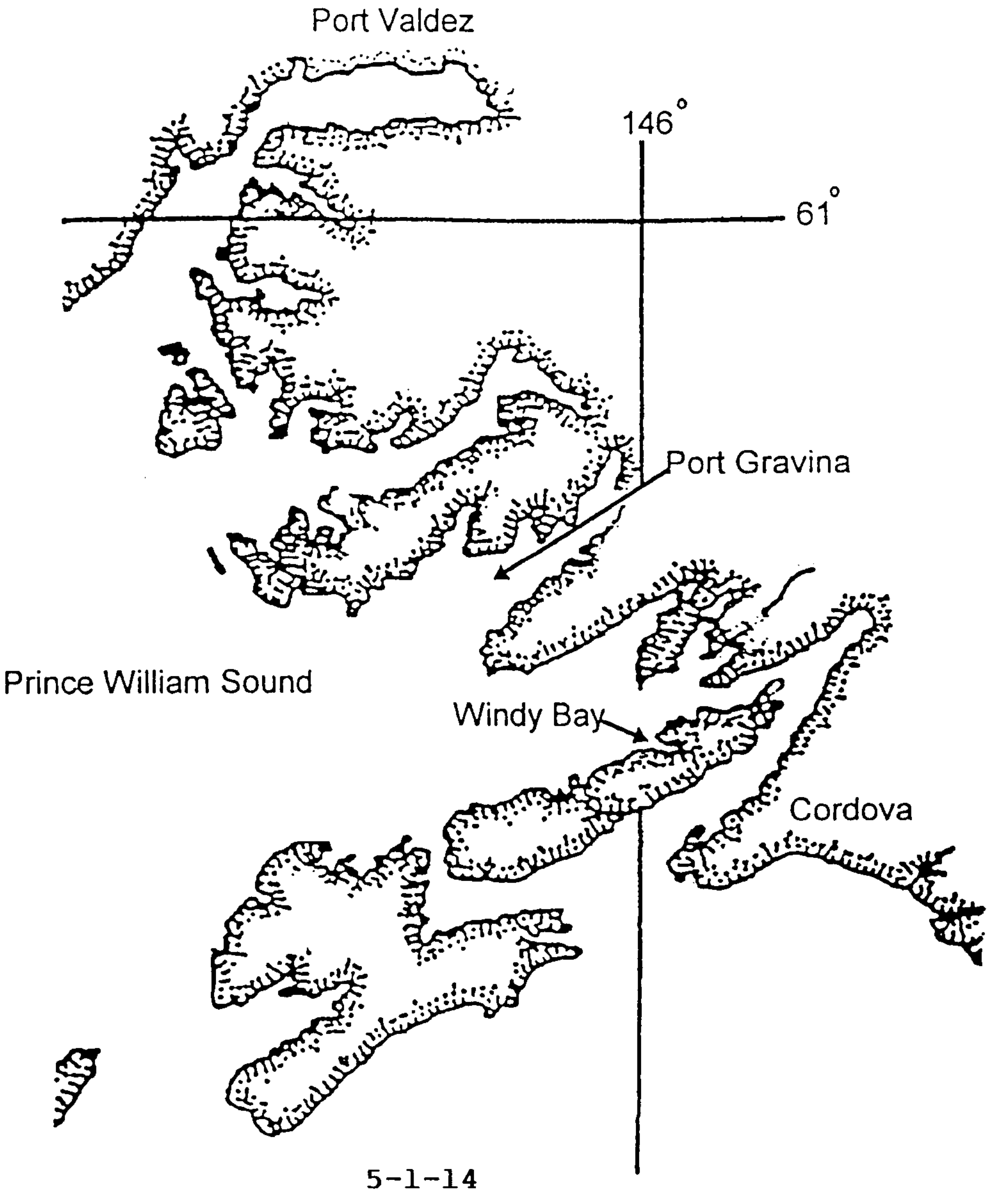
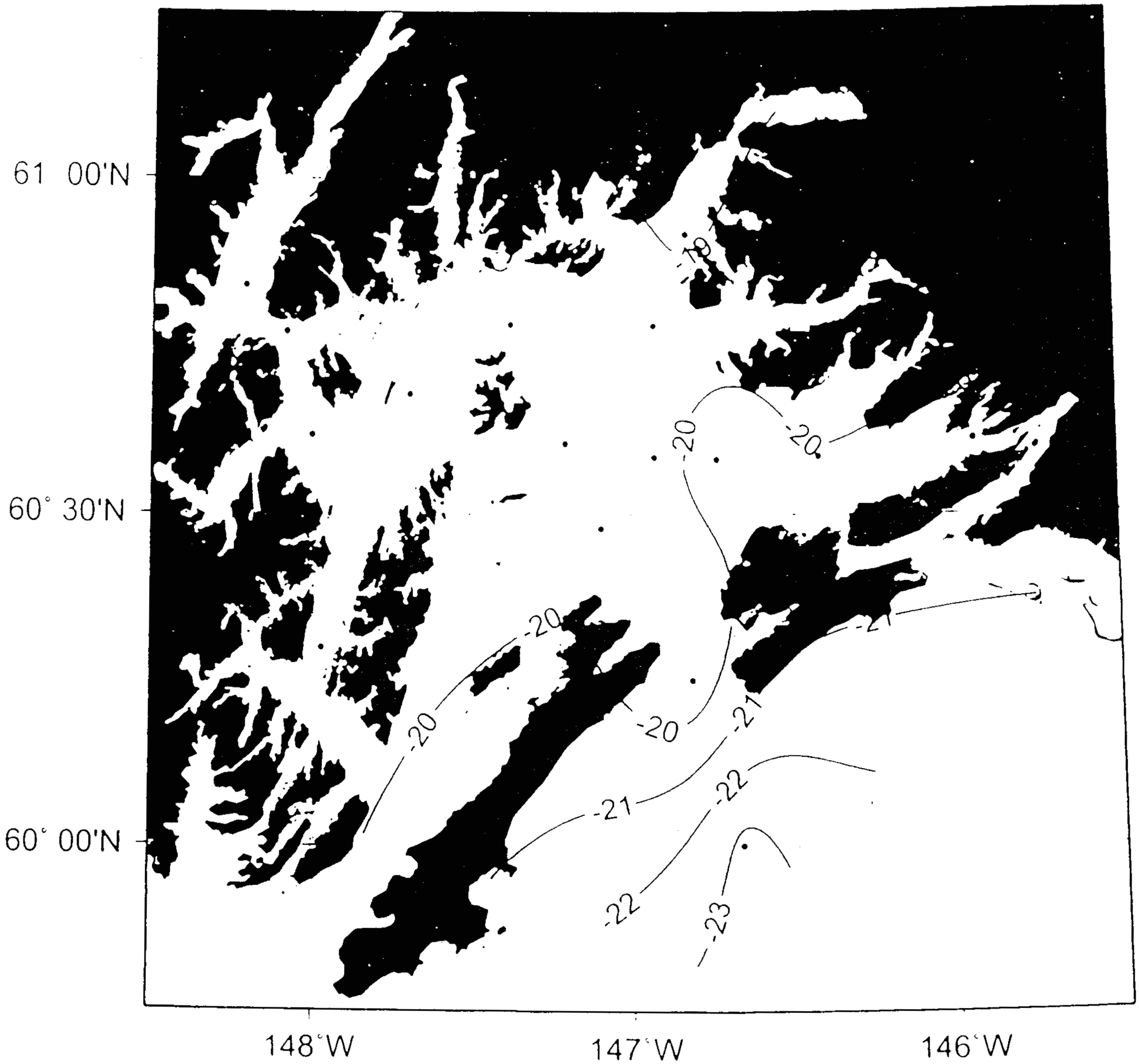
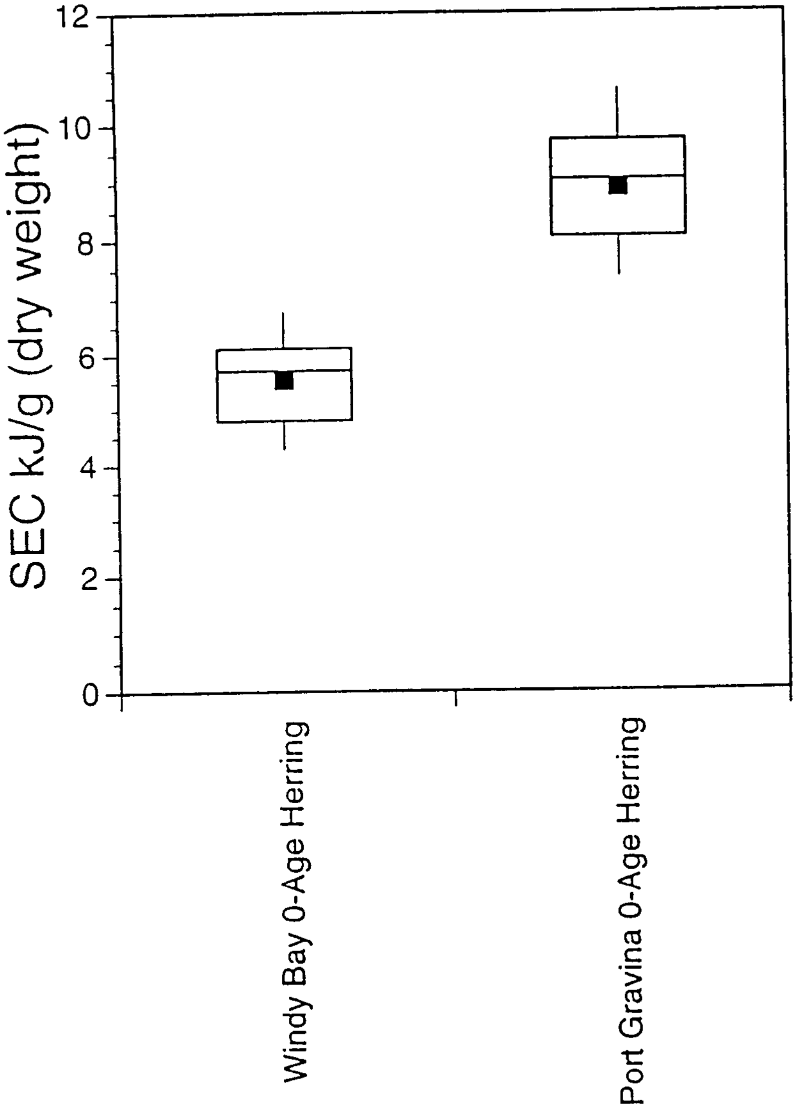

Port Valdez
146°
61°
Port Gravina
Prince William Sound
Windy Bay
Cordova

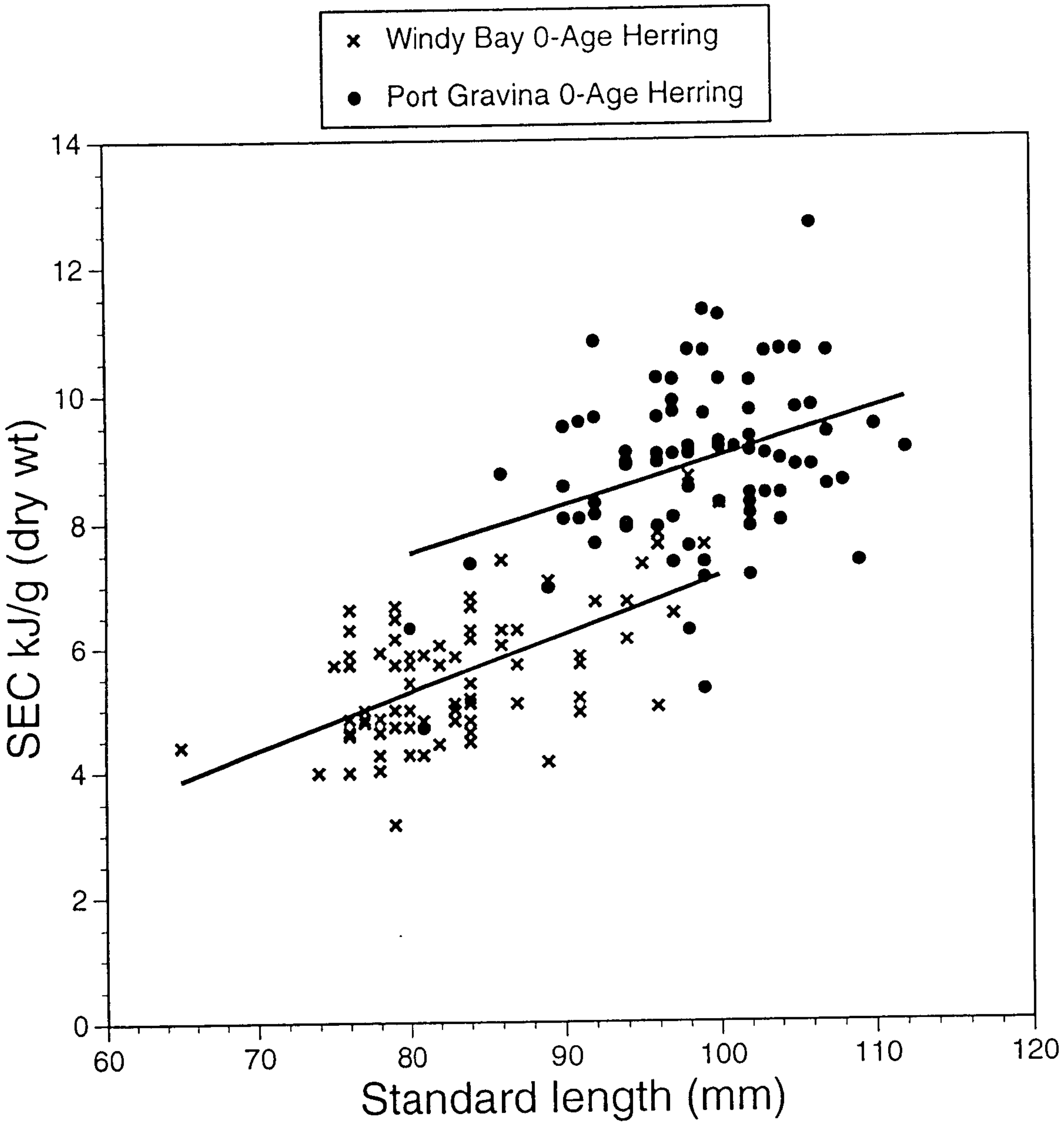
FIGURE 2



61 00'N
60° 30'N
60° 00'N
148°W
147°W
146°W
-18
-20
-20
-20
-20
-20
-21
-21
-21
-22
-22
-23

FIGURE 3


SEC kJ/g (dry weight)
12
10
8
6
4
2
0
Windy Bay 0-Age Herring
Port Gravina 0-Age Herring



× Windy Bay 0-Age Herring
● Port Gravina 0-Age Herring
SEC kJ/g (dry wt)
14
12
10
8
6
4
2
0
60
70
80
90
100
110
120
Standard length (mm)

Fig 4

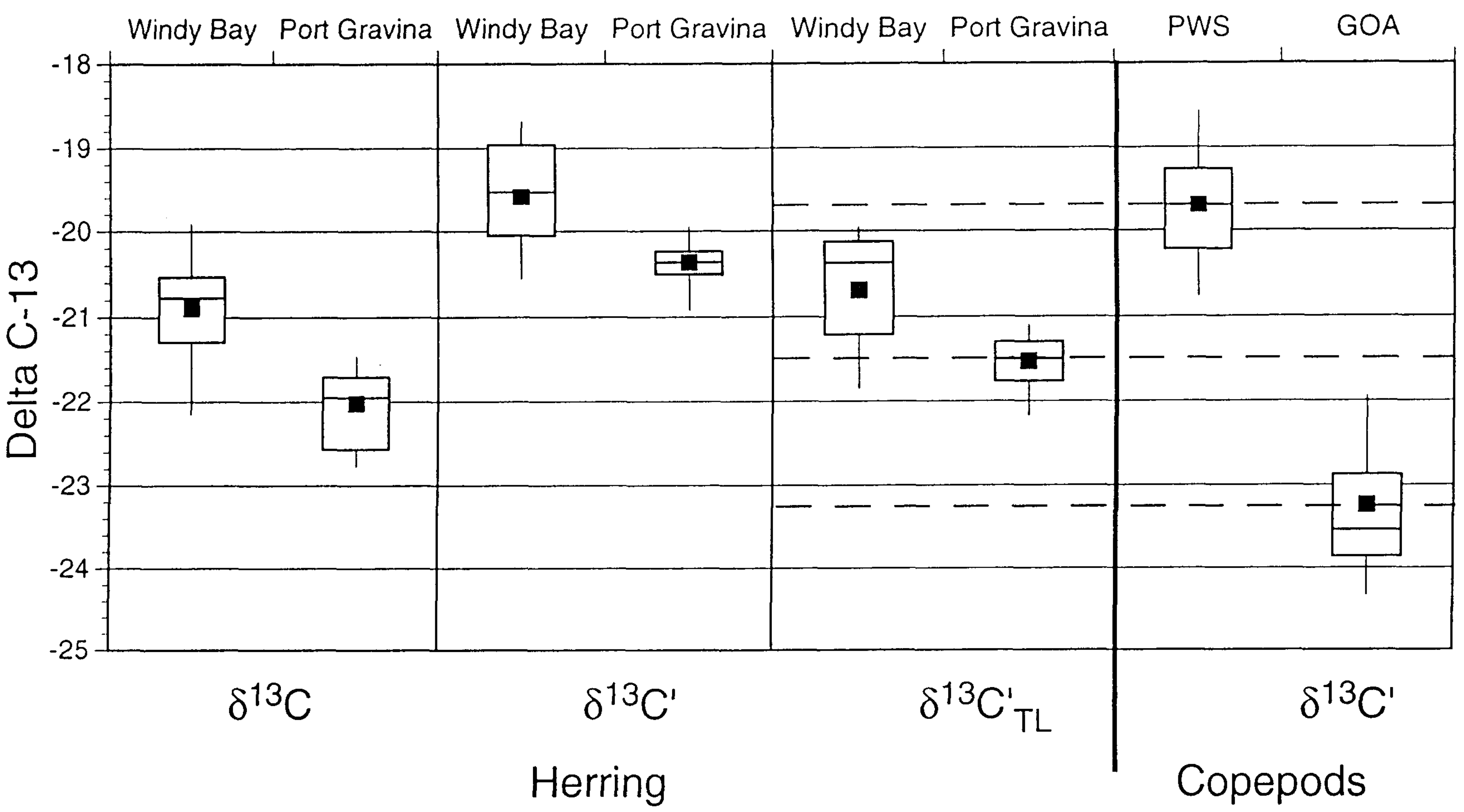
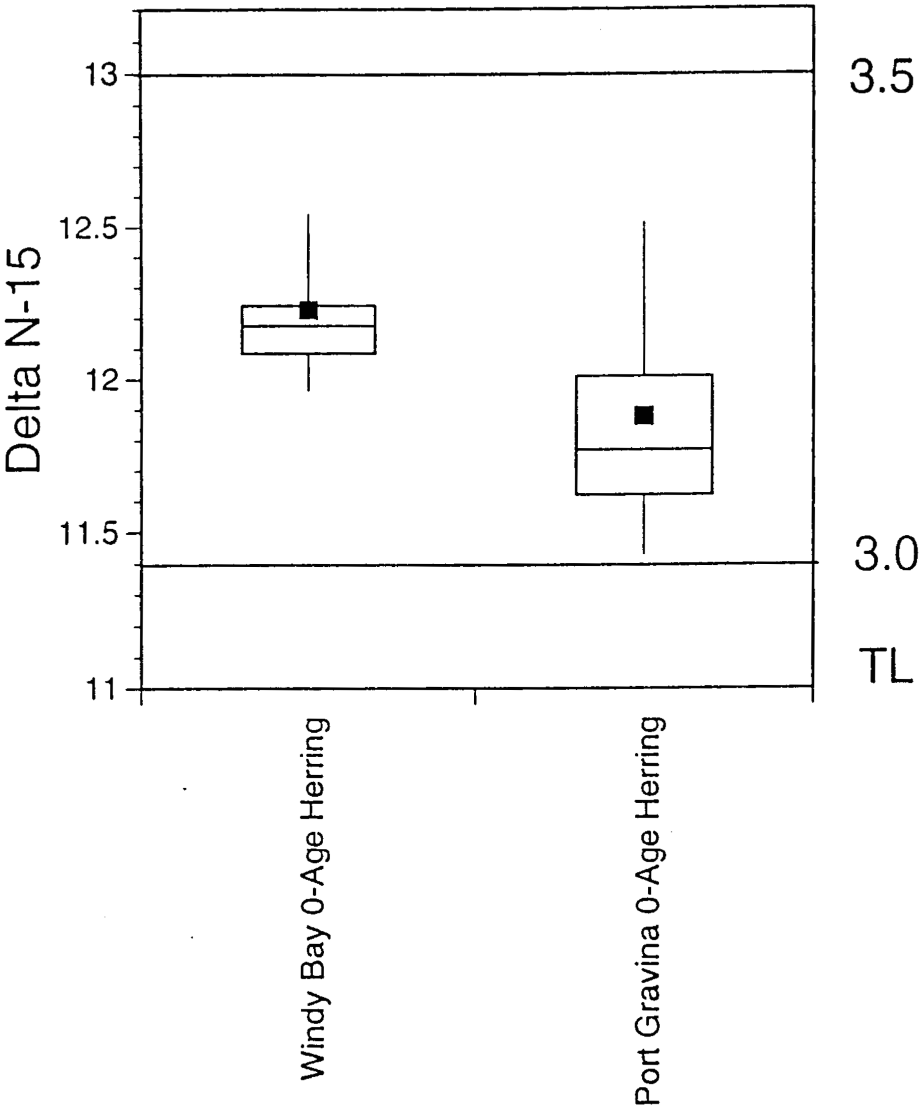

Windy Bay
Port Gravina
Windy Bay
Port Gravina
Windy Bay
Port Gravina
PWS
GOA
-18
-19
-20
-21
-22
-23
-24
-25
Delta C-13
$\delta^{13}C$
$\delta^{13}C'$
$\delta^{13}C'_{TL}$
$\delta^{13}C'$
Herring
Copepods

Fig 5

FIGURE 6



Delta N-15
13
12.5
12
11.5
11
3.5
3.0
TL
Windy Bay 0-Age Herring
Port Gravina 0-Age Herring

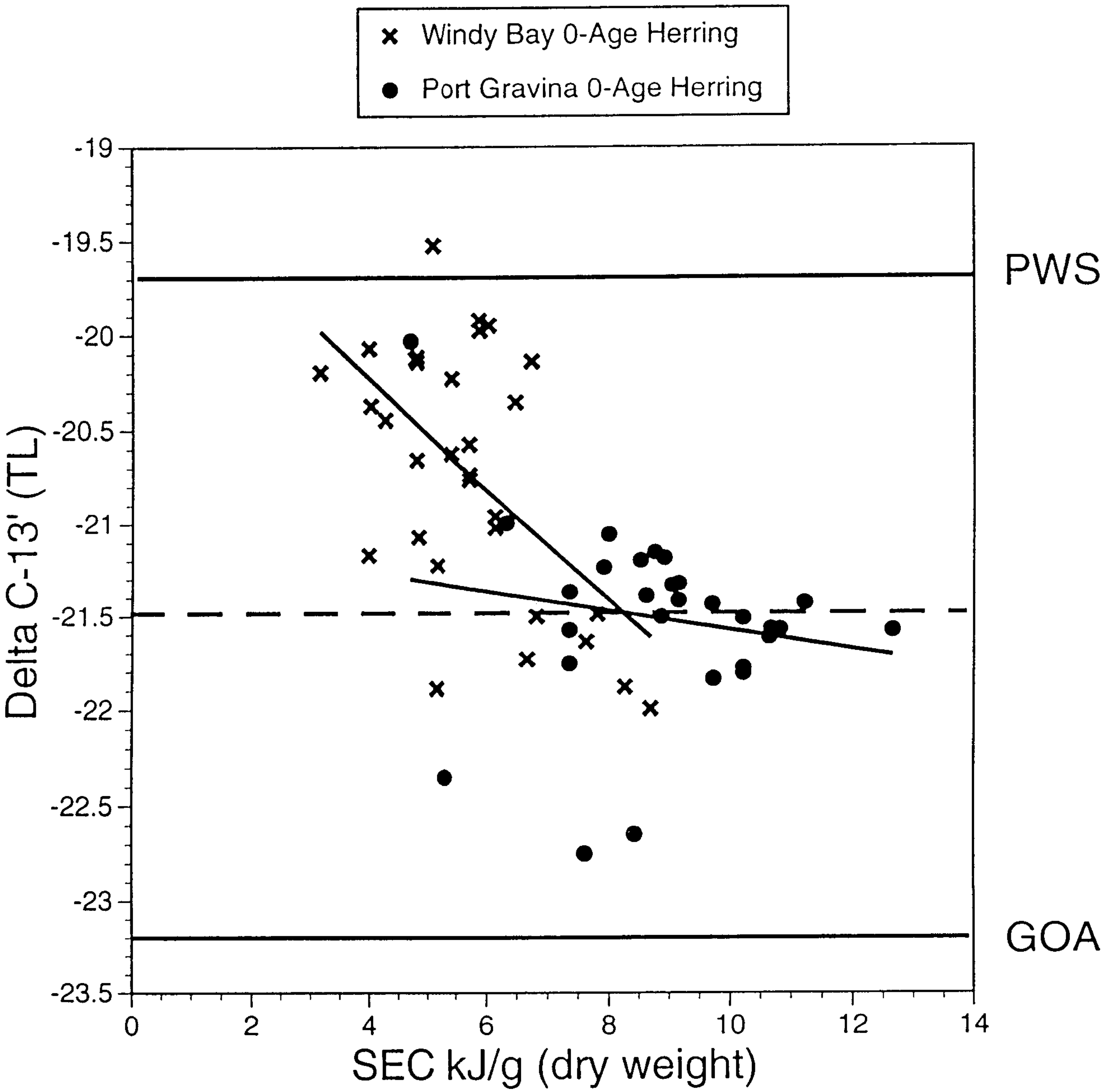

× Windy Bay 0-Age Herring
● Port Gravina 0-Age Herring
-19
-19.5
-20
-20.5
-21
-21.5
-22
-22.5
-23
-23.5
Delta C-13' (TL)
0
2
4
6
8
10
12
14
SEC kJ/g (dry weight)
PWS
GOA

Fig 7

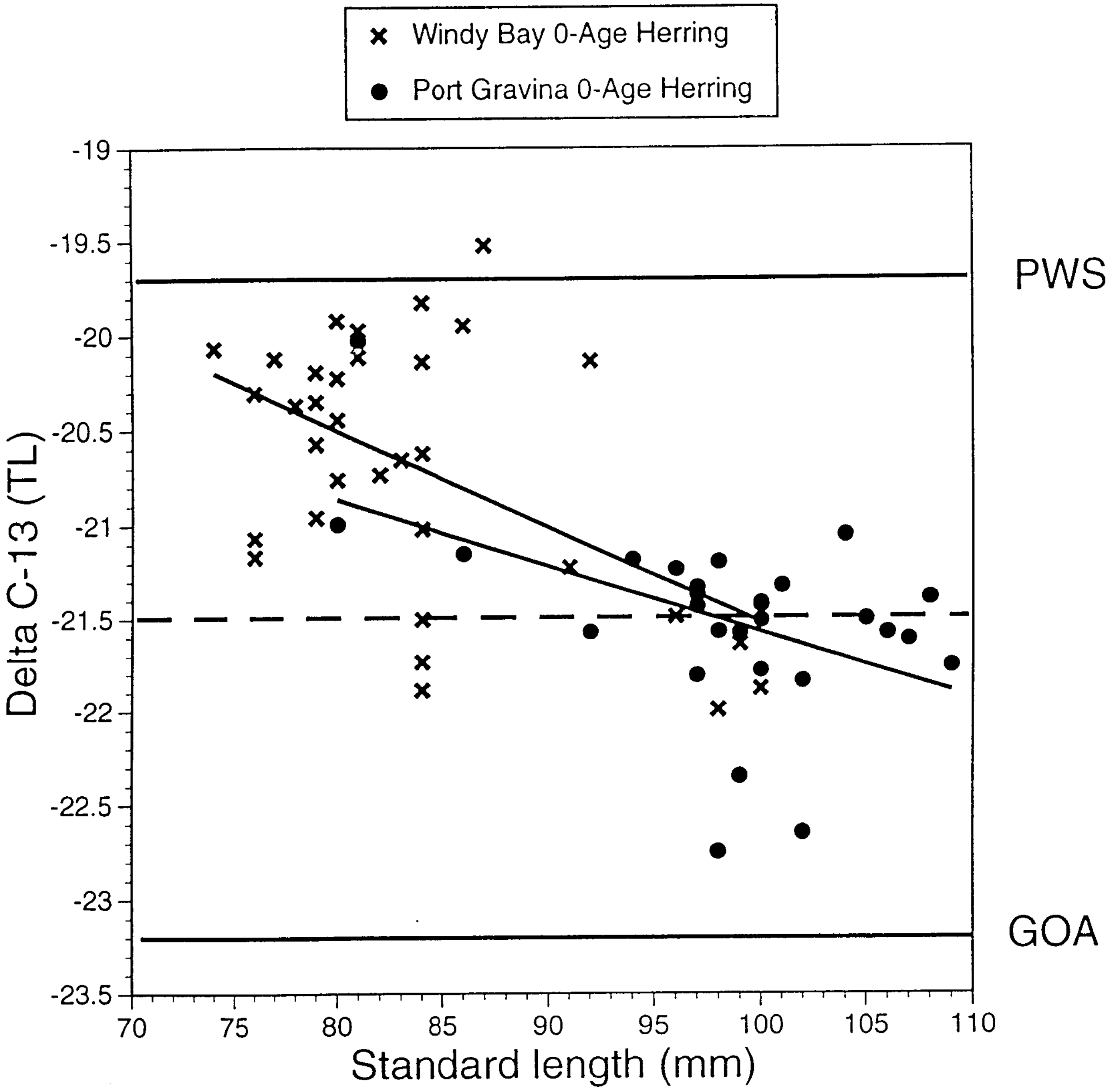

× Windy Bay 0-Age Herring
● Port Gravina 0-Age Herring
PWS
GOA
Delta C-13 (TL)
-19
-19.5
-20
-20.5
-21
-21.5
-22
-22.5
-23
-23.5
70
75
80
85
90
95
100
105
110
Standard length (mm)

Fig 8

International Symposium on the Role of Forage Fishes in Marine Ecosystems
B. Baxter (ed), Alaska Sea Grant College Program

Confirming Forage Fish Food Web Dependencies in the Prince William Sound Ecosystem Using Natural Stable Isotope Tracers

Thomas C. Kline, Jr., Ph. D.
Prince William Sound Science Center
P. O. Box 705, Cordova AK 99775
907-424-5800 (tel)
907-424-5820 (fax)
tkline@grizzly.pwssc.gen.ak.us (email)

DRAFT:
IN PRESS

Confirming Forage Fish Food Web Dependencies in the Prince William Sound Ecosystem Using Natural Stable Isotope Tracers.

Thomas C. Kline, Jr.

*Abstract

$^{15}N/^{14}N$ and $^{13}C/^{12}C$ natural abundances were measured in plankton and nekton samples collected in 1994 and 1995 throughout Prince William Sound, Alaska (PWS) and selected locations in the northern Gulf of Alaska (GOA).

$\delta^{15}N$ values were used to determine realized trophic levels (TL) of potential forage and predator nekton species using the copepod *Neocalanus cristatus* as a reference.

A $\delta^{13}C$ gradient is suggested for carbon in the study area plankton, with high ^{13}C in PWS and low ^{13}C in the GOA. The interplay of these carbon sources is hypothesized to play a role in PWS food web nutrition. The initial focus of analytical work was addressed at resolving the relationship of $\delta^{13}C$ to GOA versus PWS carbon sources. These analyses consisted of extensive isotopic analyses of individuals of the herbivorous copepod *Neocalanus cristatus* taken from bulk net plankton samples collected during oceanographic surveys in 1994 and 1995. Copepods feeding in the GOA were significantly ^{13}C depleted compared to those feeding in PWS consistent with a source isotope effect.

After removing lipid- and trophic level-isotope-effects from nekton $\delta^{13}C$, it was possible to assess significance of GOA and PWS carbon sources. This approach was used to determine the relative importance of GOA-origin carbon, which was found to vary among "forage-fish" species. By combining isotopic with energetic analyses, it is possible to ascertain which locations in PWS are most dynamic with respect to transfer of energy into food webs via forage fishes.

*Introduction

The failure of several Prince William Sound (PWS), Alaska vertebrate species to recover from population crashes following the 1989 *T/V Exxon Valdez* oil spill (EVOS), has raised concerns that shifts in food web structure may have occurred. Of particular concern is recruitment of *Clupea pallasi* (Pacific herring), presently at a historical low in abundance in PWS, a fjordlike inland sea that receives oceanic water from the Gulf of Alaska via the Alaska coastal current (Niebauer et al. 1994). The emergent hypothesis is that when large herbivorous copepods of the genus *Neocalanus* and other macrozooplankton, primary sources of food for predatory fishes (Parsons 1987), are in low abundance, these fishes resort to piscivory. Prey include *Clupea*, *Oncorhynchus* spp. fry including *O. gorbuscha* (pink salmon, also impacted by the oil spill) and other age 0+ fishes that can be regarded as "forage-fish" species. Predator species were expected to be dominated by gadid species in the pelagic system. The switch to piscivory is hypothesized to be a factor in recruitment of fishes, many of which are also important as forage for birds, and mammal species that were also affected by EVOS in PWS.

Confirmation of the hypothesis that macrozooplankton availability and related processes control fisheries recruitment are being tested in a large-scale multidisciplinary project known as Sound Ecosystem Assessment (SEA). Because of their predictable nature, stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) are providing an effective method for testing this hypothesis. Natural stable isotope ratio analysis of fishes, their prey and their predators serve as effective tracers of energy supply thus providing insight into both habitat usage and assist in quantifying amount of carbon and by extension, energy, derived from various areas of production. Nitrogen stable isotope ratios provide excellent definition of relative trophic level (Fry 1988, Wada et al. 1991, Hobson and Welch 1992, Kiriluk et al. 1995). The heavy isotope of nitrogen, ^{15}N, is enriched by about 0.34 % (or 3.4 per mil in conventional delta units, see materials and methods) with each trophic level (Minagawa and Wada 1984) and has been shown to accurately indicate the realized trophic level of species within an ecosystem (Kling et al. 1992, Cabana and Rasmussen 1994). Carbon isotope signatures can effectively be used to trace multiple sources of carbon into food webs once it can be established that these sources have distinctive isotopic signatures (Fry and Sherr 1984, Wada et al. 1991). The data obtained from stable isotope measurements are unique in that they trace assimilated material and thus can be used for accurate ecosystem process modeling (e.g., Wada et al. 1991, Nadelhofeffer and Fry 1994, Macko and Ostrom 1994, Michener and Schell 1994, and Conway et al. 1994).

Because of their predictable relationship when comparing consumers to diet, stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) effectively provide empirical evidence of trophic relationships in marine food webs. Natural abundance of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ of Prince William Sound Alaska pelagic biota were measured in samples collected from 1994 to 1995. $\delta^{15}N$ values were used to determine trophic level (TL) relative to the large herbivorous copepod *Neocalanus cristatus* whereas $\delta^{13}C$ values were used to differentiate carbon derived from Gulf of Alaska production versus carbon produced within Prince William Sound.

*Materials and Methods

**Sampling

Nekton and zooplankton were sampled from a variety of vessels ranging from a 25m trawler, *F/V Alaska Beauty*, equipped with a 40 x 28m mid-water wing trawl (2.0 cm stretch-mesh web codend) to small fry skiffs and seine boats that participated as part of the SEA project. Zooplankton samples were collected with a 335µ-mesh 0.5 m-diameter ring net towed vertically to the surface from station depth and 50 m at designated SEA project stations. Life-history-stage copepodid-V (C5) *Neocalanus cristatus* were picked from zooplankton samples and analyzed as individuals. Sampling of nekton for stable isotope analysis consisted of a section (~ 1 g) of epaxial muscle (fishes) or mantle (squid) for those with lengths > ~ 100 mm or the whole organism for those < 100 mm. Samples where frozen (-20°C) on board the vessel for later laboratory preparation for natural stable isotope abundance analysis.

**Laboratory preparation

The gastro-intestinal tract was removed from whole fish samples to remove dietary material from samples.

All samples were stored frozen until freeze dried (Labconco) and ground to a fine powder with a dental amalgamator (Crescent Dental Wig-L-Bug). Replicate aliquots of ~1.5 mg (except for individual samples of *Neocalanus* which were too small for more than one analysis) were weighed to the nearest µg and then loaded into combustion boats for mass spectrometric analysis.

**Isotopic determination

A Europa Scientific model 20/20 stable isotope analyzer equipped with a Europa Scientific Roboprep sample preparation and purification unit was used. Analytical results include $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios in standard delta units, $\delta^{13}C$ and $\delta^{15}N$, respectively, and %C and %N.

Standard delta notation is used to express stable isotope ratios, which are reported relative to international standards (air for N and Vienna Peedee belemnite for C) and defined by the following expression:

$$(1) \quad \delta^{15}N \text{ or } \delta^{13}C = \left(\frac{R_{sample}}{R_{standard}} - 1\right) * 1000 \text{ per mil}$$

where R = $^{15}N/^{14}N$ or $^{13}C/^{12}C$ (after Craig 1957). The isotope standards have delta values of 0 by definition, i.e. $\delta^{15}N = 0$ for atmospheric N_2. Naturally occurring $\delta^{15}N$ and $\delta^{13}C$ values observed in biota, range from ~0 to ~ +20 and from ~ 0 to ~ -50, respectively. The negative $\delta^{13}C$ values reflect the relative enrichment of ^{13}C in the limestone standard compared with biota.

Samples were rerun when replication was poor (difference in delta units > 0.6). Typically, replication is < 0.2 delta units. The %C and %N data were used to calculate C/N. Mean of $\delta^{13}C$, $\delta^{15}N$ and C/N replicates were used for further analysis.

**Lipid normalization

Normalization for lipid composition was by the method of McConnaughey and McRoy (1979) using their C/N lipid proxy:

$$(2) \quad L = \frac{93}{\left(1 + \frac{1}{0.246C/N - 0.775}\right)}$$

used to calculate lipid-normalized $\delta^{13}C$ (expressed as $\delta^{13}C'$):

$$(3) \quad \delta^{13}C' = \delta^{13}C + 6\left(\frac{3.9}{1 + \frac{287}{L}} - 1\right)$$

**Trophic level and normalization

The enrichment of ^{15}N that results from a feeding process (Minagawa and Wada 1984) enables one to use $\delta^{15}N$ as a good proxy for trophic level (Fry 1988, Kling et al. 1992, Cabana and Rasmussen 1994). *Neocalanus* spp. are the dominant herbivores in the plankton community of the north Pacific (Miller et al. 1984). Although *Neocalanus cristatus* are facultatively carnivorous on planktonic Protozoa, they cannot be sustained on such a diet (Gifford 1993). Thus, the a priori trophic level (TL) of 2 (i.e., herbivores) was applied to the $\delta^{15}N$ of *Neocalanus cristatus* as a baseline for estimation of TL of other taxa. The $\delta^{15}N$ values corresponding to higher TLs was estimated by adding the ^{15}N trophic fractionation factor, $\varepsilon_N = 3.4$, to the value obtained for next lower TL, e.g., 3.4 was added to the $\delta^{15}N$ of *Neocalanus cristatus* to estimate the $\delta^{15}N$ of TL = 3.

$\delta^{13}C$ values were normalized for TL as well as lipid content so as to have the residual variation reflect $\delta^{13}C$ of the carbon source. Normalization for trophic enrichment of ^{13}C using the trophic enrichment factor, $\varepsilon_C = 1$, to the reference TL (the TL of *Neocalanus cristatus*) was made using the following relationship:

(4) $\delta^{13}C'_{TL} = \delta^{13}C' - \varepsilon_C(\delta^{15}N_{sample} - \delta^{15}N_{Neocalanus})/\varepsilon_N$

where $\delta^{13}C'_{TL}$ is the TL normalized $^{13}C/^{12}C$ value of $\delta^{13}C'$, $\varepsilon_C = 1$ (DeNiro and Epstein 1978, McConnaughey and McRoy 1979, Rau et al. 1983, Hobson and Welch 1992, Fry and Sherr 1984), the $\delta^{15}N$ values are those of the sample and *Neocalanus*, and $\varepsilon_N = 3.4$ (Minagawa and Wada 1984, Owens 1987). This normalization makes it possible to make direct $\delta^{13}C$ comparisons between the sample in question with *Neocalanus*, which is being used as representative of the organic carbon pool at the herbivore level.

***Results and Discussion**

***Neocalanus* herbivore (TL = 2) reference

938 individual *Neocalanus cristatus* sampled from 1994 through 1995 had a mean $\delta^{15}N$ = 8.0 (SD = 1.8). This $\delta^{15}N$ value of 8.0 was used as the TL = 2 (herbivore) reference value. The $\delta^{15}N$ values for TL = 3 and 4 calculated using (4) were 11.4 and 14.8, respectively. $\delta^{13}C$ of stage C5 *Neocalanus cristatus* feeding (only those sampled from upper 50m during March to June, 1995) in the northern GOA just south of the entrance to PWS were found to be consistently dichotomous when compared to those from within PWS (Kline 1996). Feeding C5 *Neocalanus cristatus* from the GOA had $\delta^{13}C$ = -24.4 (SD = 1.4, N = 33) and $\delta^{13}C'$ = -23.1 (SD = 1.1, N = 33) whereas those from PWS had $\delta^{13}C$ = -20.2 (SD = 1.1, N = 101) and $\delta^{13}C'$ = -19.7 (SD = 0.9, N = 101). Thus organic carbon in the form of zooplankton from the northern GOA is ^{13}C-depleted by ~ 4 per mil compared with PWS. This gradient is similar to the ~2.5 per mil gradient in $\delta^{13}C$ between the Bering Sea and the GOA at the Aleutian passes (Schell 1996) and the 7 per mil $\delta^{13}C$ gradient found across Drake Passage (Rau et al. 1991).

**Nekton database

Data from 1592 nekton samples, consisting principally of fishes, collected in 1994 and 1995 from PWS, and analyzed for $\delta^{15}N$ and $\delta^{13}C$ are presented in this paper. Invertebrate nekton included squid (*Berryteuthis magister*) and glass shrimp (*Pasiphaea pacifica*). Nekton $\delta^{15}N$ values were plotted against length to suggest how nekton shift in TL as a function of size (Fig. 1A). This plot also provides an indication of the nekton size distribution in the database. The large cluster of nekton ≤ 180 mm in Fig. 1A have a $\delta^{15}N$ of ~ +12 suggesting a TL ~ 3 consistent with the concept of a forage class TL. Higher TLs are indicated by higher $\delta^{15}N$. Thus $\delta^{15}N$ defines a forage class by realized TL (Kling et al. 1992) and size class. Larger nekton, more likely to be predators, show considerable TL variability (from ~ TL = 2 to TL > 4) consistent with some zooplankton foraging which is expected to vary according the SEA hypotheses. $\delta^{13}C$ and $\delta^{15}N$ are expected to increase with TL (DeNiro and Epstein 1978, McConnaughey and McRoy 1979, Rau et al. 1983, Fry and Sherr 1984, Minagawa and Wada 1984, Owens 1987, Hobson and Welch 1992, Kiriluk et al. 1995) at a ratio of 1/3.4 (the ratio of $\varepsilon_C/\varepsilon_N$, the trophic fractionation factors). The scatterplot and linear regression of the nekton database (Fig. 1B) has a slope inconsistent with this ratio. This fact, the low correlation coefficient of r^2= 0.37, and the wide scatter of $\delta^{13}C$ suggests that a significant source of variation is independent of TL. Note, however, that normalization for TL (Fig. 1C) resulted in a decrease in the correlation (r^2 = 0.14). TL-normalized $\delta^{13}C$ values when plotted against C/N (Fig. 1D) show the effect of increased C/N on $\delta^{13}C$ (McConnaughey and McRoy 1979, Rau et al. 1992). When C/N was used to normalize for lipid content, in addition to TL normalization, the slopes of the regressions of the net result,

$\delta^{13}C'_{TL}$, with $\delta^{15}N$ (Fig. 1E) and C/N (Fig. 1F) was eliminated, validating the use of the C/N correction for lipid content (Rau et al. 1992). The TL- and lipid-normalized values when replotted vs. length (Fig. 1G) also had no slope. The variance in $\delta^{13}C'_{TL}$ shown in Fig. 1G thus reflects isotope effects other than lipid content or TL.

The coincidence of the large *Neocalanus* $\delta^{13}C'$ gradient between the GOA and PWS with the Nekton $\delta^{13}C'_{TL}$ (recall that the TL normalization normalizes the $\delta^{13}C'$ value to the same TL as *Neocalanus* making the $\delta^{13}C'$ values comparable) value distribution suggest that GOA-derived productivity is important for nekton. Periodic flow reversals at Hinchinbrook Entrance (Niebauer et al. 1994), downward diapause migration of C5 *Neocalanus* spp. during the late spring (Miller 1993) coinciding with deep water renewal in PWS (Niebauer et al. 1994), and simultaneous transport of zooplankton by the landward movement of coastal waters (Cooney 1986) suggest mechanisms that could transport secondary productivity into PWS. Low $\delta^{13}C'_{TL}$ values (e.g. values < ~-21) measured in the nekton are consistent with the flux of carbon from outside PWS making its way into food chains there. Thus $\delta^{13}C'_{TL}$ values of nekton provide direct evidence for the hypothesis of plankton flow into PWS influencing nekton production. From the $\delta^{15}N$-based TL determination (Fig. 1A), nekton < ~180 mm can be defined as "forage fishes". Fig. 1H shows the data from Fig. 1G, but restricted to nekton ≤ 180 mm, where it can be seen that a substantial portion of the forage class nekton has $\delta^{13}C'_{TL}$ consistent with utilization of carbon derived from the GOA. However, most data points in Fig. 1G appear between $\delta^{13}C'_{TL} = -20$ and -21 suggesting a significant overlap in use of both PWS as well as GOA carbon. Further analysis examines the forage fishes (and other nekton) by species (Fig. 2).

**Forage class nekton by species

Box and whisker plots of $\delta^{15}N$ data of nekton ≤180 mm (Fig. 2A) suggest species-level differences in realized TL (Kling et al. 1992). Whereas most species had $\delta^{15}N$ consistent with TL = 3, i.e., primary carnivores, northern lanternfish were about 0.5 TL higher. Conversely walleye pollock (these consisted of < 100 mm, young-of-the-year) were consistently lower in TL. Glass shrimp had the greatest range in $\delta^{15}N$ consistent with facultative herbivory although principally carnivorous.

Box and whisker plots of $\delta^{13}C'_{TL}$ data of nekton ≤180 mm (Fig. 2B) suggest some variance in carbon source dependencies. There was spatial variability in the degree to which GOA-derived carbon is found in young-of-the-year herring which was concordant with energetic content (Kline and Paul 1997). Those fishes with higher GOA content (i.e. more negative $\delta^{13}C'_{TL}$ values), such as capelin and pink salmon fry, are more likely to have been affected by variance in flux of zooplankton from the GOA to PWS. Conversely, those species with high $\delta^{13}C'_{TL}$, such as juvenile gadids and sandlance, are likely not to be directly affected zooplankton inputs. These results thus provide evidence of bottom-up effects with an inherent source of environmental variability. Particularly noteworthy are potential species-level differential effects that could result in the advantage of one species over another as a function of oceanographic conditions that moderate zooplankton flux from the GOA to PWS.

*Summary

1. $\delta^{15}N$ relates to trophic level and can be used to delineate forage-class species.

2. $\delta^{13}C'_{TL}$ can be related to carbon source which can be related to oceanographic processes affected nekton production.
3. Species-level differences in dependencies on GOA carbon exist within the forage fish class nekton suggesting bottom-up effects in community structure.

*Acknowledgements

The research described in this paper was part of the Exxon Valdez Oil Spill Trustee Council - funded Sound Ecosystem Assessment (SEA) project. However, the findings and conclusions presented by the author are his own and do not necessarily reflect the views or position of the Trustee Council. The author acknowledges Captain Mike Geagel, the crew of the R/V *Bering Explorer*, E. Stockmar and B. Barnett for field and laboratory assistance in zooplankton sampling. The author acknowledges the captains and crews of the F/V *Alaska Beauty* and other fishing vessels used in this study. M. Powell, K. Antonucci, and D. Salmon collected the majority of the nekton samples. E. Brown and M. Willette coordinated the nekton sampling. Preparation of samples for mass spectrometry was done by R. Sundown, K. Antonucci, and B. Barnett. B. Barnett was responsible for the mass spectrometry. Discussions with D. Schell and R. Spies on isotope gradients, with T. Cooney and L. Tuttle on *Neocalanus* life histories, and with D. Salmon and S. Vaughan on regional physical oceanography provided the author with much insight.

*References cited

Cabana, G. and J. B. Rasmussen, 1994. Modeling food chain structure and contaminant bioaccumulation using stable nitrogen isotopes. Nature 372:255-257.

Conway, N.M., M.C. Kennicut II, C.L. Van Dover. 1994. Stable isotopes in the study of marine chemosynthetic-based ecosystems. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 158 -186.

Cooney, R.T. 1986. The seasonal occurrence of *Neocalanus cristatus*, *Neocalanus plumchrus*, and *Eucalanus bungii* over the shelf of the northern Gulf of Alaska. Cont. Shelf Res. 5:541-553.

Craig, H. 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochim. Cosmochim. Acta 12:133-149.

DeNiro, M. J. and S. Epstein. 1978. Influence of diet on the distribution of carbon isotopes in animals. Geochim. Cosmochim. Acta 42:495-506.

Fry, B. and E. B. Sherr. 1984. $\delta^{13}C$ measurements as indicators of carbon flow in marine and freshwater ecosystems. Contr. Mar. Sci. 27:13-47.

Fry, B. 1988. Food web structure on the Georges Bank from stable C, N, and S isotopic compositions. Limnol. Oceanogr. 33:1182-1190.

Gifford, D. J. 1993. Protozoa in the diets of Neocalanus spp. in the oceanic subarctic Pacific. Prog. Oceanog. 32:223-237.

Hobson, K.A. and H.E. Welch. 1992. Determination of trophic relationships within a high Arctic marine food web using $\delta^{13}C$ and $\delta^{15}N$ analysis. Mar. Ecol. Progr. Ser. 84:9-18.

Kiriluk, R.M., M.R. Servos, D.M. Whittle, G. Cabana, and J. Rasmussen. 1995. Using ratios of stable nitrogen and carbon isotopes to characterize the biomagnification of DDE, mirex, and PCB in a Lake Ontario pelagic food web. Can. J. Fish. Aquat. Sci. 52:2660-2674.

Kline, T. C. . 1996. Recruitment of *Neocalanus cristatus* into Prince William Sound (Alaska, USA) evidenced by natural stable isotope abundance. EOS, Transactions A.G.U. 76(3):OS43.

Kline, T.C. and A.J. Paul. Fall isotopic and somatic energy signatures of young of the year Pacific herring at two sites in Prince William Sound, Alaska: implications for trophic studies. Submitted to the Can. J. Fish. Aquat. Sci.

Kling, G.W., B. Fry, and W.J. O'Brien. 1992. Stable isotopes and plankton trophic structure in arctic lakes. Ecology 73:561-566.

Macko, S.A. and N.E. Ostrom. 1994. Pollution studies using stable isotopes. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 45 - 62.

McConnaughey, T. and C.P. McRoy. 1979. Food-web structure and the fractionation of carbon isotopes in the Bering Sea. Mar. Biol. 53:257-262.

Michener, R.H. and D.M. Schell. 1994. Stable isotope ratios as tracers in marine aquatic food webs. *In:* K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 138 -157.

Miller, C.B., B. W. Frost, H.P. Batchelder, M.J. Clemons, and R.E. Conway. 1984. Life histories of large, grazing copepods in a subarctic ocean gyre: *Neocalanus plumchrus*, *Neocalanus cristatus*, and *Eucalanus bungii* in the northeast Pacific. Progr. Oceanog. 13:201-243.

Miller, C.B. 1993. Development of large copepods during spring in the Gulf of Alaska. Progr. Oceanog.32:295-317.

Minagawa, M., and E. Wada. 1984. Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between δ^{15}N and animal age. Geochim. Cosmochim. Acta 48:1135-1140.

Nadelhoffer, K.J. and B. Fry. 1994. Nitrogen isotopes studies in forest ecosystems. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 22-44.

Niebauer, H.J., T.C. Royer, and T.J. Weingartner. 1994. Circulation of Prince William Sound, Alaska. J. Geophys. Res. 99:113-126.

Owens, N. J. P. 1987. Natural variations in ^{15}N in the marine environment. Advances in Marine Biology 24:389-451.

Parsons, T.R. 1986. Ecological relations. In: D.W. Hood and S.T. Zimmerman (Eds.) The Gulf of Alaska: Physical Environment and Biological Resources. U.S. Government Printing Office, Washington, D.C., p. 561-574.

Rau, G.H., A.J. Mearns, D.R. Young, R.J. Olson. H.A. Schaffer, and I.R. Kaplan. 1983. Animal ^{13}C/^{12}C correlates with trophic level in pelagic food webs. Ecology 64:1314-1318.

Rau, G.H., T. Takahashi, D.J. Des Marais, C.W. Sullivan. 1991. Particulate organic matter δ^{13}C variations across the Drake Passage. J. Geophys. Res. 96:15131-15235.

Rau, G.H., D.G. Ainley, J.L. Bengtson, J.J. Torres, and T.L. Hopkins. 1992. $^{15}N/^{14}N$ and $^{13}C/^{12}C$ in Weddell Sea birds, seals, and fish: implications for diet and trophic structure. Mar. Ecol. Progr. Ser. 84:1-8.

Schell, D.M. 1996. Testing conceptual models of marine mammal trophic dynamics using carbon and nitrogen stable isotope ratios. OCS Study MMS 95-0057, U.S. Dept. Interior pp.86-96.

Wada, E., H. Mizutani, and M. Minagawa. 1991. The use of stable isotopes for food web analysis. Crit. Rev. Food Sci. Nutr. 30:361-371.

***Figure Captions (figures follow)**

Figure 1A to H. Isotopic analysis of Prince William Sound nekton.

A. Nekton $\delta^{15}N$ values suggesting trophic level (TLs indicated on right axis) change as a function of length; based on the herbivorous copepod, *Neocalanus cristatus*, reference ($r^2 = 0.56$, P = 0 .0001; β coefficient X, P = 0.0001, β coefficient X^2, P = 0.0001, β coefficient X^3, p = 0.0001).

B. Nekton $\delta^{13}C$ as a function of $\delta^{15}N$. Regression line ($r^2 = 0.37$, P = 0.0001) slope = 0.62 (SE = 0.02, P = 0.0001) which differed from the ratio of the trophic fractionation factors $\varepsilon_C/\varepsilon_N$ = 1.0/3.4 = 0.29.

C. Data in Fig. B replotted following normalization of $\delta^{13}C$ for trophic level which reduced the correlation, r^2, to 0.14 (P = 0.0001) and slope to 0.32 (SE = 0.02, P = 0.0001).

D. Trophic level normalized $\delta^{13}C$ varied as a function of C/N as expected because of lipid isotope effects ($r^2 = 0.60$, P = 0.0001; β coefficient X, P = 0.0001, β coefficient X^2, P = 0.0001, β coefficient X^3, P = 0.0001).

E. Normalization for trophic level and C/N eliminated the relationship of $\delta^{13}C$ with $\delta^{15}N$ (r^2 = 0.04, P = 0.0001; slope = 0.12, SE = 0.01,P = 0.0001; compare with Fig. 1B).

F. Normalization for trophic level and C/N eliminated relationship of $\delta^{13}C$ with C/N ($r^2 = 0.07$, P = 0.0001; β coefficient X, P = 0.0001, β coefficient X^2, P = 0.0072, β coefficient X^3, P = 0.072; compare with Fig. 1D).

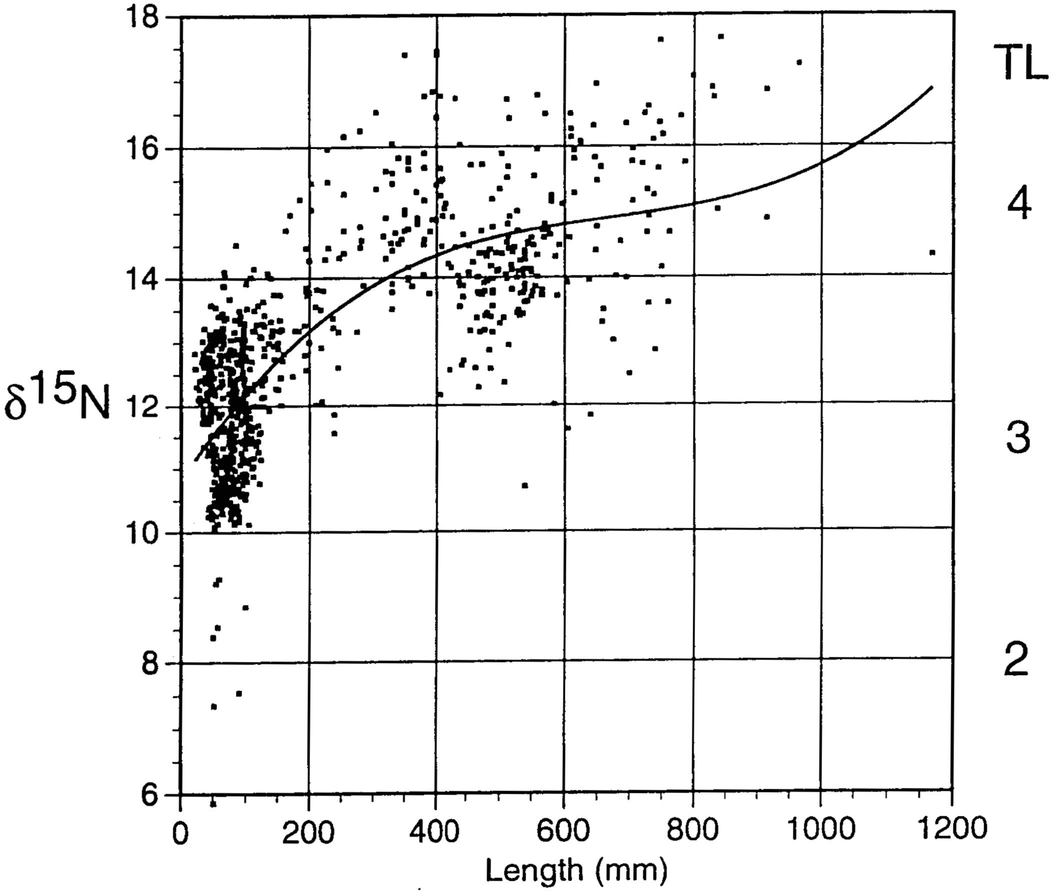
G. Relationship of $\delta^{13}C'_{TL}$ with length suggesting carbon source variation throughout size range ($r^2 = 0.04$, P = 0.0001; slope = 0.001, P =0.0001). The SD of *Neocalanus cristatus* $\delta^{13}C'$ values from PWS and the GOA indicated by bars on right axis.

H. Data from Fig. 1G expanded to show only "forage-fish", i.e. those nekton ≤ 180mm.

Figure 2A and 2B. Isotopic analysis of Prince William Sound forage-class nekton by species.

A. "Forage-fish" $\delta^{15}N$ box and whisker plots (10, 25, 50, 75, and 90th percentiles and means are indicated) and interpreted TLs suggesting species-level differences in realized trophic level.

B. "Forage-fish" (box and whisker plots as in Fig. 2A) and *Neocalanus cristatus* (SD range of samples from the GOA and PWS) $\delta^{13}C'_{TL}$ suggesting species-level differences in dependency on carbon source.



5-2-10

FIGURE 1A

5-2-11

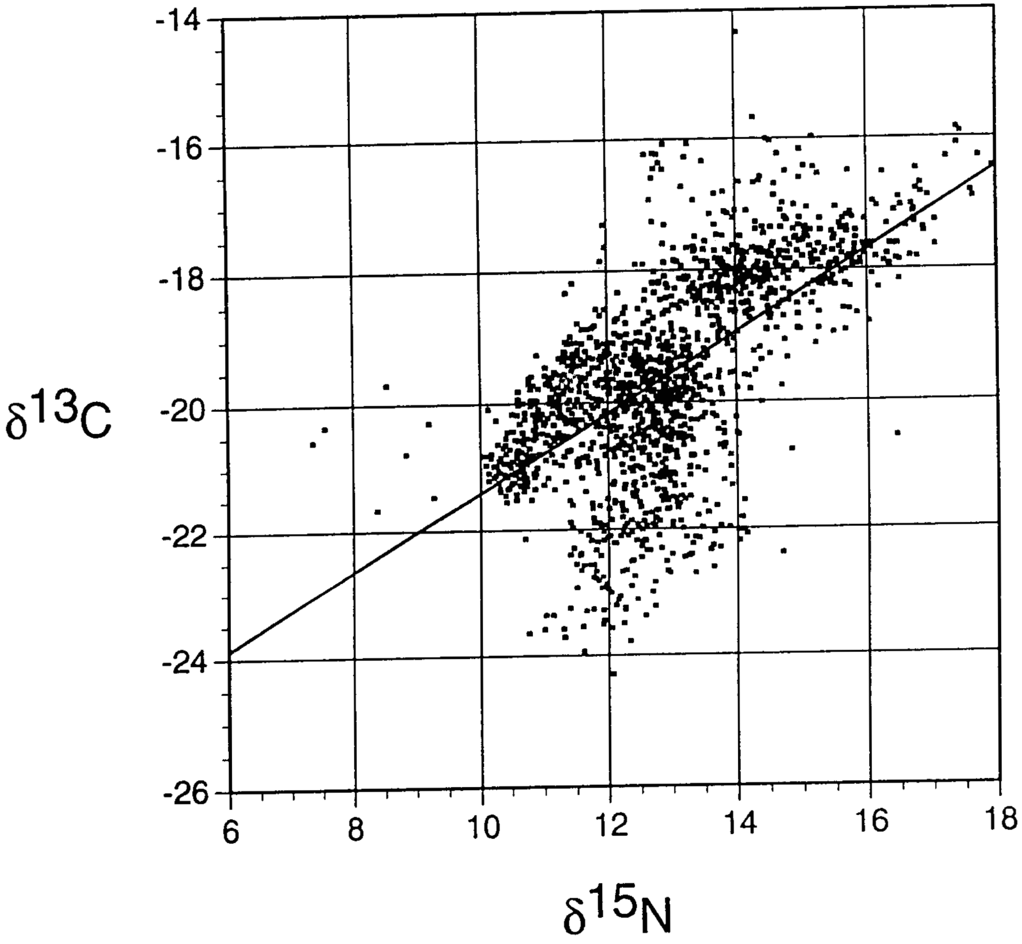


FIGURE 1B

5-2-12

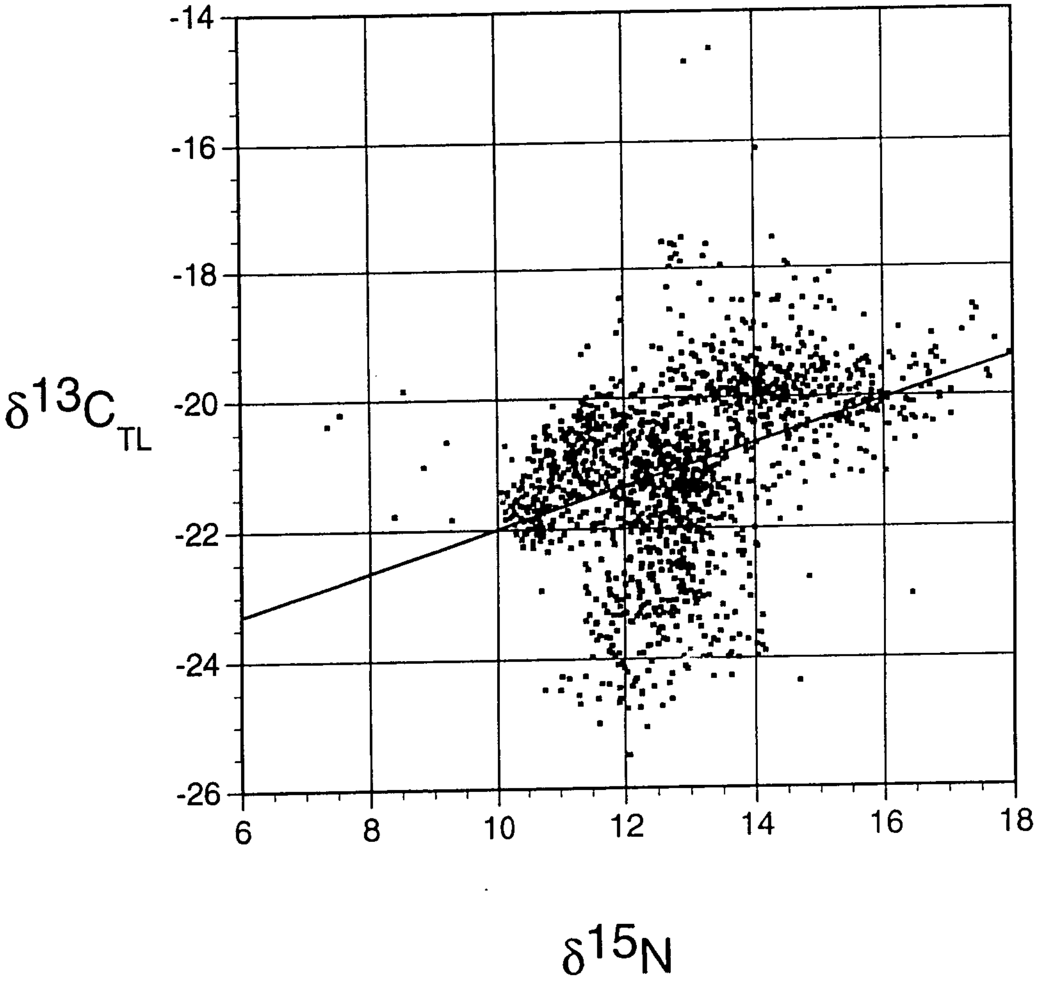


FIGURE 1C

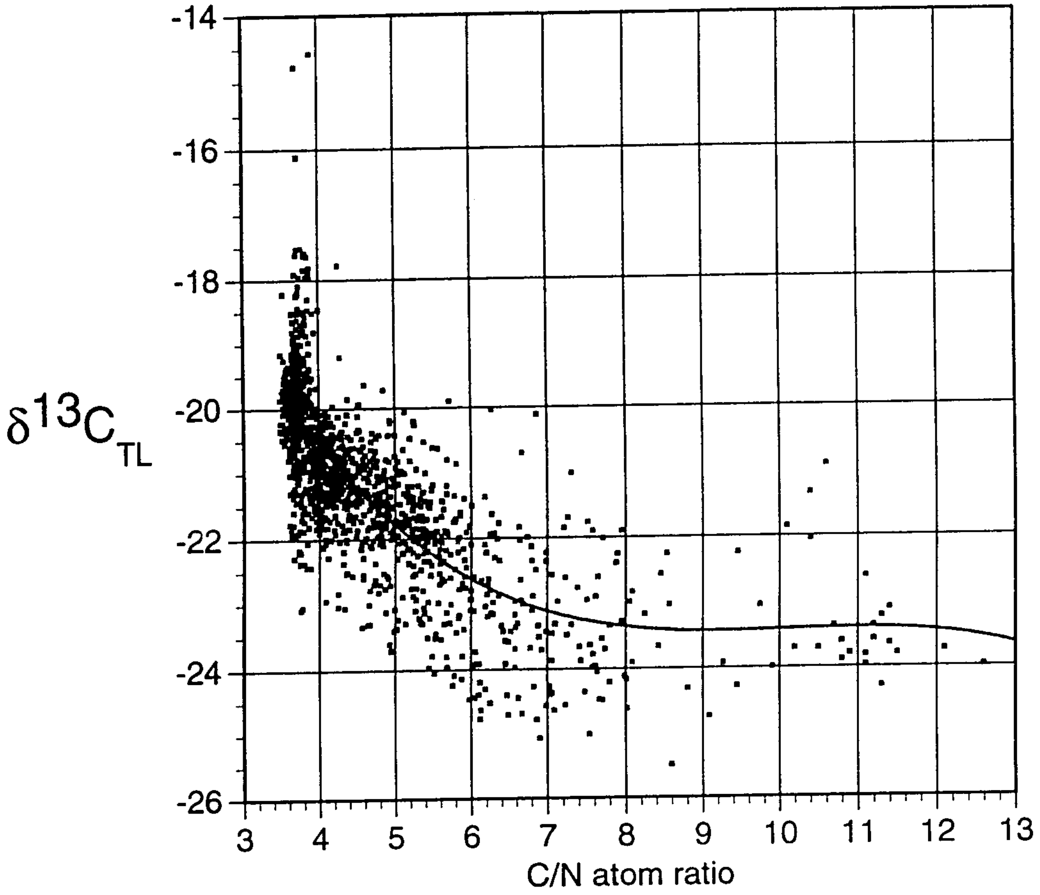

-14
-16
-18
-20
-22
-24
-26
$\delta^{13}C_{TL}$
3
4
5
6
7
8
9
10
11
12
13
C/N atom ratio

FIGURE 1D

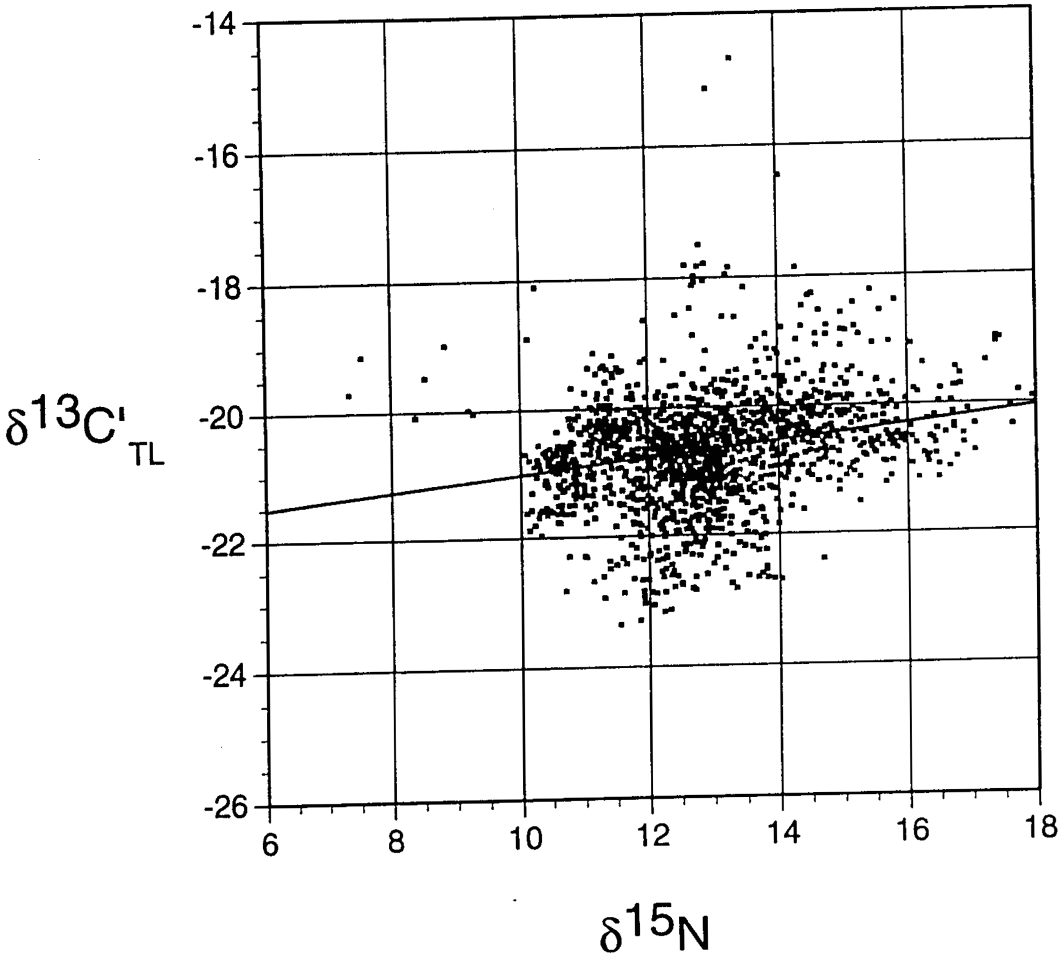
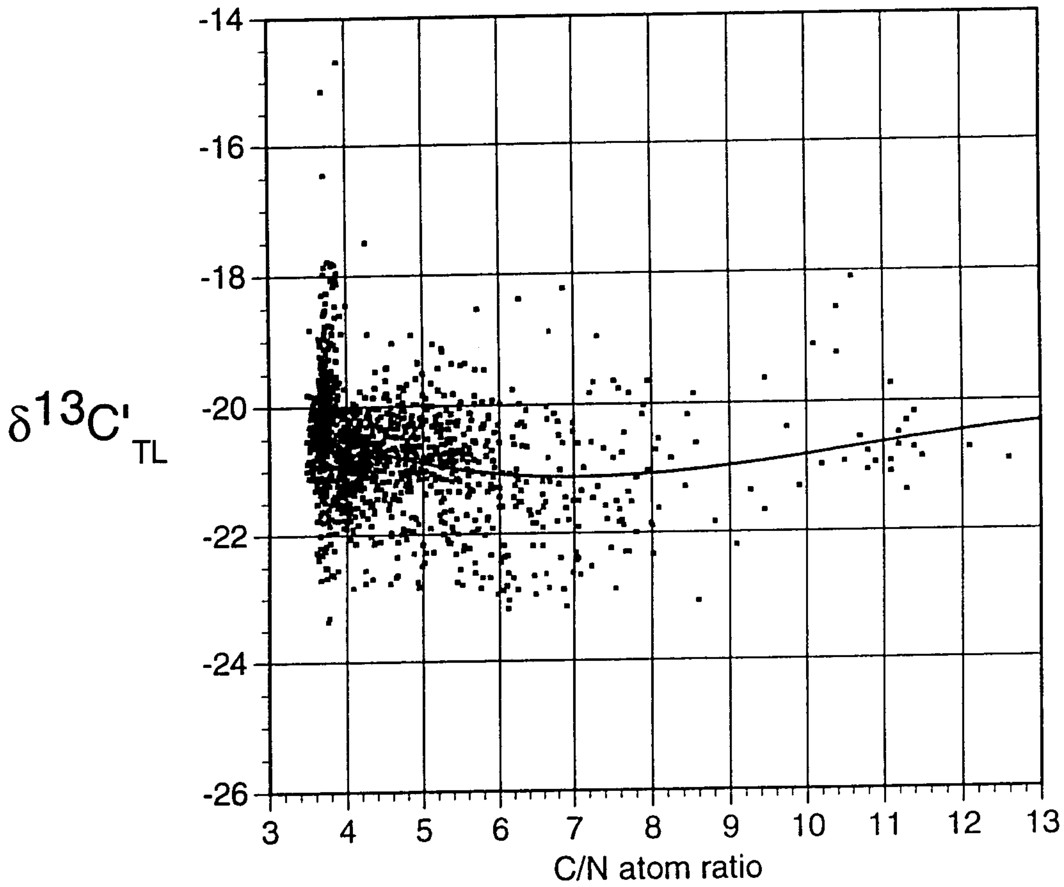
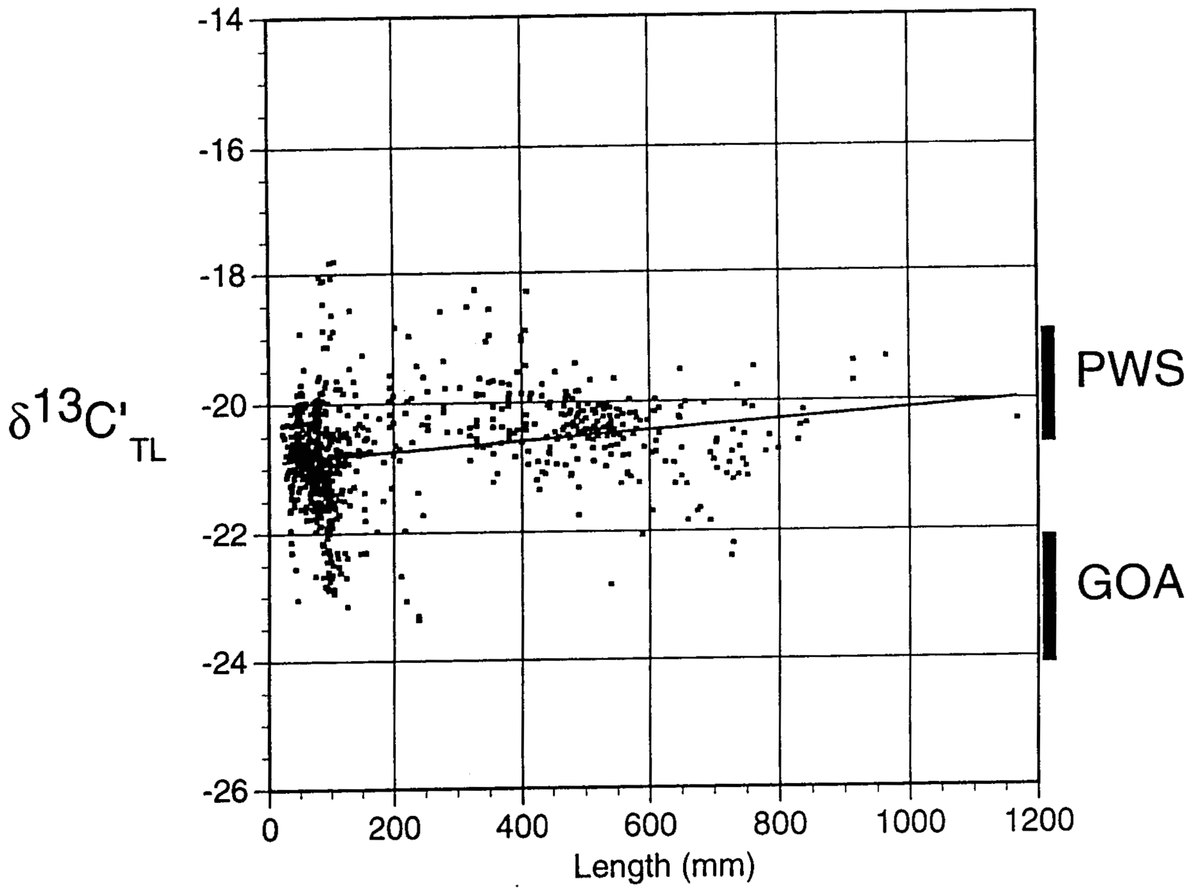


FIGURE 1E



5-2-15

FIGURE 1F



$\delta^{13}C'_{TL}$
-14
-16
-18
-20
-22
-24
-26
0
200
400
600
800
1000
1200
Length (mm)
PWS
GOA

FIGURE 1G

5-2-17

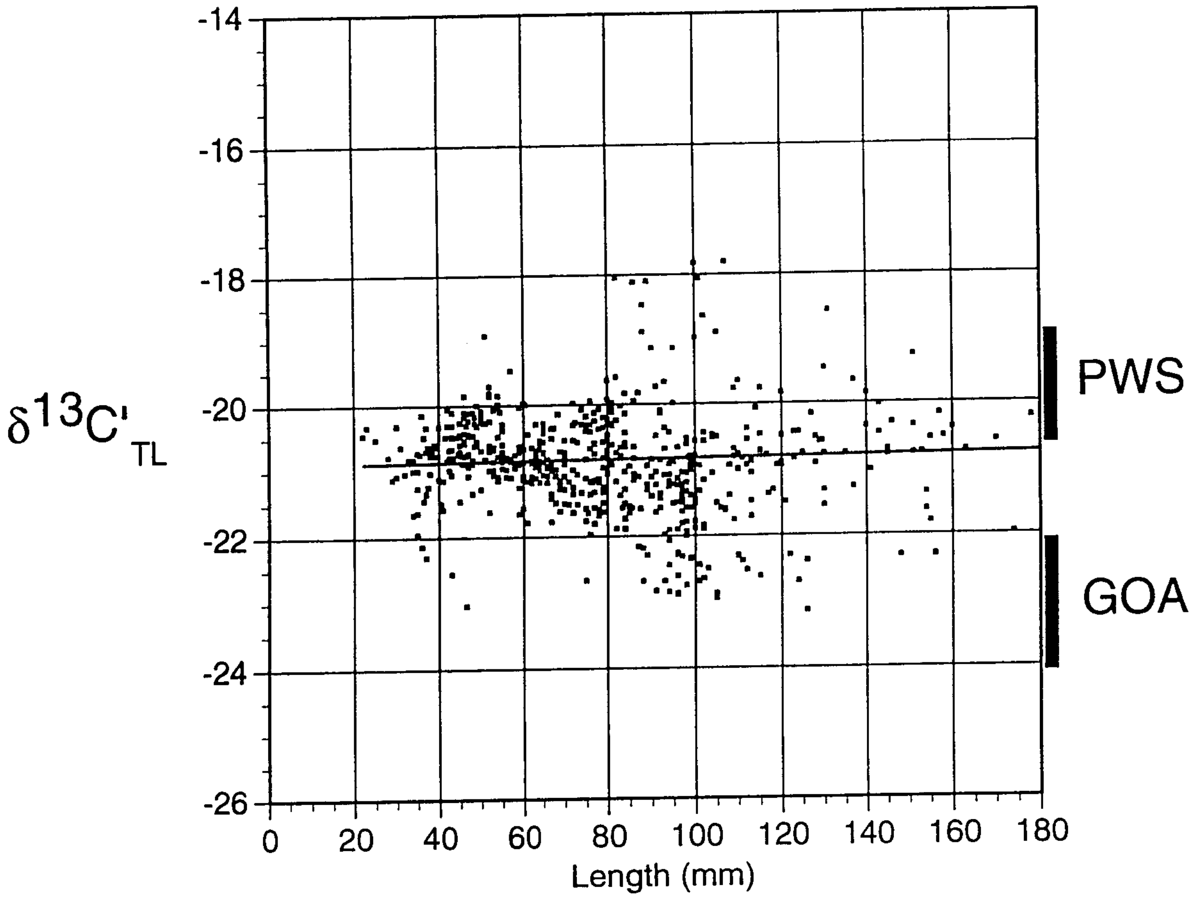


FIGURE 1H

FIGURE 2A

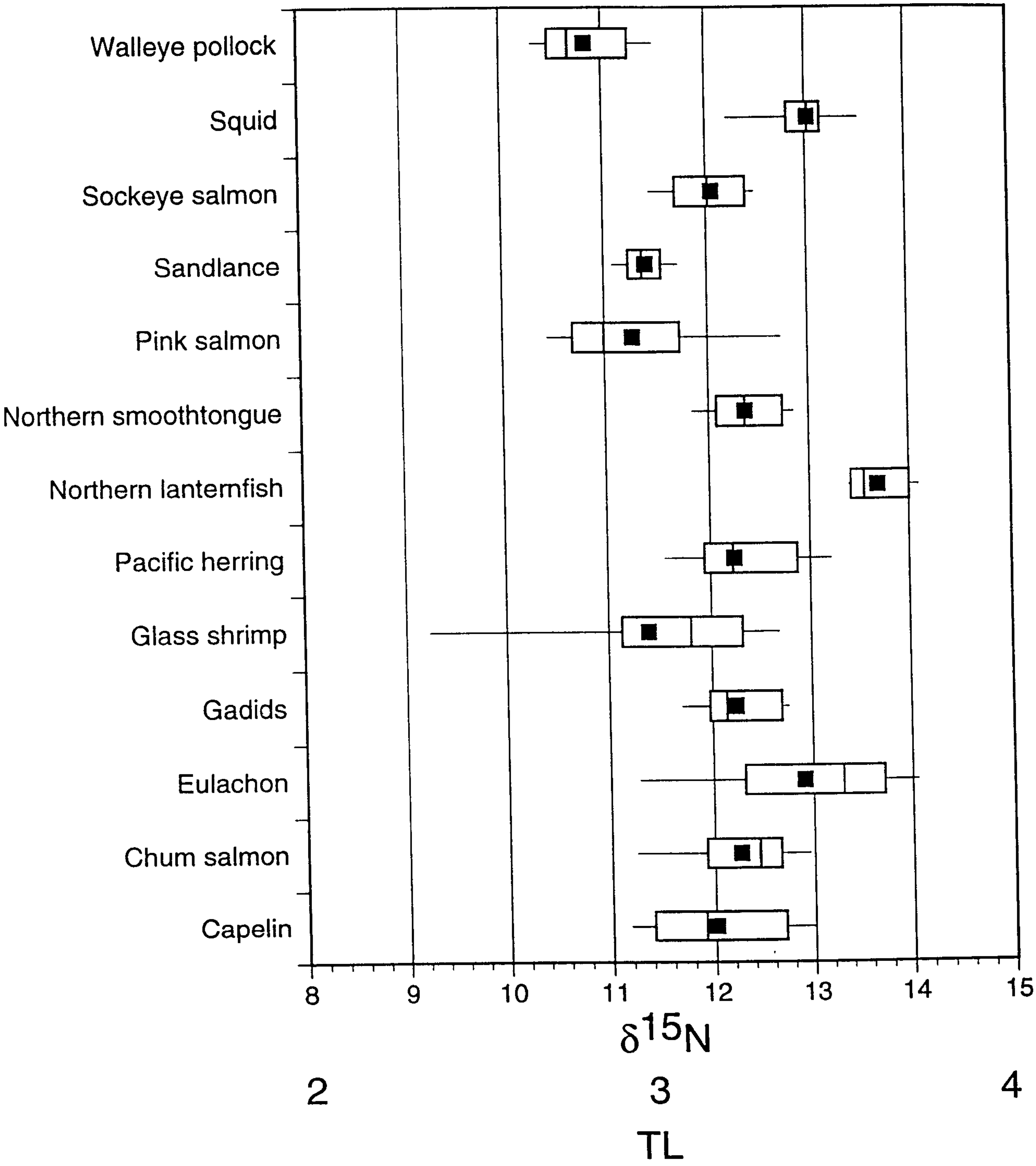
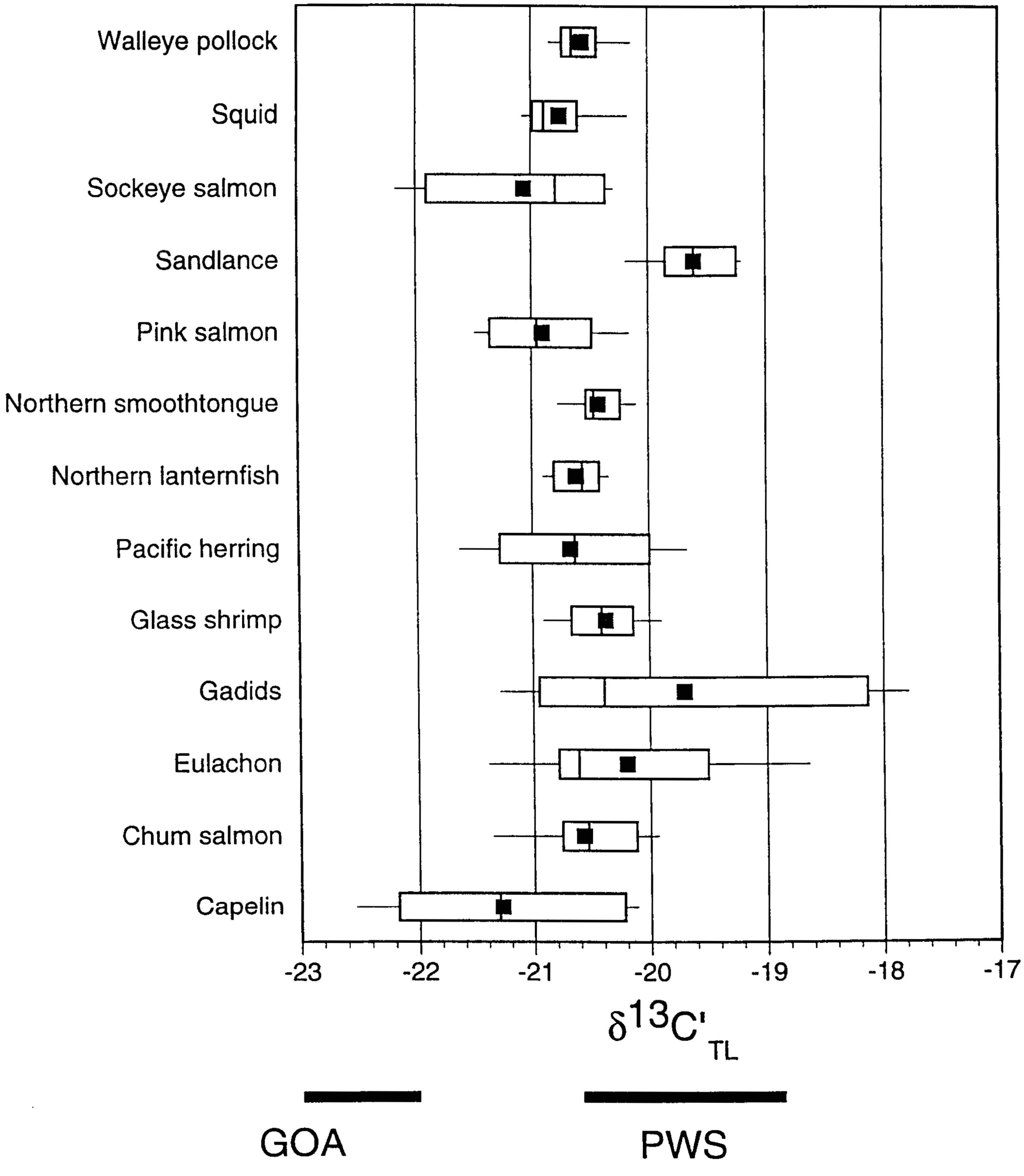

Walleye pollock
Squid
Sockeye salmon
Sandlance
Pink salmon
Northern smoothtongue
Northern lanternfish
Pacific herring
Glass shrimp
Gadids
Eulachon
Chum salmon
Capelin
8
9
10
11
12
13
14
15
$\delta^{15}N$
2
3
4
TL

FIGURE 2B


Walleye pollock
Squid
Sockeye salmon
Sandlance
Pink salmon
Northern smoothtongue
Northern lanternfish
Pacific herring
Glass shrimp
Gadids
Eulachon
Chum salmon
Capelin
-23
-22
-21
-20
-19
-18
-17
$\delta^{13}C'_{TL}$
GOA
PWS

Thomas C. Kline, Jr.[1]

[1]Prince William Sound Science Center, P. O. Box 705, Cordova, Alaska 99574 USA

Contribution to:

Pollock predation synthesis paper
by Willette et al. (*In Prep.)*

Abstract

$^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios were measured in epaxial muscle samples from adult pollock collected in 1994 and 1995 throughout Prince William Sound, Alaska (PWS). $^{15}N/^{14}N$ values were used to determine trophic level (TL) and $^{13}C/^{12}C$ values, after removal of lipid- and trophic level-isotope-effects, were used to determine source of carbon. Adult walleye pollock from bays in southwestern PWS had similar $^{13}C/^{12}C$ as those from within PWS. The $^{13}C/^{12}C$ values were consistent with PWS or hatchery salmon carbon signatures. A switch in diet to increased piscivory in the Spring of 1995 was indicated by $^{15}N/^{14}N$ from pollock sampled in May. The $^{15}N/^{14}N$ values were consistent with consuming subadult and adult herring or salmon fry following release from hatcheries.

Introduction

Because of their predictable nature, stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) provide an effective method for testing the prey-swiching hypothesis. Natural stable isotope ratio analysis of consumers, their prey and their predators serve as effective tracers of energy supply thus providing insight into both habitat usage and assist in quantifying amount of carbon and by extension, energy, derived from various areas of production (Michener and Schell 1994). Nitrogen stable isotope ratios provide excellent definition of relative trophic level (Fry 1988, Wada et al. 1991, Hobson and Welch 1992, Kiriluk et al. 1995). The heavy isotope of nitrogen, ^{15}N, is enriched by about 0.34 % (or 3.4 per mil in conventional delta units, see materials and methods) with each trophic level (Minagawa and Wada 1984) and has been shown to accurately indicate the "realized" trophic level of species within an ecosystem (Kling et al. 1992, Cabana and Rasmussen 1994). Carbon isotope signatures can effectively be used to trace multiple sources of carbon into food webs once it can be established that these sources have distinctive isotopic signatures (Fry and Sherr 1984, Wada et al. 1991). The data obtained from stable isotope measurements are unique in that they trace assimilated material and thus can be used for accurate ecosystem process modeling (e.g., Wada et al. 1991, Nadelhofeffer and Fry 1994, Macko and Ostrom 1994, Michener and Schell 1994, and Conway et al. 1994).

Natural abundance of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios of Prince William Sound Alaska pelagic biota measured in samples collected from 1994 to 1995 were used to determine trophic level (TL) relative to the large herbivorous copepod *Neocalanus cristatus* and distinguish carbon generated in the Gulf of Alaska (GOA) on the continental shelf outside Prince William Sound (PWS) from carbon generated in PWS (Kline and Paul 1997). The approach is extended here by comparing $^{15}N/^{14}N$ and $^{13}C/^{12}C$ of Prince William Sound adult pollock with herring and salmon fry to assess their TL and carbon source as a means of testing the prey-switching hypothesis.

Materials and Methods

Sampling for stable isotope analysis

Pollock, herring, and salmon fry were sampled from a variety of vessels ranging from a 25m trawler, *F/V Alaska Beauty*, equipped with a 40 x 28m mid-water wing trawl (2.0 cm stretch-mesh web codend) to small fry skiffs and seine boats that participated as part of the SEA project. Additional pollock were sampled from a pollock fishery that occured in the southwest area of PWS early 1995. Pollock and herring were sampled for stable isotope analysis by excising a section (~ 1 g) of epaxial muscle either on board the sampling or from whole carcasses brought ashore. Salmon fry samples consisted of coded wire tag recovery salmon that had been stored frozen following tag removal. All samples were stored frozen until freeze dried and ground to a fine powder.

The laboratory and data analysis procedures were as described by Kline and Paul (1997). In brief; conventional delta notation is used to express stable isotope ratios, which are reported relative to international standards (air for N and Vienna Peedee belemnite for C) and defined by the followingexpression:

$$(1) \qquad \delta^{15}N \text{ or } \delta^{13}C = \left(\frac{R_{sample}}{R_{standard}} - 1\right) * 1000 \text{ per mil}$$

where $R = {}^{15}N/{}^{14}N$ or $^{13}C/^{12}C$ (after Craig 1957). The isotope standards have delta values of 0 by definition, i.e. $\delta^{15}N = 0$ for atmospheric N_2. Normalization of $^{13}C/^{12}C$ for lipid composition and trophic level (TL) was by the method of McConnaughey and McRoy (1979) and Kline and Paul (1997) that used C/N as lipid proxy and $\delta^{15}N$ to normalize to the TL of the herbivorous copepod *Neocalanus cristatus*. TL was estimated using $\delta^{15}N$ of the samples in relation to the *Neocalanus cristatus* reference (Kline and Paul 1997).

Results and Discussion

Herring and salmon fry $\delta^{15}N$

The $\delta^{15}N$ of herring was ~ +12 to +13 corresponding to a TL slightly greater than 3 (Fig iso-1). The lowest values came from herring > 250mm in length which were adult herring. Herring in the 150 mm to 200mm size class from Green Is. and Redhead were very similar wheras the intermediate size class, 200 to 250mm fell in between. The data suggest a progressive shift to lower $\delta^{15}N$ consistent with a TL lowering. The herring > 250mm also had the most negative $\delta^{13}C'_{TL}$, (Kline unpublished data) consistent with a greater untilization of GOA carbon (Kline and Paul 1997) than the smaller size classes. The data suggest a switch to increased consumption of herbivores dependent on GOA carbon with size. Higher $\delta^{15}N$ suggests a greater proportion of carnivorous zooplankton in younger herring.

Hatchery salmon fry in PWS had highly elevated $\delta^{15}N$ shortly after release compared to 3 to 4 weeks later (Fig. iso2). The initial salmon $\delta^{15}N$ reflects the trophic enrichment (Minagawa and Wada 1984) relative to an animal protein based hatchery diet (PWSAC- ?). Rapid replacement of protein in proportion to growth (Hesslein et al. 1993) is confirmed here by the rapid change in $\delta^{15}N$ (Fig iso2). Salmon fry shortly after release as well as herring 150 to 200mm have a $\delta^{15}N \sim +12.8$. Since their predators were expected to have a $\delta^{15}N \sim 16.2$ (Minagawa and Wada 1984, this value was used in evaluating adult pollock $\delta^{15}N$ for evidence of predation on fishes. Unlike the $\delta^{15}N$ value dichotomy of alternate salmon fry nitrogen, hatchery salmon fry shortly after release and salmon fry utilzing PWS carbon had the same $\delta^{13}C'_{TL}$ values (Kline unpublished data). Thus pollock feeding on recently released hatchery salmon were expected have a similar $\delta^{13}C'_{TL}$ as pollock feeding on PWS production.

Adult pollock stable isotopes

Pollock had a very consistent $\delta^{13}C'_{TL}$ (Fig. iso3) that was very similar to the PWS carbon isotope reference value of -19.7 from Kline and Paul (1997). The $\delta^{15}N$ of adult pollock varied by ~ 1.5 per mil, equivalent to ~ 0.5 TL range (Fig. iso4). The in $\delta^{15}N$ declined ~ 1 per mil during 1994 inferred a ~1/3 TL decline. The $\delta^{15}N$ values increased in 1995 between winter and May. The May $\delta^{15}N$ value, +14.7, corresponds to 2/3 the diference between an initial value of 13.7 measured in PWS pollock in Jan and Feb (Fig iso4) and +16.2, the predicted value after consuming recently released hatchery fry or herring. Pollock could have obtained a value of +14.7 by replacing 2/3 of their protein with 100% consumption of herring or fry. A lower consumption rate of herring or fry (or other prey combination with a mean $\delta^{15}N$ similar to herring and fry) would be explained by a higher protein turnover, which, however is, unlikely (Hesslein et al. 1993). Separation of the May, 1995 pollock sample by collection site (Fig. iso5) suggests that the switch to higher $\delta^{15}N$ was localized within PWS to Port Gravina, an important herring habitat area (E. Brown - ?). The second most switched site is Esther Island in the vicinity of the Wally Nuernburg salmon hatchery. In comparison, Perry Is. pollock were more like those sampled the previous winter (Fig iso5). The stable data suggest that prey switching is likely to be localized and intense near important prey sites.

Acknowledgements

The research described in this paper was part of the Exxon Valdez Oil Spill Trustee Council - funded Sound Ecosystem Assessment (SEA) project. However, the findings and conclusions presented by the author are his own and do not necessarily reflect the views or position of the

Trustee Council. North Pacific Processors, Inc. provided the winter 1995 pollock samples obtained during the fishery. Preparation of samples for mass spectrometry was done by Kim Antonucci. Bruce Barnett, University of Alaska Stable Isotope Facility performed the mass spectrometry.

References cited

Cabana, G. and J. B. Rasmussen, 1994. Modeling food chain structure and contaminant bioaccumulation using stable nitrogen isotopes. Nature 372:255-257.

Conway, N.M., M.C. Kennicut II, C.L. Van Dover. 1994. Stable isotopes in the study of marine chemosynthetic-based ecosystems. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 158 -186.

Craig, H. 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochim. Cosmochim. Acta 12:133-149.

Fry, B. and E. B. Sherr. 1984. $\delta^{13}C$ measurements as indicators of carbon flow in marine and freshwater ecosystems. Contr. Mar. Sci. 27:13-47.

Fry, B. 1988. Food web structure on the Georges Bank from stable C, N, and S isotopic compositions. Limnol. Oceanogr. 33:1182-1190.

Hesslein, R. H., K. A. Hallard, and P. Ramlal. 1993. Replacement of sulfur, carbon, and nitrogen in tissue of growing broad whitefish (*Coregonus nasus*) in response to a change in diet traced by $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$. Can. J. Fish. Aquat. Sci. 50:2071-2076.

Hobson, K.A. and H.E. Welch. 1992. Determination of trophic relationships within a high Arctic marine food web using $\delta^{13}C$ and $\delta^{15}N$ analysis. Mar. Ecol. Progr. Ser. 84:9-18.

Kiriluk, R.M., M.R. Servos, D.M. Whittle, G. Cabana, and J. Rasmussen. 1995. Using ratios of stable nitrogen and carbon isotopes to characterize the biomagnification of DDE, mirex, and PCB in a Lake Ontario pelagic food web. Can. J. Fish. Aquat. Sci. 52:2660-2674.

Kline, T.C. and A.J. Paul. Fall isotopic and somatic energy signatures of young of the year Pacific herring at two sites in Prince William Sound, Alaska: implications for trophic studies. Submitted to the Can. J. Fish. Aquat. Sci.

Kling, G.W., B. Fry, and W.J. O'Brien. 1992. Stable isotopes and plankton trophic structure in arctic lakes. Ecology 73:561-566.

Macko, S.A. and N.E. Ostrom. 1994. Pollution studies using stable isotopes. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 45 - 62.

McConnaughey, T. and C.P. McRoy. 1979. Food-web structure and the fractionation of carbon isotopes in the Bering Sea. Mar. Biol. 53:257-262.

Michener, R.H. and D.M. Schell. 1994. Stable isotope ratios as tracers in marine aquatic food webs. *In:* K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 138 -157.

Minagawa, M., and E. Wada. 1984. Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between $\delta^{15}N$ and animal age. Geochim. Cosmochim. Acta 48:1135-1140.

Nadelhoffer, K.J. and B. Fry. 1994. Nitrogen isotopes studies in forest ecosystems. In: K. Lajtha and R.H. Michener (eds), Stable Isotopes in Ecology and Environmental Science. Blackwell. Oxford, England. p. 22-44.

Wada, E., H. Mizutani, and M. Minagawa. 1991. The use of stable isotopes for food web analysis. Crit. Rev. Food Sci. Nutr. 30:361-371.

Figure Captions (figures follow)

iso1. Herring > 150 mm δ^{15}N box and whisker plots (10, 25, 50, 75, and 90th percentiles and means are indicated) and interpreted TLs by size group and sampling location. Size group 2 = fish > 150mm up 200 mm, size group 3 = fish > 200 mm up 250 mm, and size group 3 = fish > 250 mm. N(Green-2) = 31, N(Green-3) = 41, N(Green-4) = 14, N(Redhead-2) = 51.

iso2. Hatchery salmon fry δ^{15}N by release date, hatchery and species as a function of capture date. Individual fish inidcated by points were identified by implanted coded wire tags. Hatchery codes as follow Wally Nuernburg Hatchery (WN), Main Bay Hatchery (MB) and AFK Hatchery (AFK). Species codes as follows pink salmon(P), chum salmon (C), and red salmon (R). Regression lines fitted to WN 25 April and 7 May pink salmon, WN 3 June chum salmon, and MB 28 to 31 May release cohorts suggest replacement of protein obtained fom hatchery in three to four weeks. Fry imediately after release had δ^{15}N ~ +12.8

iso3 Pollock $\delta^{13}C'_{TL}$ from PWS by sample arranged by calendar month. Samples consisted of N = 25 each from Port Bainbridge and Day Harbor and N = 47, 40, 99, 19, and 17 each from western and northern PWS sampled in April 1994, May 1994, May 1995, June 1994, and July, 1994, respectively. Data showed strong consistency to carbon derived from PWS based on Kline and Paul (1997).

iso4 Pollock δ^{15}N of same samples in Fig. iso3 and interpreted TL based on Kline and Paul (1997). A large shift in δ^{15}N between early 1995 "A" to values approaching "B" which is the estimated δ^{15}N of pollock feeding on herring < 250 mm or hatchery salmon fry within a few weeks after release.

iso5 May 1995 pollock shown in Fig. iso4 by capture site suggesting spatial variability in switching from "A" to "B" as in Fig iso4. Samples consisted of N = 34, 25, 39, and 2 from Perry Is., Port Gravina, Esther Is., and Zaikof Bay, respectively.

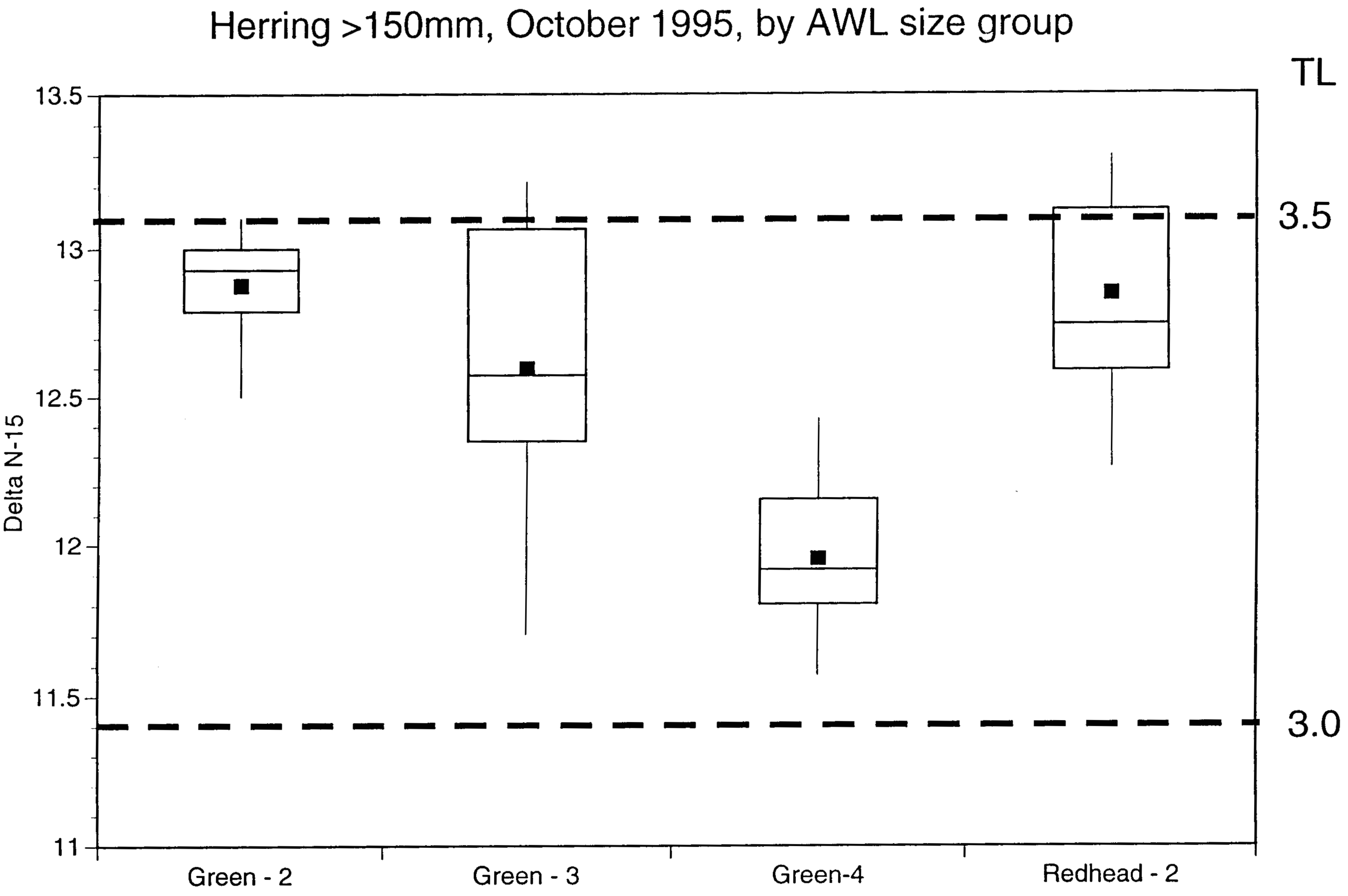

Herring >150mm, October 1995, by AWL size group
TL
13.5
13
12.5
12
11.5
11
Delta N-15
3.5
3.0
Green - 2
Green - 3
Green-4
Redhead - 2

Figure 1.

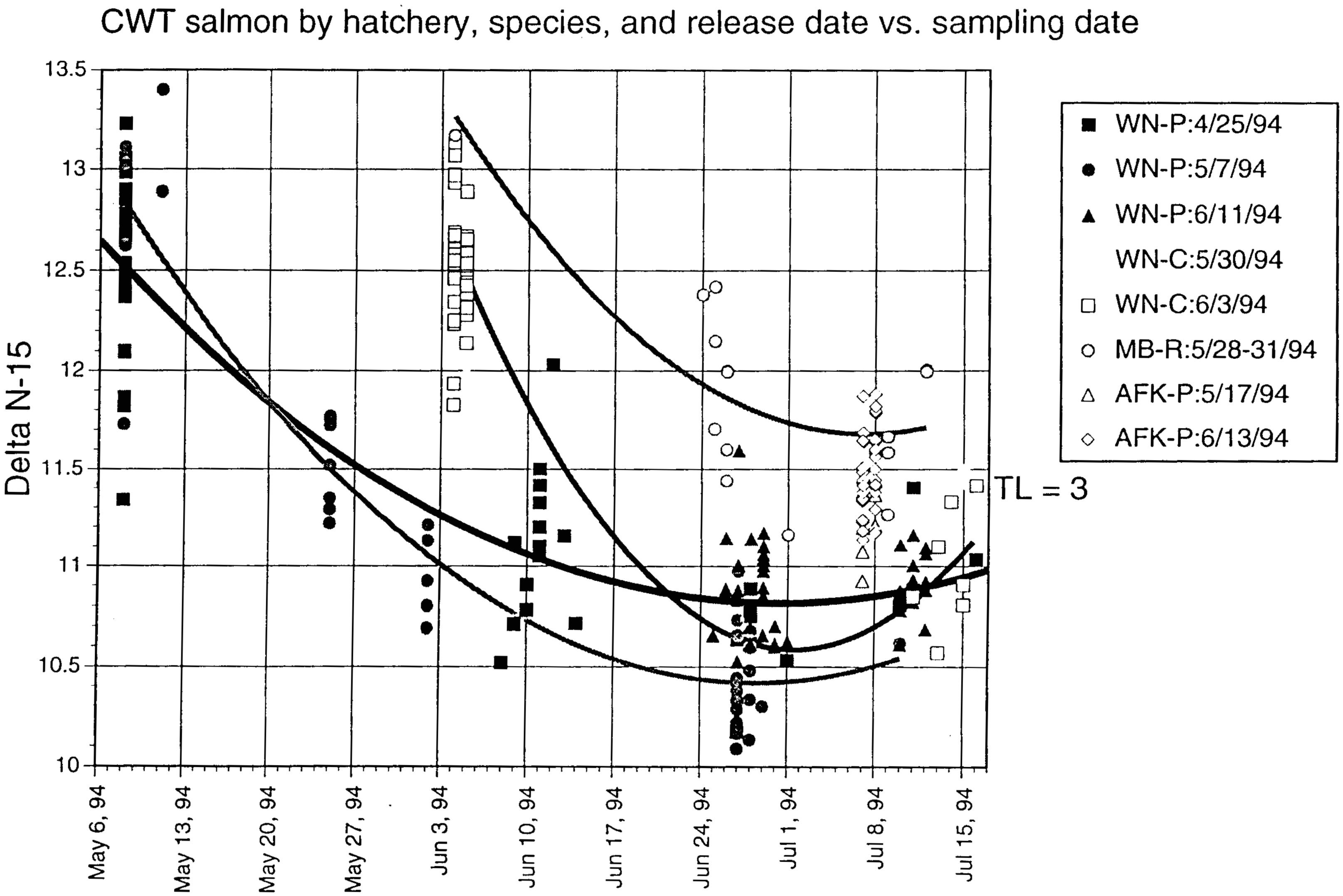

CWT salmon by hatchery, species, and release date vs. sampling date
Delta N-15
13.5
13
12.5
12
11.5
11
10.5
10
May 6, 94
May 13, 94
May 20, 94
May 27, 94
Jun 3, 94
Jun 10, 94
Jun 17, 94
Jun 24, 94
Jul 1, 94
Jul 8, 94
Jul 15, 94
TL = 3
■ WN-P:4/25/94
● WN-P:5/7/94
▲ WN-P:6/11/94
WN-C:5/30/94
□ WN-C:6/3/94
○ MB-R:5/28-31/94
△ AFK-P:5/17/94
◇ AFK-P:6/13/94

Figure 2.

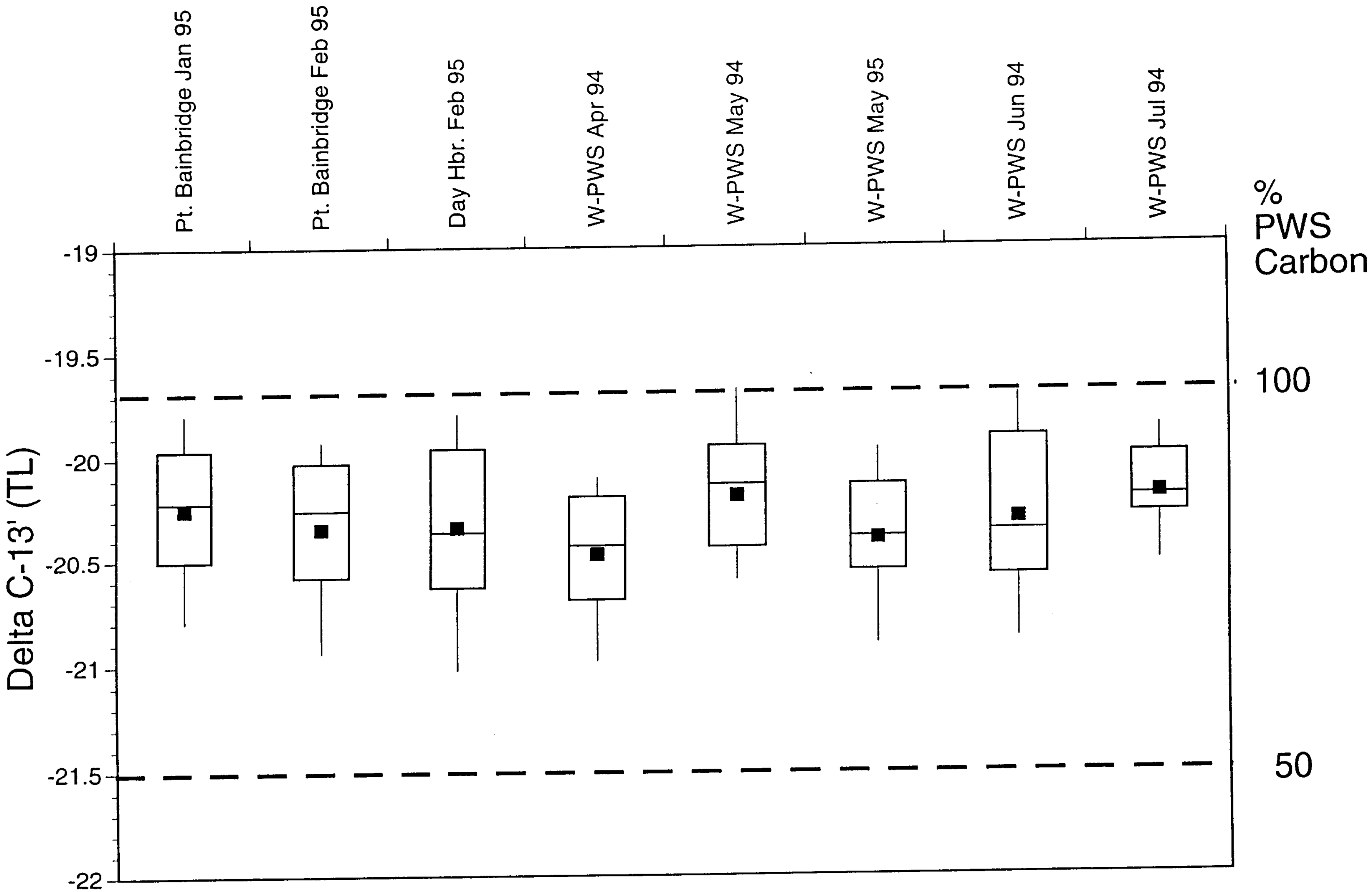

Pt. Bainbridge Jan 95
Pt. Bainbridge Feb 95
Day Hbr. Feb 95
W-PWS Apr 94
W-PWS May 94
W-PWS May 95
W-PWS Jun 94
W-PWS Jul 94
% PWS Carbon
100
50
-19
-19.5
-20
-20.5
-21
-21.5
-22
Delta C-13' (TL)
5-3-8

Figure 3.

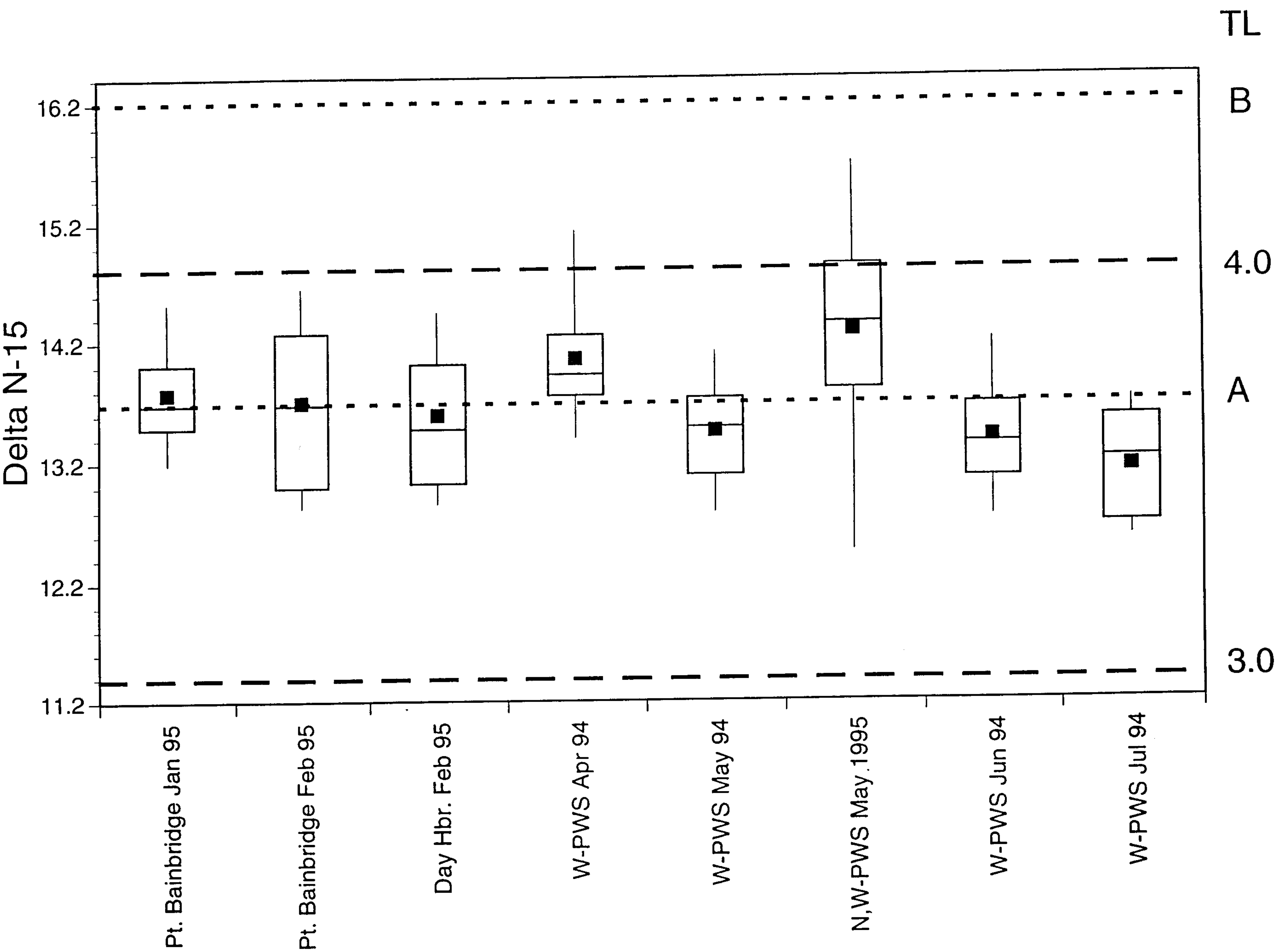

TL
B
4.0
A
3.0
Delta N-15
16.2
15.2
14.2
13.2
12.2
11.2
Pt. Bainbridge Jan 95
Pt. Bainbridge Feb 95
Day Hbr. Feb 95
W-PWS Apr 94
W-PWS May 94
N,W-PWS May 1995
W-PWS Jun 94
W-PWS Jul 94

Figure 4.

5-3-10

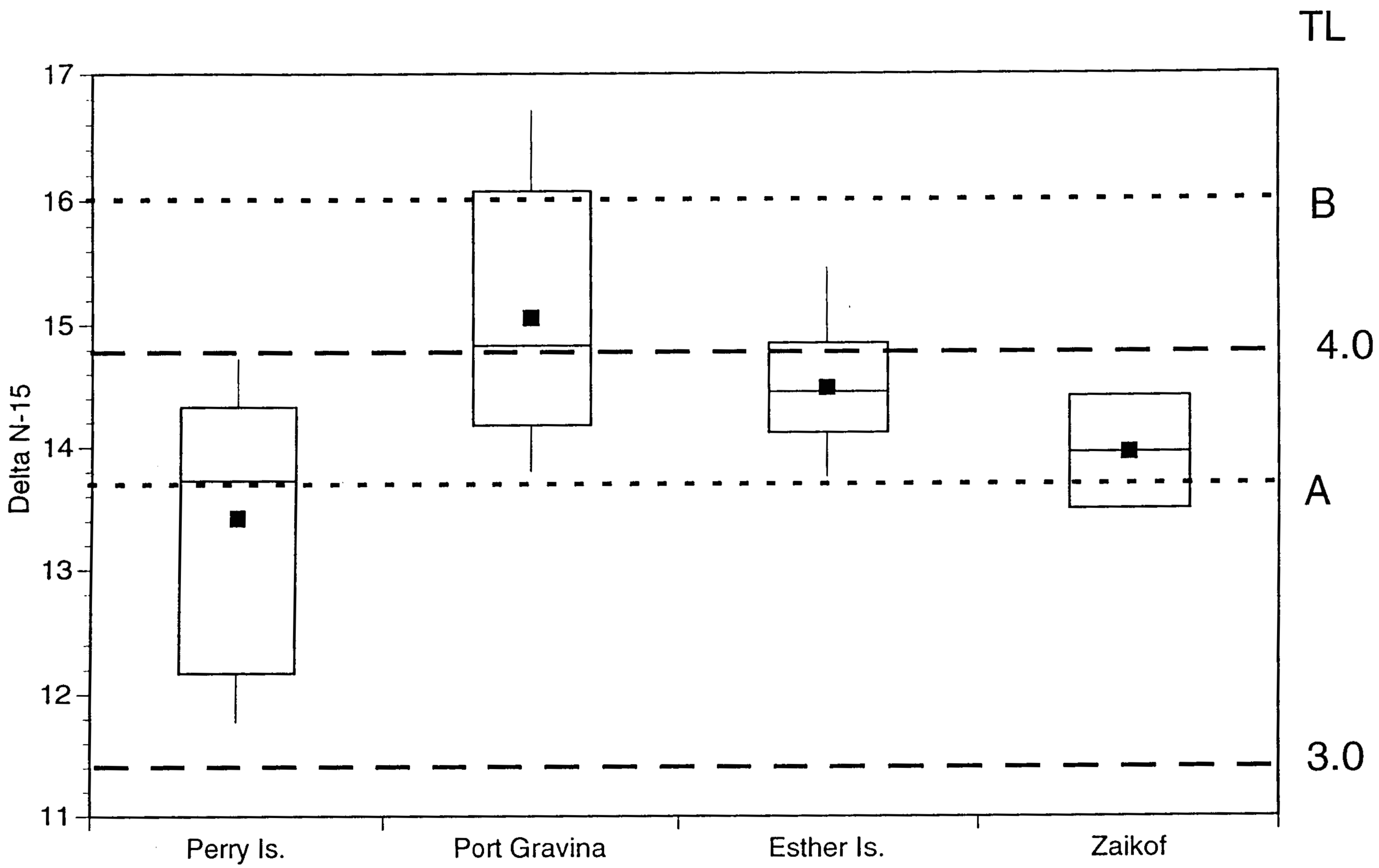


Figure 5.

Chapter 6.

Information Systems and Model Development (96320J)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Information Systems and Model Development

Restoration Project 96320-J (SEADATA)
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Principal Investigator:	Vincent Patrick	Prince William Sound Science Center
Collaborators:	Jennifer R. Allen	Prince William Sound Science Center
	Stephen Bodnar	Prince William Sound Science Center
	Gary Drew	National Biological Service, Anchorage
	Charles S. Falkenberg	Adv. Visualization Lab., U. of Maryland
	Edward Jin	Prince William Sound Science Center & U. of Toronto
	Ravi Kulkarni	Prince William Sound Science Center & Adv. Visualiz. Lab., U. of Maryland
	Doran M. Mason	Prince William Sound Science Center & Limnology Lab, U. of Wisconsin
	Christopher N. K. Mooers	Dir., Ocean Pollution Research Center, Rosenstiel Schl. Marine & Atmos. Sci., U. of Miami
	Roy Murray	Prince William Sound Science Center & Utah State University
	Ricardo H. Nochetto	Prince William Sound Science Center & Mathematics Dept., U. of Maryland
	Sridhar P. Rao	Prince William Sound Science Center
	Jia Wang	OPRC, Rosenstiel School, U. of Miami

Prince William Sound Science Center
PO Box 705
300 Breakwater Avenue
Cordova, AK 99574

April 1996

Information Systems and Model Development

Restoration Project 96320-J
Annual Report

Study History: The Sound Ecosystem Assessment (SEA) Program is based upon the *Sound Ecosystem Assessment Initial Science Plan and Monitoring Program,* Rpt No. 1, Nov. 24, 1993. It began April 1994 (Restoration Project 94320) and has continued through FY96 (Projects 95- and 96320). The Information Systems and Model Development Project (SEADATA) is a Restoration Project (9x320-J) within the SEA Program. Prior progress is described in the SEA Annual Reports to EVOS for FY94 (Ch6) and FY95 (Ch7). During this reporting period the journal *Continental Shelf Research* accepted for publication the manuscript "On the Development of a Three-Dimensional Circulation Model for Prince William Sound, Alaska" by C. N. K. Mooers and Jia Wang.

Abstract: The four main development efforts of SEADATA are reviewed: SEA database, SEA Intranet, PWS circulation model, and the nekton models for pink salmon fry and juvenile herring. During FY96 each effort was at the middle of its planned five year development period and each faced critical milestones for feasibility and for realizability of proposed end-points. The milestones were achieved. The SEA database progressed from prototype to full implementation for a subset of the archive. This demonstrates the final functional configuration and confirms the feasibility of completion within projected time and cost schedules. The SEA Intranet faced rapidly emerging technologies wherein described function very often meant software development goals. Through in-house development and collaborative agreements for pre-release software, the SEA Intranet is delivering a full set of scientific collaboration resources. The circulation modelling effort began this period with the problems of limited data for PWS. It has, in collaboration with the observational oceanography project (S. Vaughan, 96320-M), developed the needed historical climatologies and is completing the phase of model development and validation that utilizes the climatological datasets. The nekton model effort had first to implement the combined diffusion-taxis and foraging-bioenergetics model, and second to demonstrate the efficacy of that model through simulations of seasonal fry mortality for quasi-realistic outmigration scenarios. Both tasks were accomplished. A further result for the year was the realization of the first low-cost, near-realtime monitoring system for SEA: the repeater-network and the Applegate Rock meteorology station are now providing near-realtime sea surface wind and weather data. This was a year of difficult technical and operational challenges. Although all concerns described in the FY95 Annual Report were resolved, they were accomplished over a somewhat "extended" year. The project has slipped on some of its anticipated schedules by up to three months. It is possible some or all of this slippage will be recovered during FY97.

Key Words: bioenergetics, circulation model, collaborative software, database, diffusion-taxis, dispersion, *Exxon Valdez,* Mellor-Blumberg, Pacific herring, packet-radio, physical-biological model, pink salmon, Prince William Sound, Princeton Model, SEA, Sound Ecosystem Assessment, visualization, World Wide Web

Citation: Patrick, E. V., J. R. Allen, D. L. Eslinger, C. S. Falkenberg, D. M. Mason, C. N. K. Mooers, R. Murray, R. H. Nochetto, S. P. Rao, and J. Wang. 1995. Information Systems and Model Development Project (SEADATA) of the Sound Ecosystem Assessment Program, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 96320-J), Prince William Sound Science Center, Cordova, Alaska.

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EXECUTIVE SUMMARY

The four main development efforts of SEADATA are reviewed: SEA database, SEA Intranet, PWS circulation model, and the nekton models for pink salmon fry and juvenile herring. During FY96 each effort was at the middle of its planned five year development period and each faced critical milestones for feasibility and for realizability of proposed end-points. The milestones were achieved. The SEA database progressed from prototype to full implementation for a subset of the archive. This demonstrates the final functional configuration and confirms the feasibility of completion within projected time and cost schedules. The SEA Intranet faced rapidly emerging technologies wherein described function very often meant software development goals. Through in-house development and collaborative agreements for pre-release software, the SEA Intranet is delivering a full set of scientific collaboration resources. The circulation modelling effort began this period with the problems of limited data for PWS. It has, in collaboration with the observational oceanography project (S. Vaughan, 96320-M), developed the needed historical climatologies and is concluding model development and validation using seasonal climatological cycles. The nekton model effort had first to implement the combined diffusion-taxis and foraging-bioenergetics model, and second to demonstrate the efficacy of that model through simulations of seasonal fry mortality for quasi-realistic outmigration scenarios. Both tasks were accomplished. There was a further highlight. The report last year of completion for the PWS repeater-net was premature. The repeater-net and the Applegate Rock meteorology station now provide near-realtime sea surface wind and weather data. They are the first of the SEA long term, low cost monitoring implementations. This year was a period of difficult technical and operational challenges. Although concerns described in the previous report were resolved, it was achieved during an "extended" year. The project schedule has slipped approximately three months. It is possible some or all of this will be recovered during FY97.

INTRODUCTION

The Information Systems and Model Development Project (SEADATA) is one of the original projects in SEA. SEADATA was organized to deliver to the Program numerical models, a database, computing resources and networks, data visualization, computer- and network-based resources for remote collaborations and interactions, and selected sensor technologies that were judged to be sufficiently mature to have immediate impact on the cost-effectiveness of the final SEA products for long-term monitoring.

The project history and highlights are described in the FY96DPD. This and other information is available at the SEA Web site at URL

`http://www.pwssc.gen.ak.us/sea/sea.html`

This Annual Report for FY96 will follow the same format as the Annual Report (AR) for FY95. During the second quarter of FY96, due to a change of contracting agency, this project was required to prepare a Detailed Project Description (FY96 DPD) for the period of FY96 through FY98. This DPD has somewhat greater detail than the SEA Integrated DPD for FY96. Therefore this FY96 DPD will be used for assessments of the project with respect to schedules.

Throughout FY96 the tasks that were held to be the most critical were those that had been spelled out explicitly in the FY95 AR. Indeed, these issues were explicitly identified in the abstract of that report:

> **Abstract:** The four main development areas of SEADATA are reviewed: database, Internet and Web based collaboration tools, circulation model, and the fish model. Each of these has reached important milestones, but each is at midstage and facing ahead tasks that will be equally critical. For the database, the technically demanding tasks of the initial architecture have been resolved. The task ahead is to make everything fit within the available resources. The Web tools that were implemented were a significant accelerator for SEA. But more is required and the technology has now expanded unbelievably. The next steps will be all new terrain. The circulation model has been successfully implemented in a remarkably short time. The task ahead of validation and refinement will become increasingly difficult as the limitations of the available data for Prince William Sound become clearer. The fish model now has an efficient scripting code, a new algorithm, and the major parts of its foraging-bioenergetics model. It now must put these together to get the desired mortality estimates. The one message that came consistently from all quarters in this report is the need for more and better communication and coordination.

Each of the issues were pivotal. That is, each would either be successfully accomplished or that component of the project failed. Hence these were very much the focus for the year. They were all successfully addressed during this reporting period. These successes are the primary topics of this report.

The aforementioned FY96 DPD had been prepared during the month preceding the analysis and review carried out for the Annual Report. Consequently the project schedule of the FY96 DPD is more optimistic. Although each of the critical tasks was completed, some progressed more slowly than had been scheduled. This report will review what slipped and the extent of any delays. With the planned adjustments and refinements the slip of the schedule looks to be at most three months.

From the perspective of the project and its ability to achieve the project objectives, the slippage is of significantly less consequence than the successful resolution of all four of the issues in the FY95 abstract. The resolution of these four are the highlights for the year. In addition there were two further results of substantial consequence. The first is the commencement of daily transfer of data from the SEA Applegate Rock meteorological station using the SEA packet radio repeater-modem network. The time interval between of transmissions is solely a function of battery capacity at the remote site. The second is a much improved specification for the SEA modelling endpoints, and substantial progress in establishing a working dialogue with ADF&G for the identification of issues and problems for which one or more of the various development efforts of SEA, in whole and in part, has relevance.

OBJECTIVES

The purpose of SEADATA is to deliver to SEA

1. numerical models for circulation and for juvenile fish, specifically for pink salmon and Pacific herring;
2. database, computing and network resources, and Intranet functions;
3. *cost efficient measurement technologies* that address SEA's requirements for low-cost, long-term monitoring and model maintenance.
4. (newly requested.) development and implementation of methods whereby the *(reportedly) long* time interval between research result and the applications of that result in resource management is substantially reduced.

METHODS

Multidisciplinary research

The review for FY96, as in FY95, had some unexpected findings. One of these has to do with the multidisciplinary collaborations in SEA. Although finding the methods to make the collaboration more effective is a significant part of this project, a totally separate aspect emerges this year. That aspect is the unique choices, selections, and optimizations that are used by differing disciplines as the project nears completion and discrepancies between objectives, options, and resources come into focus.

Two areas in this report are good examples. A review of the database work during FY95 and during this year will show a continuing refining and evolution of the design as experience is gained with the diversity of data types, the model applications, and the quantity of data to be addressed through both the exploratory and then the monitoring stages of the work. This flexibility to move around within an extended range of database and computer science is due to the multidisciplinary structure. Such flexibility would not be possible for one attempting this task who did not have database design and development experience. There have been significant adjustments as well as a few major changes. These are all documented in the annual reports. Despite these, the database is progressing well and approaching roughly its half-way mark.

Such adjustments and corrections are increasing as the end is clearer and nearer. One such choice that is made in the nekton modelling effort is to suspend efforts on the 2D and 3D versions of the model, at least until late in this year. It was not possible to support the necessary programmer, Mr. S. Rao, after the fall of 1996. A very attractive business offer became available to him in the fall. It was the proper decision for him to take it. The model scope will meet the requirements, simply not as comprehensively. The search for ways to revive the effort will continue, for the effort is only suspended. But such effort in FY96 did not succeed.

The design of the monitoring effort to maintain the models will require the multidisciplinary insights that SEA has assembled. It was unexpected to see how the insights of the different disciplines are used to make the difficult feasible. One reason that such things are more apparent is the increased exchange between projects and investigators, a process that has been significantly enhanced with the advances of the SEA Intranet.

SEA Intranet: the development path

There are two simultaneous issues behind the concern expressed in the abstract of the FY95 AR: 1) what methods will produce quantum changes in the SEA collaborative exchanges, and 2) what software can be used to most effectively implement those methods for WWW.

There was the clear need for methods whereby the collaborative exchanges would be significantly increased and facilitated. Despite the clear need, the methods that would in fact result in an increased exchange or prove to enhance efficiency are not well understood at all. This is one of the issues of the manuscript of J. R. Allen, et al, in Appendix 2. The manuscript is being prepared for submission to the *International Journal of Human Computer Interactions, Special Issue on Innovative Applications of the World Wide Web.*

Along with the ambiguity over collaborative method is the ambiguity over software resources due to the rapidly evolving technology and industry. The task was to assess as much as possible of this highly dynamic technology, expecting that nearly everything was likely to be incomplete and inadequately specified. This was to be evaluated in the context of a problem that too was poorly specified. Throughout all of this there is the pressure of time due to the present need for solutions that will make a difference in the outcome of SEA.

The SEA Intranet is described in Appendix 2. The manuscript describes the technology that was selected for implementation now, technology that is emerging, and the technology that is expected to require considerable time to realize its potential.

Project Plan for the SEA numerical models

The overall plan for the SEA model is shown graphically in Figure 1. The detailed discussion of the chart is in the Methods section of the FY95 Annual Report, and will not be restated here.

RESULTS

The SEA Database

Status

A status report on the development of the database is provided in Appendix 1.

The progress of the database, both in content and in concept, is shown in part by the comparison of Figures 2 and 3.

SEA Intranet

Status

A status report, description, and technology background are presented in the manuscript in Appendix 2.

The Ocean Circulation Model for Prince William Sound

Publications

During FY96 Dr. Christopher N. K. Mooers and Dr. Jia Wang, along with Mr. San Jin, have completed the second year of development of the three-dimensional, primitive equation circulation model for Prince William Sound. (This effort began in FY95.) A manuscript describing the progress of this work at the early part of this reporting period was submitted by Drs. Mooers and Wang to *Continental Shelf Research* in December 1996. The manuscript, titled "On the Development of a Three-Dimensional Circulation Model for Prince William Sound, Alaska," has been accepted for publication. Elsevier Science, Ltd., the publisher of *Continental Shelf Research*, has kindly granted permission to include the manuscript in the FY96 Annual Report. The manuscript appears in Appendix 3 of this report. The letter of permission also appears in Appendix 3. The letter grants permission to reproduce as part of this report; the letter excludes distribution in electronic form.

Status

The following summarizes progress relative to the project plan of Figure 1 and the FY96 DPD. The plan of the FY96 DPD is included below in italics; status and remarks follow each item.

Certain background issues will reappear in the status remarks; these are briefly referenced here. Additional discussion of these appear elsewhere in this report. Through the beginning of FY96 three factors slowed this work:

1a) final confirmation of funding delayed through April due to transition to new contracting agency;
2a) execution of project plan partially constrained until resolution of project funding plans at March SEA meeting;
3a) although data acquisition continued without interruption, some delay in analysis with changes in the scientific staff in the Oceanography project.

Regardless, during this period Mooers and Wang completed the construction of the climatologies needed to continue. By late summer of 1996 the foregoing issues were resolved:

1b) new procedures instituted by EVOS eliminated between-year problems and funding uncertainties at the end of 1996 and beginning of 1997; momentum was maintained;
2b) funding schedule revisions provided means to proceed with project plan; however, confirmation of the revisions would not be available until August;
3b) Dr. S. Vaughan established an extremely well run observational project; throughout the second half of this period and the beginning of 1997 data gaps that were of concern in the FY95 AR were fully resolved; as noted below all open issues are resolved and an excellent coordination was established between the circulation modelling and the observation effort.

During CY96 the first two task below are of equal priority and will be addressed in parallel.

1 *<u>Model refinement:</u> The first task is the completion of the 1996 version of the model. [Fig 1: "model config 96"] The model features to be added during CY96 are*

1 *<u>tides:</u> in addition to M_2 tidal forcing, include K_1, O_1, and S_2 tidal forcing; incorporate realistic amplitude and phase values from tidal data analyses and/or larger scale tidal models.*

Tidal forcing extended to six dominant modes. Second half of the task underway. Progress at the end of the period is such (see 3b above) that open items will be resolved in 1997.

2 *<u>winds:</u> apply idealized atmospheric storms to develop scenarios for the response of PWS to storm passages in order to estimate the nature and (space-time) pattern of the PWS circulation response.*

Completed. [See "simulations of lake & river", Fig. 1] See manuscript in Appendix 3. The results of a simulation study are described in section 4.3 (pages 12-14, Figures 8 and 9a, b, c, and d).

3 *<u>resolution:</u> add more sigma levels to resolve better the surface and bottom boundary layers.*

Completed: increased from 11 to 15 sigma levels, with increased resolution in upper mixed layer.

4 *<u>inflow:</u> improve the specification of temperature and salinity fields on the inflow based on SEADATA observations.*

Completed. Throughout the latter half of the period the data available for boundary conditions has been continually expanding. [See "simulaltions" and "scenarios" in Fig. 1]

5 *<u>fresh water runoff:</u> by the end of CY96 establish the data resources and models to incorporate realistic values for freshwater runoff for the PWS watershed.*

Completed. During the early part of FY96 Mr. Harper Simmons worked with the SEA Oceanography project. His work was a freshwater runoff model, the subject of his Mater's research under Dr. R. F. Carlson, Dept. of Civil Engineering, UAF. Mr. Harper Simmons has made available to SEA the final form of his hydrology model and continues to provide support for its application to the circulation model. ("Estimation of freshwater runoff into Prince William Sound using a digital elevation model") In the 96DPD and 95 AR is was not resolved how this component would be addressed within existing schedule constraints. This issue has tentatively now been resolved.

2 *<u>Model validation:</u> The second task is the validation of the 1996 version of the model using the data resources assembled by SEA. [Fig 1: "review ocean data"] along with new oceanographic measurements. [Fig 1: "drifter studies" and "tide gauge stations"]*

Climatologies completed. Tests and validation with climatologies underway. As noted above the processing of datasets for instrumentation newly deployed for FY96 has made great strides and the latter components of this task are in progress.

3 *<u>Space-time analyses of surface winds:</u> This third task is an effort that will be conducted in collaboration with SEAOCEAN, the database effort in SEADATA, the and Trophodynamics Project. During CY96 a priority task for these four projects is the completion of the oceanic and atmospheric database.*

The databases for surface meteorological information are largely completed. This is described in some detail in Appendix 1, Appendix 2 and Appendix 4 of this report. The analysis is underway during early 1997. This data archive, both historical and near-realtim, is accessible through the SEA web site. The question of additional meteorological stations [see "addit'nl met stations" in Fig. 1] has largely been resolved with the successful completion of the Applegate station and near-realtime data system described in Appendix 4.

4a *<u>Model coupling and ecosystem processes:</u> This task draws upon tasks #1, #2 and #3 to establish a collection of meteorological and oceanological scenarios and corresponding* *seasonal and annual circulation histories for PWS. The purpose is to identify physical features associated with "river" and "lake" annual variations of PWS circulation. The principle result for CY96 is a collection or catalog of model output simulations and an initial set of quantitative descriptors whereby the physical and the biological classifications of "river year" and "lake year" are made more complete and precise.*

4b *The second part of this task is to collaborate with the Trophodynamics Project and develop the coupled plankton-ocean model within which the catalog of circulation scenarios and simulations is used to produce a corresponding catalog of seasonal macrozooplankton production and distribution.*

This component of the FY96 plan is not fully addressed during this period. [See "collection of lake & river one yr scenarios & simulations" in Fig. 1] A partial set of simulations is described in the manuscript in Appendix 3 (Section 4, Simulation Results). This component is slipped to 1997. In part this is a result of the constraints described at the outset. However, it is also due to a rescheduling whereby the collection of scenarios and substantial simulations with circulation forcing will follow a more complete set of validation studies. Hence, more of the validation work, especially with the climatological datasets, has been conducted during this period than is indicated in Figure 1. Conversely, less of the scenario construction work has scheduled for this period.

On the other hand, certain topics scheduled for 1997 in Figure 1 were addressed during the past period. Most notable is the herring larval drift work. Preliminary trials were run during this period and the results are described in Appendix 3 (section 4.4, page 14).

The Nekton Model for pink salmon and Pacific herring

This report on the nekton modelling effort will be in several parts:

1) ***Status*** of the project relative to the project plan of Figure 1 and the FY96 DPD;
2) ***Chronology*** for the reporting period;
3) a ***Summary*** of the results from the simulations for estimates of fry mortality during spring outmigration.

Status

The format of the foregoing section is followed here: the plan of the FY96 DPD is included below in italics; status and remarks follow each item. Figure references are to the project PERT chart in Figure 1.

One of the background issues discussed above applies here as well: items 2a and 2b were factors for the first and second halves of the reporting period, respectively.

1 <u>*Remaining foraging/Bioenergetics models:*</u> *During CY96 remaining foraging/bioenergetics models will be completed. These include models for age 1 and age 2 walleye pollock and age0+ through age 2 Pacific herring.*

Partially completed. Most of the components for the models were assembled during the period but they were not fully implemented in the format of the SEA foraging-bioenergetics model. For the simulations of fry mortality it sufficed for initial runs to work with the adult pollock model and the pink salmon fry models. These two had been fully implemented during FY95 and are described in the FY95 AR. During FY96 priority was given to combining the foraging-bioenergetics model with the dispersion model and to obtaining the first simulation-based estimates for fry mortality. There was further work on the juvenile herring bioenergetics model during the last part of the period to as part of the herring overwintering work.

During the early part of FY97 further work is scheduled for a second level of refinement and validation of the foraging-bioenergetics models in conjunction with the next series of fry mortality test simulations.

2 <u>*The combined dispersion-foraging/bioenergetics model:*</u> *The most important task for CY96 is the development of the complete nekton model incorporating both the Version 4 dispersion model and the foraging/bioenergetics models. This combination of the two models is an non-trivial task and it is fully expected that several versions of the combined model will be developed during CY96 through CY98. For CY96 the most simple form of the combined model will be implemented.*

Completed. During this period version 1.0, 1.1, and 1.2 of the Combined model were developed. See chronology for FY96 below.

3 <u>*Simulations of fry mortality using hypothetical scenarios:*</u> *During CY96 initial estimates of fry mortality during outmigration will be computed from combined model simulations for a variety of hypothetical scenarios for spatially and temporally varying physical conditions, macrozooplankton distribution, predator distributions and population structures, fry distribution, and outmigration timing and duration.*

Completed. During the last part of the period simulations for fry mortality were run. The results were presented at the EVOS January 1997 reviews. See the simulation "walk-through" below.

4 <u>*Preview version of the long term monitoring-modelling facility:*</u> *At the end of CY96 a preliminary version of the final SEA long-term monitoring and modelling plan will be prepared using currently available knowledge from both the field measurements and the model simulations. This preview version will provide an first estimate of the how the monitoring-modelling facility scheduled for delivery in CY98 will function. A block diagram for the facility is shown in the 1998 panel of Figure 1.*

Initial monitoring plans were formulated. A subset of these was presented to EVOS in the proposal for FY98 submitted by G. L. Thomas and E. V. Patrick (representing the SEA collaboration) for a pilot monitoring effort.

5 *Version 5: The next version (Version 5) will replace the one spatial dimension of Version 4 with 2-dimensional and then a 3-dimensional code. Version 5 will be developed during the end of CY96 and the beginning of CY97.*

Significant first steps toward the 2D and 3D versions of the model were initiated. See chronology below.

Chronology

The status of the effort at the beginning of this reporting period is described in FY95 AR: a mixed method finite element solution (*Aw version 4*) for the diffusion-taxis model had been implemented, and a foraging-bioenergetics model for pink salmon fry and adult pollock (*gut version 2*) had been completed. Simulations from each had been run.

The foraging-bioenergetics model *gut v2* had successfully captured both the foraging (sub-hour time scale) **and** growth (time scale of days) processes of fry as described by Godin (1981, 1981a, 1984). It had also successfully reproduced feeding sessions (or episodic or "glut" feeding) that has been suggested as a candidate feeding pattern for adult pollock. The diffusion-taxis model requires feeding patterns and responses as factors to drive distribution changes. Hence, the combining of these two is an essential step, and certainly required for estimates of fry survival.

A second priority in the model development is the migration of the model from the present one-dimensional form to two- and three-dimensional models.

Winter and spring, 1996. During this period R. H. Nochetto and S. Rao conducted an in depth review of available options for the migration of the nekton model code to 2- and 3-dimensions. In this effort they evaluated numerous mesh generation codes and combined finite element solvers (typically for elliptical pdes) and mesh generators. In selected cases codes were installed and tests were conducted with the nekton model. In particular, work was begun on the task of coding the equations in multiple dimensions.

A progress report for their work for this period is contained in Appendix 4. A summary list of the items accomplished for the 2D effort up to July 1996 was prepared by S. Rao.

1. Model Formulation
    a. Hybrid solver implemented
        o This method is now being implemented
        due to its desirable properties for our

case.

   b. Mixed solver used for comparison

2. Exponential fitting issues.
      - Redo exponential fitting with 2d elements in mind.
      - Implement an exponential scaling using a two dimensional approach.
3. Adaption and refinement schemes.
      - Recursive approaches studied.
      - Recursion allows for a transportable approach to mesh solving and can hence be applied to multiple domains and problems.
4. Iterative Solving.
      - Studied the GMRES solver (Generalized Minimal RESidual).
      - Offers a good solution to a non-symmetric problem such as ours.
5. Review of FEM packages.
   a. KASKADE
      - C++ based and somewhat slow.

   b. MGGHAT
      - FORTRAN based and fast, but offers little flexibility as far as migration to 3D.

   c. Baensch
      - FORTRAN based but offers great deal of flexibility.
      - Collaborations with the author of the code and methods used there-in offer an advantage in development with regards to our problem.
6. Review of numerical packages.
   a. LASPACK
      - C based but somewhat slow.

   b. LAPACK
      - FORTRAN based and could suit our needs.

   d. Doerfler
      - FORTRAN based and offers an advantage in that it is used by Baensch.
7. Coding of 2D solvers.
   a. Implementation of Baensch code with our formulation.
      - Linking FORTRAN with C routines to allow for eventual migration to an Alewife scheme.
      - Testing new 2D solver with our formulation.

Summer 1996, Part 1. Much of the above effort was in anticipation of the visit during July of Dr. Eberhard Baensch of the University of Freiburg, Germany. He had developed mesh generation code that was formulated for both 2D and 3D. As noted in the above list, although there were a variety of options for mesh generators, the better ones typically were written only for 2D, and there was no clean way to extend to 3D. However, the work of Baensch already had been developed for 3D. It would enable us to do initial development in 2D and have at hand the tools to extend to 3D.

It was and interesting and productive two week session. Dr. Baensch is interested in two aspects of this work: a) the ecological application, and b) the exponential fitting methods employed by Nochetto for this class of pde models. He will return for a second visit in October 1997. The visit was moved back until the coming fall for reasons to be discussed below.

Prior to the visit, the 2D studies led to the realization that the hybrid form of the finite element solution was significantly simpler than the mixed method form. Consequently, the code for *Aw v4* was rewritten with the simpler model. This simplification has been of considerable significance in the last half of the period.

During the visit the model code in hybrid form and with 2D formulation was merged with the code that Baensch brought for the visit. Some initial tests were made conducted.

To illustrate his algorithms and to begin to set up a test simulation for the 2D nekton model, Baensch generated the mesh in Figure 4 for a generic vertical "water column" 2D domain typical of Prince William Sound.

Summer 1996, Part 2. In addition to the work on 2D and 3D codes, the visit of Baensch led to useful test questions regarding the stability of the nekton model for various extremes of population densities and various taxis-diffusivity ratios. A first analysis was carried out during the second half of the summer of 1996.

The major work of this period was the implementation of the combined code. The diffusion taxis code had been developed in C. The code for the foraging-bioenergetics had be written in IDL. One of the two had to be selected for the first combined code. The C language had been used for portability, and this was certainly advantageous when merging codes with prior work of Baensch. On the other hand, prototyping could be done more quickly in IDL. It was further preferred to have the prototype code generate graphical output during the simulation rather than having to wait for the completion of the run. This enabled both debugging and model analysis to proceed more quickly. Finally, the simplicity of the new hybrid code made the transfer of the diffusion-taxis solver to IDL significantly simpler than converting the foraging-bioenergetics code to C.

The results from the first combined code were presented at the SEA Seward meeting in September, 1996.

Fall, 1996. During the fall of 1996 further analysis was completed for model stability. Following a review of model functioning by M. Willette in October, the combined model was further developed by

1) a comprehensive set of graphical representations of the various states of the model during a simulation were implemented;
2) a submodel for fry schooling was added;
3) a submodel for two distinct feeding modes by adult pollock was added:
    a. particulate feeding, and
    b. suspension or filter feeding.

and during any feeding period the fish chooses whichever method provides the greater consumption in terms of mass per unit time.

The implementation of these additional modules constitute version 1.2 of the Combined model. This version was used for the fry mortality simulations described below.

Summary

The following is a brief and partial description of the manner in which the nekton model captures the simultaneous processes described by the various SEA hypotheses in the determination of fry mortality. It was found to be very helpful to use time animation in such a description, and that was done for the EVOS January review. An animation server is planned for the nekton model during 1997. This report will only overview selected functions. The full function can only be described by the model equations, and technical manuscripts are in preparation. The next best resource will be an on-line animation server.

There is considerable additional detail regarding model features in the FY95 Annual Report. This is a 1-dimension implementation, and for fry-adult pollock interactions the model is used to capture in-shore to off-shore population distribution changes in time, due both the predation and to movement. A typical domain of one spatial dimension would be the cross-passage domain shown in Figure 5. Along this "line" observations have determined the relative distribution of the various zooplankton species from off-shore to nearshore.

Simulations were conducted using simplified forcing and with no coupling between the zooplankton and nekton populations. That is, zooplankton densities were assumed to be given, and for these tests they were assumed constant throughout the simulation. Similarly, physical variables such as temperature were assumed constant. The processes that the nekton model captures for these simulations are the feeding of the fry and the adult pollock and changes in spatial distribution in response to feeding, predation, and any other factors affecting distribution. Here only feeding and predation are included in the taxis responses. Throughout these tests the total pollock population "in the domain" is assumed constant, though free to redistribute along the domain. That is, total predator abundance is not changed. Similarly, except for one case, the initial fry distribution is the same for all simulations. Zero mortality for adult pollock is assumed.

With these assumptions and configuration the following mortalities were obtained for four simulations.

zooplankton density (max density #/m^3	timing of feeding	fry survival
pseudocal: 150 neocal C4: 200	day and dawn	10da: 88% 25da: 60% 65da: 40%
pseudocal: 100 neocal C4: 100	0-10da: day & dawn 10-30da: day & dawn	10da: 97% 25da: 60% 65da: 40%
pseudocal: 150 neocal C4: 450 neocal C5: 350	mixed	10da: 99.5% 25da: 97% 65da: 95%
pseudocal: 250	n/a	10da: 50% 25da: 2%

The larger values for zooplankton density persist only for one to two weeks at most, so the assumption of constant density is solely to examine the interaction of the model components.

The last entry is a baseline case. There are now alternative prey for the adult pollock; the fry are the only prey item. The fry have the one prey zooplankton pseudocalanus. For the calibration used in version 1.2 of the model for the parameters regulating the mobility and feeding rates of pollock, the pollock consume available fry within a month.

The first two cases show were selected in anticipation that the second, with fewer zooplankton, would surely have higher fry mortality (lower survival). Instead it resulted in the opposite. This is due to the interaction between assumptions regarding the feeding mode for pollock and the schooling behavior of fry. Because of the substantial impact of this interaction it will a first issue addressed in 1997.

The third scenario is represents the upper end of zooplankton density. Here their role as alternative prey and the switching of pollock between particle and suspension feeding is a factor.

A complete presentation of the model behavior will be documented during 1997; it will be necessary to first implement suitable formats for presention.

Monitoring and Model maintenaance

Achieving near-realtime data from remote stations has been a goal of this project since the beginning. The first continuously running installation realizing that objective came alive during this reporting period. It was through the tenacity of Mr. Steve Bodnar, the patient and persistent engineering of Mr. Roy Murray, and the assisted software leap to the world wide web provided by J. R. Allen that this long sought objective is now daily delivering information about the western sound. The story and how to access it via the web is told in Appendix 5.

DISCUSSION

Design and development selections

From this review a different theme emerges. For the FY95 Annual Report there were concerns regrading the resolution of pivotal technical issues. Those critical issues were resolved in FY96. In assessing the outcome for the year that is definitely good news.

With that progress the outcome for the effort is becoming clearer. With that it is also clearer where choices must now be made. There are aspects of the original plan that at this time do not have solutions regarding resources for full implementation. Considerable effort during the past year went into finding cost-sharing projects that would help sustain, for example, programming help to continue the 2D/3D implementation. That did not develop and that aspect of the work is on hold. The scope of the models will be adequate for the task at hand. It is a function range that has been adjusted to match the resources.

Prudent design and development decisions are seen in all aspects of the project. They indicate proper attention to the final objectives on the part of all of the investigators in SEADATA.

PROJECT BIBLIOGRAPHY

See also bibliographies of manuscripts included as Appendices

Blumberg, A. F. and G. L. Mellor, 1987. A description of a 3-D coastal ocean circulation model. In *Coastal and Estuarine Sciences 4*, N.S. Heaps, ed., Amer. Geophys. Union, Washington D.C. pp 1-16.

Brandt, S. B., D. M. Mason, and E. V. Patrick. 1992. Spatially-explicit models of fish growth rate. *Fisheries,* 17(2) pp 23-35.

Eslinger, D. L., 1990. The effects of convective and wind-driven mixing on springtime phytoplankton dynamics as simulated by a mixed-layer model, 127pp., Ph. D. Dissertation, Florida State University.

Falkenberg C. S. and R. Kulkarni 1995. Using Spatial Access Methods to Support the Visualization of Environmental Data. In *Proceedings of Visualization '95*, Atlanta GA, November 1995, IEEE Computer Society Press, pp 400-403.

Gallacher, P. C. and P. A. Rochford, 1995. Numerical simulations of the Arabian Sea using tracers as proxies for phytoplankton biomass. *J. Geophys. Res.,* 100, pp 18,565-18,579.

Gerritsen, J., and J. R. Strickler. 1977. Encounter probabilities and community structure in zooplankton: a mathematical model. *J. Fish. Res. Board Can.* 34 pp 73-82.

Godin, J.-G. J. 1981a. Effect of hunger on the daily pattern of feeding rates in juvenile pink salmon, *Oncorhynchus gorbuscha Walbaum. J. Fish Biol.* 19 pp 63-71.

Godin, J.-G. J. 1981b. Daily patterns of feeding behavior, daily rations, and diets of juvenile pink salmon (*Oncorhynchus gorbuscha*) in two marine bays of British Columbia. *CJFAS* 38 pp 10-15.

Godin, J.-G. J. 1984. Temporal variation in daily patterns of swimming activity and vertical distribution in juvenile pink salmon (*Oncorhynchus gorbuscha*). *Can. J. Zool.* 62 pp 72-79.

Howick, G. L., and W. J. O'Brien. 1983. Piscivorous feeding behavior of largemouth bass: an experimental analysis. *Trans. Am. Fish. Soc.* 112 pp 508-516.

Mason, D. M., and S. B. Brandt. 1996. Effects of spatial scale, capture efficiency, and the spatial distribution of predators on the predictions made by spatially-explicit models of fish growth rate. *Environmental Biology of Fishes,* 45(3) pp 283-298.

Mason, D. M. and E. V. Patrick. 1993. A model for the space-time dependence of feeding for pelagic fish populations. *Trans. Am. Fisheries Soc.,* 122(5) pp 884-901.

Mooers, C. N. K. and D.-S. Ko. 1994. Nowcast system development for the straits of Florida. *Estuarine and Coastal Modelling III, Proc. of the 3rd Intern. Conf.,* pp 158-171.

Mooers, C. N. K. and Wang, J., 1996. The second generation of the Straits of Florida nowcast/forecast system. In *Conference on Coastal Oceanic and Atmospheric Prediction,* Atlanta, Jan. 28-Feb. 2, American Meteorological Society, Boston, pp 28-35.

Mooers, C. N. K. and Wang, J., 1997. On the Development of a Three-Dimensional Circulation Model for Prince William Sound, Alaska. *Continental Shelf Research*, in press.

Niebauer, H. J., T. C. Royer and T. J. Weingartner, 1994. Circulation of Prince William Sound, Alaska. *J. of Geophysical Research*, 99, pp 14,113-14,126.

Stonebreaker, M. 1994. Sequoia 2000: A Reflection on the First Three Years. *IEEE Computational Science & Engineering* Winter 1994, pp 63-72.

Wang, J. and C. N. K. Mooers, 1996. Modelling Prince William Sound ocean circulation. In *Conference on Coastal Oceanic and Atmospheric Prediction,* Atlanta, Jan. 28-Feb. 2, American Meteorological Society, Boston, pp 36-43.

Wang, J., L.A. Mysak and R.G. Ingram, 1994. A 3-D numerical simulation of Hudson Bay summer circulation: Topographic gyres, separations and coastal jets. *J. Phys. Oceanogr.*, 24, pp 2496-2514.

FIGURES

Figure 1. Project plan for the SEA model
Figure 2. The SEA Datasets and the SEA Database FY95
Figure 3. The SEA Datasets and the SEA Database FY96
Figure 4. Test mesh for simulated 2D vertical domain in PWS
Figure 5. One-dimensional spatial domain

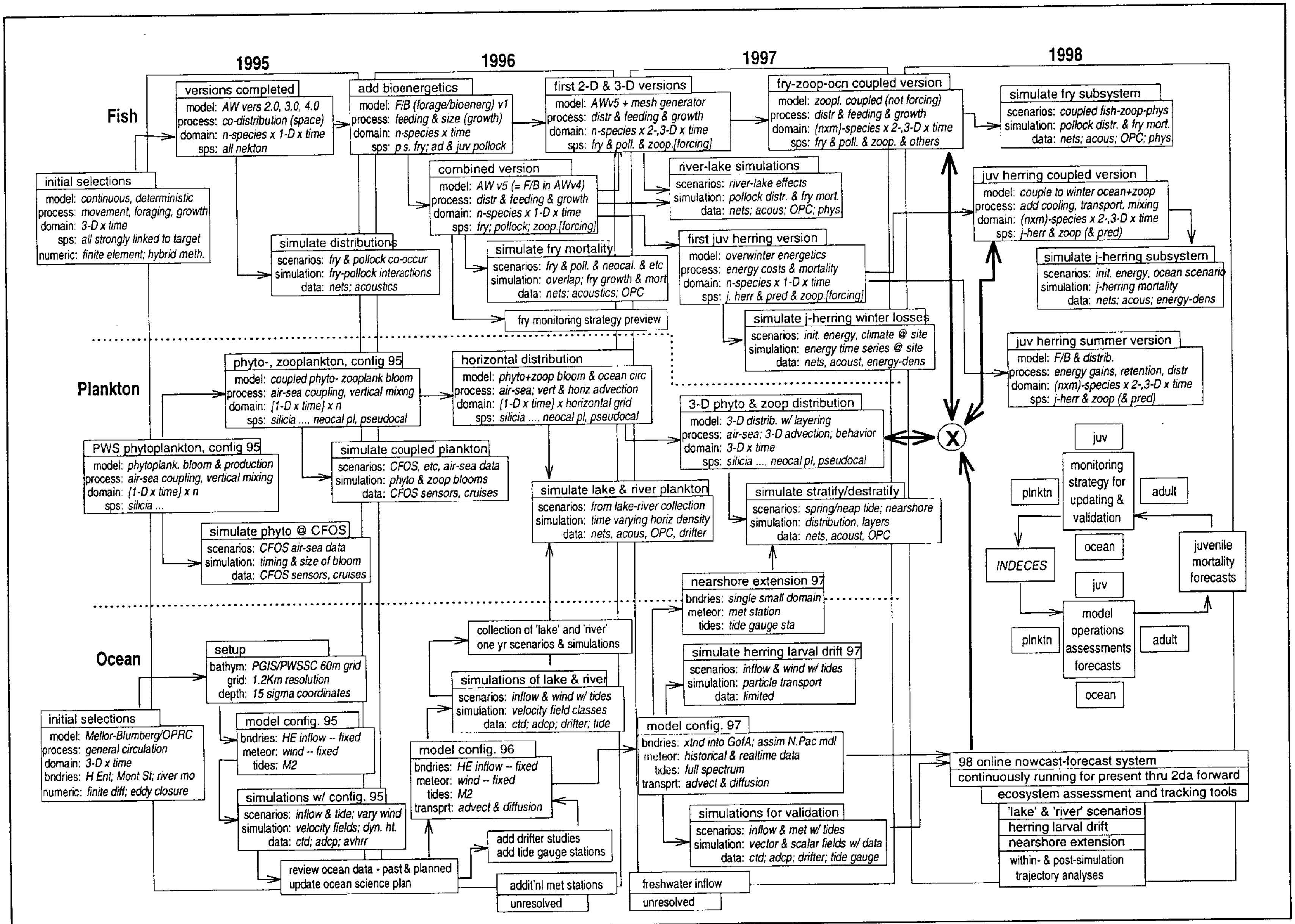

Figure 1. The SEA models: status, development plan, dependencies, and endpoints.

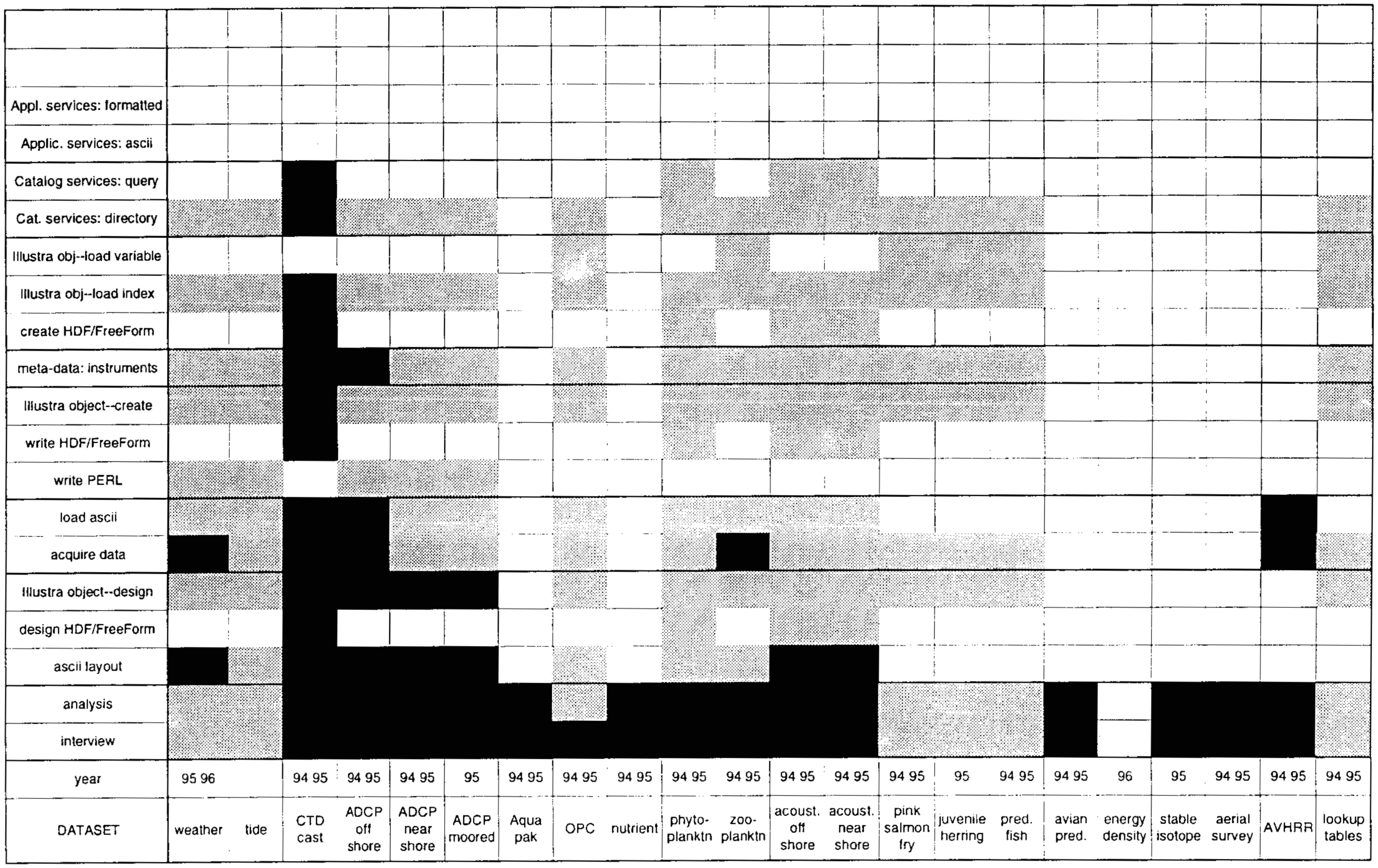

Figure 2. The SEA Datasets and the SEA Database; status for Oct. 95 (black), expected status for Oct. 96 (gray).

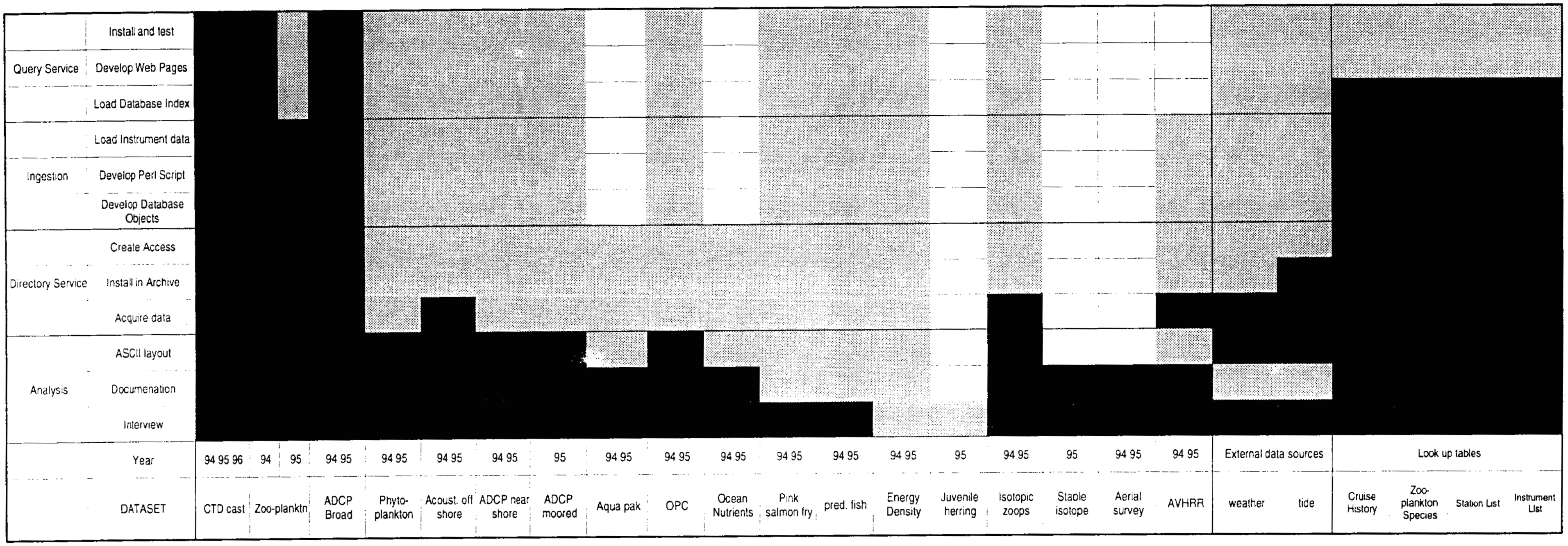

Figure 3. The SEA Datasets and the SEA Database: status at the conclusion of 1996 (black), expected status for 1997 (gray).

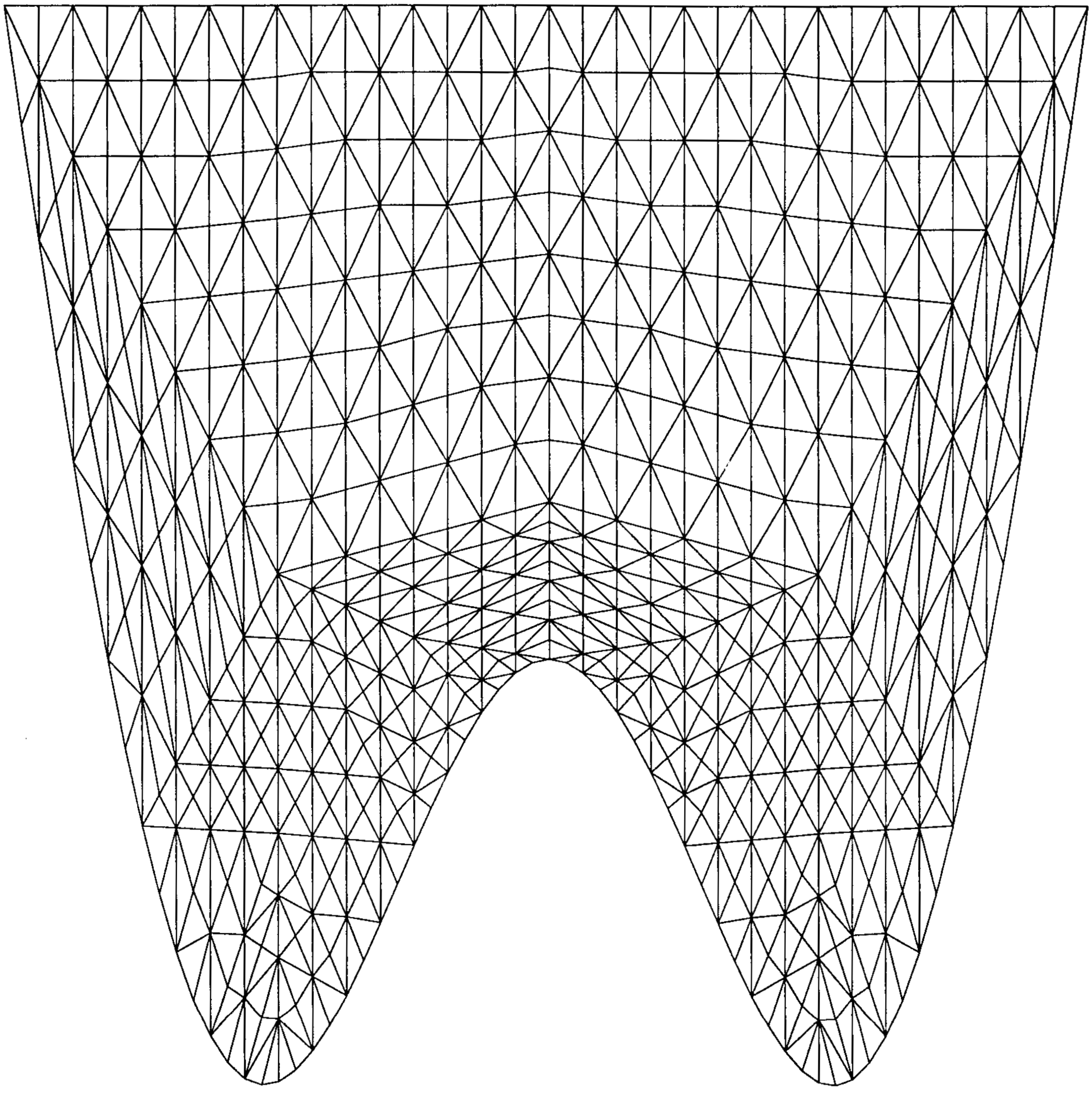

Figure 4. Test mesh for simulated 2D vertical domain in PWS. Generated by E. Baensch, Univ. of Freiburg, during visit to explore development of 2D and 3D codes for SEA nekton model, July 1996.

Figure 5. Cross-passage direction and upper layer of water column in neighborhood of maximum zooplankton abundance: modelled as a one-dimensional domain.

Appendix 1

Report on the Development of the SEA Database during FY96

Report on the Development of the SEA Database during FY96

Charles Falkenberg

Summary

While the focus of the FY95 database work was design and prototyping, the FY96 effort has concentrated on implementation. As a result, the SEA database has been brought online through the SEA DataWeb intra-net. This Netscape application unifies the access to SEA datasets and provides for the retrieval and processing of the data needed for integrated analysis of the ecosystem of Prince William Sound. The implementation milestones for FY96 include:

Purchasing and installing the Illustra software at 3 of the SEA sites.
Training a SEA collaborator at each site on Illustra.
Developing and installing the SEA DataWeb.
Collecting and ingesting the meta-data needed to index SEA datasets.
Ingesting several datasets from the 94, 95 and 96 field seasons.
Initial use of the database with the SEA models.

With the establishment of the DataWeb, SEA researchers can use the Netscape browser, or other advanced WWW browsers, to select from multiple SEA datasets using a wide variety of meta-data. The resulting list can be viewed or displayed on an interactive map of Prince William Sound. The map shows the positions of all selected datasets and can display a list of datasets at each location. The datasets can then be downloaded, in a single step, to any of the SEA hardware platforms. Allowing multiple types of datasets to be selected using the same criteria unifies the process of analyzing these datasets together. This level of data integration is required by the ecosystem models developed by SEA. Although more datasets need to be brought online in FY97, the current availability of many of the higher demand datasets and the establishment of the SEA DataWeb is a major milestone for the SEA database.

In addition to the creation of the DataWeb, the database development effort had several other significant accomplishments in FY96. These include:

Establish public data access and visualization of PWS weather data. (Allen & Bodnar)
Mirroring the DataWeb and archive to provide fault tolerance.
Compiling a description of all SEA datasets for the EVOS CD.
Begin retrieving and cataloging tide data from NOAA.
Upgrading the cruise planner for the 97 field season.

As part of the SEA effort we are collecting and analyzing weather data from around Prince William Sound. SEA is making these data, and the visualization of these data, available to the public over the World Wide Web. Jenny Allen and Steve Bodnar have created a set of web pages for selecting and graphing a wide range of weather data for Prince William Sound.

The data archive and the DataWeb tools are being mirrored to allow faster access for a wider number of researchers and provide some fault tolerance if any site is experiencing problems. Finally, we produced a unified document for the upcoming CD which is being put out by the Alaska Department of Natural Resources for EVOS. This document met the specifications of Carol Fries at ADNR and describes all of the datasets being collected by SEA in a concise manner.

The main effort in FY97 will be to bring several new dataset types online, and to add data from recent field seasons to the datasets currently online. Support for the modeling effort will also increase and provide input to the SEA models as well as an archive for the output from the models. Finally, the DataWeb will be expanded to include datasets which are derived from external data including tides, stream runoff and weather.

Using the DataWeb

The DataWeb provides three levels of data access; a directory service, a query service, and a modeling service. Directory service is the initial level, allowing files to be retrieved by dataset and year. Although these are limited selection options, this directory service provides immediate availability to the datasets in the SEA archive. It acts as shared data directory for SEA. Individual SEA projects can make their data quickly available to other members as the initial analysis is under way.

Query service provides access to multiple types of SEA datasets through a database query. Here, datasets can be selected using a wide range of meta-data which has been extracted from the dataset and used as an index. These meta-data include geographic location, collection date, cruise and instrument ids, and value ranges from the data variables. A researcher using the query service enters one or more of these attributes through the browser and a list of all datasets meeting the criteria is displayed.

The selected datasets can then be displayed on an interactive map of Prince William Sound. The scale of the map can be changed and if one of the locations is selected with the mouse, a list of datasets at that point will be shown. This list includes the type of dataset, the station or transect name, the date and time of collection, and any relevant notes associated with that dataset.

All of the files associated with the selected datasets can also be listed and downloaded. Individual files can be browsed or downloaded or they can be retrieved together in a single ZIP file. Each researcher can then work from a local computer on any of the SEA datasets which meet the specific criteria of a project. With the use of Netscape and ZIP, the DataWeb becomes accessible to all researchers in SEA, regardless of the computer platform.

The Modeling service provides the most advanced set of database functions. Using the Netscape browser, a query which is tailored to a particular modeling requirement, results in a set files which contain reformatted data from several different datasets. The query is a proximity query which returns datasets throughout the region and time period being monitored or modeled. Specific variables are extracted from these datasets an mapped into the space described by the model.

Although it is still in it formative stages, the modeling service provides the foundation for integrated modeling and long term monitoring. The database will store both the data needed as input by the models and the data output by the models. Data supplied by the database will provide three initial functions. Boundary conditions for the model, such as ocean currents or temperatures, will place the model in a spatial and temporal context. Data may be assimilated into the model as it runs. And Finally, data may be used to validate the model results. These results will then be placed back in the database and possibly used as input to a subsequent modeling effort

Under the Hood of the DataWeb

The DataWeb uses the Illustra Database Management System (DBMS) to store and search the dataset indexes. Illustra is the leading object-relational DBMS and was, as a result, purchased by Informix which is incorporating the Illustra model into its own DBMS product. Illustra (and soon Informix) supports spatial indexing, allowing an index of datasets to be created using the latitude and longitude of the sample files. Illustra was originally used to support the Sequoia 2000 project which, like SEA, has integrated environmental data from a wide number of sources.

Informix is one of the top 3 DBMS vendors. With the adoption of an object-relational approach Informix presents a formidable challenge to the other major DBMS vendors, Oracle and Sybase. NASA is considering switching from Sybase to Informix for it large EOS project and Oracle is now pursuing the object-relational approach as well.

The DataWeb tools are also based on some emerging technologies for database access through the web. Illustra's Web Datablade provides server side interpretation of HTML pages and allows the results of SQL statements to be embedded in the pages before they are returned to the Netscape browser. This product became available in December of 1996 and was used as an integral part of the initial DataWeb pages.

In addition to the Web Datablade, Perl was used extensively to generate the pages needed in DataWeb. An API is available for Perl which allows access to Illustra. This Perl library is being used to select datasets for the SEA models as well as to create the ZIP file which is used to download the datasets.

In order to support JavaScript, and the HTML forms needed by DataWeb, the latest web server and the Netscape browser were installed in the summer of 1996. JavaScript is used heavily to validate the input needed by the DataWeb. Fields such as year, month, day, latitude, longitude all require extensive validation to insure that they can be used in a database query. In addition, JavaScript is used to create a list of dataset files at the browser and reduce the overhead of a second database query.

One of the other advanced features of the Illustra system is the ability to create functions that are executed by the Illustra server during the processing of an SQL statement. The DataWeb includes several of these server side function which tailor the output of query to meet the needs of the application. One of these functions is used by the modeling service to project the lat/lon of the dataset polygons into an albers projection. This is required in order to provide accurate proximity queries for the SEA models.

The DataWeb tools and the SEA data archive are being mirrored in Cordova and at the Advanced Visualization Lab in Maryland. This provides high speed, fault tolerant access to a wider range of SEA researchers. The Maryland site provides collaborators in Fairbanks and in the lower 48 to have access to the SEA datasets with the speed of a terrestrial data link. A development environment has also been established in Maryland and in Cordova. This allows the development and testing of new DataWeb modules to be done without interfering with the use of the production version of DataWeb.

Status of Development

The database effort can be broken down into two categories: software development and dataset ingestion. The software development work includes the design, programming, testing and installation of the DataWeb tools as well as the cruise planner and several productivity aids. The major thrust of the FY96 effort was the installation of the DataWeb tools. These tools, described above, provide the foundation for retrieving all of the SEA datasets. These tools will be refined and expanded as time goes on but the largest part of the development is now complete.

In addition to the DataWeb development several datasets were ingested in FY96 and made available through the DataWeb tools. The ingestion effort includes four general phases which are shown in Figure 3 from bottom to top. First, the analysis of the dataset includes interviews and documentation. Next, the data are acquired and made available with a simple directory based lookup. The third step, is the largest part of the overall ingestion and includes the creation of the programs which build the database objects and indexes. Finally, several dataset specific web pages are added to the DataWeb Tools.

The focus of FY96 dataset work was on four datasets: the CTD, Zooplankton and ADCP datasets and the meta-data needed to index these. The columns of figure 1 represent the datasets and these 4 are now available through the Query Service portion of the DataWeb. The first three of these datasets include data samples which were collected by SEA. The meta-data tables, or lookup data, includes the cruise history, ship and instrument inventories, SEA station lists, and zooplankton species list. These meta-data tables are used to validate the datasets during ingestion and as selection criteria in the DataWeb tools.

As an example, each dataset has a SEA cruise number which can be used to select the datasets for a single cruise. A meta-data table containing all cruise numbers is used during the ingestion processes to validate the cruise number in each of the datasets. This table is also used by the DataWeb to present a list of possible cruise numbers. Once one or more cruises have been selected from the list, the cruise index is used to quickly locate all datasets for those cruises. The cruise meta-data table, therefore, insures consistancy within the database and greatly simplifies the entry of the selection criteria.

The current inventory of datasets available through query services includes the CTD dataset from 94 through 96, the ADCP dataset from 94 and 95 and the Zooplankton dataset from 94. The Zooplankton data will be brought current in the spring of 97 and additional ADCP dataset may be available in summer 97. The main goal of FY97 is to bring several new datasets into the archive and make them available through the DataWeb.

The database effort received about 6 months of funding in FY96 and about 22% of that was devoted to EVOS related projects. These included the EVOS meetings, the EVOS CD and year end reporting. About 40% of the FY96 database effort was devoted to installing software and creating the various parts of the DataWeb tools. Finally, about 38% of the effort went into populating the archive with meta-data tables and the initial datasets. The three main datasets required about 4 to 5 weeks a piece to ingest and some of this was done in FY95. It should be noted that the individual projects which submitted the datasets were actively involved and devoted a fair amount of time to the ingestion effort as well. It is anticipated that the other datasets will require about the same amount of effort. Some are more complex than others, however, and will require additional time. As with FY96, the future database effort will be divided between adding datasets to the archive and enhancing the DataWeb tools. In addition, as the modeling effort matures a great deal of work will be needed to supply the data in the model specific formats.

Shared Data and Interdisciplinary Research

As a large scale interdisciplinary research project, SEA faces many unique data sharing challenges. In many regards the SEA approach to sharing data is closer to a corporate model than to the traditional scientific model. Scientific analysis of sample data has traditionally been done in relatively closed environments. A small number of researchers, who have exclusive access to their data, can set their own data standards and establish their own data management scheme. Larger research projects must face the difficulties of sharing the management of data and large multidisciplinary projects must create shared standards across disparate disciplines. SEA has embraced both of these challenges as part of its interdisciplinary character.

A significant part of the SEA program has been to collect field data on a wide range of physical and biologic parameters. As a result, 15 or 20 datasets will be created, consisting of some 200 thousand sample files. From the beginning SEA has recognized the importance of cataloging these data and making them available within SEA during the proprietary phase and, following that, to the public at large. The SEA DataWeb is the cornerstone of this effort.

This data sharing strategy is closer in many ways to an enterprise which maintains a common database and provides a consistent view of those data to all departments. Therefore, the SEA DataWeb utilizes many of the emerging technologies found in corporate intra-nets. The DataWeb has a client-server architecture using a secured sub-net of the World Wide Web. The datasets are indexed using a transaction oriented, object-relational, Database Management System which supports spatial indexing. The current version of JavaScript is used to validate the query input and the results are displayed on web pages which are dynamically generated at the server.

The goal of the DataWeb, however, is to support science and not an enterprise. This makes it much harder to anticipate the types of synthesis and integration that will done with the SEA data. Science is discovery, and that requires unplanned synthesis. The DataWeb provides 3 levels of access in order to support this uncertainty. Data can be submitted to the archive and made available through the directory service while it is being processed and indexed. An integrated view is then available through the query service. Once the modeling requirements are established the same indexes can be used to select the cross section of the data needed by the model.

As inter-disciplinary research becomes more common and the gains are realized, data sharing strategies like those used by SEA will no longer be rare. The process of establishing shared standards and conducting integrated data analysis may itself change the way in which data are collected and cataloged. For instance the sampling strategies employed for long term monitoring will be effected, at least in part, by the demands of integrated classification and analysis.

Appendix 2

The SEA Intranet

with 10 figures

Figure 1: Components ...
Figure 2: A consistent imagemap-based menu bar ...
Figure 3: An example of a cruise report ...
Figure 4: Example of results layout by the Oceanography group ...
Figure 5: Examples of results displays ...
Figure 6: The SEA Discussion Area ...
Figure 7: Example of an individual message posted to the discussion area ...
Figure 8: The opening page of the SEA Papers Collaboration Work Area ...
Figure 9: The individual panel of tools ...
Figure 10: Interface to the file upload utility.

The SEA Intranet:

Scientific collaboration in a shared information space by a multidisciplinary, geographically-dispersed research team

Jennifer R. Allen[1], E. Vincent Patrick[1] and R. Ted Cooney[2]

[1]Prince William Sound Science Center
P.O. Box 705, Cordova AK 99574
907-424-5800 {jrallen | patrick}@grizzly.pwssc.gen.ak.us

[2]Institute of Marine Science
University of Alaska Fairbanks, AK 99775-7220
907-474-7407 cooney@murre.ims.alaska.edu

Research supported by the Exxon Valdez Oil Spill Trustee Council as part of Restoration Project #96320-J

RUNNING TITLE: The SEA Intranet
KEYWORDS: Intranet, world wide web, computer support for collaborative work, ecosystem, Prince William Sound Alaska

ABSTRACT

The term *Intranet* refers to the use of Internet and world wide web protocols for internal communication within an organization. The web-based approach to cooperative work includes both functions mediated directly by the HTTP protocol and those where the browser as universal client serves as a hypermedia interface to other protocols or applications. This paper describes a working Intranet that has been used since September 1995 as part of the Sound Ecosystem Assessment (SEA) program in Prince William Sound, Alaska. SEA is a multidisciplinary, ecosystem-level study comprised of more than a dozen integrated projects with research teams distributed over eight institutions from Fairbanks, Alaska, to Miami, Florida. Coordination, data sharing and joint synthesis are essential to accomplishing the program's mission. The SEA Intranet provides mechanisms for user-driven, problem-oriented group interaction and information sharing via a single seamless web interface. Key components include a dynamic results archive; a threaded discussion server featuring user identification, notification, and multimedia attachments; and a fully interactive project-oriented papers collaboration work area incorporating file upload and retrieval. Strengths and limitations of an HTTP based collaborative technology are discussed. Findings from the first 18 months of use indicate that a web-based approach is ideally suited to a circumscribed set of coordination and communication functions in distributed research groups, and that obstacles to be overcome are as much social as technical. Achieving a critical mass of users was essential to establishing Intranet utility and depended on optimizing a cost-benefit balance. To the degree that a scientific project is truly cooperative, collaborative tools offer tangible benefits. However, successful introduction of cooperative tools requires sensitivity to the social and political concerns that characterize joint scientific work.

INTRODUCTION

Collaboration and communication are central to scientific research. Large scale cooperative research programs involving pooled resources and shared information are increasingly required to address complex scientific problems. Although the computing revolution has brought obvious benefits to science, the impact of technology on the scientific collaborative process itself has been insignificant when compared with expectations for the near future (Kouzes, 1996). The spectrum of applications ranges from in-house repositories of hyperlinked data to interactive virtual collaboration environments on the global information network.

The term *Intranet* refers to the use of Internet and world wide web protocols for internal communication within an organization. At its simplest, an Intranet uses a hypertext transfer protocol (HTTP) based internal web server, with a web browser as universal client, to share multimedia files within organizations (Bednarcyk, 1994). The concept, rapidly embraced in the corporate world, has been described as a new paradigm that is predicted to replace client-server architecture as the dominant construct of distributed computing (Gallant and Naik, 1996). An Intranet is a cross-platform solution that avoids problems of heterogenous networks, operating systems, devices and formats; it exploits low-cost, easy to use browser software already ubiquitously deployed; and it is based on open standards and protocols which allow organizations to leverage innovation from the whole industry rather than committing to a single vendor. Over the past two years, corporations have discovered that Intranets provide a powerful mechanism for organizing and accessing internal information using search engines, forms-based queries and web interfaces to legacy databases. Standardized application programmable interfaces (APIs) supporting the Java language offer the spectre of a platform-independent launching vehicle for entire software applications. Netscape Navigator's incorporation of email and chat/whiteboard features portends the beginning of a seamless web browser interface to asynchronous and synchronous communications tools. As of March, 1996 at least 22% of Fortune 500 companies were using web technology for internal information transfer, and another 40% were considering or preparing to do so (Bruno, 1996). Currently about 70% of all new web server sales are estimated to be for Intranet applications (Gallant and Naik, 1996). Intranets are reported to enhance internal communications, improve efficiency, and promote teamwork (Cline, 1996).

Despite this strong endorsement from the commercial sector, application of Intranet technology to scientific collaboration has lagged behind its adoption in the corporate sphere. For the last fifteen years, collaborative use of the Internet by scientists has largely been confined to e-mail, FTP and Gopher protocols. However, the very genesis of the world wide web, which dates to 1989 and the invention of HTML and the first Mosaic browser, was inspired not by commercial objectives but by the need for collaborative data access by physicists at the European Particle

Physics Laboratory (CERN). An internal web today remains ideally suited to sharing of results and information among cooperating scientists, and it offers unparalleled potential as a vehicle for coordinated work among geographically separated researchers. Federal initiatives are increasingly stimulating research on technology to support Internet-based scientific collaboration tools (Cerf, 1993; Weymouth, 1994; Kouzes, 1996). This paper describes a working Intranet that has been used since September 1995 to coordinate and integrate a multidisciplinary, multi-institution, ecosystem-level research project in Prince William Sound (PWS), Alaska.

BACKGROUND AND OBJECTIVES

The Sound Ecosystem Assessment (SEA) Program is a five year study designed to investigate several ecosystem-level hypotheses regarding recovery of pink salmon and Pacific herring populations in PWS following the *Exxon Valdez* oil spill. SEA is an integrated study comprised of more than a dozen individual research projects. Its research teams are scattered over eight institutions from Fairbanks, Alaska, to Miami, Florida, including academic, government and private organizations.[1] The observational studies covered by the individual projects include oceanography; remote sensing; abundance and distribution of nutrients, phytoplankton and zooplankton; abundance, distribution, habitat, diet composition and energetics of the fish species, their prey and predators, including seabirds; and foodweb assessment by stable isotope analysis. The program's three numerical modelling teams are creating (1) a continuously running four-dimensional general circulation model of PWS; which will be used to drive (2) a trophodynamic model linking physical parameters to biological production rates; which in turn will serve as one of the forcing inputs to (3) a coupled multispecies diffusion-taxis model predicting juvenile fish survival. Each of the dozen program components is a complete project in its own right. However, these individual projects were all conceived, designed and developed in a single integrated SEA plan. Their fieldwork is coordinated, uses shared resources and conducts cooperative synoptic measurements at several spatial scales. Each project's data is gathered into a central SEA database, from where it is available to the group and is used both for model validation and for collective refinement of the group's understanding of the system. The deliverables from the program include the set of working coupled models plus a synthesized evaluation of the underlying ecosystem-level processes.

The ultimate success of this program depends critically on solving coordination problem across distance and disciplines. In addition to the basics of scheduling and data sharing, the day to day

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[1] Participating institutions include the University of Alaska, Fairbanks; the UAF Seward Marine Center in Seward, AK; the Prince William Sound Science Center and the Alaska Department of Fish and Game, both in Cordova, AK; the University of Miami; the University of Maryland; the University of Wisconsin and the University of Toronto, Canada.

tasks include joint assessment and assimilation of large volumes of data across disciplinary boundaries; preparation of joint presentations, reports and manuscripts; and timely reassessments and revisions to plans for joint work based on accumulating information and insight. A major challenge is maintaining convergence of the field and modelling efforts through model validation and tightly coupled dialog between the mathematical modellers and the field researchers. The ongoing quest is to integrate the observations, expertise and knowledge of each investigator into a joint system-wide synthesis, with translation into management and monitoring applications.

Clearly, interaction and exchange of ideas between all SEA components is essential to accomplishing these tasks. In the second year of the program, SEA coalesced organizationally into three hypothesis-based workgroups. However, the quality and frequency of interactions within and between groups was hindered by geographic dispersion, a demanding timetable and habituation to conventional more solitary approaches to data analysis and reporting. Because of the remoteness of the Alaskan study site and the wide separation of research teams around the country, face to face meetings of the whole program team were feasible at most a couple of times a year. Intervening teleconferences did not occur often, and were often regarded as inefficient. The SEA Intranet was developed to supplement and augment conventional meetings and to catalyze and facilitate the collaborative interactions critical to SEA's mission.

The approximately 45 SEA researchers all have Internet access. With the exception of the Seward site, all connections are digital links at 256 kbs^{-1} or better; the Seward center has dialup access only. The SEA team members have varying levels of computer expertise and operate from a range of platforms including networked Macintosh, DOS, and Windows 3.1 / 95 / NT machines as well as a variety of DEC Alpha, SGI and Sun Solaris Unix workstation environments. The overriding objective in design of the SEA Intranet was to create a uniform, integrated, seamless collaborative environment which would be equally accessible regardless of platform and computer skills and that would be *used.* Achievement of these goals presented both social and technical challenges.

The following requirements were imposed as design constraints. The solution should:

1. Be platform independent; provide core functions compatible with the lowest common denominator of access technology; be comprised of modular components and compatible subsystems; provide adequate security.
2. Be user-driven, that is, empower users through a system that is not "administered" but rather facilitated; be easy to use; minimize for researchers as far as possible the additional overhead (time, effort) required to participate.
3. Be rapidly implementable with existing technology; but nevertheless allow for expansion and increased sophistication to occur while in use.

The core capabilities needed by the SEA researchers included the following:

- Ability to **locate** and **browse** project documents, calendars or news quickly and easily.
- Ability to **post** (make available to others) new results, quickly and easily; and ability to **view** (see and have access to) new results of others, quickly, with context and interpretation.
- Ability to **brainstorm** over results with others, from multiple locations, while interactively viewing a common display of data products.
- Ability to **exchange** (upload and retrieve) draft copies of joint documents in progress, transparently, regardless of platform.
- Ability to **annotate** objects; and ability to carry on **sustained dialogs** in an open group forum, from multiple locations, without being limited by schedule conflicts and meeting costs.
- Ability to **stay connected** (keep current and involved) with the activities of others and the evolution of group thinking.

COMPONENTS OF THE SEA INTRANET

The SEA Intranet uses an NCSA httpd server, version 1.5, running under Solaris 2.5 on a Sun Sparc20 workstation located at the Prince William Sound Science Center (PWSSC) in Cordova, Alaska. At 2,500 residents, the township of Cordova on the eastern shore of PWS is a remote fishing community accessible only by air and water; nevertheless, dedicated frame relay Internet connectivity allows the 9-workstation PWSSC local area network in Cordova to serve as the hub of communications for the SEA program. The HTTP/1.0-compatible NCSA httpd is a small, efficient server which provides built-in support for directory indexes, user directories, imagemaps, server side includes and user authentication. Access to the Intranet is restricted to SEA personnel by means of group and password files maintained in an ASCII flat file format.

The layout of the SEA Intranet is diagrammed in Figure 1. To facilitate orientation and navigation, a clickable menu bar, incorporating a graphical indicator of current location, appears on each page (Figures 2). The key web site components include (1) a dynamic results archive, (2) a threaded discussion server, and (3) a fully interactive papers collaboration work area. These are discussed in more detail below. In addition, the site offers hierarchically arranged informational documents including calendars, maps, cruise plans, cruise reports (Figure 3), and announcements. There are also links to SEA web documents in the public domain, as well as to the internal web interface for the SEA database. To minimize browsing time, a What's New section directs a user's attention to specific updates since the last visit.

Dynamic Results Archive

The dynamic results archive was the first SEA Intranet component implemented, by virtue of being the most urgently needed. It is designed to disseminate awareness of emergent SEA data products rapidly across all SEA researchers. A distinction here is made between *data* and *data products*: the former denotes large files of raw or relatively unprocessed alphanumeric values; the latter refers to summarized and interpreted results including annotated tables, figures and animations.

Mechanisms for shared access to SEA's archived raw data are being addressed in a multi-year database design project which has been previously described (Falkenberg and Kulkarni, 1995). The SEA database architecture exploits the spatial indexing capabilities of the object-relational *Illustra*™ database management system, enabling selection of datasets within an arbitrary region defined by a bounding space-time polygon in addition to standard metadata-based queries. These features are essential to full utilization of the synoptic sampling design inherent in the SEA program. *Illustra's* built-in web application interface ("web datablade") mediates web forms-based queries on standardized selection criteria across all SEA data sets. Query results consist of a list of datasets which meet the search criteria; the web interface then allows retrieval of the selected data sets from the HDF and/or ASCII archive in which they reside (Falkenberg, 1995).

By contrast, the SEA Intranet's Results section does not provide retrieval of raw data but instead gives rapid access to interpreted summaries of current results, usually in the form of tables and figures, for discussion, integration and preliminary model validation purposes. The actual and intended use of this area has been primarily in rapid sharing of new observations for discussion and synthesis. The area is used extensively in both asynchronous viewing and simultaneous conferencing modes, particularly in preparation of joint presentations. A secondary use which has emerged is that of an organized catalog of results and figures: providing a convenient, centralized reference repository. Within the Results area, data products are organized by project and displayed with most recent findings first. Postings more than 3 months old are moved off the "current" page but are archived and accessible retrospectively by project, subject and date. Figure 4 shows an example of the New Results archive for the SEA Oceanography project, where data products are in the form of two-dimensional contour profiles through the water column. Figure 5 shows two examples of the use of GIF animations to display complex data: a three dimensional rendering of current vectors spatially oriented within the PWS bathymetry, animated over tide stages; and output from the nekton model showing evolution over time of spatially dependent model variables.

The mechanisms by which researchers contribute their data products into the Results area vary according to researcher ability and preference, with concomitantly varying degrees of involvement by the Intranet Administrator (IA). The spectrum ranges from (a) a fully user-maintained web site on a separate server, in one case; through (b) user-managed project-based results trees in user directories provided by the SEA Intranet server, with links and maintenance overseen by the IA; (c) user-driven file upload via custom utilities (see below) into designated directories, with layout and links managed by the IA; to (d) user-initiated emailing of pointers to desired graphics files, with format conversion and posting performed by the IA. It was found advantageous to maintain a range of mechanism choices for this procedure, in order to minimize the net cost to researchers of participating in the system. In fact, it was necessary, since even within this relatively small group no single method existed which was optimal for every member. It was recognized to be as much a hardship for programming-literate members to relinquish control of their results layout as it was for others to be forced into unfamiliar procedures of format conversion and linking; and it was apparent that attempts to impose a middleground solution would meet dissatisfaction from both ends. It was, however, possible to find a mechanism suiting any individual from the range above. Under this system, users have as much or as little direct involvement as they wish in creating and maintaining their "results web", and the only requirement to be a team player is to make current images available. The IA's task then becomes to manage postings to ensure a seamless top level look and feel. The web structure lends itself well to this approach, since below the single IA-constructed interface the resource locations pointed at are transparent to the user.

Threaded Discussion Server

Numerous web-based discussion software options, including *HyperNews*, were evaluated for use in SEA, and three (*WebThreads*, *Netscape's News Server*, *InterBoard*) were installed for trial periods. Of these, *InterBoard* (The Forge Foundation, Woburn, MA) was selected as the most full featured and best suited to the needs of a scientific Intranet. In fact, this was the only software found which satisfied all of SEA's key requirements of multilevel threaded organization, searchable archive, seamless web browser interface, and capacity for attachments. The attachment feature was added ahead of schedule by The Forge in response to the needs of the SEA group.

InterBoard runs as a separate server on its own port, thus providing improved performance over CGI-based alternatives plus intrinsic access authentication. A customizable interface allows transparent integration of the software into an existing Intranet, including for example the ability to incorporate the standard SEA clickable menu and locator bar into the Discussion area display. Discussion contents are organized into forums and threads or topics within forums (Figure 6). Forums are created by the administrator. Users are free to initiate new threads, which can be nested without limit, and to reply to messages in existing threads. A useful set of administrator tools includes prune-and-graft utilities, which allow a portion of a thread that has deviated from the original topic to be transplanted to the start of a new thread. A number of access options are provided, including the useful ability to make forums invisible to users for whom they are not relevant; for example an "Executive Committee" forum might appear on the opening menu of that committee's members only.

The server keeps track of messages read by each user, notifies users of new messages on each visit, and automatically selects only unread messages for display. The message display screen includes a navigatable diagrammatic outline of context, in which both history and replies to the message are shown in a clickable tree diagram (Figure 7). By means of a typical web browser button-type interface, a user can sort messages by subject, author or date; restrict messages for display by date range; expand the display to show all messages and replies or collapse it to list just main topics; and perform boolean text searches on subject, author and content. New messages and replies are posted via an intuitive forms interface. Postings remain editable at any time by the author, can be written in plain text or any valid HTML, and automatically translate valid URL's into hyperlinks. Attachments can be included on messages via a point-and-click browse selection dialog box. These can be in any format and will be handled appropriately by the message viewer according to MIME type. For example .ps or .dvi files attached to messages will be viewable by users with appropriate helper applications (ghostview or xdvi respectively) installed for their browser; .gif or .txt attachments will be directly viewable; and unrecognized formats such as spreadsheet files will initiate a download prompt in response to an access request.

Together these features provide a powerful user-driven collaborative tool. The SEA Discussion area provides a vehicle for sustained, threaded, asynchronous group dialog which is almost entirely directed by the users. The advantages of communication in this form extend well beyond those of the email alternative, in that: (a) the dialog is open to all and not restricted to people who the original correspondents may have guessed would be interested, thus maximizing the chances of serendipitous sparking of ideas; (b) attachments allow easy uploads and rapid contribution of "what do you think of this?" type messages regardless of computer literacy; and (c) the discussion files plus attachments provide an organized, searchable, centrally located archive of the brainstorming and commentary processes, in essence a multimedia group electronic notebook. However, care is required in definition of the forums. It was found that having too few forums can lead to lack of focus and unconnected rambling threads; while having too many presents an impediment to regular message browsing by busy researchers.

Papers Collaboration Work Area.

As SEA entered its third year, there emerged a preeminent need for mechanisms to facilitate joint writing and joint communication of findings to the rest of the scientific community. SEA's multiple collaborating teams of authors work under conditions of geographic separation and highly compressed time schedules. Their specific needs include mechanisms to stay in touch with what others are writing; to circulate manuscripts efficiently for internal review; and to exchange drafts within the author group. These requirements go beyond simple annotation tools provided by contemporary group-writing software packages, since, in contrast to many cases where papers are written by a senior author and then circulated for minor edits by coauthors, most collaborative papers in SEA are truly multi-disciplinary and therefore true multi-author constructions.

The Papers Collaboration Work Area (PCWA) was designed to address these needs by providing a single central repository and work area for papers in progress. SEA researchers contribute updates on their work in progress into this area for two reasons: (1) As a courtesy to their SEA colleagues, the simplest way to keep the larger group informed; and (2) To enhance the efficiency of their writing process. Although the area's name and this discussion refers mainly to preparation of manuscripts, it applies equally to group presentations and has been used by the whole of SEA to prepare a single collective presentation series for peer review.

Within the PCWA, there are two top level arrangements. The first is by discipline: papers are filed according to the discipline of the lead author, with extensive hypertext-mediated cross-referencing to all other areas involved (Figure 8). The second is by hypothesis or ecosystem-level issue: synthesis papers are filed according to the fundamental SEA issue addressed, again with extensive cross-referencing back to the areas of the contributing disciplines. Summary tables show work in progress listed by investigator, giving an at-a-glance summary of contributions underway and commitments made by each team member. The hypertext nature of web-based storage and retrieval lends itself ideally to this multidimensional web-like filing system where a single resource is accessible transparently from many different request perspectives.

Each paper registered with the PCWA is allocated a directory area and a workspace. The PCWA interface for an individual paper is shown in Figure 9. The left hand column allows a user to browse the abstract, outline and figures for the paper. The central column provides access to file upload utilities for posting new drafts of the paper onto the website. Draft manuscripts can be uploaded in any format, including plain text, Postscript, or any word processing binary format. The interface to the file upload utility is shown in Figure 10. The user specifies the file to be uploaded via a browse button, which invokes a platform-appropriate widget for selecting files from the user's local disk. File type is not inferred but is specified on the upload form by the user from four radio button choices. The default type is application/octet-stream i.e. unspecified filetypes are treated as binary files. A storage name for the uploaded file is requested since this will often be different in information content from the storage name on the local machine. Optionally, unlimited notes on the draft can be typed or pasted into the comments box; these are uploaded as a companion file with the same name as the draft plus the extension ".notes". File upload is achieved using the FILE option of the TYPE attribute for the INPUT tag, and specifying ENCTYPE="multipart/form-data" in the HTML form (RFC1867). On activation of the SUBMIT tag, all parts of the form's data, including the contents of the selected file, are sent by the browser in the order specified, as a multipart stream separated by a unique boundary string. A simple CGI script locates the boundary string, parses the stream and writes the draft and accompanying notes file, if any, to the designated directory for the paper.

The right hand column of the PCWA interface for each paper (Figure 9) provides two key tools. The first is a direct link to a discussion forum dedicated to the paper, via which comments can be posted and online dialog can proceed. The second link accesses an index listing of the drafts directory for the paper. This allows the user to scan the directory of uploaded drafts, including filenames, sizes, upload dates, plus the optional accompanying notes files, and then to either view (text) or download (binary) draft files. Setting the double period (..) as a non-displayable directory entry in the httpd server configuration provides a simple way of allowing the convenience of directory listing while restricting the listing to the designated directory. Together the file upload and directory index features provide a simple document exchange loop: a push-button send/retrieve mechanism that is totally independent of platform and circumvents frustrations of formats, mailer incompatibilities and uuencoding. In these small dynamic authoring groups, complex annotations and version tracking are less important than efficiency of document exchange and communication of ideas. The PCWA provides a task-oriented electronic work space offering net gains in efficiency of joint authoring. It also serves as a focus for exchange of ideas and a catalyst for discussion relating to evolving ecosystem concepts.

Synchronous Communications

SEA has installed several applications for synchronous communication, including *ShowMe*, *Collage* and *CoolTalk*. These each provide realtime conferencing with a chat text text window, audio link, and shared whiteboard. *ShowMe* also has shared application capability, by which software running on a host machine is displayed simultaneously to one or more other terminals. All three function as standalone applications, although *CoolTalk* is now bundled with *Netscape Navigator*. The upcoming *Netscape Communicator* promises a more integrated interface as well as multicasting capability. In a recent discussion, Kouzes (1996) drew attention to the immaturity of the synchronous protocols, high bandwidth costs and poor quality connections, concluding that "The perceived benefit of videoconferencing is not sufficient to overcome the problems of using available systems. Cross platform whiteboards and shared screens use less bandwidth than video but remain in an early state of development. Synchronous collaboratory tools need several more years of research until they will be mature enough to be acceptable to end users." This is in accord with the experience in SEA, where bandwidth limitations are such that realtime computer conferencing has not yet replaced teleconferencing. Use of *CoolTalk* audio and whiteboard between two parties is now routine, but group conferencing is still undertaken by telephone. However, a web extension to teleconferencing that has become common in SEA is synchronized viewing of web-posted results. Two or more team members post results they wish to review with colleagues, then access them simultaneously while conversing on the telephone. This marriage of technologies draws the best from both modalities and has been one of the most valued uses of the dynamic results archive. A useful extension is offered by innovative software enabling linked group web tours, such as *Virtual Places* by

Ubique Inc., and this type of "similtour" capacity is the next planned addition for the SEA Intranet.

DISCUSSION

At the national level, efforts are underway to deploy technology that will enable scientific researchers from any geographic location to interact with colleagues, access instrumentation, share data and computational resources, and retrieve information from digital libraries. Prototype efforts to implement such electronic "collaboratories" include the Upper Atmospheric Research Center (UARC) Collaboratory at the University of Michigan, funded by CISE and NSF, which focuses on shared access to solar wind observation instruments, and the DOE Distributed Collaboratory Experiment Environments Program, underway at the Argonne, Lawrence Livermore and Pacific Northwest National Laboratories. The DOE initiative seeks to create a web-based virtual environment encompassing the resources of the National Laboratory system that will allow scientists from around the world to participate in solving national research questions. The vision behind these endeavors is based on technology that already exists (email, world wide web and other Internet protocols), technology that is still maturing (audio and video conferencing), and technology that is still being created (such as telepresence) (Kouzes, 1996). The present report is concerned with implementation of existing web technology for synthesis and coordination within a single project: a cooperative study of a remote site by an integrated but geographically-distributed research team. Findings from the first 18 months of use indicate that a web-based approach is ideally suited to a circumscribed set of coordination and communication functions; and that obstacles to be overcome are as much social as technical in nature.

HTTP (Berners-Lee, 1996) is a stateless, file-based, object-oriented protocol developed for static file delivery, to which a degree of interactivity can be added by means of the common gateway interface. Its advantages include global accessibility, platform independence, scalability, replication through cacheing, and security. From the group work perspective HTTP also presents distinct limitations: firstly, it cannot accommodate some traditional groupware functionality such as notification, access control, and transaction management; and, secondly, it has no provision for synchronous communications. The first limitations have been addressed by developers through server side enhancements (for example, Bentley et al., 1996) or client side helper applications. However in scientific collaborations these particular limitations tend to be less an impediment than they may be in business applications. In interdisciplinary scientific groups, concurrency issues and version tracking, for example, are far less a priority than support for discussion of concepts, efficient exchange of documents, and access to interpreted summaries and analyses. The second deficiency of HTTP, lack of synchronous communications ability, is an inherent feature of the protocol. "Web-based" collaboration systems that incorporate chat and other synchronous features are of course not using web transport for those features. However, from its inception the web browser was designed as a convenient resource access tool that could point to diverse information sources via gateways to FTP, Gopher, SMTP, NNTP and WAIS protocols. In this sense even though the web protocol is inadequate for synchronous services it can usefully function as a transparent access mechanism pointing to those services, as discussed by Dix (1996). The "web-based approach" to cooperative work therefore includes both functions mediated directly by the HTTP protocol and those in which the universal client paradigm extends browser functionality to that of a hypermedia interface to other protocols or applications.

It has been shown that in problem-solving teams where each member possesses only partial information, the process of interaction itself, not just the exchange of information per se, is an important part of the problem-solving process (ref). Experience in SEA with twice yearly face-to-face gatherings of the entire group has demonstrated this phenomenon clearly. A principal objective of SEA Intranet development was to attempt to duplicate this high productivity environment during the extended intervals between meetings, by providing opportunity and mechanisms for user-driven, problem-oriented online interaction and information sharing.

The result has been an implementation of a single seamless interface to joint information access and retrieval, interactive asynchronous discussion, and dynamic document exchange for authoring. The strengths of a hypertext approach are invaluable in this context where the same piece of information is often needed by many different people for a number of different purposes. Hypertext linking via an image map is also the basis of the navigation menu bar consistently present through the discussion/results/papers areas; which allows users to move easily back and forth between an object (result or paper) and the discussion relating to it, or to display them concurrently in adjacent windows. This contributes useful deictic reference ability and alleviates a frequent problem in groupware, namely the inability to reference the work domain from the conversation domain (Dix, 1996). The new capability for multimedia attachments to discussion postings is similarly important, as many quanta of scientific dialog relate to a finding that can be illustrated in an attached one-page image. A particularly useful web ability has been the capacity to post animations illustrating the space-time evolution of either field observations or model output. Use of the browser to load and run multiple animated GIFs simultaneously in tiled windows allows visual comparisons of complex, concentrated information that is not easily presented or absorbed via other modalities. In addition, results created and normally only viewable with specialized software can be shared interactively with all colleagues, the only display requirement being a web browser.

A system to enhance cooperative work is only useful to the extent that it is used. For this reason a principal obstacle to the success of a new technology is obtaining a critical mass of users (Grudin, 1988). In a cost-benefit analysis of a cooperative system, the costs to a given user are relatively constant but the benefits increase dependent on the number of other users. At some number of participants a critical crossover point is reached; and only then can mainstream users be predicted to stay with the system. Conversely, below the critical mass, any sensible user judging solely on an objective basis will abandon the system (Dix, 1996). Successful establishment of the SEA Intranet was therefore critically dependent on adoption by an initial core group of enthusiastic participants who could see the potential offered by the system. These people were key to getting the Intranet off the ground, as predicted by Grudin and as reported by others in early experiences with web applications (Bednarcyk and Bond, 1994). The concept of critical mass was in the forefront of consideration during implementation of the SEA Intranet and was addressed both by attempts to minimize costs and attempts to maximize early paybacks. In practice, it proved easier to accomplish the former than the latter, because of the ultimate dependency of benefits upon adoption and participation by the whole group. The remainder of this discussion considers the nature of the costs, benefits, and measures taken to try to optimize the balance between them.

Malone (1994) lists one (among about a dozen) definition of coordination as "the additional information processing performed when multiple connected actors pursue goals that a single actor pursuing the same goals would not perform"; in other words: costs are inevitable and collaborating is more work than working alone. The issue of major interest is what factors influence the balance point in the cost-benefit tradeoff.

A report by Cole (1994) provides interesting insight into features of workgroup structure that influence adoption of computer conferencing (his term for threaded discussion forums) and is particularly relevant to the SEA experience. Cole's study evaluated the first year of use of computer discussion forums by three separate workgroups within a company: a research team, a senior management team, and a product development team. In all three cases, the team leader announced the goal of implementing the technology and instructed team members to use it. At the end of a year, despite an initial effort, use of the discussion system had dwindled to perfunctory in two of the three workgroups (research and management) and it was non-contributory to the work of those two groups. Reasons given for this by the research team members centered around feeling little social pressure to contribute to the forum when others were not, feeling that if something were important it would come by email, and objecting to having two different systems to check. Comments from the management team additionally referred to low value of the material posted: managers were required to post reports, but they were of interest only to the vice-president and none of the other managers ever read them. By contrast, in the product development team, the discussion forum became a central focus of the workgroup's activities. Discussions involved most of the team members in generating ideas or giving feedback. Day to day questions or issues that arose would frequently be addressed by opening a topic in the discussion forum. The team leader participated in the conference and actively encouraged people to use it, and most members reported a daily habit of reading the forums first thing in the morning over coffee. Use was consistent throughout a project but was most intensive close to deadline. Analysis by Cole identified four factors contributing to these differences among the workgroups: leadership, task fit, process fit, and group learning. Acceptance of the tool was strongly influenced by the degree to which the leader integrated the technology, established expectations for its use, provided incentives and or consequences for its use, and, most importantly, reinforced and modelled its value through his own use. Acceptance was also affected by the degree to which the tool provided tangible assistance in performing tasks of value; and the degree to which the technology accommodated the normal culture of the group. Of the three groups studied, the product development team was engaged in high energy, project and deadline oriented, critically inter-dependent cooperative work which required both coordination and collective problem-solving. Work in the research group was more individually independent. Work in the management group was more isolated due to mistrust and competition.

These observations by Cole suggest reason for some optimism concerning the usability of computer technology in scientific collaborations, but also point to potential pitfalls. To the degree that a scientific project is truly cooperative, such as an ecosystem study where each person's contribution is one piece of the final picture, then collaborative tools offer tangible benefits to the process. However, professional competition, isolationism, lack of perceived rewards, and ambiguous leadership are potentially jeopardizing influences. Any introduction of cooperative tools must be sensitive to the to the issues of autonomy and trust and must pay vigilant attention to the social and political concerns that characterize joint scientific work, including authorship, acknowledgement, and individual recognition for joint results and products.

Within SEA, reservations and resistance to using the Intranet system centered around the time cost and inconvenience of having to remember to check the web, having to make time to interact, and doubts that the new way offered any advantages over existing tools of telephone, email and fax machine. A technology often exists without being used because it is perceived as adding little or no value (Kouzes 1996) and this was initially the case with many SEA researchers. About three months after implementation, however, the Intranet attained active use by more than half the program members. This occurred during preparation for a major program review, where synthesis and synchronization were urgent and imperative. The Intranet tools, which focused largely on the dynamic results archive at that time, offered advantages of speed, access, and utility in planning and exchange of information that was not available by other means within the operative time constraints. In other words, critical mass was attained during a time of intense need marked by a confluence of the tasks at hand with the capabilities of the technology, as predicted by Cole (1994). Today SEA remains in a period of active synthesis in its final active year, and the same type of need, perhaps magnified, obtains. The central role of the Intranet through the remaining phases of the project therefore seems assured.

The SEA researchers are a closeknit team who work in a shared information space of data, images, concepts, discussion arguments, and the papers being written to describe them. The attributes of this team include a strong common sense of purpose, commitment to the joint research product, strong leadership, and personal and professional compatibility among team members. Their activities are goal oriented and highly interdependent. In many ways the SEA team is most like the product development group in Cole's study. In the context of these natural advantages, a number of design aspects of the SEA Intranet may have assisted it in gaining acceptance. Design was approached from a service-oriented basis rather than attempting to create impressive technology for technology's sake. Costs to researchers were greatly reduced by the choice of the web approach, since the already familiar browser software guaranteed a minimal learning curve on the client end and removed frustrations of platform incompatibilities. On the content creation side, individual comfort levels were accommodated by providing a range of possible involvement levels while still defining minimum thresholds for good citizenship. On the content browsing and interaction side, the inherent passivity of the web presented a problem: initiative for awareness of change resides with the user. Several SEA mechanisms address this. The discussion system automatically flags new messages and by default displays to each user only the postings unread by that user. The "what's new" page is kept current and serves to cut down browsing effort. One measure of the utility of this page is that it is set by some researchers to be the default opening page on startup of their browser. These two, still passive, mechanisms are augmented by active notification via email. This procedure was instigated at the request of several researchers and involves emailing essentially a copy of the what's new page to a distribution list, at varying time increments depending on web activity level. Dix (1996) has commented that, in collaborative systems, pace (how often one interacts) is usually more important than bandwidth (how much one communicates); and that, provided it is not so frequent as to constitute interruptions (as for example automatic email every time any post is added), explicit notification may be desirable to reduce the initiative required and hence increase the pace in web systems. This has been found beneficial in the SEA system and requires little additional work on the part of the IA. The decision to organize a major work area around manuscripts, rather than more loosely around hypotheses, problems or other tasks, was made intentionally in attempt to maximize the paybacks for participation. A number of other arrangements could potentially have stimulated the same discussion of concepts and review of joint findings. Successful interaction in the papers collaboration work area culminates, however, in a paper, which constitutes tangible reward in the currency of the scientific system.

Most of the SEA researchers have contributed to development of their Intranet through feedback in various forms. Although much of the system's current functionality was developed in response to user requests and suggestions, there is a continuing need for its developers and administrator to stay attuned to the needs of the user group and to anticipate their evolution. Both technical and human obstacles still remain and present challenges to keeping the Intranet growing and useful. Nevertheless, the SEA experience has demonstrated that simple web-based tools can provide a productivity enhancing contribution to the joint work of a collaborative scientific research team.

ACKNOWLEDGEMENTS

This work was supported by the Exxon Valdez Oil Spill Trustee Council as part of Restoration Project 96320-J. The first author thanks Dr. L. Massinter for electronic correspondence regarding the multipart form data type specification.

REFERENCES

Bednarcyk, L.A. and Bond, K.D. (1994) A local web for information delivery. Second International Conference on the World Wide Web, Chicago, USA, October 17-20, 1994. *http://www.ncsa.uiuc.edu/SDG/IT94/Proceedings/CorInfSys/bednarcyk/bednacyk.html*

Bentley, R., Horstmann, T., Sikkel, K. and Trevor, J. (1995) Supporting collaborative information sharing with the world wide web: The BSCW shared workspace system. Fourth International Conference on the World Wide Web, Boston, Massachusetts, USA, December 11-14, 1995. *http://www.w3.org/pub/Conferences/WWW4/Papers/151*

Berners-Lee, T., Fielding, R. and Frystyk, H. (1996) Hypertext Transfer Protocol - HTTP/1.0. Network Working Group RFC 1945.

Bruno, L (1996) Groupware Vs. Webware. Data Communications 25, 123.

Cerf, V.G. et al. (1993) National Collaboratories: Applying Information Technologies for Scientific Research. National Research Council Committee Toward a National Collaboratory: Establishing the User-Developer Partnership. Washington, D.C.: National Academy Press.

Cline, G.P. (1995) Web servers and the rise of the corporate 'Intranet'. International Journal of Network Management. 5, 322-325.

Cole, P. (1994) The impact of group context on patterns of groupware use: A study of compuer conferencing as a medium of workgroup communication and coordination. Massachusetts Institute of Technology Center for Coordination Science, Technical Paper #182.

Dix, A. (1996) Challenges and perspectives for cooperative work on the web. Proceedings of the ERCIM Workshop on CSCW and the Web, Sankt Augustin, Germany, February 7-9, 1996.

Falkenberg, C. (1995) Design and implementation of the SEA database. 46th Arctic Division Science Conference, American Association for the Advancement of Science, Fairbanks Alaska, September 1995.

Falkenberg, C. and Kulkarni, R. (1995) Using spatial access methods to support the visualization of environmental data. Visualization 95, IEEE, Atlanta Georgia, October 1995.

Gallant, J. and Nail, U. (1996) Intranets will rule. Network World, July 96, p. 41.

Grudin, J. (1988) Why CSCW applications fail: Problems in design and evaluation of organizational interfaces. In: CSCW88 Proceedigs on the Conference on Computer Supported Cooperative Work, pp. 85-89.

Kouzes, R.T., Myers, J.D. and Wulf, W.A. (1996) Collaboratories: Doing science on the Internet. IEEE Computer, 29,

Malone, T.W. and Crowston, K. (1994) The interdisciplinary study of coordination. ACM Computing Surveys, 26, 87-119.

Weymouth, T. (1994) The upper atmospheric research collaboratory: UARC. Second International Conference on the World Wide Web, Chicago, USA, October 17-20, 1994. *http://www.ncsa.uiuc.edu/SDG/IT94/Proceedings/CSCW/weymouth/Weymouth.html*

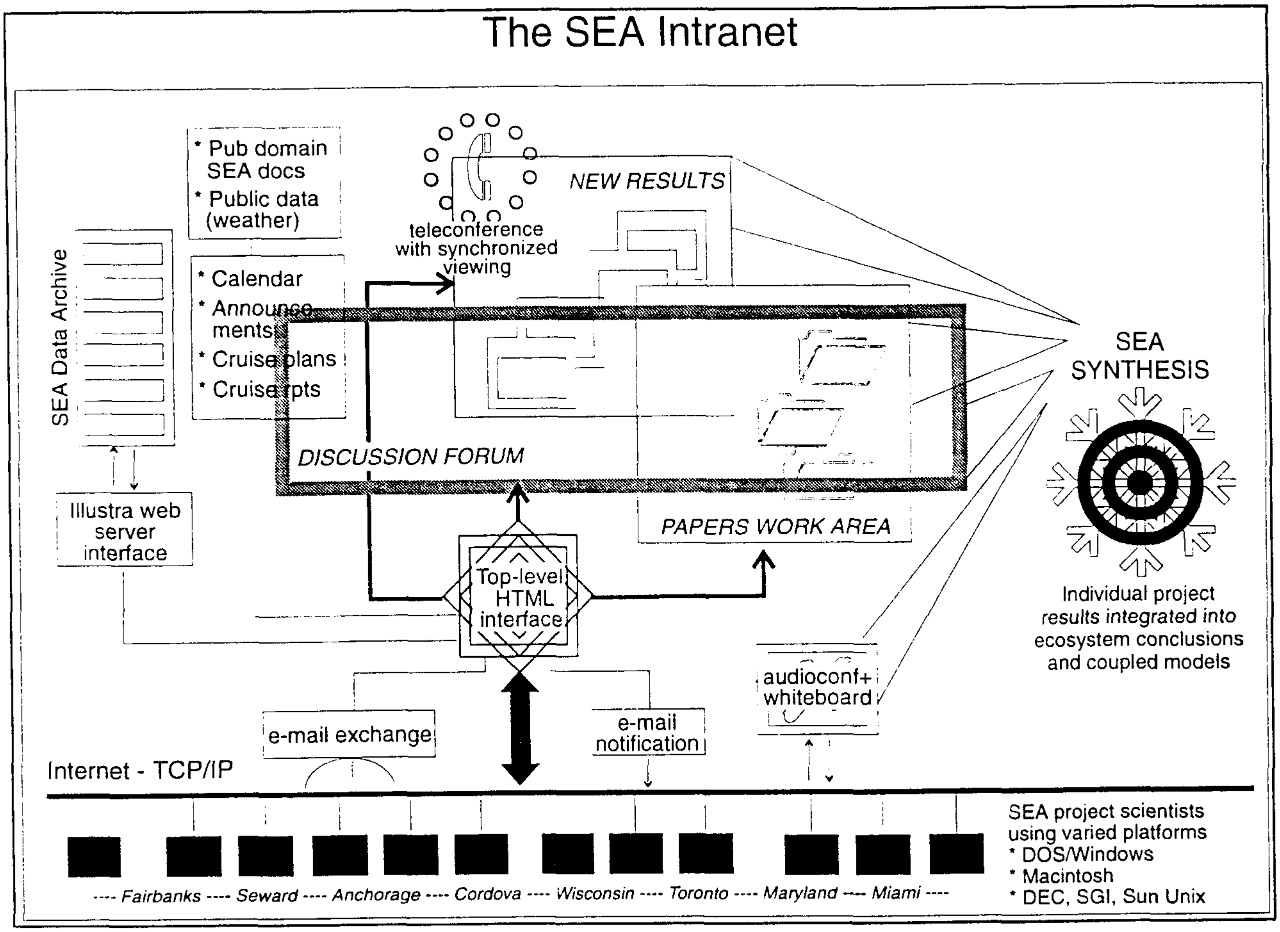
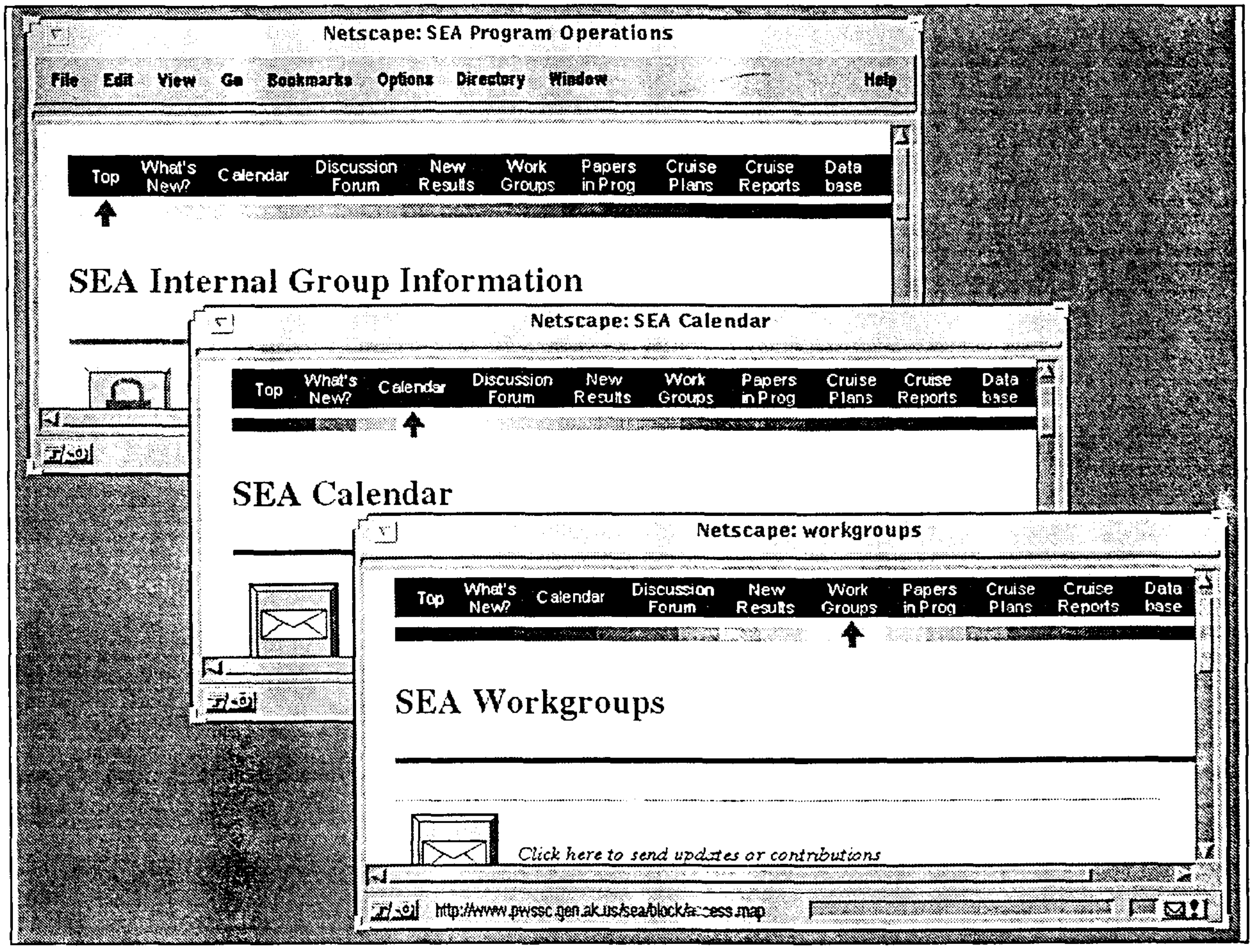


Figure 1: Components of the SEA Intranet



SEA Internal Group Information

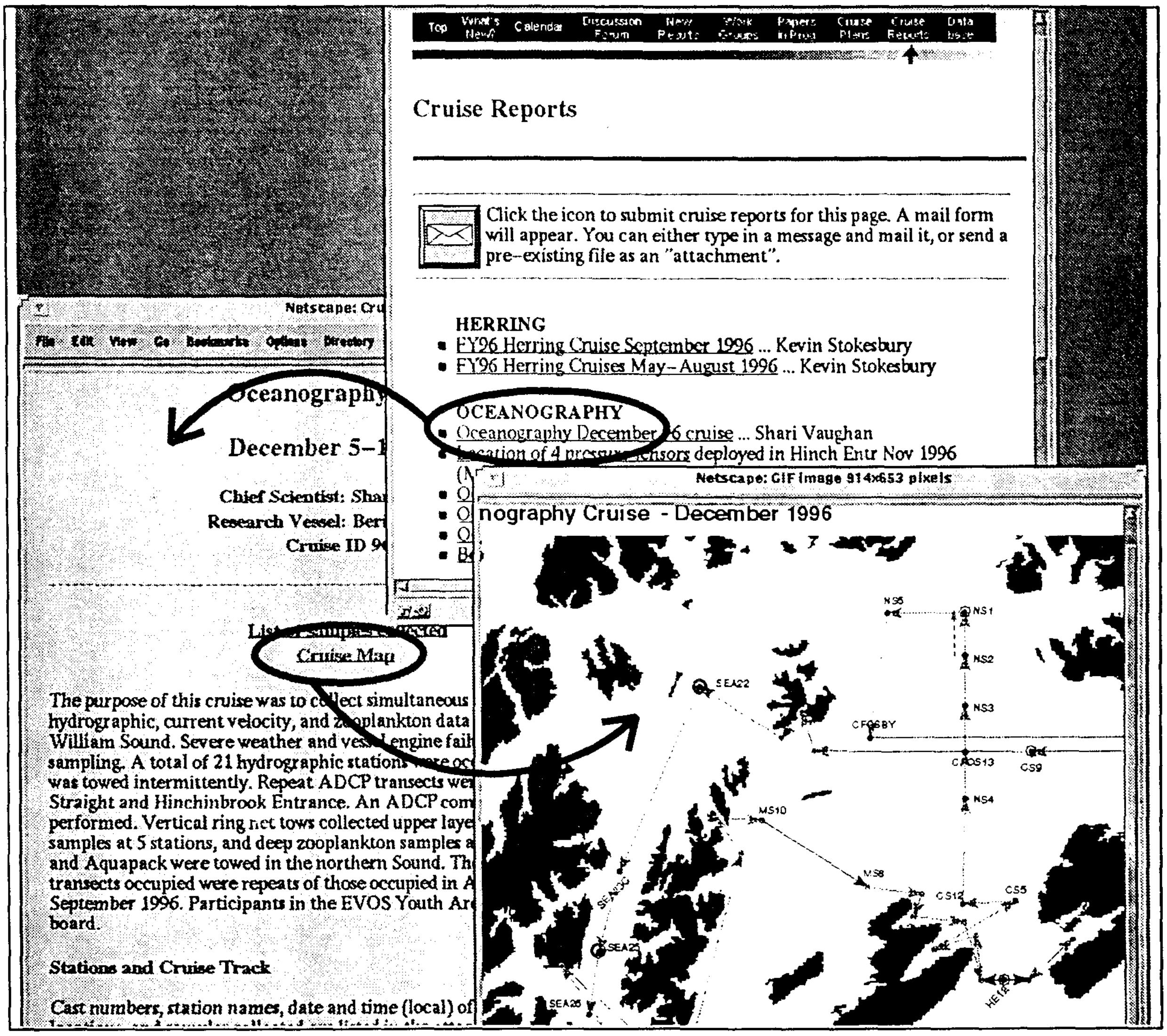
SEA Calendar

SEA Workgroups

Click here to send updates or contributions

http://www.pwssc.gen.ak.us/sea/block/access.map

Figure 2: A consistent imagemap-based menu bar with location indicator is present throughout the SEA internal web site, providing a means of rapid navigation around the web tree.



Cruise Reports

Click the icon to submit cruise reports for this page. A mail form will appear. You can either type in a message and mail it, or send a pre-existing file as an "attachment".

HERRING

- FY96 Herring Cruise September 1996 ... Kevin Stokesbury
- FY96 Herring Cruises May-August 1996 ... Kevin Stokesbury

OCEANOGRAPHY

- Oceanography December 96 cruise ... Shari Vaughan
- Location of 4 pressure sensors deployed in Hinch Entr Nov 1996

Oceanography

December 5-1

Chief Scientist: Sha

Research Vessel: Ber

Cruise ID 9

List of samples collected

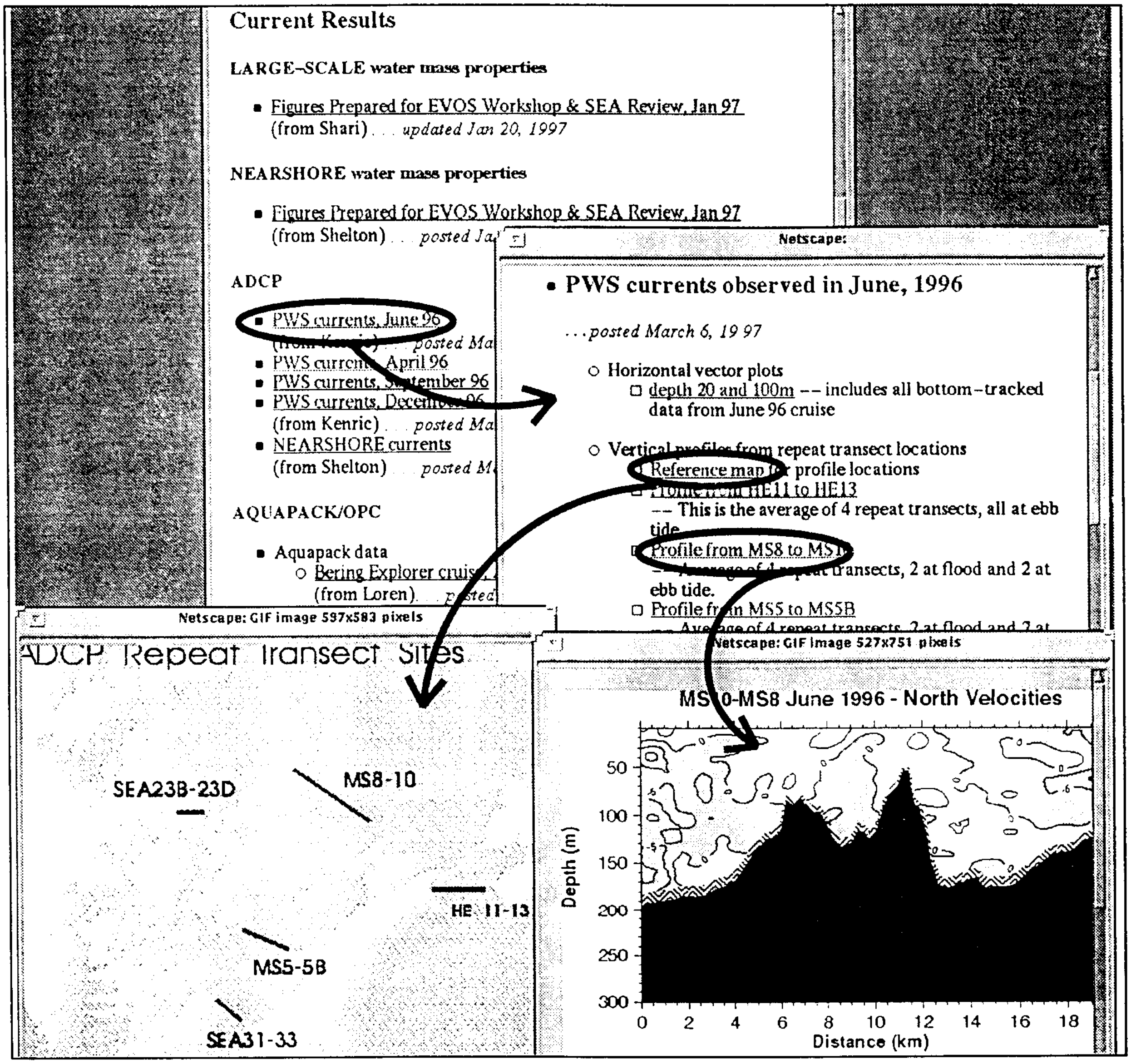
Cruise Map

The purpose of this cruise was to collect simultaneous
hydrographic, current velocity, and zooplankton data
William Sound. Severe weather and vessel engine fail
sampling. A total of 21 hydrographic stations were oc
was towed intermittently. Repeat ADCP transects we
Straight and Hinchinbrook Entrance. An ADCP com
performed. Vertical ring net tows collected upper laye
samples at 5 stations, and deep zooplankton samples a
and Aquapack were towed in the northern Sound. Th
transects occupied were repeats of those occupied in A
September 1996. Participants in the EVOS Youth Ar
board.

Stations and Cruise Track

Cast numbers, station names, date and time (local) of

Figure 3: An example of a cruise report posted in one of the coordination/information areas of the Intranet. Hypertext links facilitate natural hierarchical arrangements of documents, lists and maps.



Current Results

LARGE-SCALE water mass properties

- Figures Prepared for EVOS Workshop & SEA Review, Jan 97
  (from Shari) . . . *updated Jan 20, 1997*

NEARSHORE water mass properties

- Figures Prepared for EVOS Workshop & SEA Review, Jan 97
  (from Shelton) . . *posted Ja*

ADCP

- PWS currents, June 96
  posted Ma
- PWS curren April 96
- PWS currents, tember 96
- PWS currents, Decem 96
  (from Kenric) . . *posted Ma*
- NEARSHORE currents
  (from Shelton) *posted M*

AQUAPACK/OPC

- Aquapack data
  ○ Bering Explorer cruis
    (from Loren). . *p sted*

Netscape:

- **PWS currents observed in June, 1996**

  . . .*posted March 6, 19 97*

  ○ Horizontal vector plots
    □ depth 20 and 100m -- includes all bottom-tracked data from June 96 cruise

  ○ Vertical repeat transect locations
    Reference map r profile locations
    HE11 to HE13
    -- This is the average of 4 repeat transects, all at ebb tide
    Profile from MS8 to MS1
    ansects, 2 at flood and 2 at ebb tide.
    □ Profile fr n MS5 to MS5B

Figure 4: Example of results layout by the Oceanography group in the Dynamic Results Archive. Data products for this group are often in the format of 2-dimensional contour plots showing horizontal profiles at a certain depth or vertical profiles through the water column (seen here).

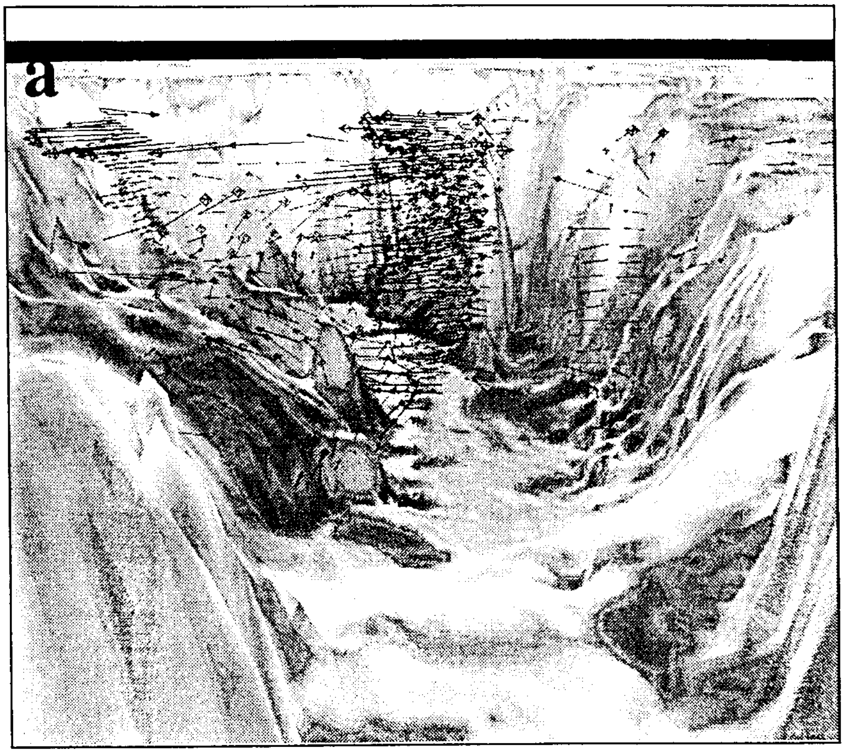
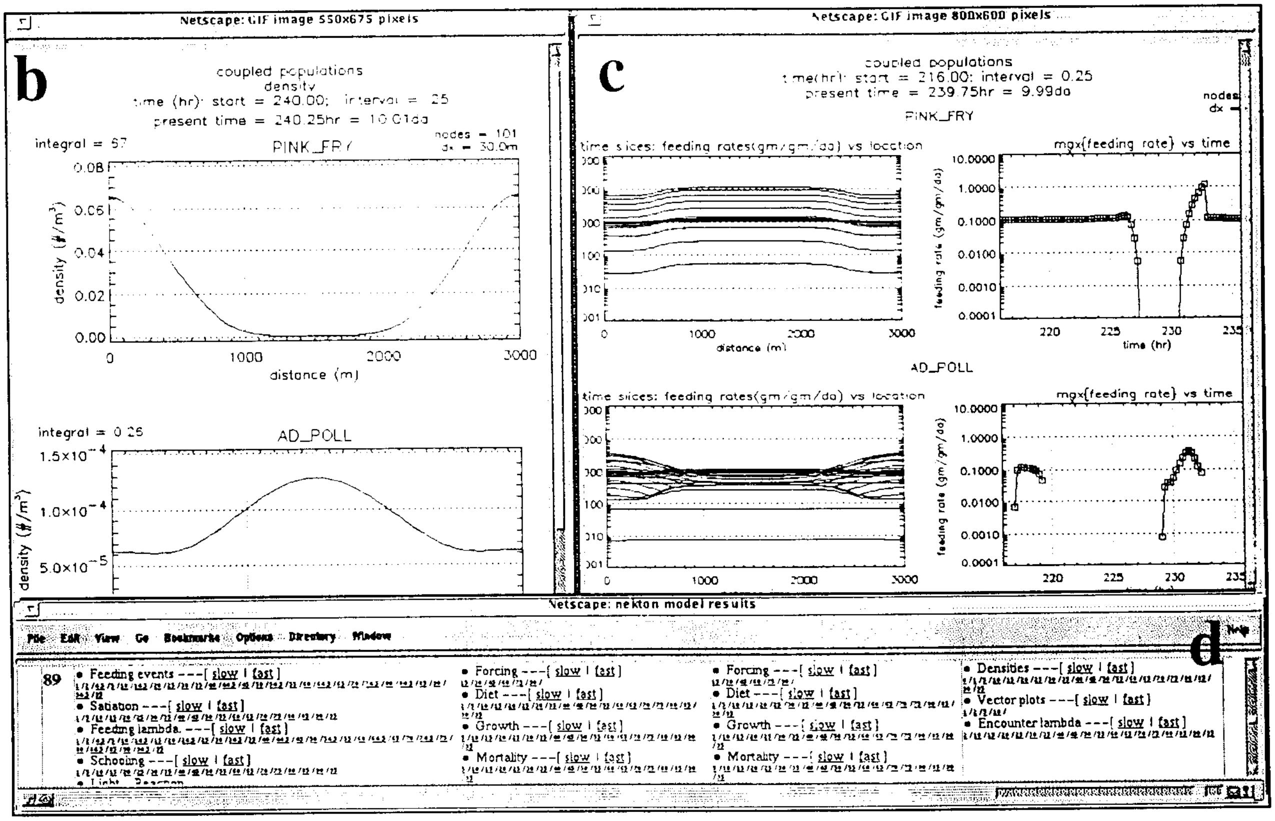
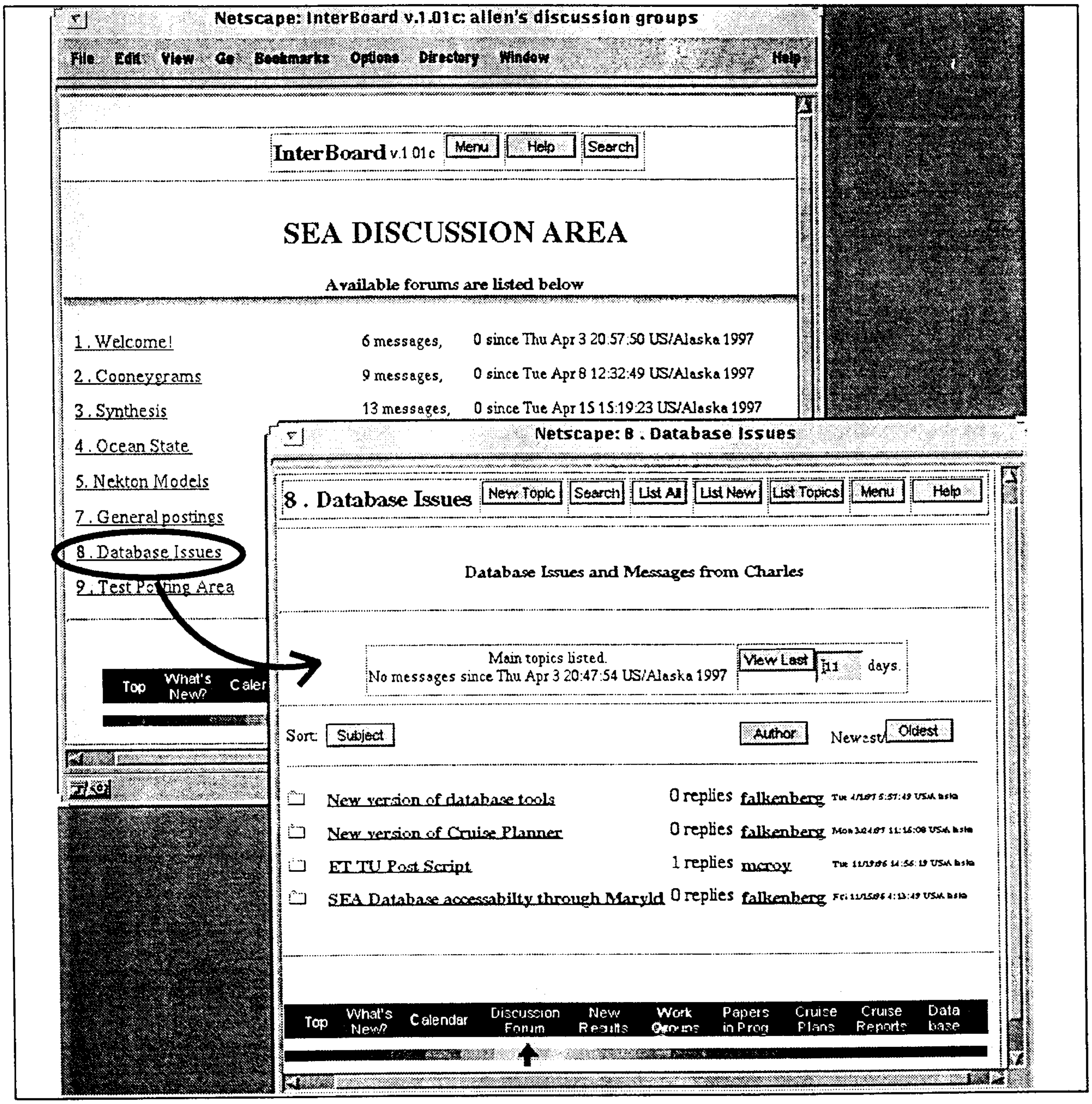


Figure 5: Examples of results displays that use GIF animations. **a:** Three-dimensional current flow observations. The arrows indicate current direction and speed. ***Below:*** Multi-panel display of nekton model output, showing spatial and time evolution components. **b:** Density changes in populations of pink salmon fry and walley pollock, a major predator, animated over 90 days on a transect across the migration pathway channel. **c:** Feeding event patterns of salmon fry and walleye pollock. **d:** Control panel for running the model output animations.



89

- Feeding events ---[slow | fast]
- Satiation ---[slow | fast]
- Feeding lambda. ---[slow | fast]
- Schooling ---[slow | fast]
- Forcing ---[slow | fast]
- Diet ---[slow | fast]
- Growth ---[slow | fast]
- Mortality ---[slow | fast]
- Forcing ---[slow | fast]
- Diet ---[slow | fast]
- Growth ---[slow | fast]
- Mortality ---[slow | fast]
- Densities ---[slow | fast]
- Vector plots ---[slow | fast]
- Encounter lambda ---[slow | fast]



SEA DISCUSSION AREA

Available forums are listed below

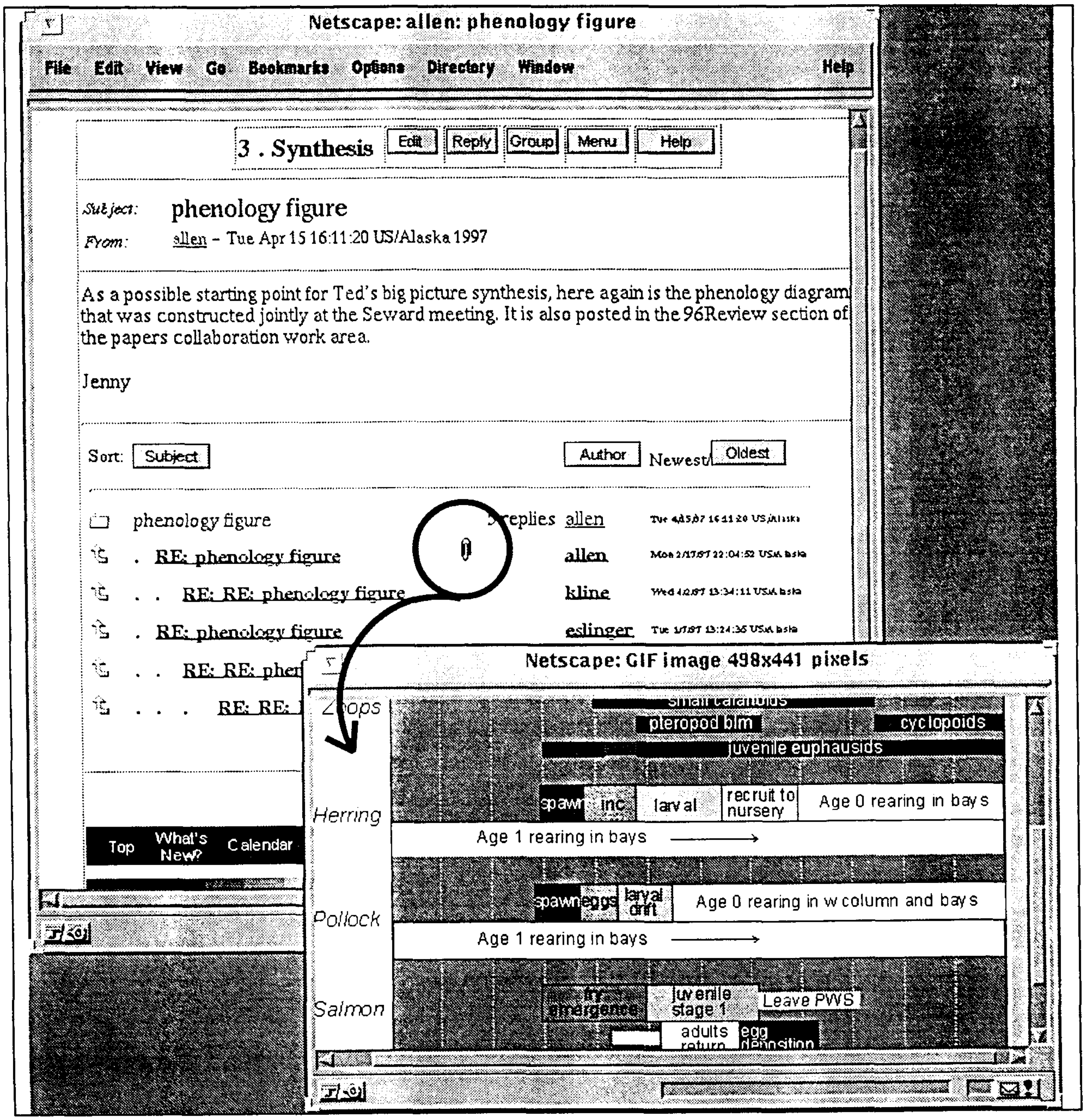
1. Welcome! 6 messages, 0 since Thu Apr 3 20:57:50 US/Alaska 1997
2. Cooneygrams 9 messages, 0 since Tue Apr 8 12:32:49 US/Alaska 1997
3. Synthesis 13 messages, 0 since Tue Apr 15 15:19:23 US/Alaska 1997
4. Ocean State
5. Nekton Models
7. General postings
8. Database Issues
9. Test Posting Area

Database Issues and Messages from Charles

Main topics listed.
No messages since Thu Apr 3 20:47:54 US/Alaska 1997

New version of database tools 0 replies falkenberg Tue 4/1/97 5:57:49 US/Alaska
New version of Cruise Planner 0 replies falkenberg Mon 3/24/97 11:16:08 US/Alaska
ET TU Post Script 1 replies mcroy Tue 11/19/96 14:56:19 US/Alaska
SEA Database accessabilty through Maryld 0 replies falkenberg Fri 11/15/96 4:13:49 US/Alaska

Figure 6: The SEA Discussion Area. The opening menu lists available forums and indicates the number of messages posted since this user's last visit. Entering any forum brings up a display of messages within the forum. Messages can be sorted by subject, author or date and are searchable on subject, author, and content.



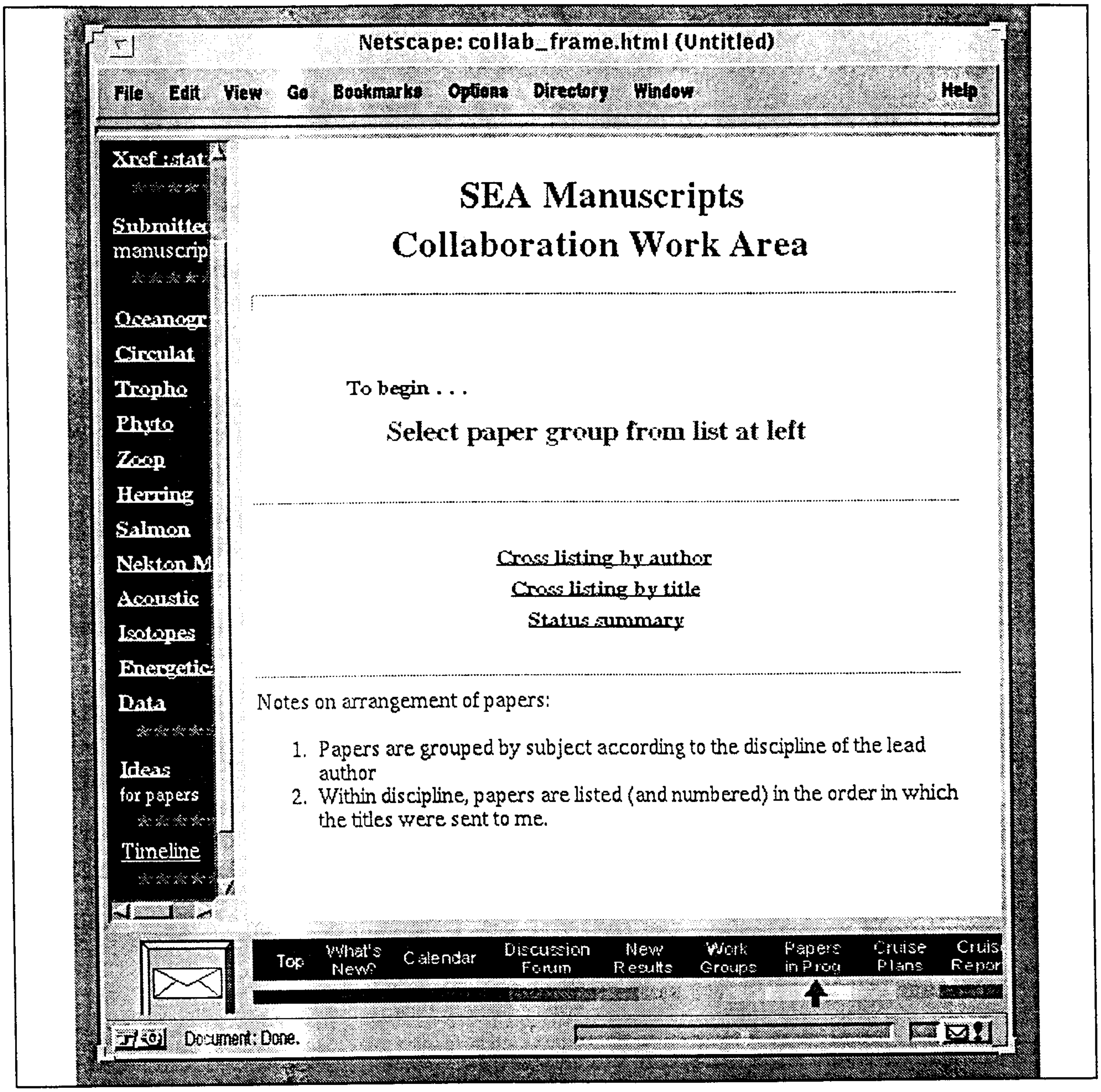
Subject: phenology figure
From: allen - Tue Apr 15 16:11:20 US/Alaska 1997

As a possible starting point for Ted's big picture synthesis, here again is the phenology diagram that was constructed jointly at the Seward meeting. It is also posted in the 96Review section of the papers collaboration work area.

Jenny

phenology figure 5 replies allen Tue 4/15/97 16:11:20 US/Alaska
. RE: phenology figure allen Mon 2/17/97 22:04:52 US/Alaska
. . RE: RE: phenology figure kline Wed 4/2/97 13:34:11 US/Alaska
. RE: phenology figure eslinger Tue 1/7/97 13:24:36 US/Alaska
. . RE: RE: phen
. . . RE: RE:

Figure 7: Example of an individual message posted to the discussion area. Below the header and message text is a clickable tree layout indicating the context of this message and its replies. The (clickable) paperclip symbol indicates an attachment to the message, in this case a figure (lower panel) which is the subject of the discussion thread. Buttons at the top of this screen allow the author of the message to edit it, and other users to post replies.



SEA Manuscripts
Collaboration Work Area

To begin . . .

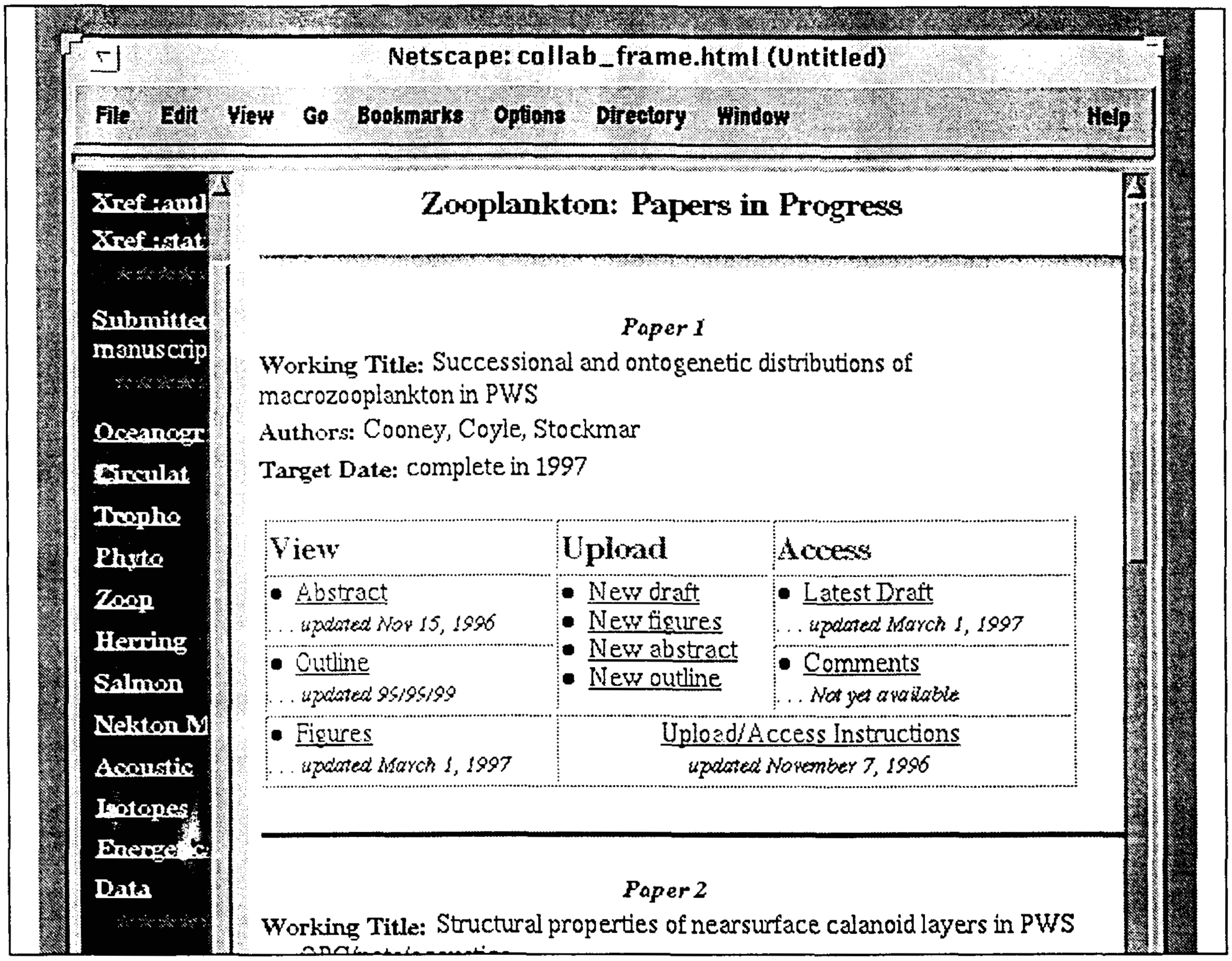
Select paper group from list at left

Cross listing by author
Cross listing by title
Status summary

Notes on arrangement of papers:

1. Papers are grouped by subject according to the discipline of the lead author
2. Within discipline, papers are listed (and numbered) in the order in which the titles were sent to me.

Figure 8. The opening page of the SEA Papers Collaboration Work Area. The left hand frame serves as a subject index and allows rapid navigation between subject groups.



Zooplankton: Papers in Progress

Paper 1

Working Title: Successional and ontogenetic distributions of macrozooplankton in PWS

Authors: Cooney, Coyle, Stockmar

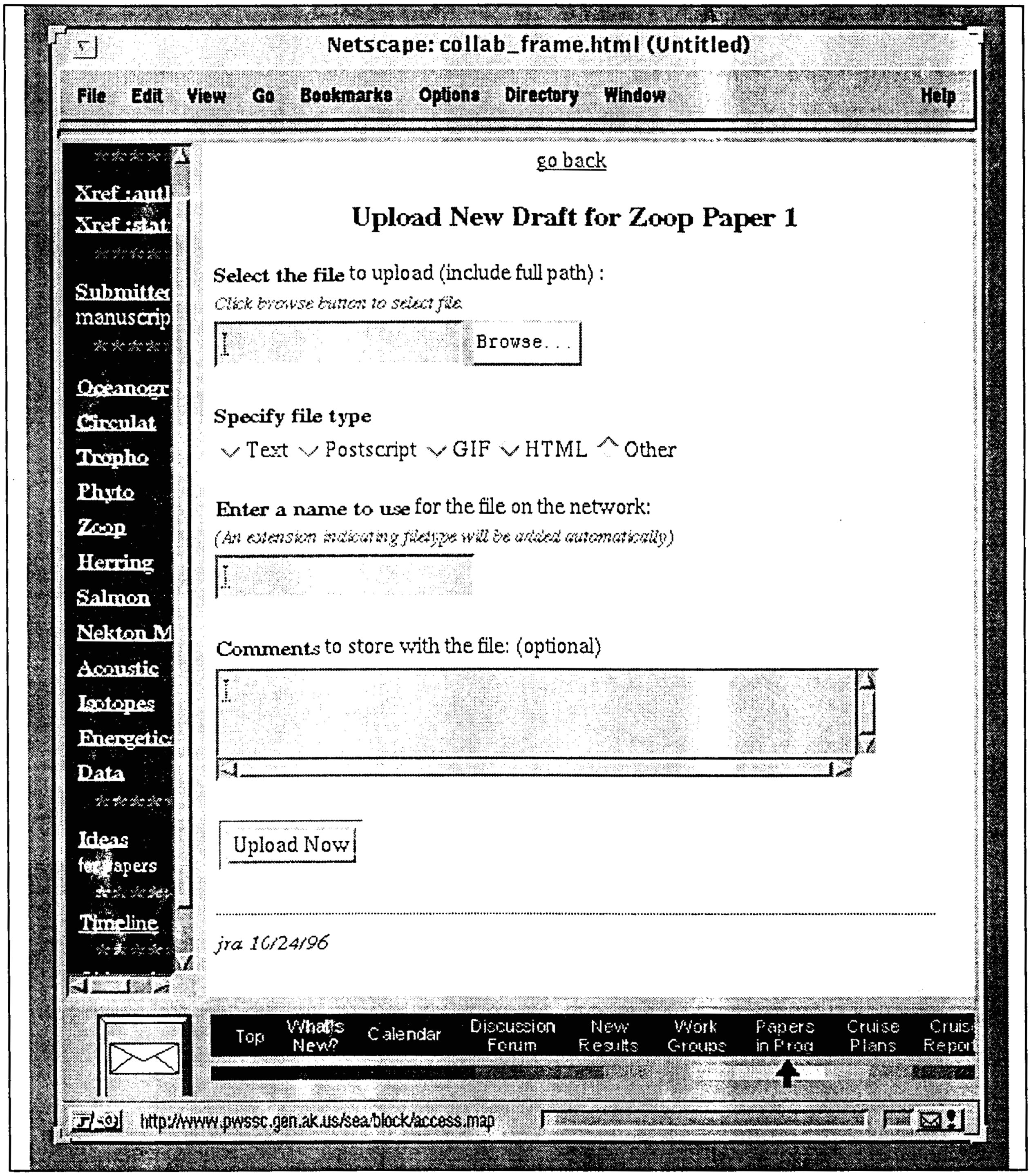
Target Date: complete in 1997

View	Upload	Access
• Abstract . . . *updated Nov 15, 1996*	• New draft • New figures • New abstract • New outline	• Latest Draft . . . *updated March 1, 1997*
• Outline . . . *updated 99/99/99*		• Comments . . . *Not yet available*
• Figures . . . *updated March 1, 1997*	Upload/Access Instructions *updated November 7, 1996*	

Paper 2

Working Title: Structural properties of nearsurface calanoid layers in PWS

Figure 9: The individual panel of tools set up for each paper in the papers collaboration work area. Choices here allow the user to view the paper's abstract, outline or figures; upload new versions of the manuscript in any format; view and/or retrieve previously uploaded versions; and access discussion dialog relating to the paper.



Upload New Draft for Zoop Paper 1

Select the file to upload (include full path) :

Click browse button to select file.

Specify file type

✓ Text ✓ Postscript ✓ GIF ✓ HTML ^ Other

Enter a name to use for the file on the network:

(An extension indicating filetype will be added automatically)

Comments to store with the file: (optional)

jra 10/24/96

Figure 10: Interface to the file upload utility. The browse button activates a platform-appropriate file selection widget. Additional notes typed or pasted into the comments box are saved as a companion file, allowing any meta-information desired by the user to accompany the uploaded file.

Appendix 3

On the Development of a Three-Dimensional Circulation Model for Prince William Sound, Alaska

to appear in

Continental Shelf Research

The permission of the publisher, Elsevier Science, Ltd., to include the follwing manuscript in the SEA FY96 Annual Report to EVOS is gratefully acknowledged.

with 25 figures (Fig. 1 through Fig. 12, most with multiple figures)

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On the Development of a Three-dimensional Circulation Model
for Prince William Sound, Alaska

which is to appear in

Continental Shelf Research

received from Elsevier Science 17 April 1997

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On the Implementation of A Three-Dimensional Circulation Model for Prince William Sound, Alaska

Christopher N.K. Mooers and Jia Wang

Ocean Prediction Experimental Laboratory and
Division of Applied Marine Physics
Rosenstiel School of Marine and Atmospheric Science
University of Miami, Miami, Florida 33149 USA

(Submitted to **Continental Shelf Research**, December 1996; Revised May 1997)

Abstract

The POM (Princeton Ocean Model), a three-dimensional, primitive equation ocean circulation model, is applied to Prince William Sound (the Sound or PWS), Alaska. A 3-D concentration equation for passive tracers is added to POM to explore transport pathways and rates. The 3-D structures of the current, temperature, salinity, density, and concentration are examined for realistic bottom topography, typical Alaskan coastal water inflow/outflow, and wind forcing. Based on the observational evidence and ecological concerns, the "lake/river hypothesis" (i.e., the effect of weak versus strong throughflow) is explored to determine the importance of its influence on the circulation and transport patterns. Strong inflow through Hinchinbrook Entrance (river-like case) is crucial to the vigorous cyclonic circulation in the Sound, while with a weak inflow (lake-like case), the circulation in the Sound is much weaker and decoupled from offshore influences. Mesoscale eddies are induced in the deep basins that have not yet been studied observationally. The anomalous advection of buoyant (relatively warm and fresh) water and high concentration coastal water into the Sound significantly influences the circulation pattern and environmental conditions inside the Sound. Typical winter and summer wind forcing generate characteristic surface circulation patterns and are important to the transport of passive tracers.

1. Introduction

Prince William Sound (the Sound or PWS) is a combination of multiple basins, fjords, channels, islands, inlets and estuaries along the coast of Alaska (Fig. 1). Its area, including estuaries and arms, is approximately 120x120 km (about 70% covered by water) with an average depth of about 190m.

The observational studies conducted before 1989 are described below. Because North America's largest oil spill by T/V Exxon Valdez on 24 March 1989 seriously impacted the ecosystem in the Sound and the adjacent downstream waters, extensive observational programs have been carried out since then. The SEA (Sound Ecosystem Assessment) Program is one of these major efforts. This multidisciplinary project started in 1994 with major focus on salmon, halibut, herring, plankton ecology, and physical oceanography. The physical oceanography component consists of a field program and the numerical model to be described here. This paper presents numerical simulations of PWS circulation to help understand the dynamical mechanisms, to depict typical flow regimes, and to set the stage for simulations with more comprehensive (e.g., seasonal heating/cooling and runoff) and realistic (seasonal and synoptic) wind forcing.

The water exchange between the Sound and the coastal Gulf of Alaska (GOA) strongly influences the circulation pattern and biomass distribution. The exchange of the waters inside and outside the Sound through Hinchinbrook Entrance and Montague Strait is an important factor influencing the PWS circulation and water properties (T, S, and other variables) (Schmidt, 1977). The water exchange depends on synoptic scale atmospheric forcing and the seasonal variation and interannual variability of the large-scale Aleutian sea-level pressure (Royer, 1988). There is low (high) pressure center during the winter (summer), indicating that westward (eastward) winds prevail in the winter (summer) season. The autumn and spring seasons are transitional. During winter, onshore surface Ekman transport dominates, producing coastal downwelling along the Alaskan coast offshore of PWS, while during summer, offshore surface Ekman transport dominates, producing coastal upwelling. The coastal upwelling and downwelling influence the water exchange between GOA and PWS. However, the local winds must also be important in driving the circulation of the Sound and their influence will be examined here.

The spatial scale of the Sound is barely large enough for a recirculation to develop because the baroclinic Rossby radius of deformation is about 5km (50km) in the winter (summer) season (Niebauer et al., 1994). Based on data from two moored current meters (one located in Hinchinbrook Entrance and the other in Montague Strait, Fig. 1) and from an ADCP (acoustic Doppler current profiler), Niebauer et al. (1994) examined the transport through the two openings and the baroclinic current. (Their observed transport will be used for the boundary condition in our model). Because the barotropic component was removed by a differencing between the upper and lower level velocity values, the resultant cyclonic circulation pattern obtained by Niebauer et al. (1994) only reflected the baroclinic current. Thus, it is necessary to understand the general circulation (both baroclinic and barotropic components) pattern in the Sound using a 3-D model to interpret the on-going field studies.

PWS is very rich in the production of salmon, halibut, herring, and other fish species. Its economic potential strongly depends on how well the fishcatch can be managed and how well the pollution can be minimized in the presence of a major oil tanker route. Naturally, understanding of the circulation patterns is essential to understanding PWS ecology and environmental risks (Royer et al., 1990). Thus, this study will offer, for the first time, a 3-D view of the PWS circulation, as well as the advective mechanisms for dispersal of passive tracers.

Based on the subsurface drogued (about 40m deep) Lagrangian trajectory observations conducted since 1973 in the Sound (Royer et al., 1979) and along the Alaskan coast (Royer, 1975), the Alaskan Coastal Current (ACC) usually intrudes into the Sound from Hinchinbrook Entrance and drives the basin-scale cyclonic circulation. However, there are strong modulations due to synoptic scale, seasonal, and interannual variability.

This modeling study is part of the Sound Ecosystem Assessment (SEA) Program that involves observational and modeling studies of several trophic levels as well as the physical regime. The SEA Program is build, in part, to test the "river/lake" hypothesis, i.e., that there is large variability in the PWS ecosystem associated with the regime shifts due to the occurrence of a strong throughflow from the ACC (river) or a weak (lake) throughflow.

The purpose of this study is to 1) implement a 3-D numerical model for simulating the PWS circulation pattern under different atmospheric forcing and coastal inflow/outflow conditions; 2) examine the river/lake hypothesis which is essential for understanding the ecosystem variability of the Sound; 3) study wind-generated circulation under typical winter and summer wind forcing; and 4) develop a 3-D concentration model linked to the 3-D ocean model for examining the transport processes in the Sound. Oceanic tidal motion (which has current speeds of order of the throughflow currents treated here and hence, probably influence the mean circulation), seasonal heating/cooling and evaporation/precipitation, and local freshwater runoff are important topics in the Sound which will be addressed in separate studies.

Section 2 summarizes the observational background. Section 3 describes the 3-D numerical model and the passive tracer transport model, plus the model configuration, model parameters, initial and boundary conditions, and forcing. Section 4 presents the simulation results: general circulation, wind-driven circulation, mesoscale features, and passive tracer dispersal. Finally, section 5 summarizes the results and outlines the future effort.

2. Observational Background

The upper layer general circulation pattern is known to be cyclonic with an amplitude of 0.2 to 0.3 ms^{-1} due to the inflow from Hinchinbrook Entrance. In July 1976, three satellite-tracked, buoys (drogued at 40m) were deployed in GOA (Royer et al., 1979). The summer drifter tracks followed the ACC along the Alaskan coast and entered the Sound through Hinchinbrook Entrance. The drifters travelled through the Sound in a cyclonic loop. Generally speaking, the ACC advects fresher and warmer coastal water into the Sound in summer when there is inflow to the Sound, depending on coastal water properties (Schmidt, 1977; Salmon et al., 1996). Based on several ADCP cruises, dynamic height charts, and current meter moorings, Niebauer et al. (1994) found that in summer (August and September) 1978, the ACC entered the Sound through Hinchinbrook Entrance and exited from Montague Strait (Fig. 7 of Niebauer et al. 1994). The throughflow dominates the upper layer circulation pattern, which is also called the river-like regime, and a cyclonic gyre occurred in September 1978. In contrast, the intermediate and deep circulations have not been observed.

3. Description and Implementation of the Model

A version of the Princeton Ocean Model (POM, Blumberg and Mellor 1987), which has been successfully applied to the circulation of Hudson Bay (Wang et al., 1994), is utilized. It is based on the primitive equations (that include hydrostatic and Boussinesq approximations) and has the following features: (1) horizontal curvilinear coordinates (not used in PWS); (2) an Arakawa C grid; (3) sigma (terrain-following) coordinates in the vertical with realistic bottom topography; (4) a free surface; (5) a level 2.5 turbulence closure model for the vertical viscosity and diffusivity (Mellor and Yamada, 1982); (6) a mean flow shear parameterization for horizontal viscosity and diffusivity (Smagorinsky, 1963); (7) a semi-implicit scheme for the shallow water equations (Blumberg 1991; Wang et al. 1994); and (8) a predictor-corrector scheme for the time integration to avoid inertial instability (Wang and Ikeda, 1995, 1996, 1997a).

To simulate the transport of passive tracers (pollutants, biological particles, chemical substances, etc.), the following 3-D concentration transport model has been added to POM:

$$\frac{\partial C}{\partial t} + L(C) = \frac{\partial}{\partial z}\left(K_H \frac{\partial C}{\partial z}\right) + F_C - T_D C + Q_{source} - Q_{sink}. \qquad (1)$$

where C is the concentration of the passive tracer, T_D is the decay time scale for C, $L(C)=\partial(uC)/\partial x + \partial(vC)/\partial y + \partial(wC)/\partial z$, K_H is the vertical diffusivity calculated from the Mellor-Yamada level 2.5 turbulence closure model, and F_c is the horizontal diffusivity term (applied in sigma space, cf. Mellor and Blumberg (1985)) whose diffusivity coefficient is calculated from the Smagorinsky parameterization, defined similarly to the temperature and salinity diffusivity terms. Source and sink terms, Q_{source} and Q_{sink}, for the variables of interest (e.g., biological species, fish larvae, pollutants, etc.) can be readily added to the right hand side of (1)

The model domain includes the entire PWS with two open boundaries (Hinchinbrook Entrance and Montague Strait, Fig 1), allowing water exchange with the Alaskan coastal waters (Schmidt, 1977). The model grid spacing is 1.2 km, which is eddy-resolving because the internal

Rossby radius of deformation is about 5 km (Niebauer et al., 1994). There are 15 vertical sigma levels, with a relatively dense resolution in the upper 50m to resolve the upper mixed layer. The integration time step is 62.1 seconds which is about six times CFL (Courant-Friedrichs-Lewy) constraint because the semi-implicit scheme has been used for the shallow water equations (Wang et al. 1994).

According to the observations at Hinchinbrook Entrance (Niebauer et al., 1994), the coastal inflow varies seasonally: from 0 to 0.3 Sv (Sverdrup; 1 Sv=10^6 m^3s^{-1}). The outflow through Montague Strait is of the same order of magnitude, although the water volume in the Sound may increase or decrease in response to transient forcing. Hence, an inflow of 0.3 Sv was specified for the summer season (Niebauer et al., 1994) through Hinchinbrook Entrance, while a radiation boundary condition (with self-adjusted outflow of 0.3 Sv) was applied to Montague Strait.

The initial temperature and salinity fields used are based on typical early summer profiles (Fig. 2, solid) as observed at the central Sound in July 1991 (Salmon et al. 1996) and spring profiles (Fig. 2, dashed) as observed at the same location in March 1995, and are specified to be horizontally uniform. The model was spun-up from these initial conditions for 30 days to reach a dynamical steady state, i.e., when the total kinetic energy and eddy kinetic energy have been constant for about 10 days. The restart file was saved for use as the initial condition for the next prognostic runs. The surface heat and salt fluxes were specified to be zero. The vertical viscosity is determined from the Mellor-Yamada 2.5 turbulence closure model with a background viscosity of 10^{-5} m^2s^{-1} (i.e., the value used if the calculated viscosity is smaller than this minimum value). The horizontal viscosity is determined from the Smagorinsky parameterization with the non-dimensional coefficient, C or HORCON equal to 0.2; the typical computed horizontal viscosity is about 5 to 10 m^2s^{-1}.

4. Simulation Results

4.1 General Circulation Pattern with Throughflow (Control Run, No Wind-forcing Case)

The vertical distribution of the specified inflow decreases linearly from the surface to 150m depth, and it is horizontally uniform. There is no wind-forcing in this case. The inflow temperature and salinity profiles were kept constant and equal to the initial (summer) interior profiles that were specified horizontal uniform, i.e., the zero horizontal gradient condition was used; thus, there were no defeasive and advective heat and salt fluxes into PWS.

The flow pattern at 3m depth (for the summer stratification) on day 33 (beginning from the restart fields) (Fig. 3a) indicates a coastal inflow entering the Sound through Hinchinbrook Entrance and exiting through Montague Strait, forming a cyclonically looping throughflow. The throughflow has three branches, the primary one between Knight Island and Montague Island, one through the channel between Knight Island and Naked Island (NI), and the other turning to the northeast to form a persistent cyclonic gyre in the northern Sound. (The term "gyre" is used here to distinguish between such persistent features and transient mesoscale eddies.) These two secondary branches join in the northwestern Sound and pass through Knight Island Passage (to the west of Knight Island).

At 100m (intermediate layer, Fig. 3b), the basin-scale pattern is cyclonic, while there are several mesoscale gyres: for example, the largest ones are near Hinchinbrook Entrance (cyclonic) and in the central (anticyclonic), north-central (cyclonic), and northwestern Sound (cyclonic).

At both 3m and 100m, the outflow is largely channelled through Knight Island Passage to Montague Strait.

At 300m depth (deep layer), there are several smallscale eddies constrained to the narrow deep basins (Fig. 3c). The positions of the eddy centers are displaced from those at 100m (Fig. 3b), indicating strong baroclinicity (Fig. 4a versus Fig. 4b) and tilted axis between 100m and 300m depths (Wang and Ikeda, 1997b). Obviously, some of these eddies do not exist at 3m depth.

The vertical structure of the meridional (V) and zonal (U) velocity is demonstrated with zonal and meridional transects. Along the zonal (60.4N) transect (Fig. 4a), the meridional velocity is northward (up to 30 cm s^{-1}), flowing along the eastern coast, while the southward current (up to 15 cm s^{-1}) flows along the eastern coast of Knight Island. In Knight Island Passage, a southward flow (up to 10 to 15 cm s^{-1}) is confined to the upper 200m layer, while below there is a weak northward flow, indicating a baroclinic structure. Along the meridional (147.2W) transect (Fig. 4b), the zonal velocity distribution is dominated by three gyres, the primary throughflow and other two (Fig. 3b). The maximum velocity cores of the primary throughflow and the gyre in the northern Sound have vertical tilts, indicating a moderate vertical shear of the horizontal velocity (Wang and Ikeda 1996).

The vertical structures of density along the same meridional and zonal transects (Fig. 5) indicate typical summer stratification. However, along the zonal (60.4N) transect (Fig. 5a) there is a density dome in the central Sound; along the meridional transect (Fig. 5b), there is a density dome adjacent to Montague Island, both consistent with the cyclonic throughflow circulation. Along the meridional (147.2W) transect (Fig. 5b), there is a density dome in the lower layer between 200m and 300m, indicating a cyclonic eddy (Fig. 4b).

A parallel experiment to the summer stratification (Fig. 2, solid) was conducted using the spring stratification (Fig. 2, dashed). The 3m flow pattern (Fig. 3d) indicates the absence of the recirculations and gyres to the north of Montague Island, in the central Sound, and to the northeast of Naked Island. The primary throughflow jet and one secondary branch towards north from the east of Naked Island are strong, while the branch through the channel between Knight Island and Naked Island is relatively weak. Thus, the flow pattern (Fig. 3d) is quite different from that under the strong stratification (Fig. 3a). The 100m intermediate flow pattern (not shown) is quite similar to the surface one. However, in the 300m deep layer, there are smallscale eddies (not shown) confined in the narrow basins, indicating baroclinicity in the deep layer flow pattern.

The inflow to the Sound has seasonal and interannual variability (Niebauer et al. 1994), which needs further field studies and numerical simulations to define better the variations. As a first step in this direction, the influence on the PWS circulation pattern of larger and smaller inflows through Hinchinbrook Entrance are examined. In the following experiments, the inflow was doubled (0.6 Sv) and halved (0.15 Sv) relative to the control run value (0.3 Sv). Overall, the resulting circulation patterns are similar but the separation of the inflow differs (Fig. 6). However, the basic throughflow pattern (i.e., inflow from Hinchinbrook Entrance and outflow through Montague Strait), the primary branch and the two secondary branches, is similar.

For the doubled-inflow case (Fig. 6a), the main stream has two very strong separations southeast of Naked Island, one branch flowing northeast to form a cyclonic gyre plus a pair of anticyclonic/cyclonic gyres and the other branch flowing westward through the channel south of

Naked Island to form a cyclonic gyre northwest of Knight Island. For the halved-inflow case (Fig. 6b), the two branches near Naked Island are relatively weak, with an anticyclonic gyre in the central Sound and an anticyclonic gyre northwest of Knight Island, differing significantly from the doubled-inflow case.

Therefore, the circulation pattern in the Sound is significantly influenced by the magnitude of the inflow from Hinchinbrook Entrance, particularly in the northern and the central Sound. In the control run, the primary throughflow branch penetrates to 60.55N, while the doubled-inflow case penetrates to 60.65N, corresponding to an extreme river-like regime, and the halved-inflow case penetrates to only 60.45N, corresponding to a lake-like regime.

4.2 Buoyant Throughflow

To examine the inflow accompanied by the fresher Alaskan coastal water (i.e., buoyant throughflow), an inflow of 0.3 Sv (same as the control run) is specified at Hinchinbrook Entrance, together with a negative density flux (i.e., positive buoyancy) in the upper 40m layer (-1 kg m^{-3}, i.e., the density is 1 kg m^{-3} lower than the interior value) injected for four days, representing a coastal event on a synoptic time scale.

The advection of the fresh Alaskan coastal water is demonstrated (Fig. 7). At day 8, the fresh water of 22.9 kg m^{-3} is advected to the central region of the throughflow. Along the coasts of the Sound, there is higher density water (higher than 23 kg m^{-3}). Thus, there are two regimes in the density pattern. At day 8, a low density filament east of Naked Island is due to the advection. At days 8 and 33, the low density water of 22.9 kg m^{-3} occupies Montague Strait and a filament has been advected to the northeast of Naked Island. The two distinct regimes, lower (fresher) density in Montague Strait and higher density along the coasts, are the consequence of the advection of fresher Alaskan coastal water.

4.3 Wind-Driven Circulation

As mentioned earlier, monthly averaged wind regimes over the Sound vary seasonally with changes in the position and strength of the Aleutian Low in winter and the North Pacific High in summer. Eastward (i.e., winds blowing from the west) winds (i.e., coastal upwelling-favorable winds) and northward winds tend to occur during summer when the North Pacific High strengthens, while strong westward and southwestward winds (i.e., coastal downwelling-favorable winds) tend to occur during winter when the Aleutian Low strengthens. Thus, the surface current fields under forcing from eastward, southward, westward, and northward winds of 7 ms^{-1} (the windstress is about 0.1 Newton m^{-2}=0.1 Pa=1 dyne cm^{-2}) are examined together with the same inflow as the control run.

To determine the steady-state response of the PWS circulation to wind forcing, the growth rate of eddy kinetic energy (EKE), following the approach of Wang and Ikeda (1996), is examined (Fig. 8). The EKE growth rate responds to the eastward wind at the inertial frequency in less than 4 days. The time scale to reach a steady state is about 4 to 5 days. Thus, the wind-generated circulation patterns are examined at day 4 in the following.

After applying westward wind for four days (Fig. 9a), the two secondary branches at 3m near Naked Island are stronger than those without wind forcing (Fig. 3a). In the eastern Sound, a coastal current is generated and flows along the northern coast, a strong branch of which flows northeastward and reaches the Valdez Arm due to Ekman transport. Along the northern coast, the alongshore current flows into Port Wells (i.e., near Whittier). The southwestward flow through Knight Island Passage is much weaker. By contrast, the flow pattern with eastward wind-forcing has a quite different pattern (Fig. 9b) compared to the westward wind-forcing, particularly away from the inflow jet. The surface current in the central, northern, and western Sound is southward due to Ekman flow. There are no branches near Naked Island. Consequently, the southward surface current through Knight Island Passage is much stronger than in the control run.

With northward wind-forcing, the eastward Ekman flow dominates the surface pattern and there is only one strong secondary branch near Naked Island that flows northeastward (Fig. 9c). This branch flows directly into the Valdez Arm. A strong eastern coastal current is also generated. In the northern Sound, there is a weak cyclonic gyre, similar to the control run. There is no southward flow through Knight Island Passage, similar to the westward wind-forcing case (Fig. 9a). With southward wind-forcing, the westward Ekman flow dominates the surface flow (Fig. 9d), while the jet flow is more or less the same as the control run (Fig. 3a). However, there is no cyclonic gyre north of Montague Island, and there is only one secondary branch from the jet that flows through the channel between Knight Island and Naked Island. The southward flow through Knight Island Passage is enhanced.

In summary, the PWS surface flow pattern is sensitive to the local wind forcing. The position of the throughflow jet displaces according to the wind direction and magnitude. The secondary branches separated from the primary jet to the south of Naked Island vary, depending on wind direction. Similarly, the southward and eastward (northward and westward) winds enhance (block) the southward flow through Knight Island Passage. Thus, the transient circulation in the Sound is an important factor in most regions away from the primary throughflow jet, in response to the synoptic wind forcing.

4.4 Passive Tracer Transport

Due to the Valdez Exxon oil spill event, the ocean pollution and ecological research has become a priority for the restoration of the ecosystem in the Sound. From a purely ecological point of view, the transport of offshore water and biota into and within the Sound needs to be examined.

In the following, five passive tracer transport experiments are conducted using the circulation patterns derived from the above section. The control run, for example, uses the 3-D current field with no wind-forcing, and the other runs use the 3-D current fields with wind-forcing from the four different directions. The concentration source was placed within the upper 40m at Hinchinbrook Entrance, representing a coastal pollutant or phytoplankton bloom intrusion into the Sound. After four days, the concentration source was cut off, and the passive tracers were tracked to investigate the movement and distribution in the Sound.

For the control run at 3m, the tracer (concentration, C, varying from 0 to 100) has been advected by the throughflow jet to Montague Strait on day 4 (Fig. 10a). Some of the tracer also passes through the channel between Knight Island and Naked Island. However, there is little advection through Knight Island Passage.

On day 8 (Fig. 10b), a tracer filament has been transported 25km to the northeast of Naked Island. By day 12, the north central Sound has been covered by the tracer, while most of the tracer has been removed from the southern Sound (Fig. 10c). By day 25 (not shown), although most of the tracer has been transported out of the domain, there are a few places with high concentration, such as the northern and western coasts of Montague Island (due to a cyclonic gyre), northeast of Naked Island (due to a cyclonic gyre), and northwest (due to very weak advection), and Knight Island Passage. By day 33 (Fig. 10d), almost all of the tracer along the throughflow has been transported out of the Sound; however, there are low concentration (around 10% of the source) zones, indicating the residence time in those zones under these conditions (throughflow and no wind) is much longer than one month. Thus, under river-like regime conditions, passive tracer from Alaskan coastal waters can reach the northern and northwestern Sound.

When the wind blows in different directions, the tracer distributions vary (Fig. 11) depending heavily on the different flow patterns, as discussed in the above section. For example, by day 4, the westward wind transports much of the tracer to the northeastern Sound (Fig. 11a), while eastward wind (Fig. 11b) transports much of the tracer to the south into Montague Strait. Similarly, the northward wind (Fig. 11c) transports the tracer to the eastern Sound and decreases the tracer advection into Montague Strait, while the southward wind (Fig. 11d) transports the tracer further into Montague Strait, and to the west through the channel between Knight Island and Naked Island.

To quantify how much of the tracer still resides in the Sound after an integration of one month, time series of volume averaged concentration (VAC) for the five cases are examined (Fig. 12). On day 4, of course, VAC reaches a maximum (2.1 or 2.2) for each case. On day 33, the control run (solid line) has a VAC of 0.9, which is about 43% of the source volume. Southward wind-forcing, which often occurs in winter, is most efficient in removing the tracer from the Sound. Similarly, eastward wind-forcing is the secondmost efficient compared to the other cases. The northward and westward winds increase the residence time in the Sound.

5. Concluding Remarks

POM has been applied to the Sound and some important dynamical factors influencing the circulation pattern have been demonstrated. The simulation results indicate that PWS-POM has produced basically correct circulation patterns under throughflow and wind-forcing. Vigorous mesoscale gyres are a prominent phenomenon and may be important for biomass distribution, because they influence the biomass concentration, residence time, and possibly abundance. Furthermore, different wind conditions change the residence time by changing the surface Ekman flow, the circulation pattern, and stratification. The present investigations are summarized as follows:

1) If the Alaskan Coastal Current enters the Sound, the throughflow jet dominates the basic circulation pattern. Two secondary branches separate south of Naked Island are due to topographic blocking. In the intermediate (100m) and deep (300m) layers, there are strong baroclinic mesoscale eddies and gyres. The strength of the separated branches depends strongly on the magnitude of the inflow;

2) There are two distinct density regimes if fresh Alaskan coastal water enters from Hinchinbrook Entrance. In Montague Strait, the fresher water dominates and differs from the dense water along the coasts of the Sound;

3) The other circulation pattern depends heavily on the wind direction. The areas most sensitive to wind forcing are those away from the throughflow jet, particularly in the eastern, central and northern Sound; and

4) The transport of a passive tracer released in the upper layer of Hinchinbrook Entrance, therefore, is largely controlled by the throughflow and determined by the surface circulation

pattern driven by the wind. Southward and eastward winds increase the removal rate of passive tracers from the Sound, while northward and westward winds decrease the removal rate. The residence times in these cases are much longer than one month, although the advection time scale of the throughflow jet is of the order of a few days.

Acknowledgements: Financial support from the SEA Program of the Exxon Valdez Oil Spill (EVOS) Trustees Council through Prince William Sound Science Center, Alaska is appreciated. Discussions of the PWS circulation with Drs. T.C. Royer, Z. Kowalik, D. Salmon, V. Patrick, S. Vaughan, and W. Johnson are gratefully acknowledged.

References

Blumberg, A.F., 1991. A primer for ECOM-si. Technical Report for HydroQual, Inc., Mahwah, NJ, 66 pp.

Blumberg, A.F. and G.L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. In Coastal and Estuarine Sciences 4: Three-Dimensional Coastal Ocean Models, N.S. Heaps, ed., American Geophysical Union, Washington D.C.: 1-16.
18: 775-787.

Foffonoff, N.P., 1962. Physical properties of sea-water. **The Sea**, Vol. 1, 3-30. Wiley-Intersci.

Kowalik, Z., J.L. Luick and T.C. Royer, 1994. On the dynamics of the Alaska Coastal Current. **Contin. Shelf Res.**, 14: 831-845.

Mellor, G.L. and A.F. Blumberg, 1985. Modeling vertical and horizontal diffusivities with sigma coordinate system. **Mon. Rea. Rev.**, 131: 1379-1383.

Mellor, G.L. and T. Yamada, 1982. Development of a turbulence closure model for geophysical fluid problems. **Rev. Geophys. Space Phys.**, 20: 851-875.

Muench, R.D. and G.M. Schmidt, 1975. Variations in the hydrographic structure of Prince William Sound. IMS Rep. R75-1, Institute of Marine Science, Univ. of Alaska, Fairbanks, 135 pp.

Niebauer, H.J., T.C. Royer and T.J. Weingartner, 1994. Circulation of Prince William Sound, Alaska. **J. Geophys. Res.**, 99: 14,113-14,126.

Royer, T.C., 1976. Seasonal variations of waters in the northern Gulf of Alaska. **Deep Sea Res.,** 22: 403-416.

Royer, T.C., D.V. Hansen and D.J. Pashinski, 1979. Coastal flow in the northern Gulf of Alaska as observed by dynamic topography and satellite-tracked drogued drift buoys. **J. Phys. Oceanogr.,** 9: 785-801.

Royer, T.C., J.A. Vermersch, T.J. Weingartner, H.J. Niebauer and R.D. Muench, 1990. Ocean circulation influencing the Exxon Valdez oil spill. **Oceanography**, 3-10.

Salmon, D., J.M. Murphy, T.M. Thomas and S.M. Gay, 1996. Hydrography and circulation in Prince William Sound, Alaska during spring, summer, and fall of 1994. (unpublished ms.)

Smagorinsky, J., 1963. General circulation experiments with the primitive equations, I. The basic experiment. **Mon. Wea. Rev.**, 91: 99-164.

Schmidt, G.M., 1977. The exchange of water between Prince William Sound and the Gulf of Alaska, M.S. thesis, 116 pp, Univ. of Alaska, Fairbanks.

Wang, J. and M. Ikeda, 1995. Stability analysis of finite difference schemes for inertial oscillations in ocean general models. In **Computer Modeling of Seas and Coastal Regions,** eds. C.A. Brebbia et al., Computational Mechanics Publications, Southampton.

Wang, J. and M. Ikeda, 1996. A 3-D ocean general circulation model for mesoscale eddies-I: Meander simulation and linear growth rate. **Acta Oceanologica Sinica**, 15: 31-58.

Wang, J. and M. Ikeda, 1997a. On inertial stability and phase error of time integration schemes in ocean general circulation models. **Mon. Wea. Rev.** (in press).

Wang, J. and M. Ikeda, 1997b. Diagnosing ocean unstable baroclinic waves and meanders using quasi-geostrophic equations and Q-Vector method. **J. Phys. Oceanogr.,** 27: 1158-1172.

Wang, J., L.A. Mysak and R.G. Ingram, 1994. A 3-D numerical simulation of Hudson Bay summer circulation: topographic gyres, separations and coastal jets. **J. Phys. Oceanogr.**, 24: 2496-2514.

Figure Captions

Fig. 1. Bottom topography of Prince William Sound (depths in meters).

Fig. 2. The summer (solid lines) and spring (dashed) vertical temperature, salinity, and density distributions in the central Prince William Sound.

Fig. 3. The mean velocity fields under forcing of inflow/outflow of 0.3 Sv only at 3m (a), at 100m (b), at 300m (c) under summer stratification, and at 3m under spring stratification (d).

Fig. 4. The vertical distributions of meridional velocity (V) along the 60.4N west-to-east transect (upper panel) and of zonal velocity (U) along the 147.2W south-to-north transect (lower panel).

Fig. 5. The same as Fig. 4, except for density.

Fig. 6. Same as Fig. 3a, except under forcing of 0.6 Sv (a) and 0.15 Sv (b).

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Fig. 8. The series of eddy kinetic energy growth rate under constant eastward wind-forcing of 7 ms^{-1}.

Fig. 9. The same as Fig. 3a, except under forcing of wind of 7 ms^{-1} a) westward, b) eastward, c) northward, and d) southward.

Fig. 10. The 3m concentration (or pollutant) distribution under no wind condition (control run, Fig. 3) on days 4 (a), 8 (b), 12 (c), and 33 (d). The units are from 0 to 100. The contour interval is 5% for a, b, and c; and 1% for d.

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Fig. 12. The time series of volume averaged concentrations in Prince William Sound for the control run (no wind case, solid line), and for the wind forcing a) westward (denoted by E), b) eastward (denoted by W), c) northward (denoted by S), and d) southward (denoted by N).

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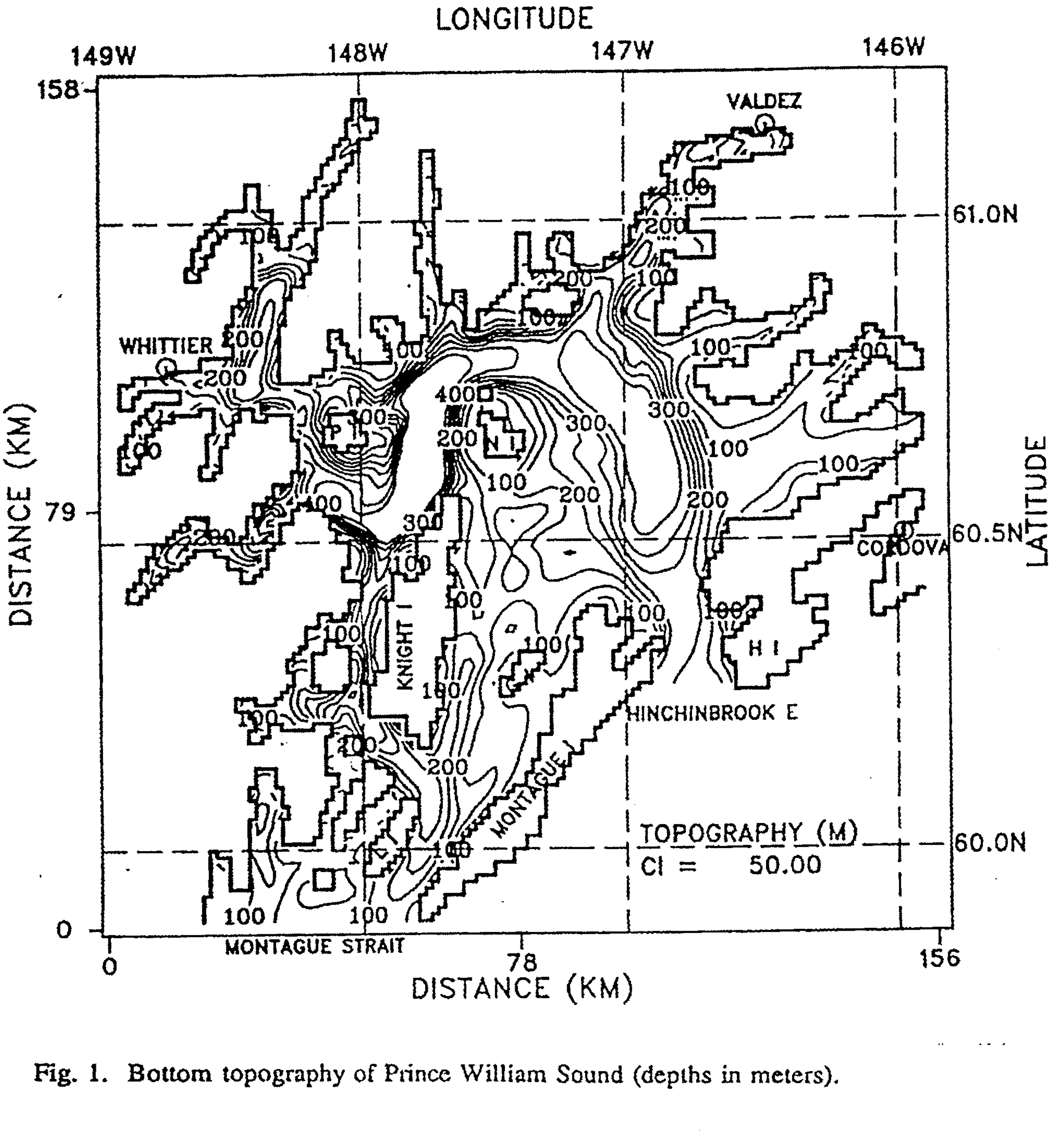

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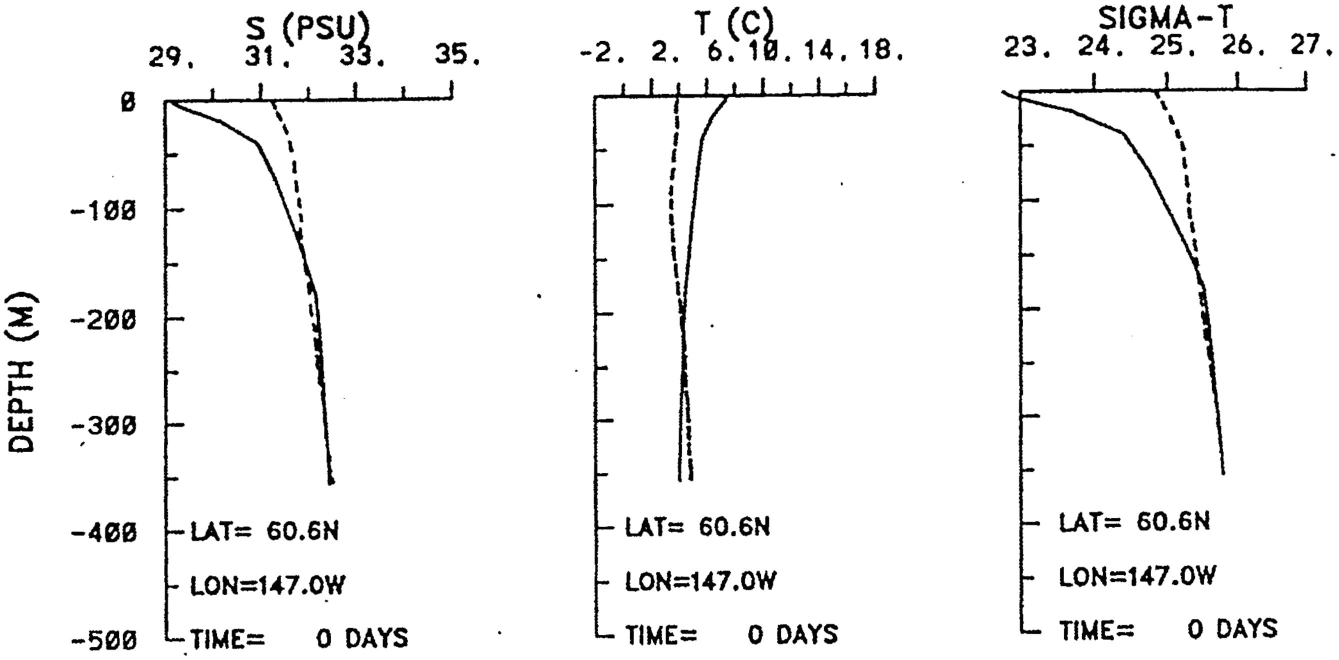

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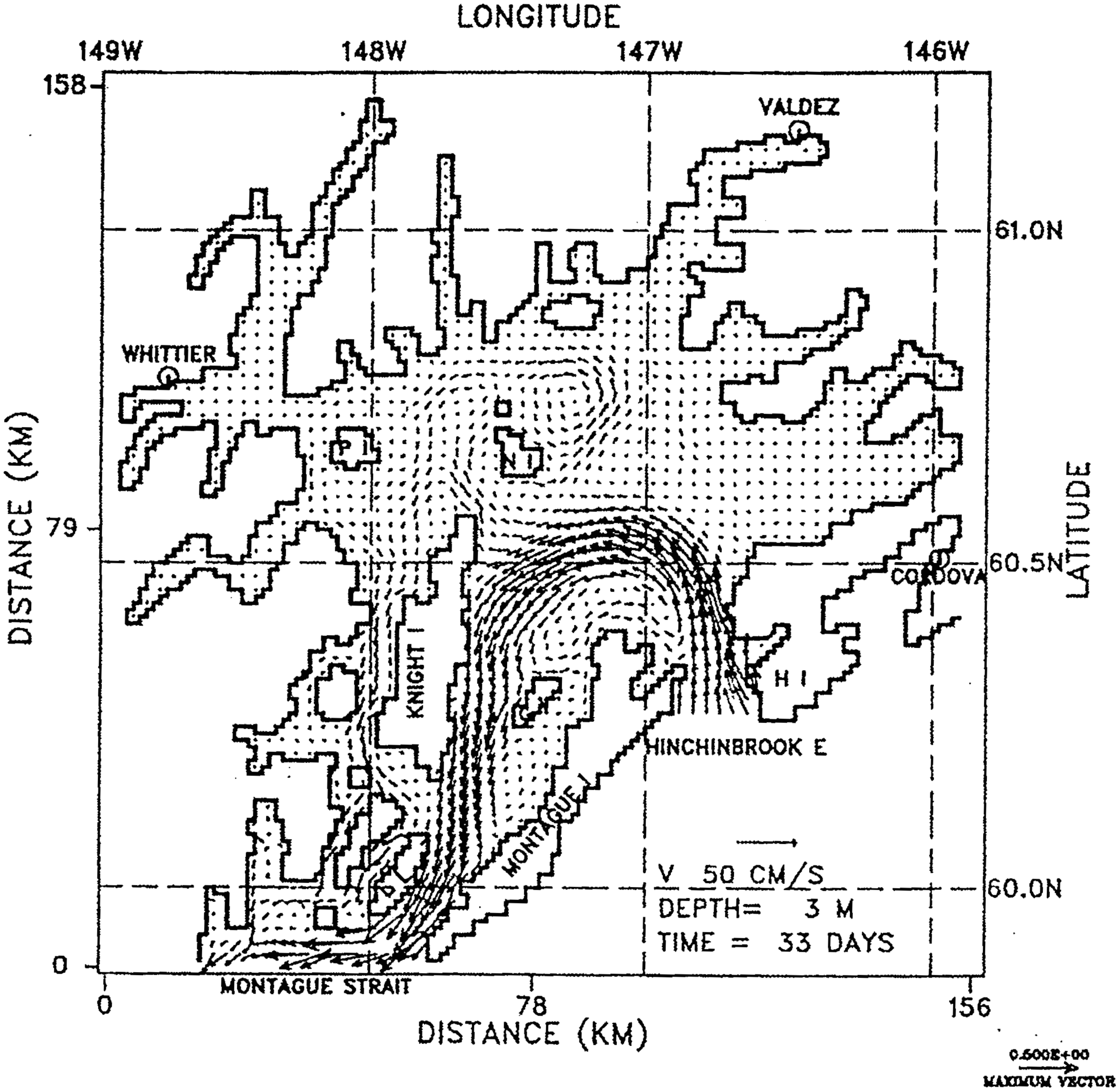

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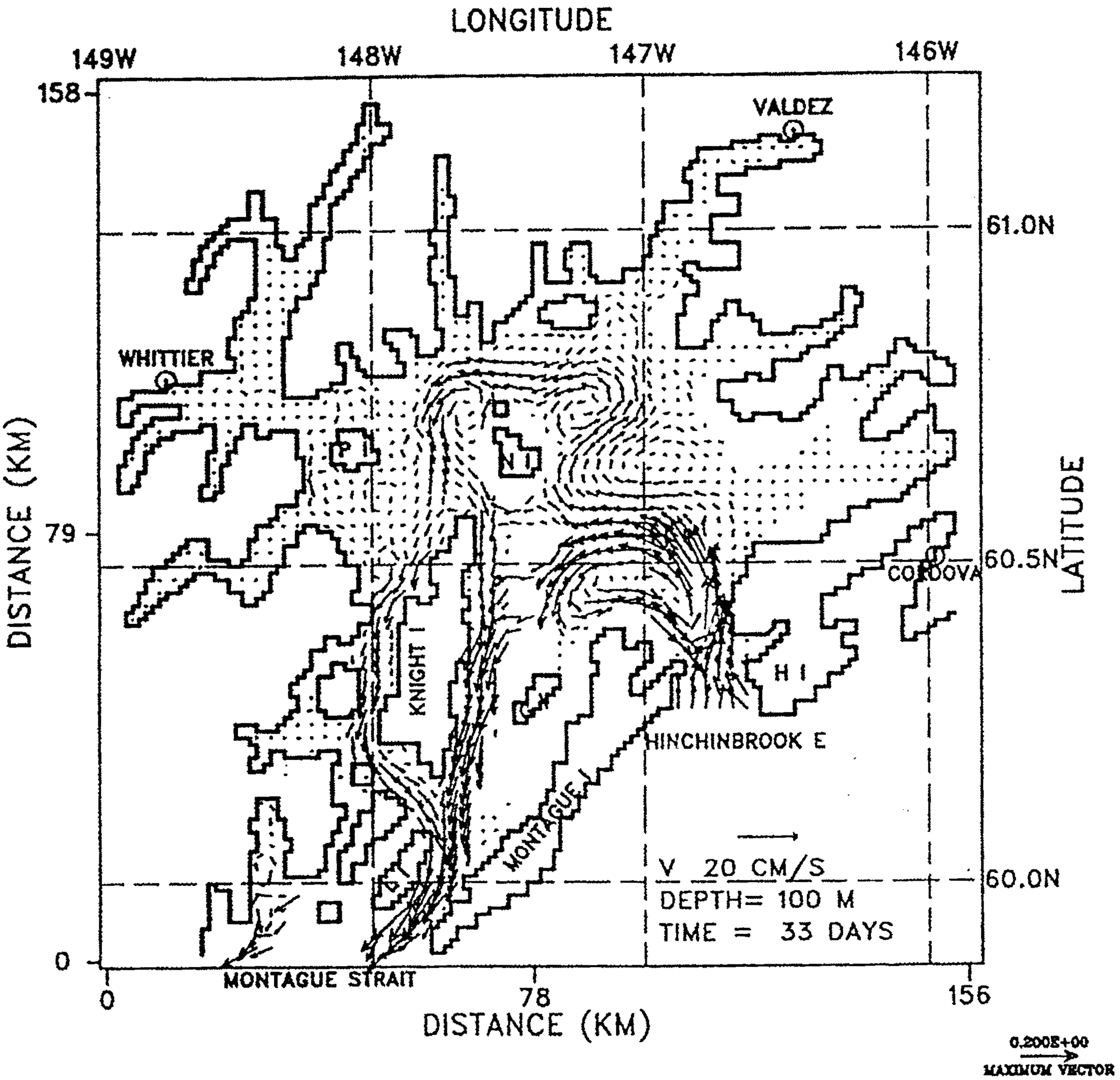
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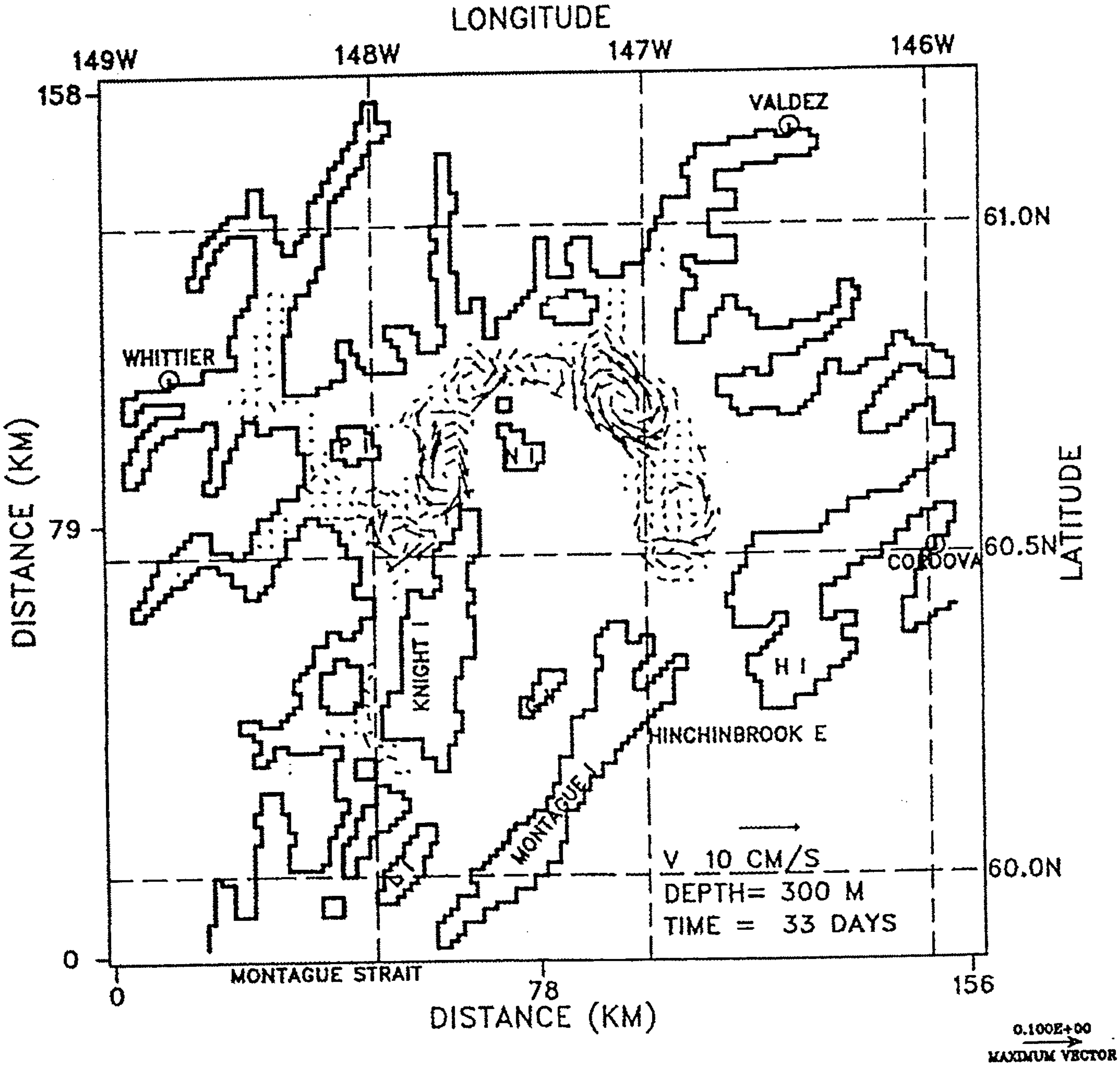
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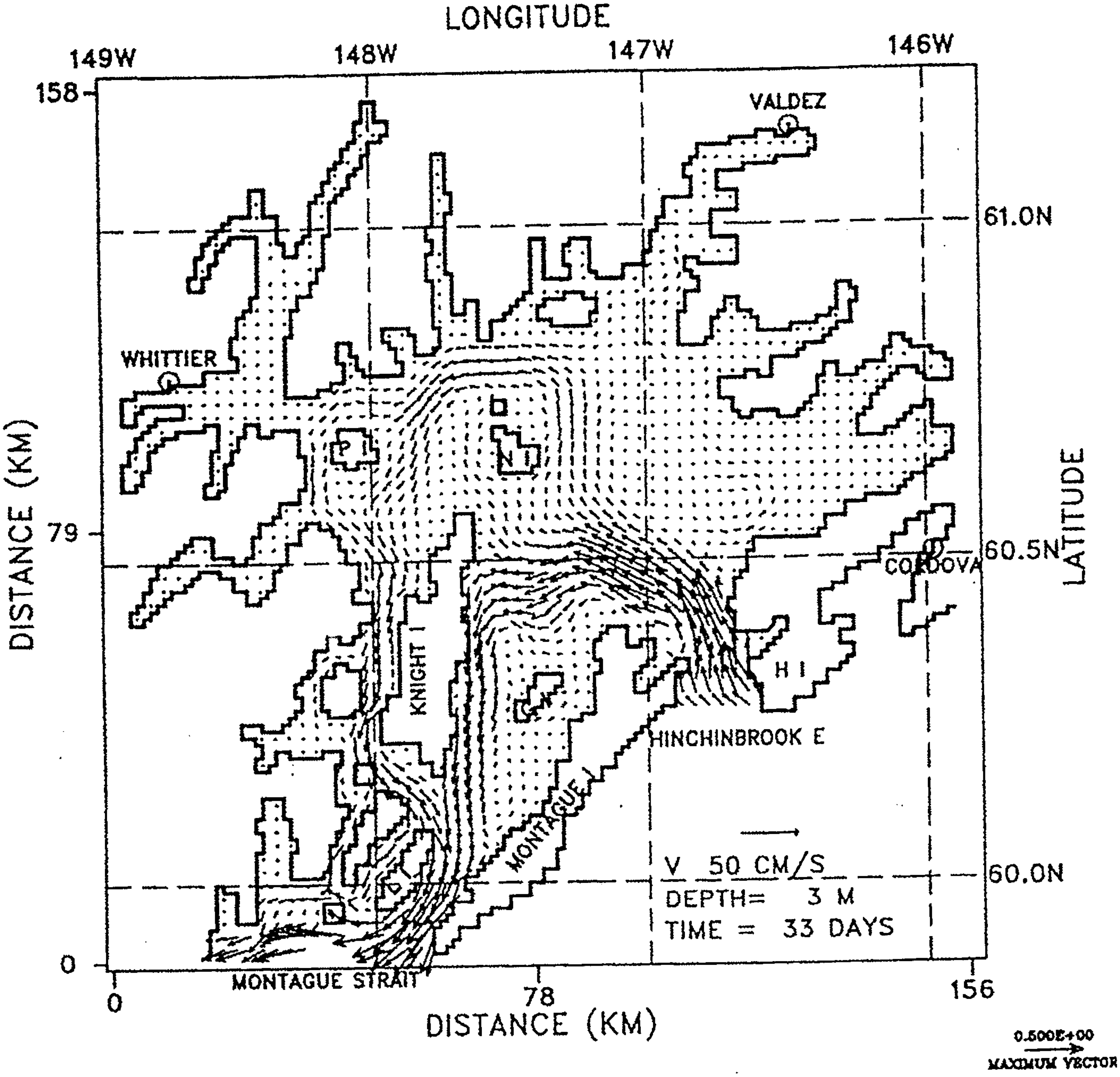
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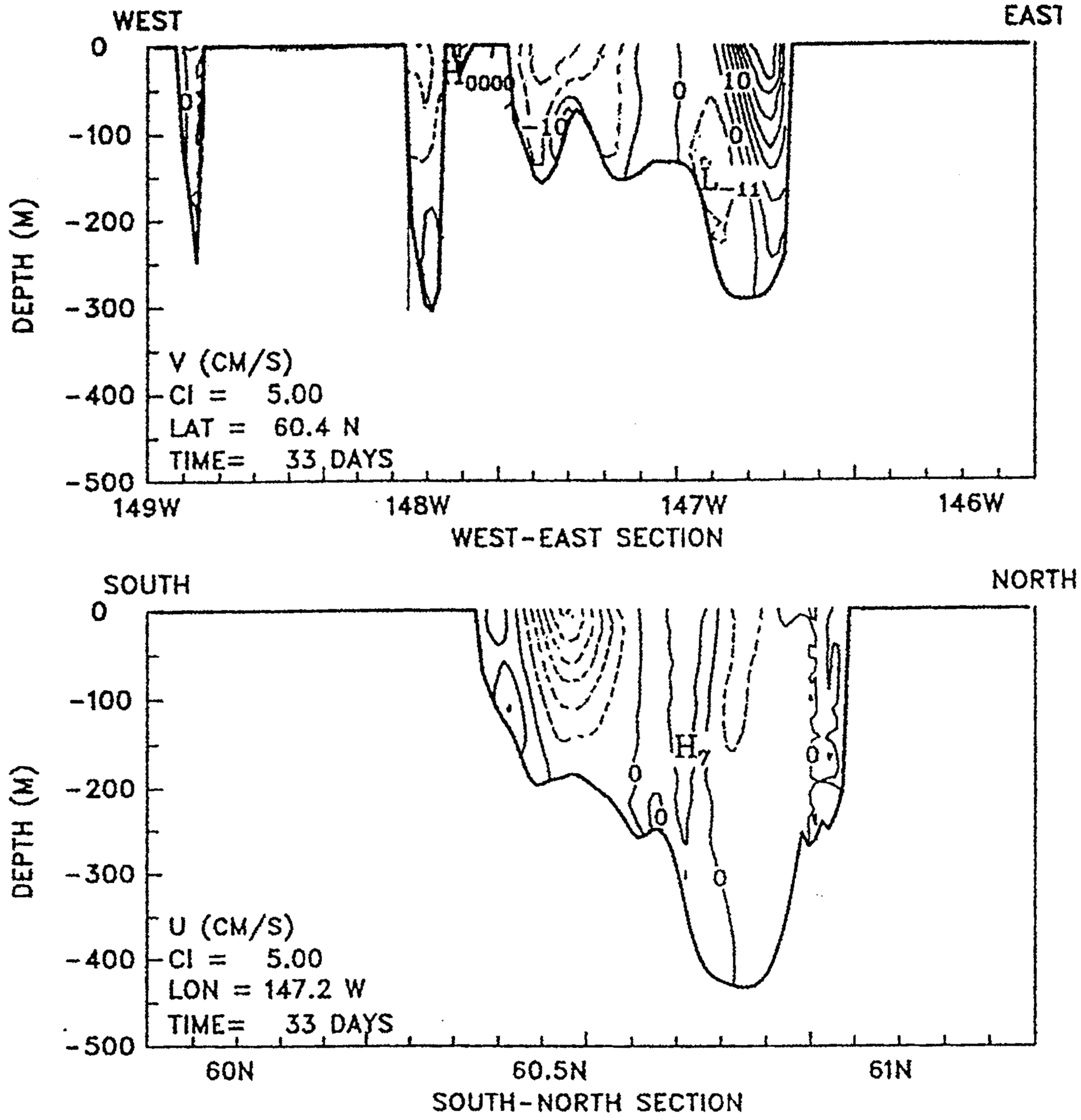

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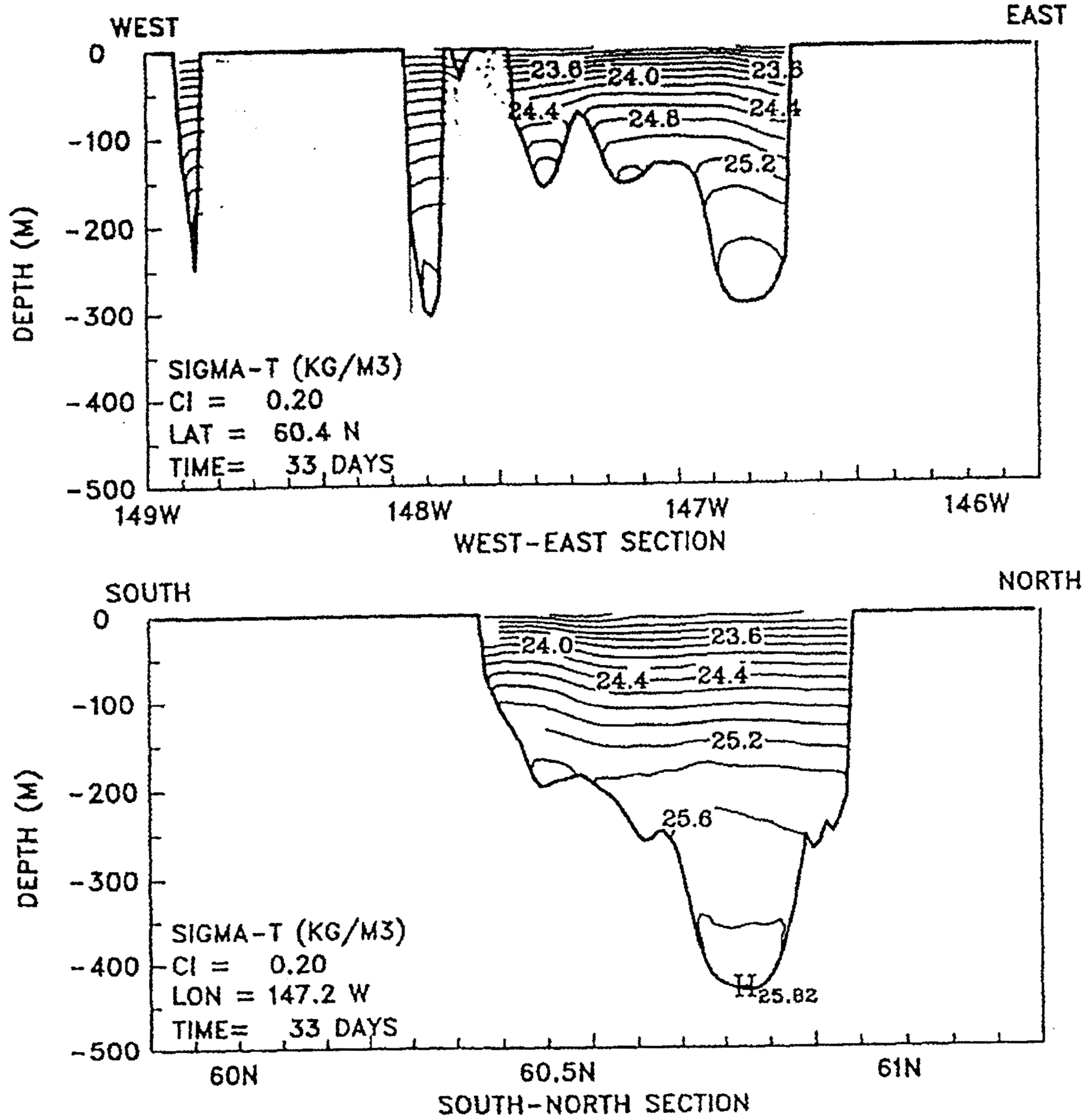

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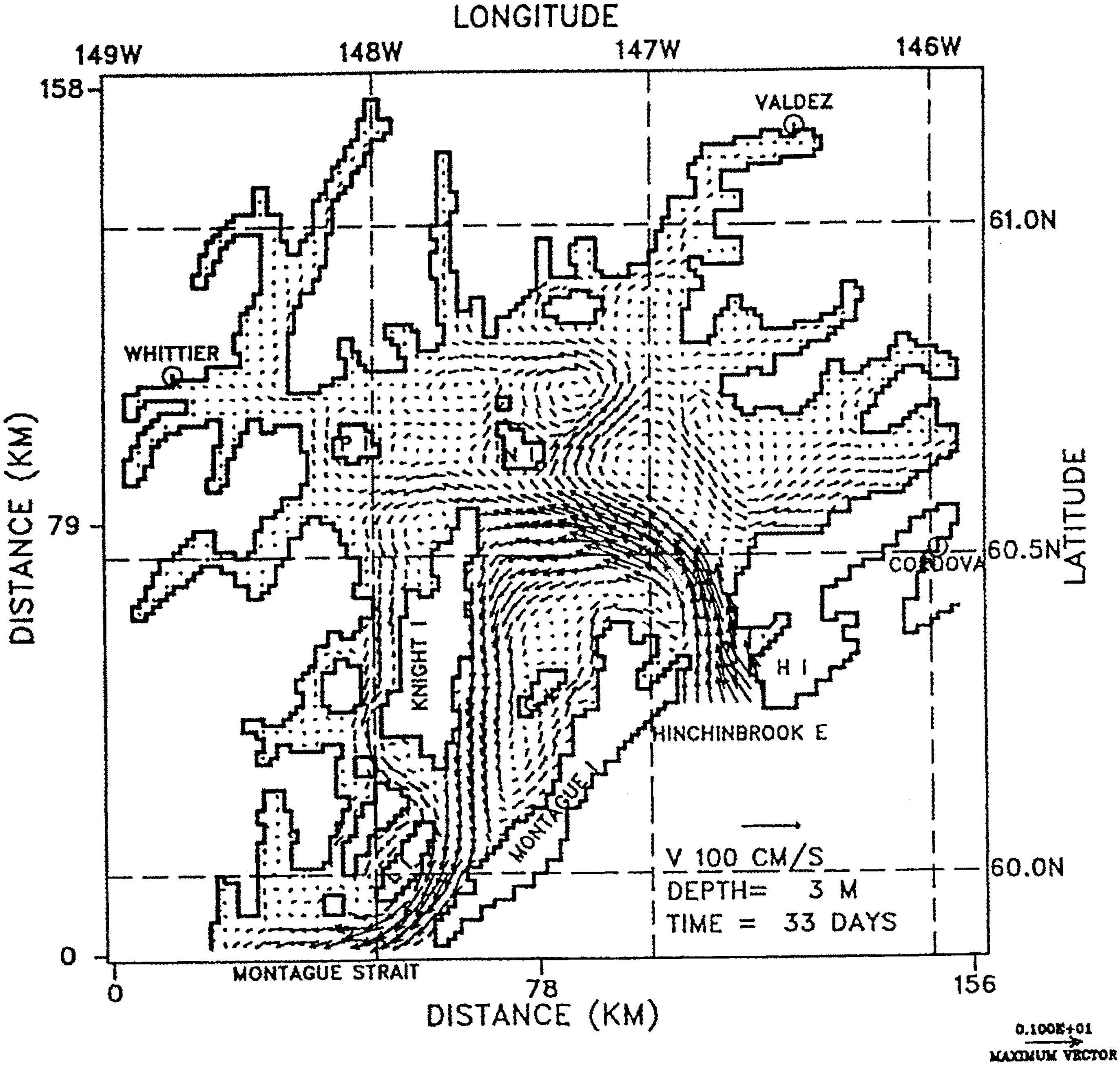

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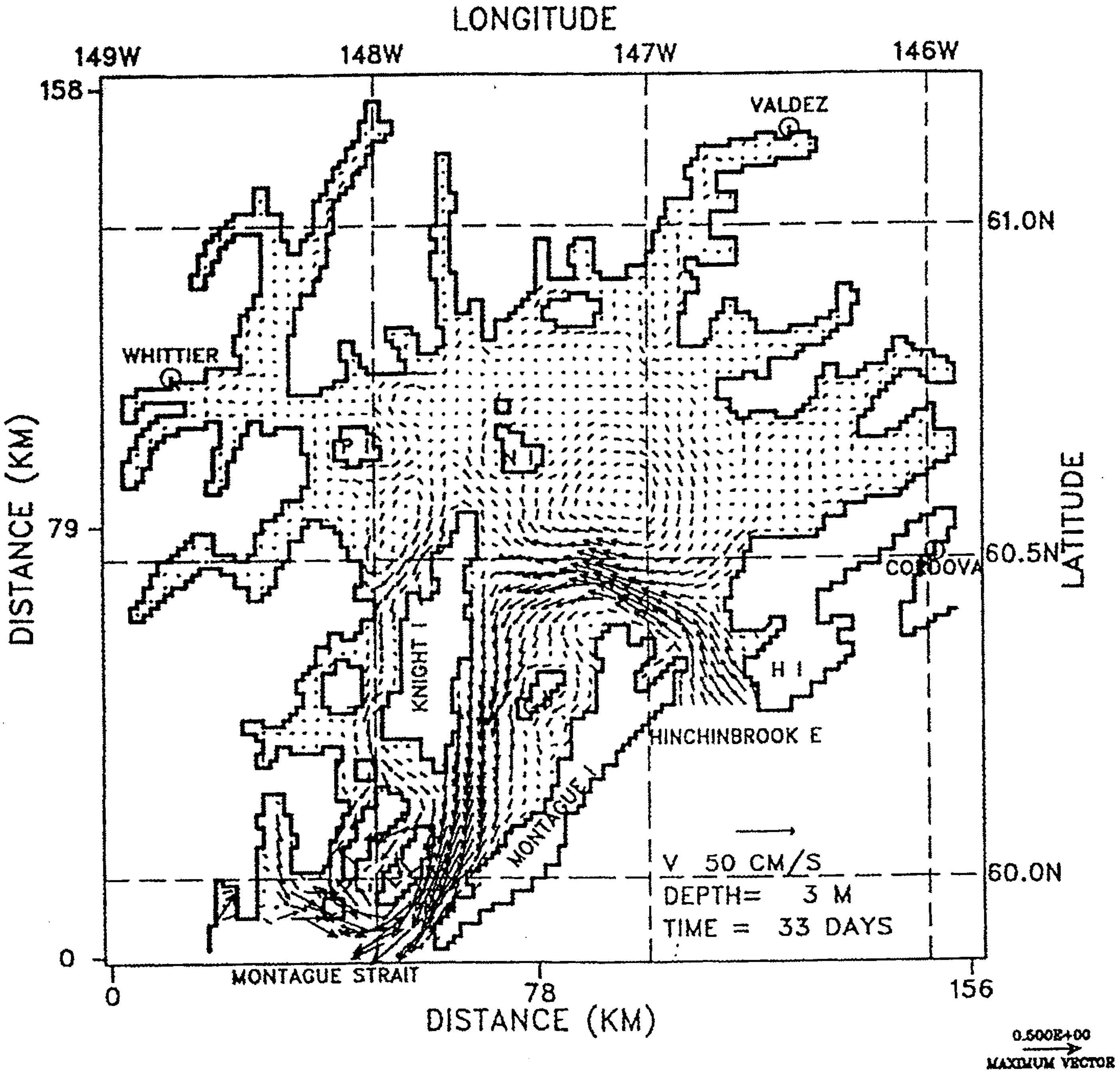
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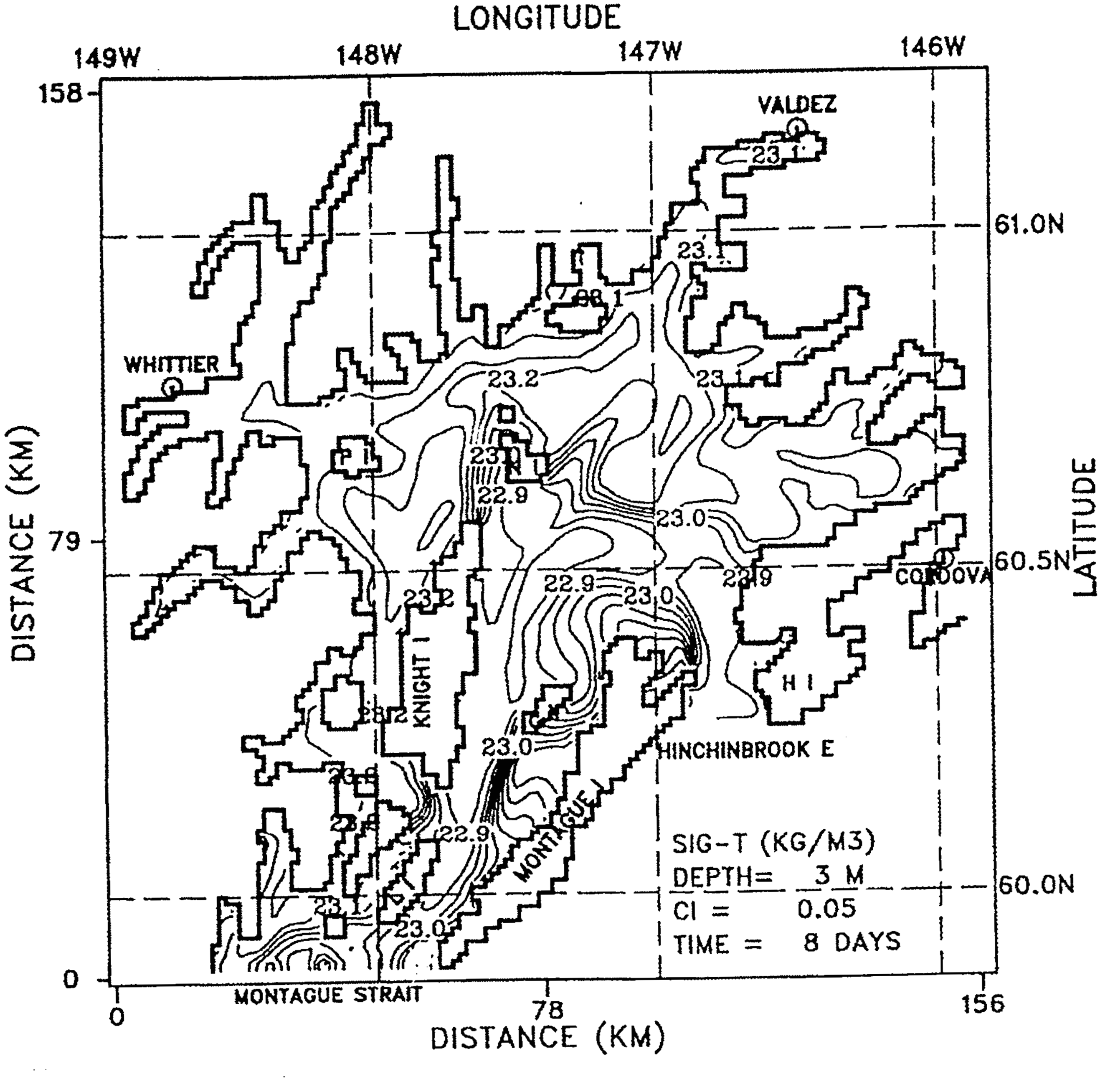

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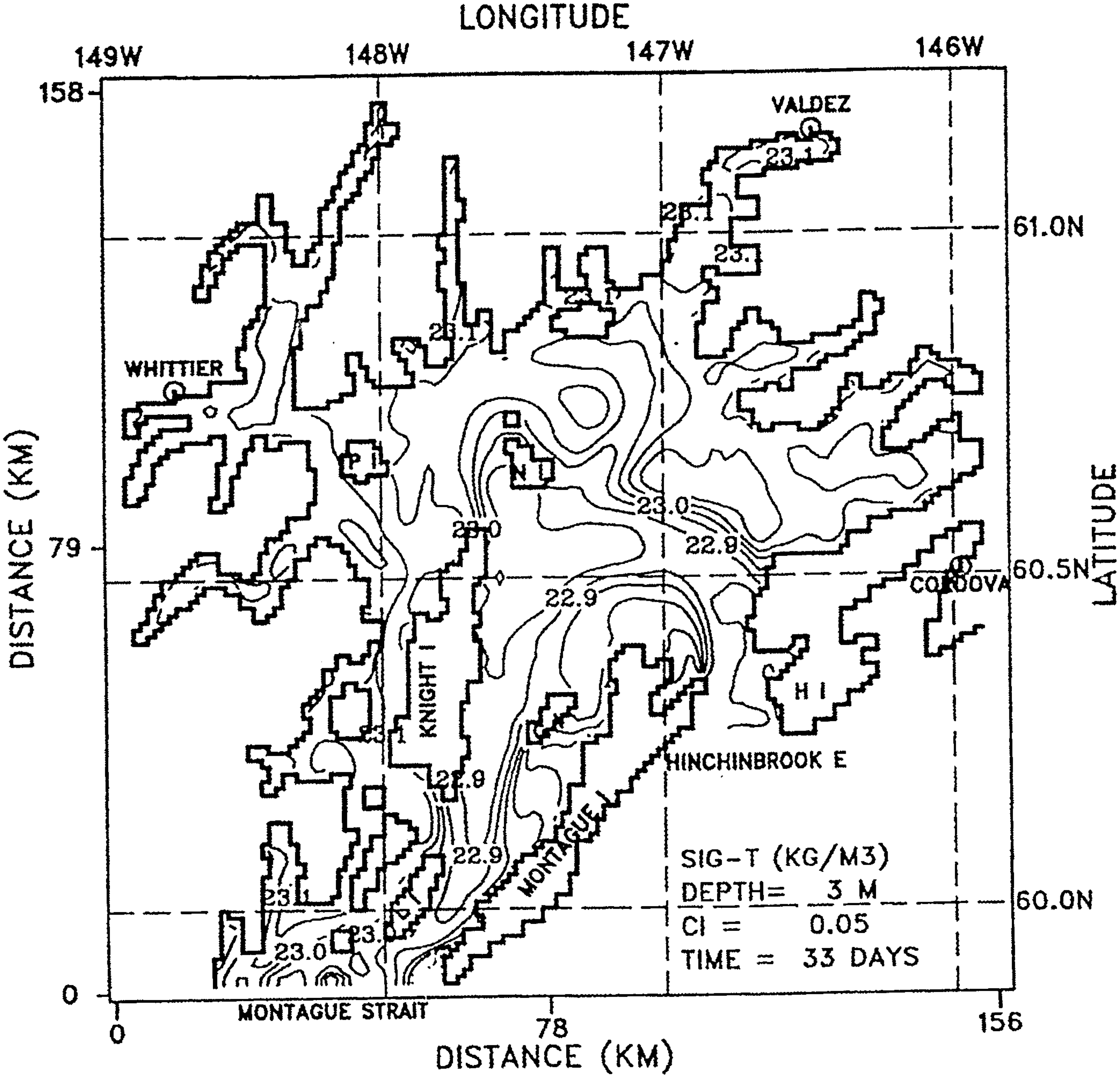
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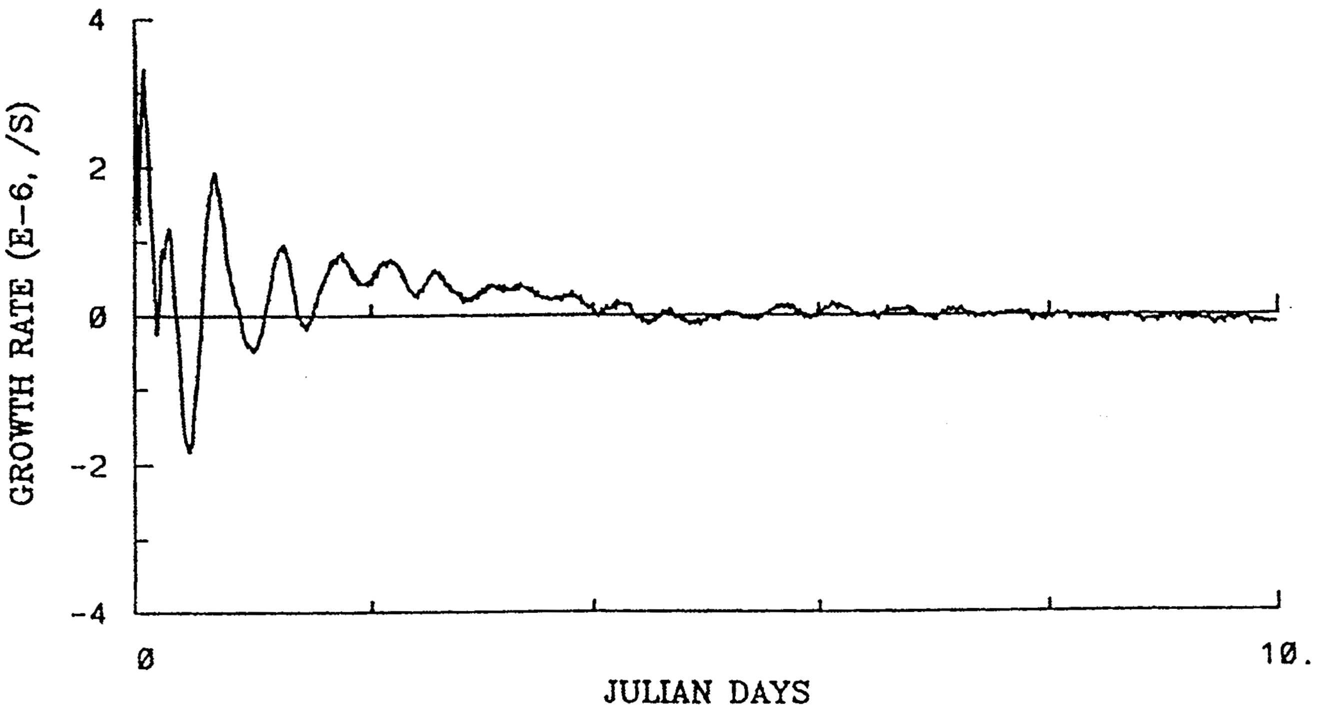

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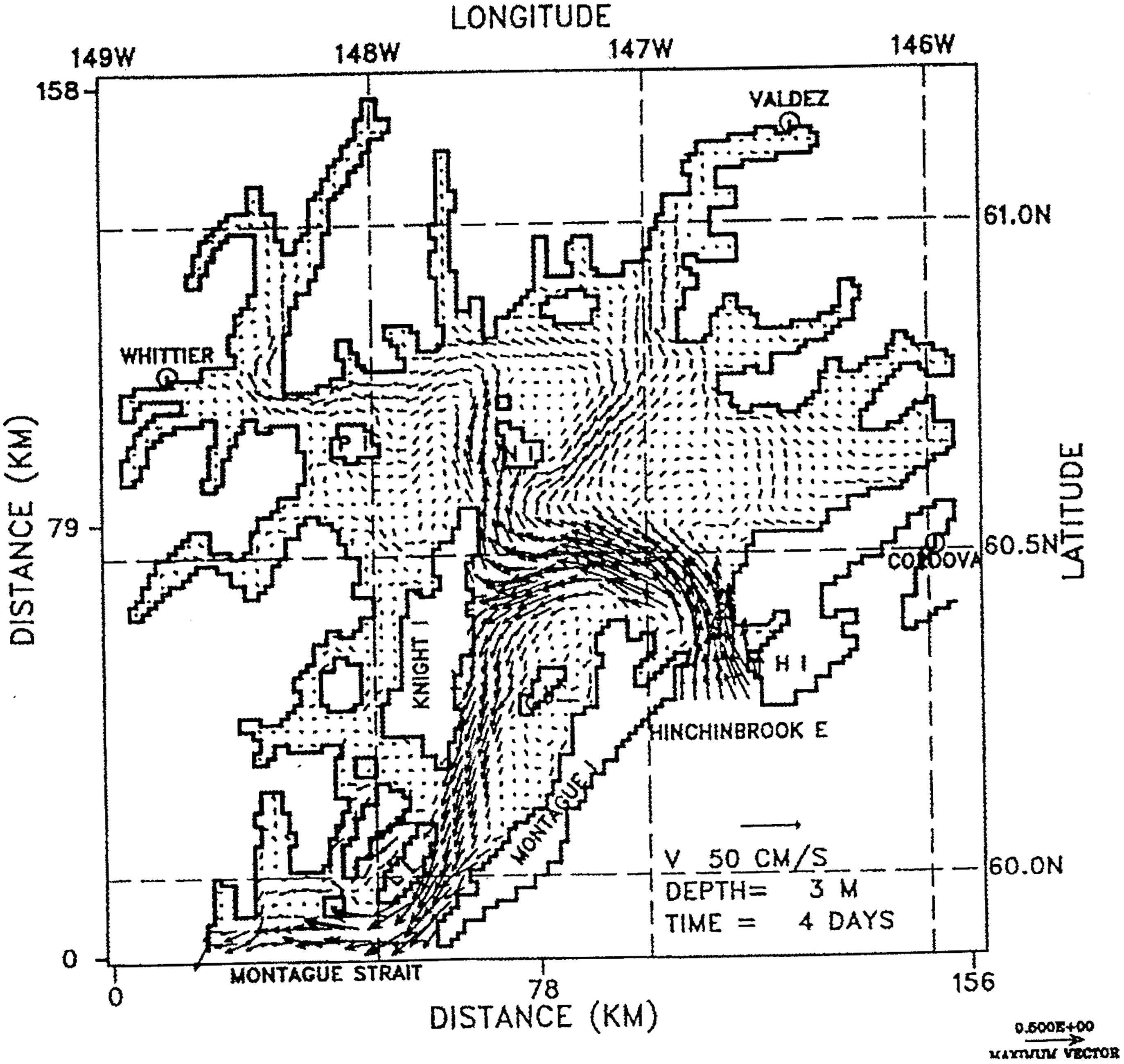

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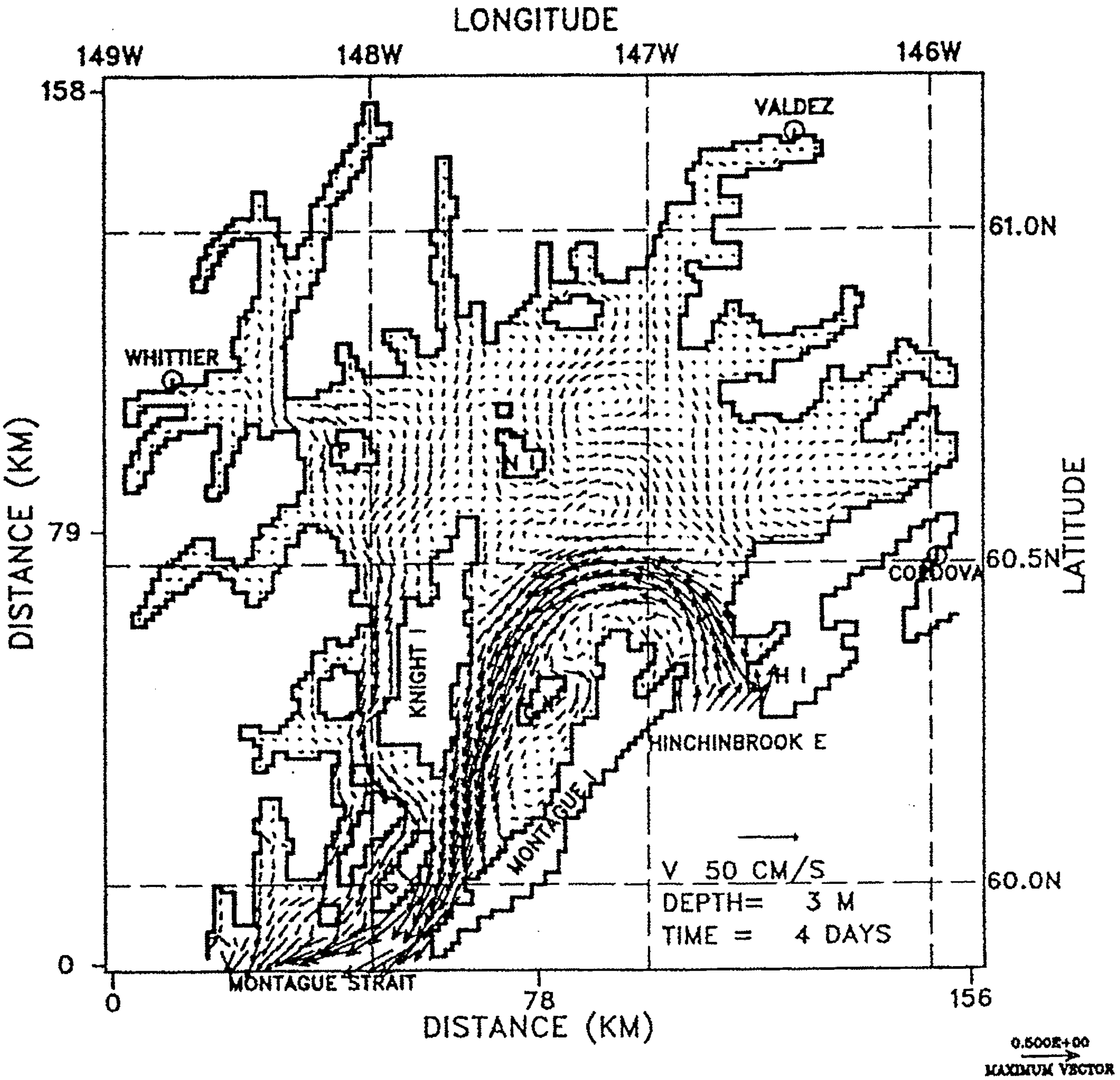
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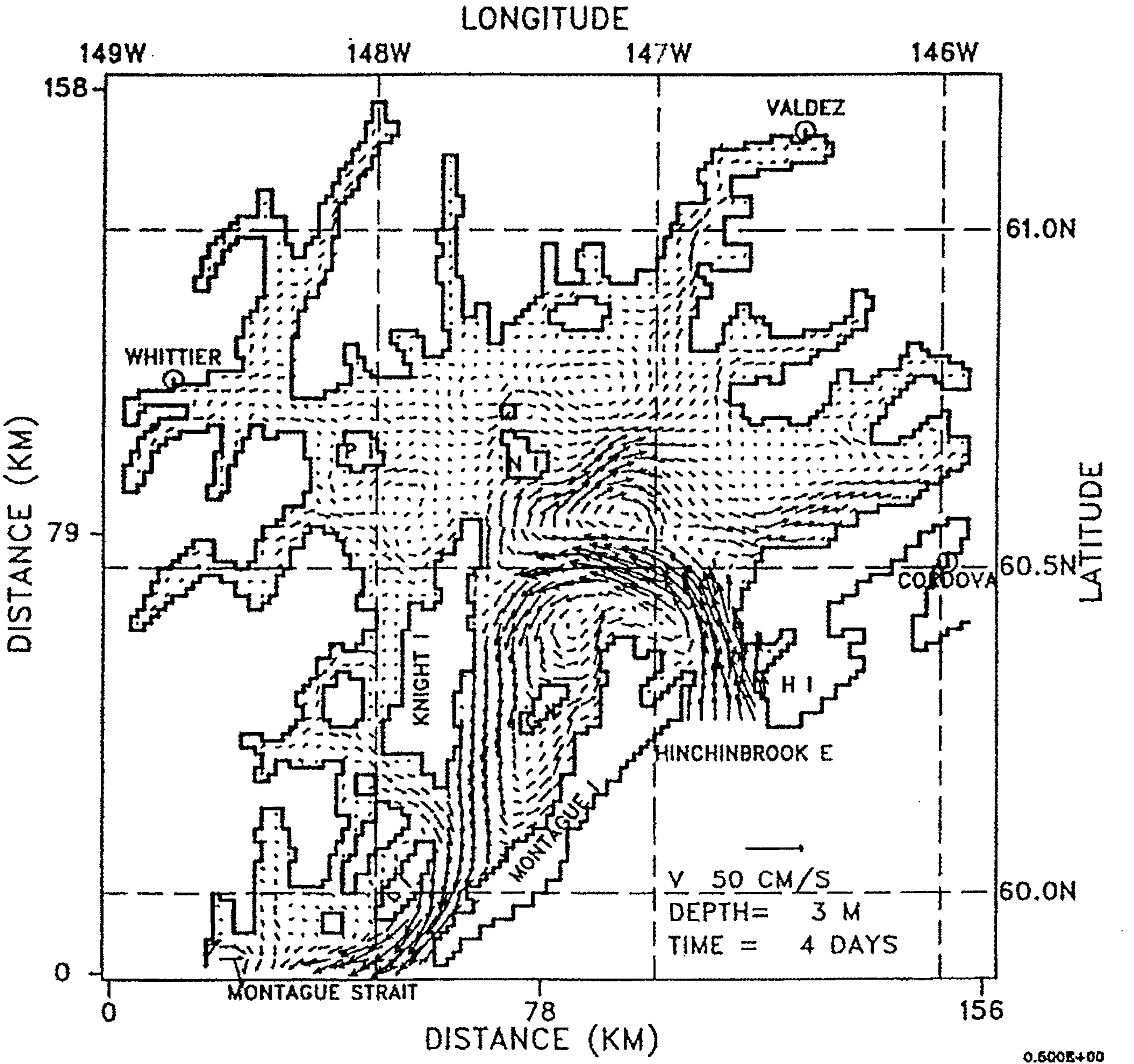
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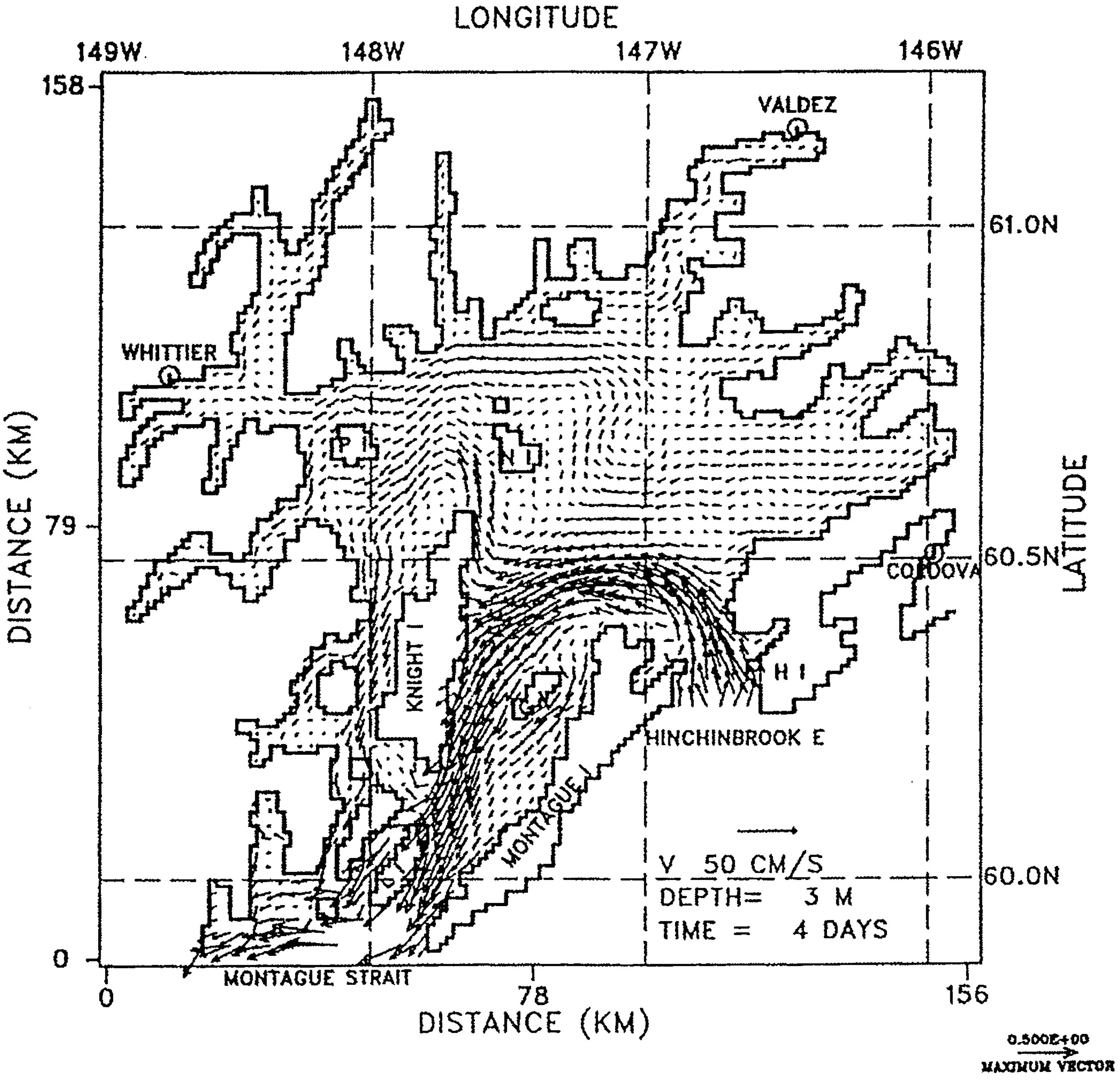
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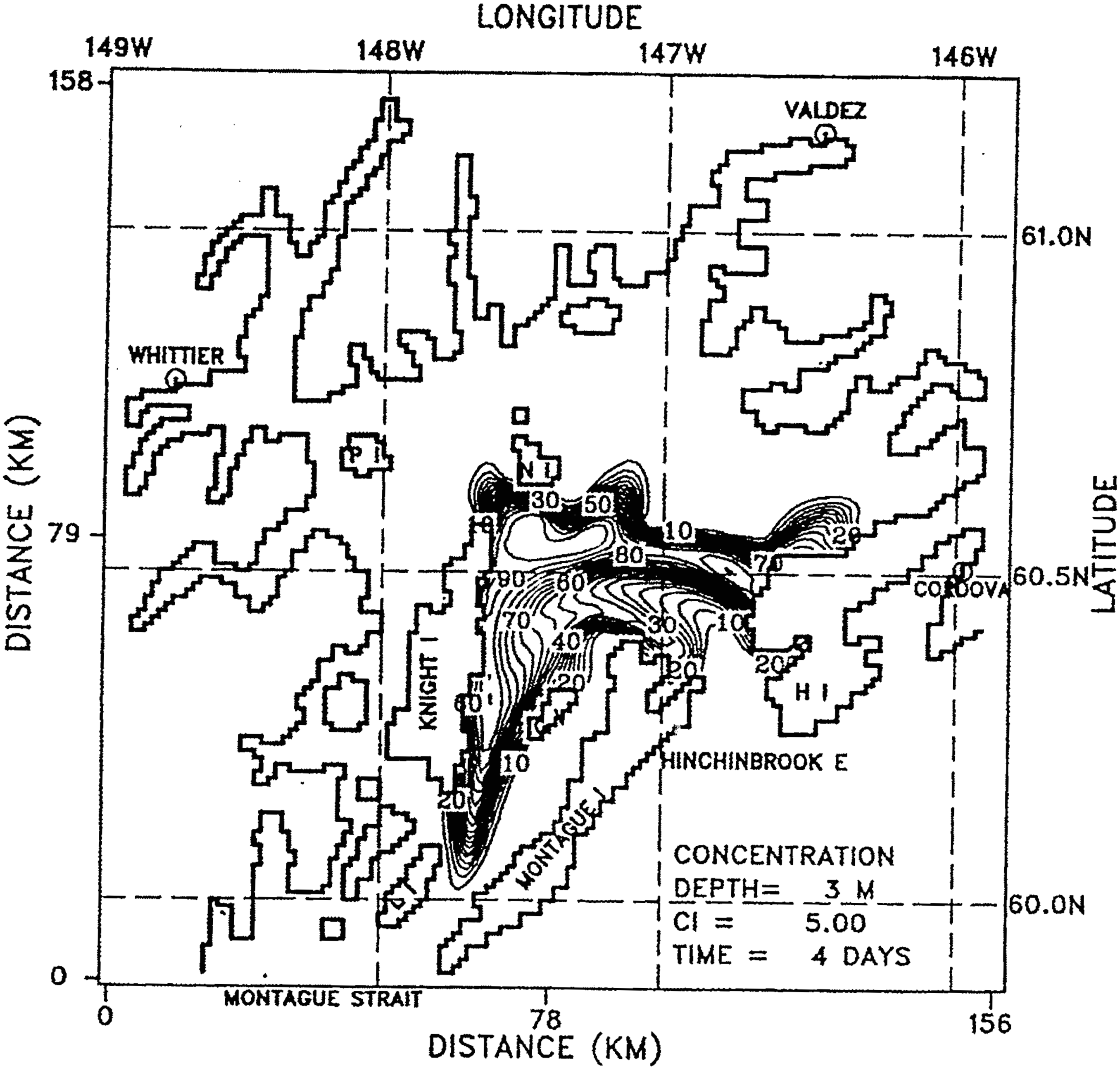

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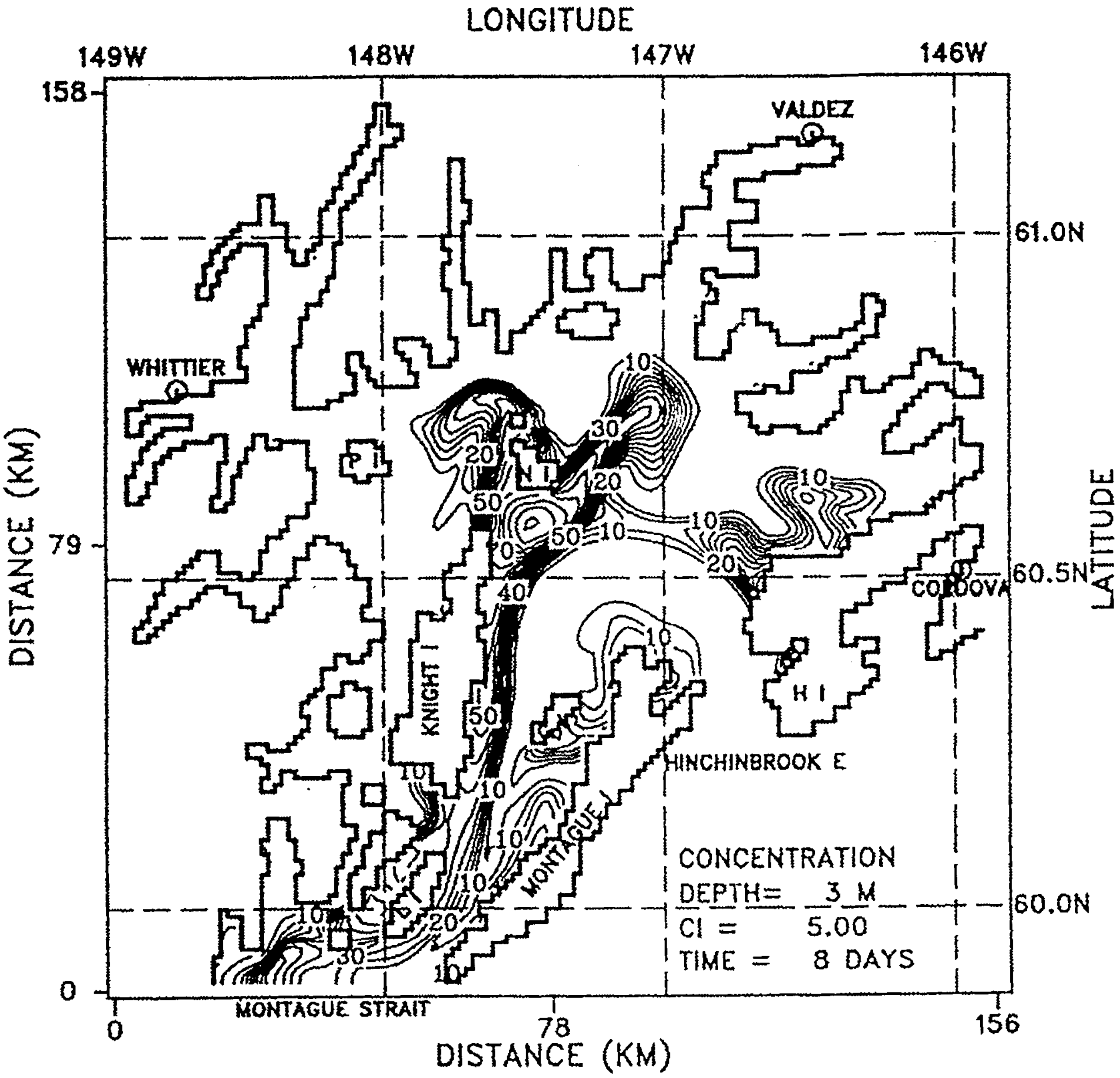
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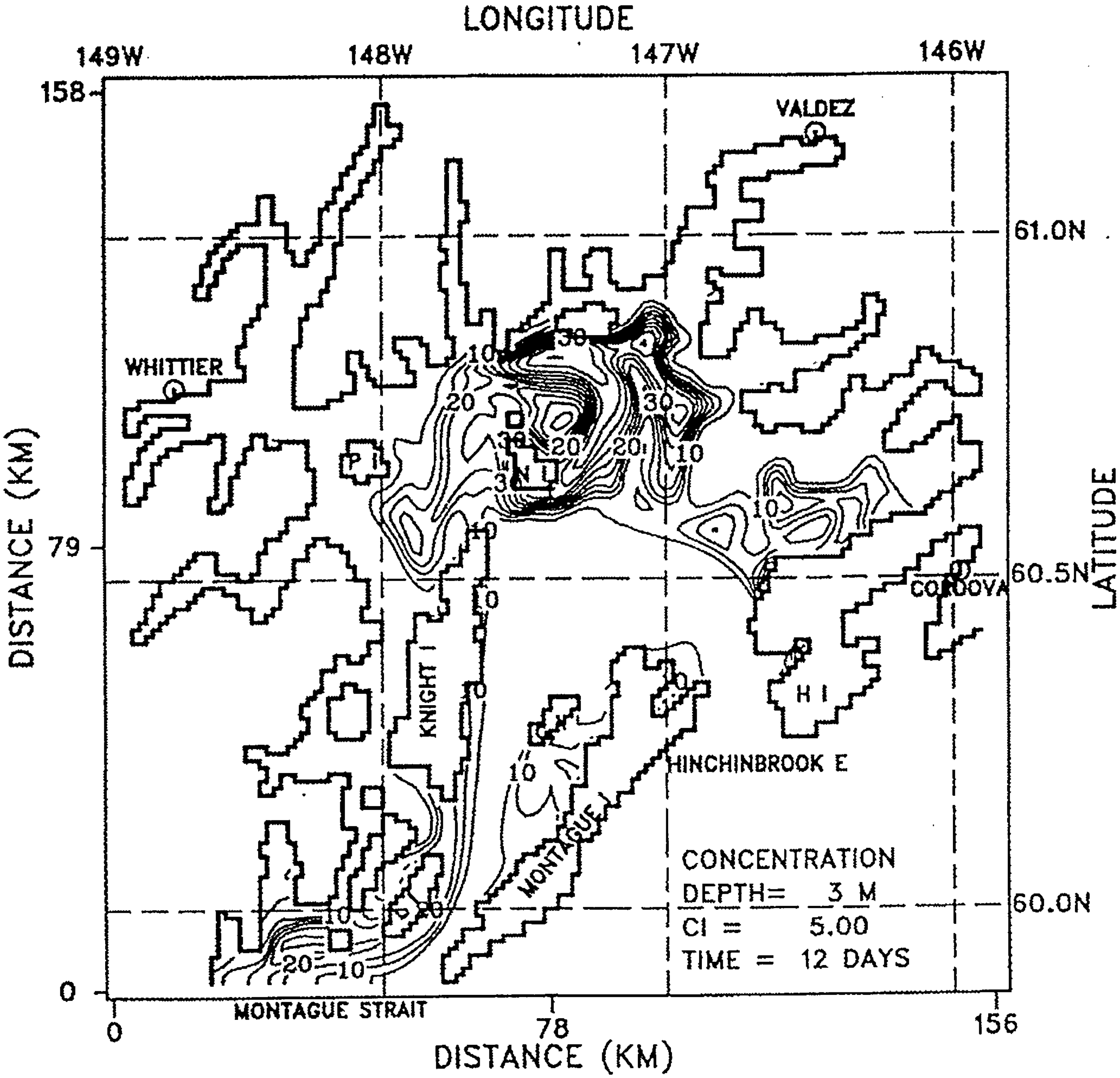
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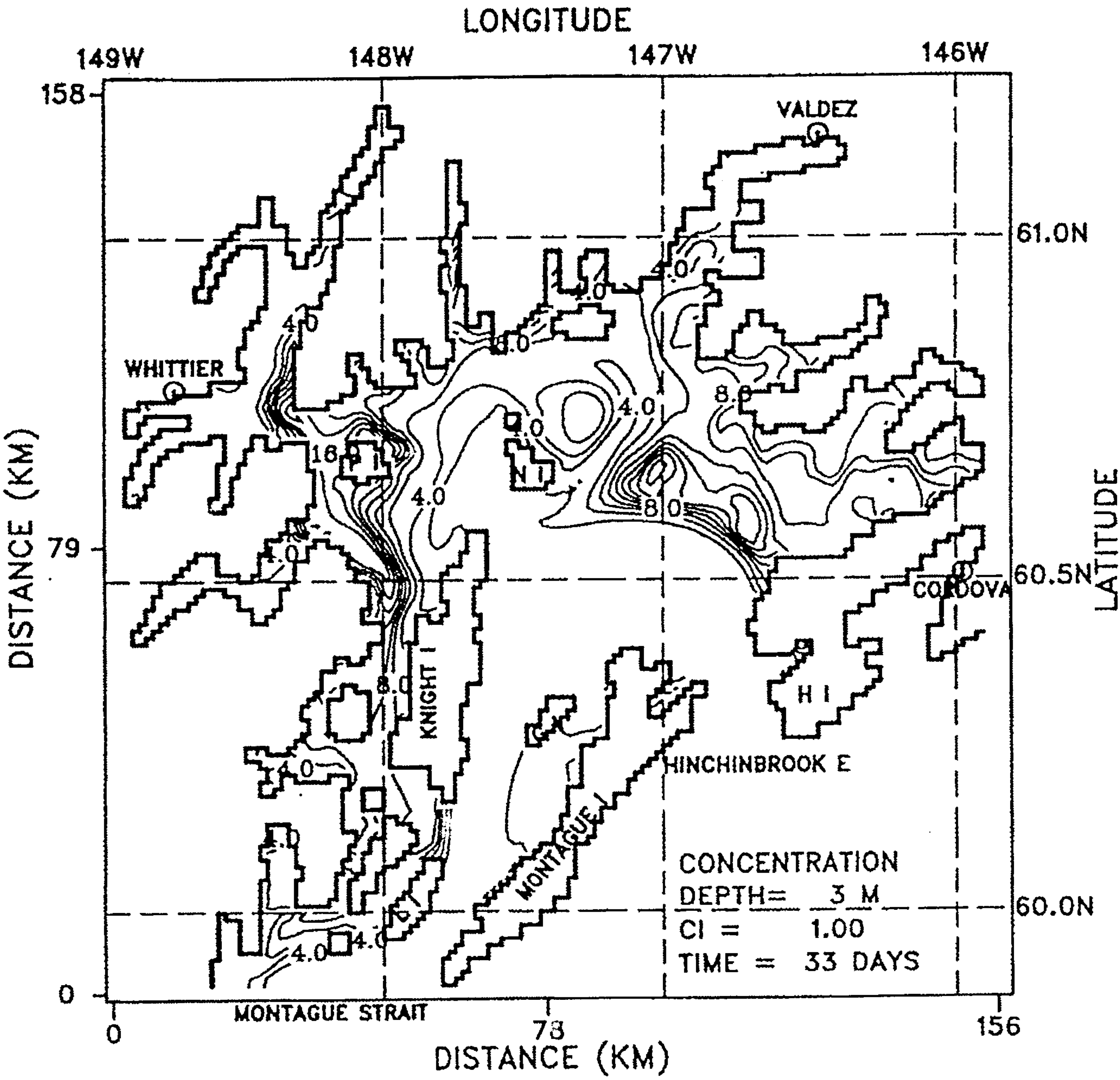
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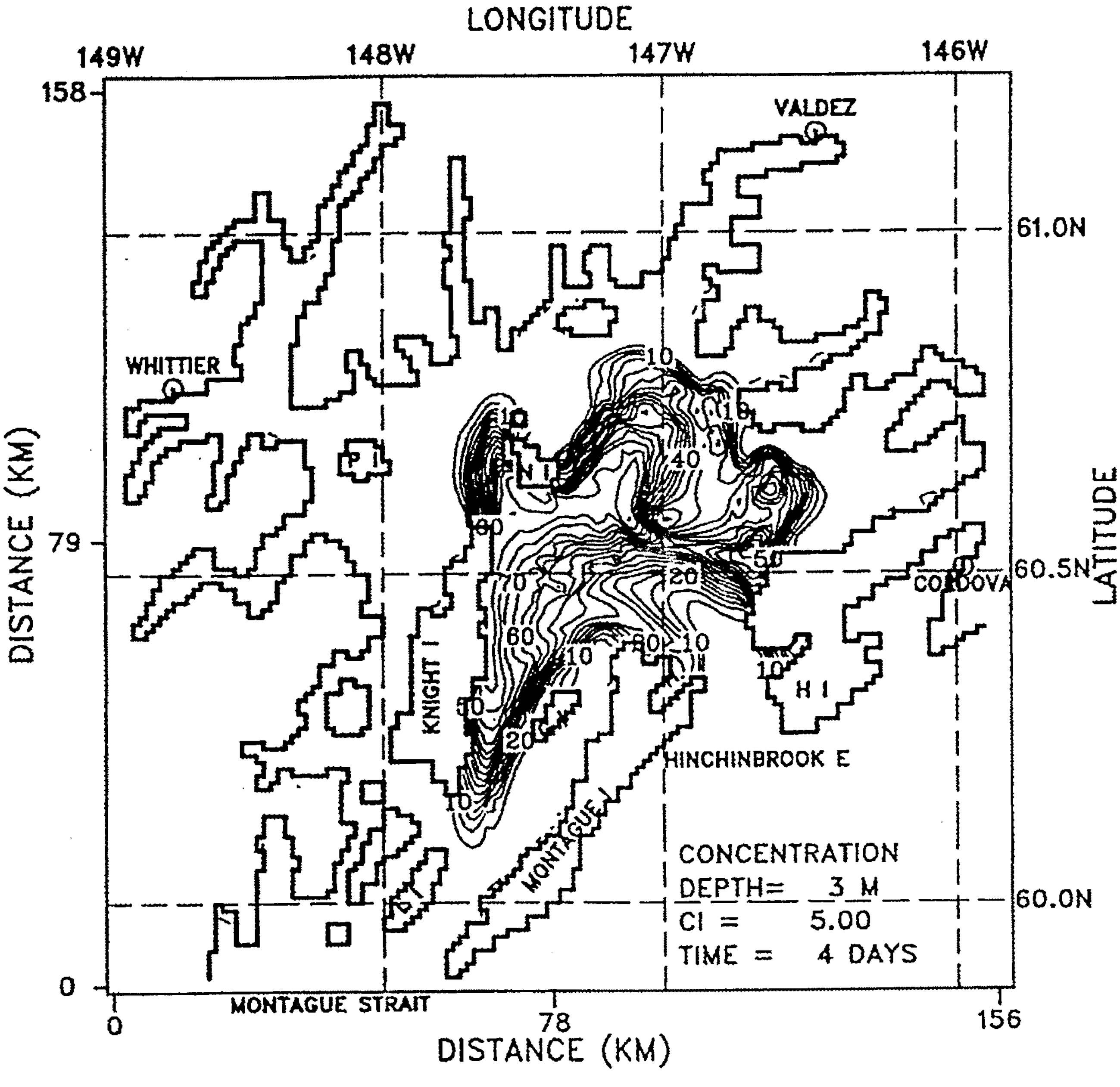

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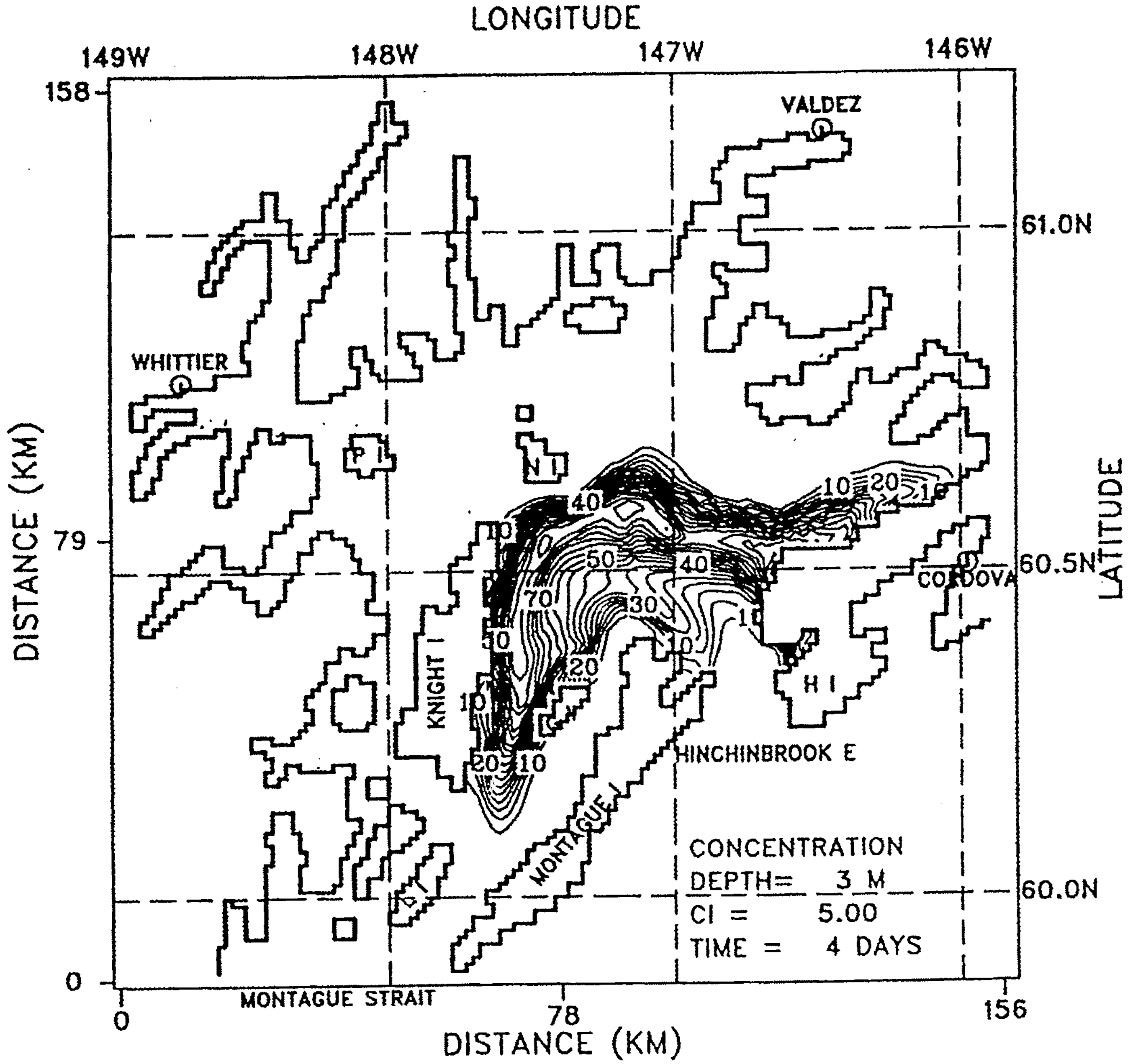

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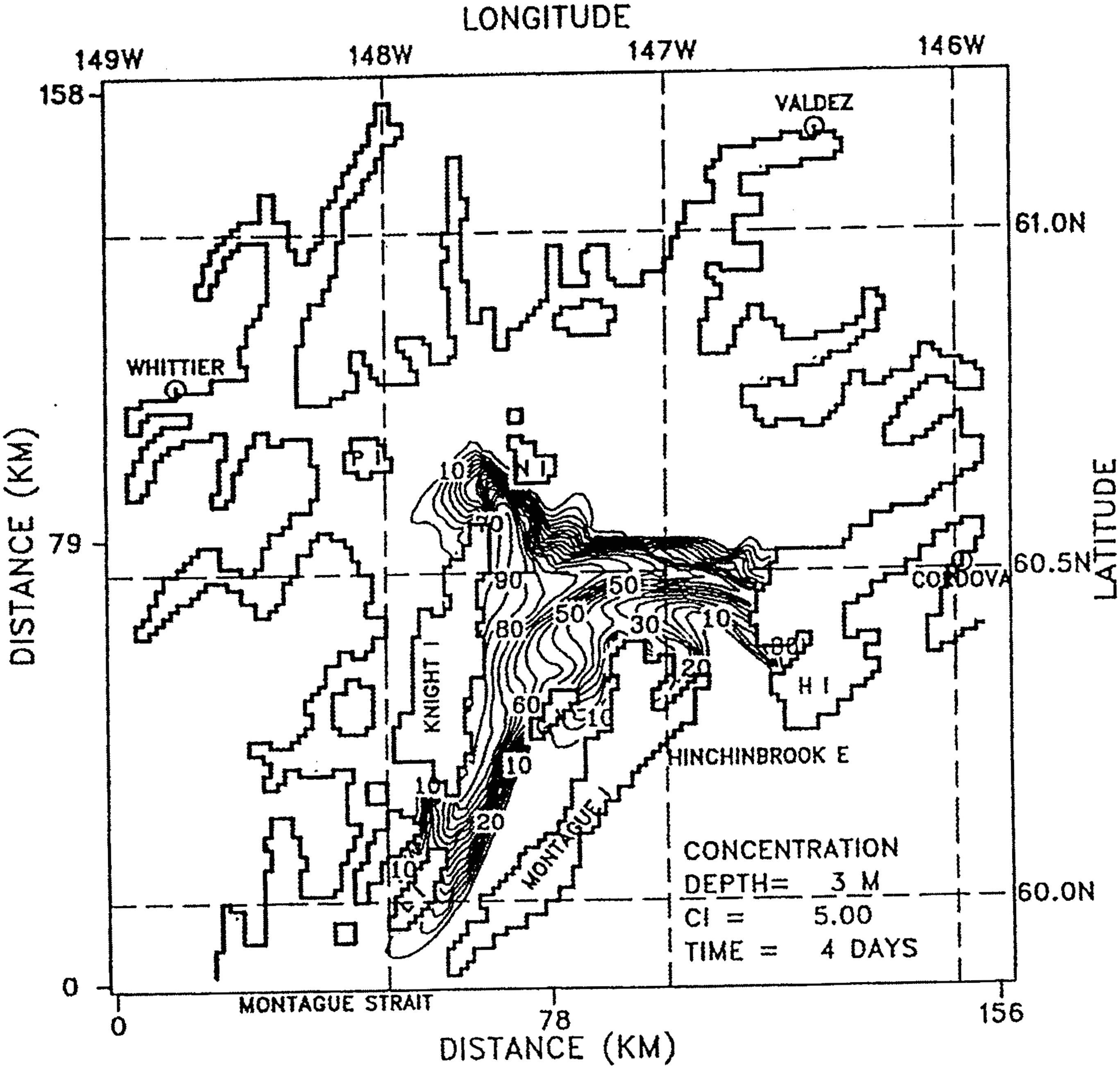
CI = 5.00
TIME = 4 DAYS
0
78
156
DISTANCE (KM)


LONGITUDE
149W
148W
147W
146W
158
79
0
61.0N
60.5N
60.0N
LATITUDE
DISTANCE (KM)
VALDEZ
WHITTIER
CORDOVA
P I
N I
KNIGHT I
H I
HINCHINBROOK E
MONTAGUE I
MONTAGUE STRAIT
0
78
156
DISTANCE (KM)
CONCENTRATION
DEPTH= 3 M
CI = 5.00
TIME = 4 DAYS

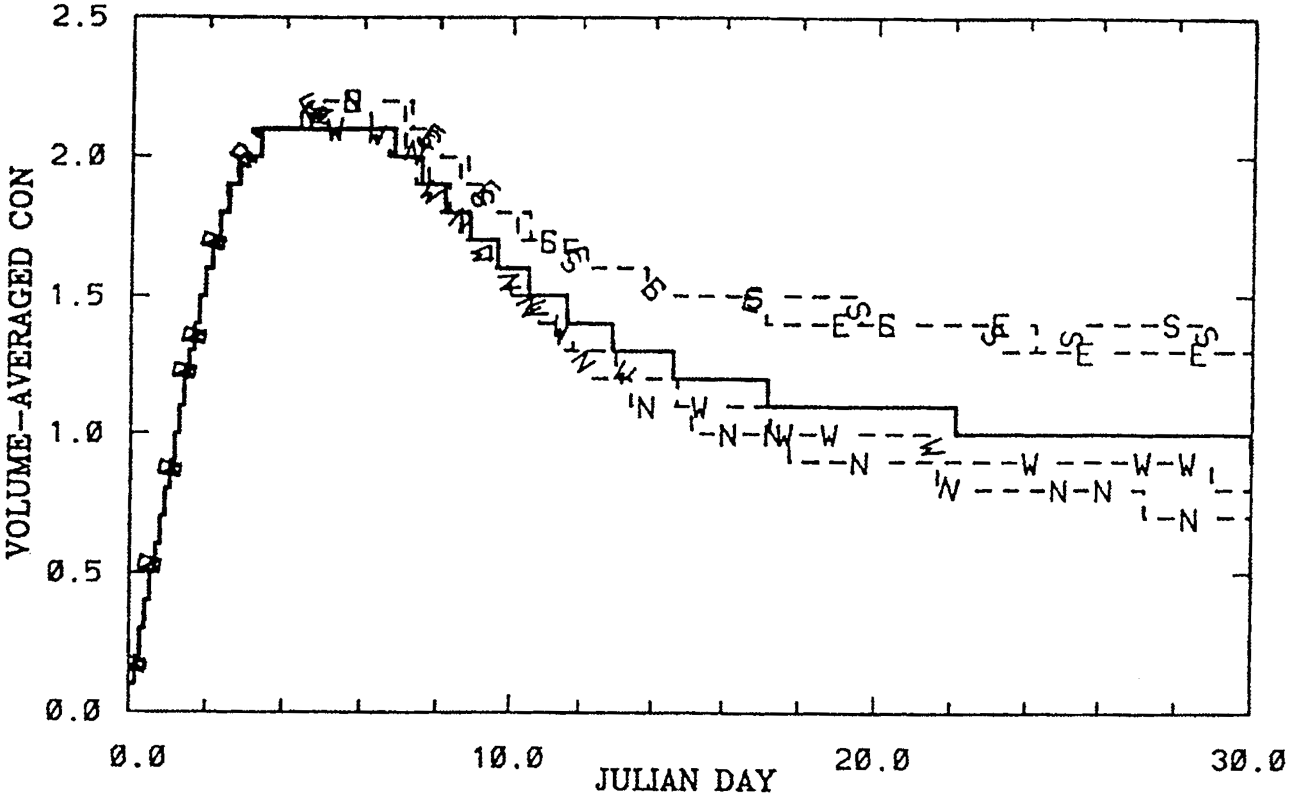


Fig. 12. The time series of volume averaged concentrations in Prince William Sound for the control run (no wind case, solid line), and for the wind forcing a) westward (denoted by E), b) eastward (denoted by W), c) northward (denoted by S), and d) southward (denoted by N).

Appendix 4

Progress Report 1 (1996) on the development of the 2D and 3D SEA nekton model

PROGRESS REPORT 1 (1996)

RICARDO H. NOCHETTO and SRIDHAR RAO

1. Formulation of 2D hybrid and mixed methods. Consider the scalar advection-diffusion PDE arising from the taxis model for population interactions

$$\partial_t u - \text{div}\,\left(D\nabla u + \chi\ u\nabla\lambda\right) = f \qquad \text{in } \Omega.$$

Here u is the population density and Ω is a bounded, but otherwise arbitrary, domain in $\mathbf{R}^2$. After discretization in time with backward finite differences with time-step Δt, and using exponential fitting, (1) can be converted into the following elliptic PDE with variable diffusivity for the new unknown $\rho = u^n\ \exp(\lambda/\varepsilon)$ with $\varepsilon = D/\chi$:

$$\exp(-\lambda/\varepsilon)\rho - D\Delta t\ \text{div}\,\left(\exp(-\lambda/\varepsilon)\nabla\rho\right) = u^{n-1} + \Delta t f^{n-1}. \tag{2}$$

We devised both a hybrid and mixed method for space discretization of (2), thereby extending the results of [3,4]. The former, which is being implemented, exhibits exact mass conservation, a very desirable property.

2. Scaled exponentials in 2D. The resulting method in the variable ρ is symmetric but subject to severe limitations due to the occurrence of exponentials. This is much like what happens in 1D, as is a way around it. The idea is thus to rescaled back to the original variables u, which should possess a moderate size. This destroys the symmetry, and requires a carefull elementwise calculation of compensating exponential that allow for cancellation. This computation is performed exactly, since quadrature may yield unacceptably large errors and limit the applicability of our scheme. The desired integrals are thus computed on the master element, depending on the relative values of taxis λ at the nodes. This has already been implemented and is being tested.

3. GMRES. The effective solution of the resulting *nonsymmetric* linear system has been carried out by LU decomposition in 1D. The computational cost of this direct method may be prohibitive in 2D, and specially in 3D, due to fill-in. The generalized minimal residual method (GMRES) of [7] appears to be the iterative method of choice. We studied its fundamentals, and practiced with several implementations of it. The critical point, still to be assessed for (2), is the design of an effective preconditioner.

4. Recursive enrichment/coarsening mesh adaptation. To optimize the computational effort, and make it possible in 3D, it is crucial to exploit mesh and time stepping adaptation capabilities. The simplest and most effective way to migrate from 2D to 3D is to use bisection techniques for mesh adaptation. We studied its use for enrichment/coarsening of a mesh [1], along with its recursive implementation [5]. This is an essential component of Bänsch code, and is rather problem independent. What remains to be studied is an error estimator suitable for (1) in both advection dominated and diffusion dominated regimes.

Typeset by $\mathcal{A}_{\mathcal{M}}\mathcal{S}$-TEX

5. Review of finite element packages. We have experimented with several codes for finite element computations in 2D, namely KASKADE [2], MGGHAT [6], and a code by Bänsch that is very flexible and incorporates the recursive enrichment/coarsening strategies of §4. We will experiment more with the latter, and work in collaboration with Bänsch in the design, implementation, and full testing of a code for 2D simulations of the taxis model (1).

REFERENCES

1. E. Bänsch, *Local mesh refinement in 2 and 3 dimensions*, Impact Comput. Sci. Engrg. **3** (1991), 181–191.
2. R. Beck, B. Erdmann, and R. Roitzsch, *KASKADE 3.0 User's Guide* (1996).
3. F. Brezzi and M. Fortin, *Mixed and Hybrid Finite Element Methods*, Springer, New York, 1991.
4. F. Brezzi, L.D. Marini, and P. Pietra, *Two-dimensional exponential fitting and applications to drift-diffusion models*, SIAM J. Numer.Anal. **26** (1989), 1342–1355.
5. I. Kossaczky, *A recursive approach to local mesh refinement in two and three dimensions*, J. Comput. Appl. Math. **55** (1994), 275–288.
6. W.F. Mitchell, *MGGHAT User's Guide Version 1.1* (1995).
7. Y. Saad and M.H. Schultz, *GMRES: A generalized minimal residual algorithm for solving non-symmetric linear systems*, SIAM J. Sci. Statist. Comput. **7** (1986), 856–869.

Appendix 5

Task Report
Applegate Rock Meteorological Station

with 4 figures

Figure 1: The SEA web site home page ... SEA weather page ...
Figure 2: The web interface to the Applegate Rock weather data.
Figure 3: Applegate data presentation, tabular format.
Figure 4: Applegate data presentation, graphic format.

TASK REPORT:
Applegate Rock Meteorological Station

Stephen Bodnar and Jennifer Allen

April 1996

ABSTRACT

Installation of meteorological monitoring equipment at Applegate Rock, northeast of Green Island in Prince William Sound, and development of an automated system for data download and processing, were completed as part of EVOS restoration project #96320J. Half-hourly observations of nine air temperature, air pressure, wind direction, wind speed and light intensity parameters are downloaded daily via the SEA packet radio network. The data are served in tabular and graphic form via the SEA weather site on the world wide web.

TECHNICAL REPORT

The objective of the Applegate Rock weather station is to provide near realtime weather data for two primary purposes: (1) informing the SEA project regarding local weather conditions in the important herring spawning areas of Green Island and the north end of Montague Island; and (2) providing nowcast/forecast forcing input to the ocean circulation model.

The weather station equipment was installed on April 19, 1996. Modifications and maintenance were performed on 7/5/96, 9/6/96, 11/7/96, 2/14/97, 2/18/97, 3/1/97. The following instruments are present:

Wind:	R. M. Young 05103-5 Wind Monitor
Air Temperature:	CS-107B thermistor
Barometric Pressure:	Vaisala PTB101B
Pyranometer:	LiCor LI200X
Datalogger:	Campbell Scientific CR10
Power Supply :	9 x 1.5v AirCel batteries, nonrechargeable

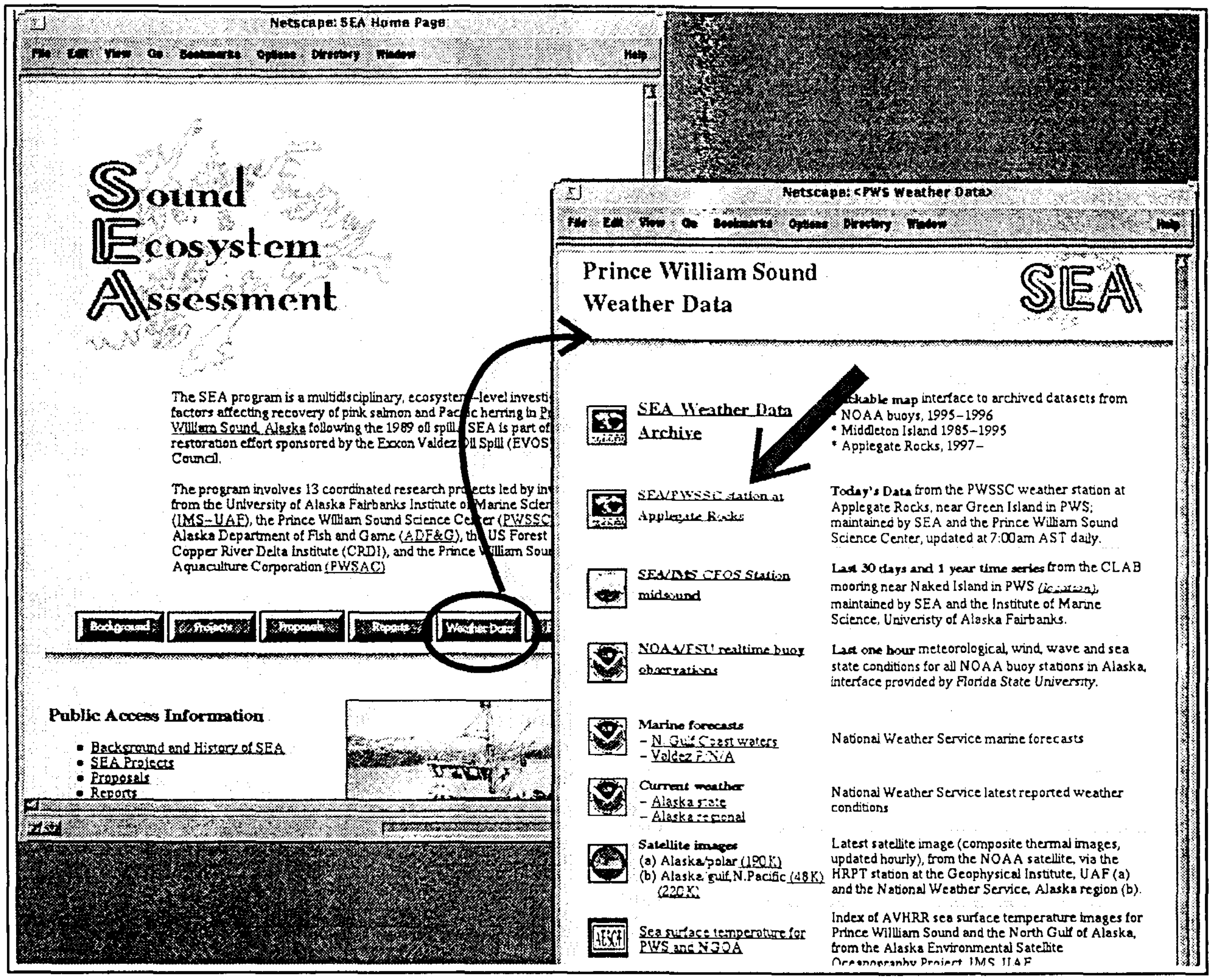
Half-hourly observations of minimum, maximum and mean air temperature, mean wind speed, maximum wind gust speed, wind direction and deviation, barometric pressure, and light level are stored in the CR10 datalogger, which also functions as the system clock. Once daily, for 3 hours beginning at 7:00 am, the datalogger switches on the computer and communications system. On bootup, the 486 communications controller executes a batch file which moves the most recent data from the datalogger to permanent storage on the computer. Before terminating, the batch file initializes the radio modem, putting it into standby mode. The modem then awaits daily contact, initiated by the weather data host computer at the Prince William Sound Science Center (PWSSC), to download the current 24 hours of data via the UHF packet radio network. This download from Applegate Rock to PWSSC is transmitted via the SEA packet radio repeater (digipeater) on Naked Island and is controlled by custom interrupt-driven DOS-based communications software written by Roy Murray of the SEADATA group.

Downloaded data are transferred immediately to the SEA Unix-based network by FTP to the PWSSC dataserver workstation, replacing the previous day's data which is automatically concatenated onto a year-to-date data file. At the same time the current system date and time is automatically stored for reference by the web server. The last line of the download/transfer script invokes a second script which automatically performs several functions preparatory to serving the data on the SEA world wide web site. This script (1) reformats the data from a comma delimited steam to a tab delimited table; (2) extracts four columns (mean temperature, air pressure, wind direction, wind speed) to be plotted; and (3) iteratively calls a plotting routine which plots the day's time series for each variable, converts each plot to GIF format, and generates an HTML coded file packaging the plots.

The data are served via the Applegate link on the SEA Weather web page (reached by the weather button at http://www.pwssc.gen.ak.us/sea/sea.html) (Figure 1). The Applegate page (Figure 2) is dynamically generated by a GCI script which creates the layout page, reads the date.txt file and displays a "date of last update" message at the top of the web page, as well as providing links to static information such as a map, photographs, key to variable units, documentation and history of the site. Two buttons near the bottom of this page provide access to the current day's data. The TABLE button activates a CGI script which generates a dynamic html header showing the last updated time-date of the data, and then reads and serves the previously formatted data table. It also provides links to a Julian day lookup table (Figure 3). The PLOT button links to the previously formatted HTML file containing the current day's plots (Figure 4).

This system allows automated processing of the downloaded data without human intervention, but without compromising speed of web access for users of the data. The table and plots are transparently generated and moved to web tree directories once per day at download time, thereby minimizing delay on responses to subsequent web access requests. Use of a CGI script behind the Applegate web page allows incorporation of dynamic date and time data or message information, but the retains speed by assembling the web pages from pre-built components.

Appendix 5, Figure 1



The SEA program is a multidisciplinary, ecosystem-level investi
factors affecting recovery of pink salmon and Pacific herring in Pr
William Sound, Alaska following the 1989 oil spill. SEA is part of
restoration effort sponsored by the Exxon Valdez Oil Spill (EVOS
Council.

The program involves 13 coordinated research projects led by inv
from the University of Alaska Fairbanks Institute of Marine Scien
(IMS-UAF), the Prince William Sound Science Center (PWSSC
Alaska Department of Fish and Game (ADF&G), the US Forest
Copper River Delta Institute (CRDI), and the Prince William Sou
Aquaculture Corporation (PWSAC)

Public Access Information

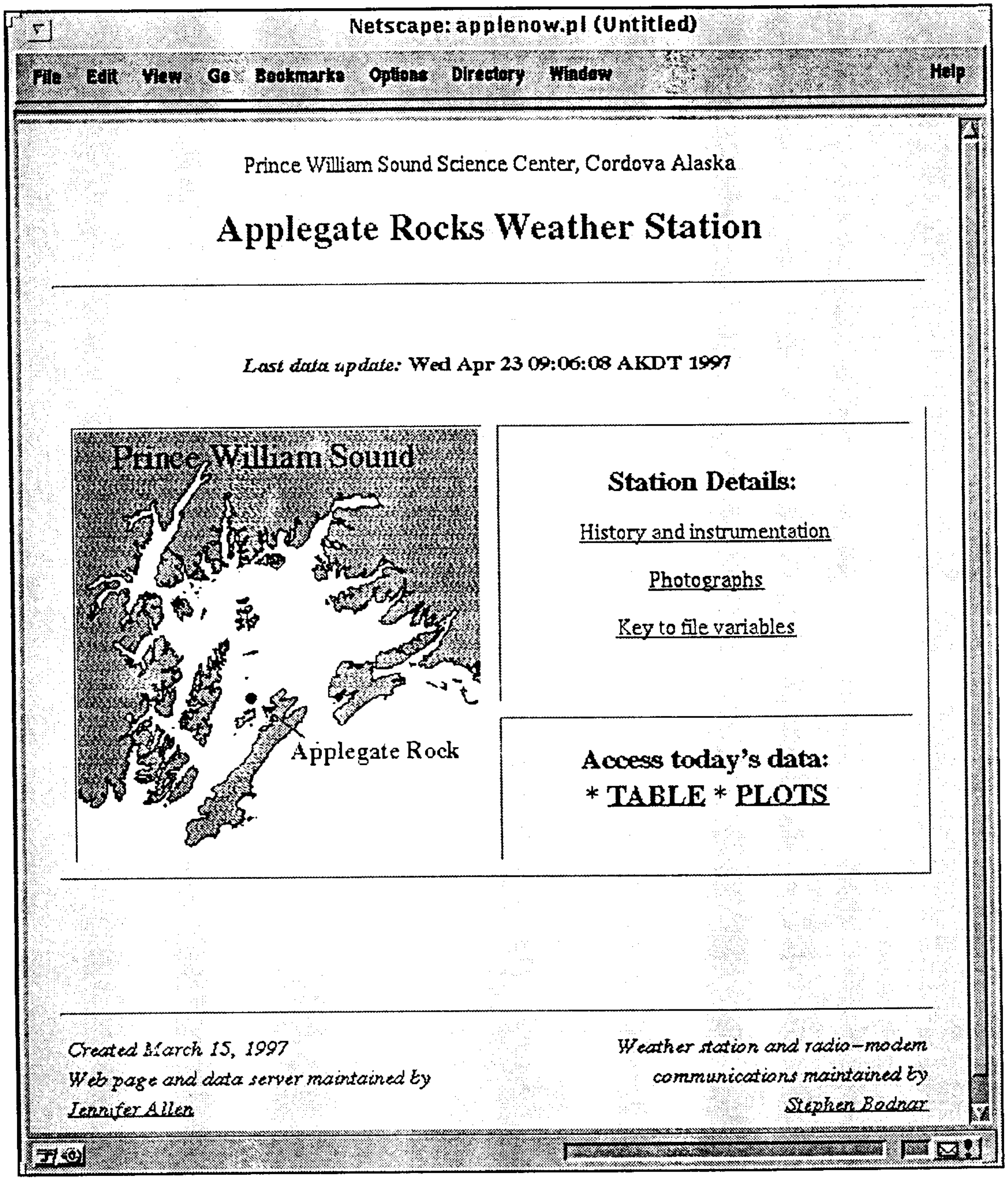
- Background and History of SEA
- SEA Projects
- Proposals
- Reports

Prince William Sound Weather Data

SEA Weather Data Archive	**ckable map** interface to archived datasets from * NOAA buoys, 1995–1996 * Middleton Island 1985–1995 * Applegate Rocks, 1997–
SEA/PWSSC station at Applegate Rocks	**Today's Data** from the PWSSC weather station at Applegate Rocks, near Green Island in PWS; maintained by SEA and the Prince William Sound Science Center, updated at 7:00am AST daily.
SEA/IMS CFOS Station midsound	**Last 30 days and 1 year time series** from the CLAB mooring near Naked Island in PWS (location), maintained by SEA and the Institute of Marine Science, Univeristy of Alaska Fairbanks.
NOAA/FSU realtime buoy observations	**Last one hour** meteorological, wind, wave and sea state conditions for all NOAA buoy stations in Alaska, interface provided by *Florida State University*.
Marine forecasts – N. Gulf Coast waters – Valdez F.N/A	National Weather Service marine forecasts
Current weather – Alaska state – Alaska regional	National Weather Service latest reported weather conditions
Satellite images (a) Alaska/polar (190K) (b) Alaska/gulf,N.Pacific (48K) (220K)	Latest satellite image (composite thermal images, updated hourly), from the NOAA satellite, via the HRPT station at the Geophysical Institute, UAF (a) and the National Weather Service, Alaska region (b).
Sea surface temperature for PWS and NGOA	Index of AVHRR sea surface temperature images for Prince Willliam Sound and the North Gulf of Alaska, from the Alaska Environmental Satellite Oceanography Project, IMS, UAF

Figure 1: The SEA web site home page (left) and main SEA weather page. The Applegate link is indicated

Appendix 5, Figure 2



Prince William Sound Science Center, Cordova Alaska

Applegate Rocks Weather Station

Last data update: **Wed Apr 23 09:06:08 AKDT 1997**

Station Details:

History and instrumentation

Photographs

Key to file variables

Access today's data:

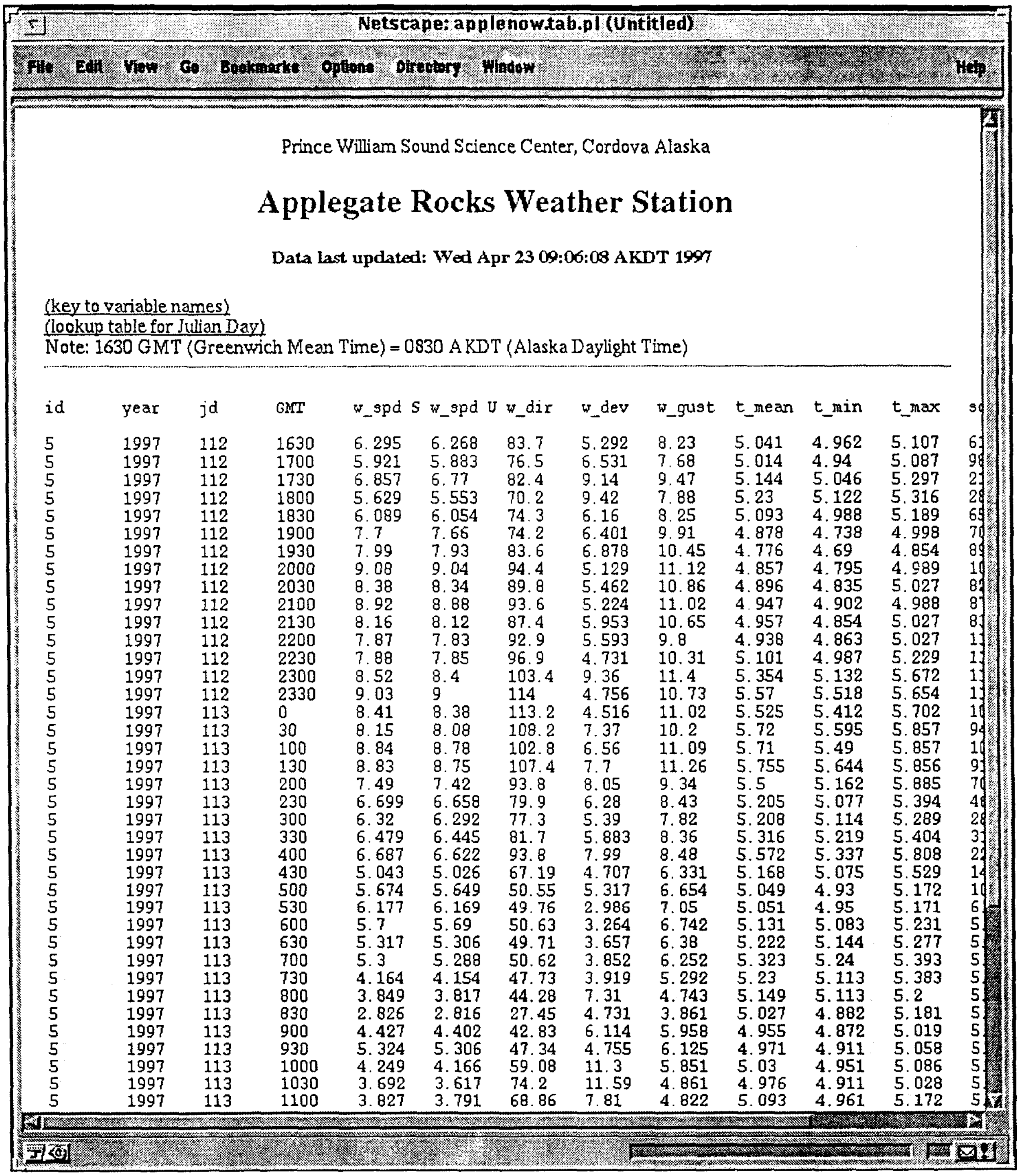
*** TABLE * PLOTS**

Created March 15, 1997
Web page and data server maintained by
Jennifer Allen

Weather station and radio-modem
communications maintained by
Stephen Bodnar

Figure 2: The web interface to the Applegate Rock weather data.

Appendix 5, Figure 3



Prince William Sound Science Center, Cordova Alaska

Applegate Rocks Weather Station

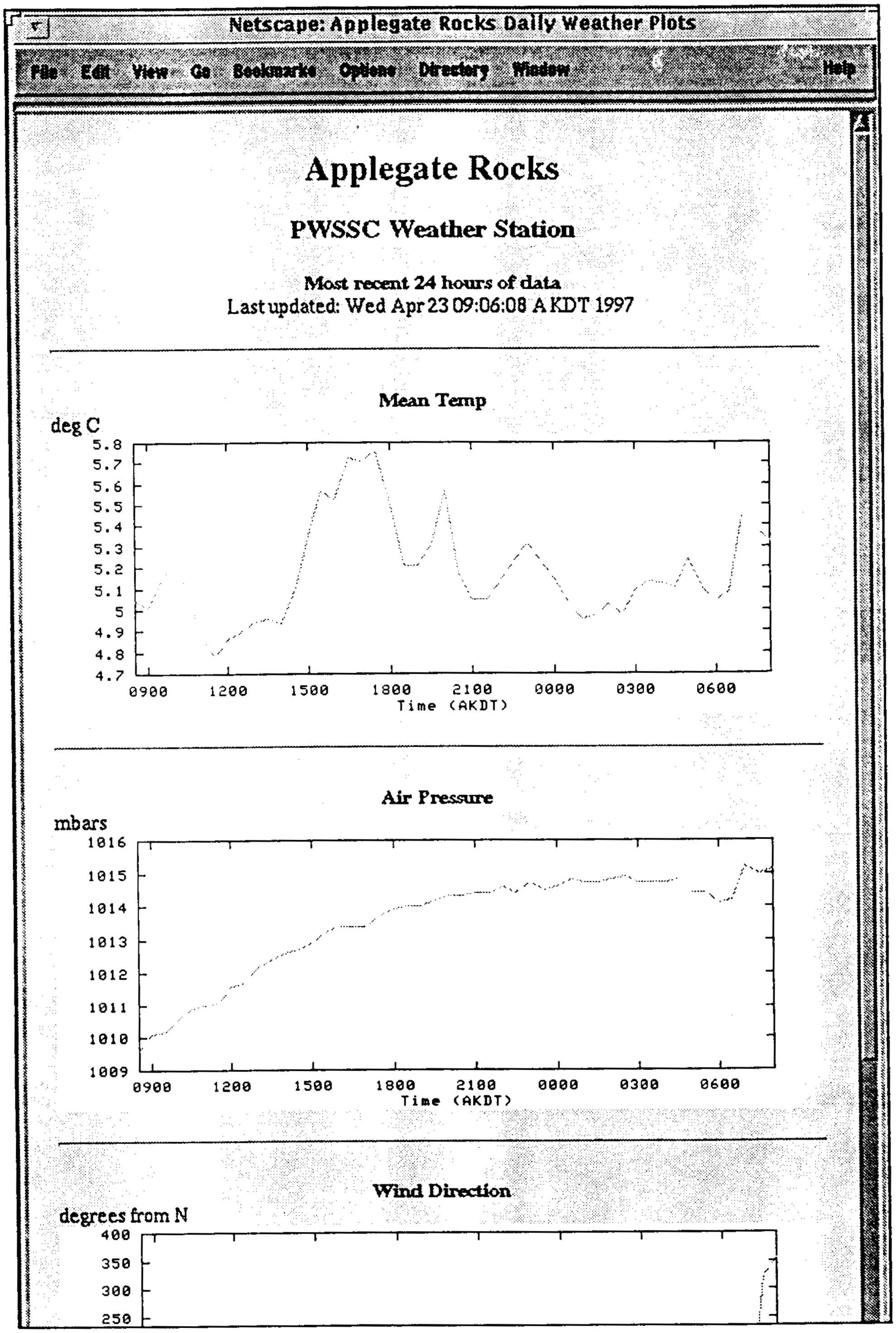
Data last updated: Wed Apr 23 09:06:08 AKDT 1997

(key to variable names)
(lookup table for Julian Day)
Note: 1630 GMT (Greenwich Mean Time) = 0830 AKDT (Alaska Daylight Time)

id	year	jd	GMT	w_spd S	w_spd U	w_dir	w_dev	w_gust	t_mean	t_min	t_max
5	1997	112	1630	6.295	6.268	83.7	5.292	8.23	5.041	4.962	5.107
5	1997	112	1700	5.921	5.883	76.5	6.531	7.68	5.014	4.94	5.087
5	1997	112	1730	6.857	6.77	82.4	9.14	9.47	5.144	5.046	5.297
5	1997	112	1800	5.629	5.553	70.2	9.42	7.88	5.23	5.122	5.316
5	1997	112	1830	6.089	6.054	74.3	6.16	8.25	5.093	4.988	5.189
5	1997	112	1900	7.7	7.66	74.2	6.401	9.91	4.878	4.738	4.998
5	1997	112	1930	7.99	7.93	83.6	6.878	10.45	4.776	4.69	4.854
5	1997	112	2000	9.08	9.04	94.4	5.129	11.12	4.857	4.795	4.989
5	1997	112	2030	8.38	8.34	89.8	5.462	10.86	4.896	4.835	5.027
5	1997	112	2100	8.92	8.88	93.6	5.224	11.02	4.947	4.902	4.988
5	1997	112	2130	8.16	8.12	87.4	5.953	10.65	4.957	4.854	5.027
5	1997	112	2200	7.87	7.83	92.9	5.593	9.8	4.938	4.863	5.027
5	1997	112	2230	7.88	7.85	96.9	4.731	10.31	5.101	4.987	5.229
5	1997	112	2300	8.52	8.4	103.4	9.36	11.4	5.354	5.132	5.672
5	1997	112	2330	9.03	9	114	4.756	10.73	5.57	5.518	5.654
5	1997	113	0	8.41	8.38	113.2	4.516	11.02	5.525	5.412	5.702
5	1997	113	30	8.15	8.08	108.2	7.37	10.2	5.72	5.595	5.857
5	1997	113	100	8.84	8.78	102.8	6.56	11.09	5.71	5.49	5.857
5	1997	113	130	8.83	8.75	107.4	7.7	11.26	5.755	5.644	5.856
5	1997	113	200	7.49	7.42	93.8	8.05	9.34	5.5	5.162	5.885
5	1997	113	230	6.699	6.658	79.9	6.28	8.43	5.205	5.077	5.394
5	1997	113	300	6.32	6.292	77.3	5.39	7.82	5.208	5.114	5.289
5	1997	113	330	6.479	6.445	81.7	5.883	8.36	5.316	5.219	5.404
5	1997	113	400	6.687	6.622	93.8	7.99	8.48	5.572	5.337	5.808
5	1997	113	430	5.043	5.026	67.19	4.707	6.331	5.168	5.075	5.529
5	1997	113	500	5.674	5.649	50.55	5.317	6.654	5.049	4.93	5.172
5	1997	113	530	6.177	6.169	49.76	2.986	7.05	5.051	4.95	5.171
5	1997	113	600	5.7	5.69	50.63	3.264	6.742	5.131	5.083	5.231
5	1997	113	630	5.317	5.306	49.71	3.657	6.38	5.222	5.144	5.277
5	1997	113	700	5.3	5.288	50.62	3.852	6.252	5.323	5.24	5.393
5	1997	113	730	4.164	4.154	47.73	3.919	5.292	5.23	5.113	5.383
5	1997	113	800	3.849	3.817	44.28	7.31	4.743	5.149	5.113	5.2
5	1997	113	830	2.826	2.816	27.45	4.731	3.861	5.027	4.882	5.181
5	1997	113	900	4.427	4.402	42.83	6.114	5.958	4.955	4.872	5.019
5	1997	113	930	5.324	5.306	47.34	4.755	6.125	4.971	4.911	5.058
5	1997	113	1000	4.249	4.166	59.08	11.3	5.851	5.03	4.951	5.086
5	1997	113	1030	3.692	3.617	74.2	11.59	4.861	4.976	4.911	5.028
5	1997	113	1100	3.827	3.791	68.86	7.81	4.822	5.093	4.961	5.172

Figure 3: Applegate data presentation, tabular format

Appendix 5, Figure 4



Applegate Rocks

PWSSC Weather Station

Most recent 24 hours of data
Last updated: Wed Apr 23 09:06:08 AKDT 1997

Figure 4: Applegate data presentation, graphic format

Chapter 7.

Experimental Fry Releases (96320K)

Exxon Valdez Oil Spill
Restoration Project Annual Report

PWSAC - PWS System Investigation - Experimental Fry Release

Restoration Project 96320K
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Howard Ferren
Jeff Milton

Prince William Sound Aquaculture Corporation
P.0. Box 1110
Cordova, Alaska 99574

for:

Alaska Department of Fish and Game
Habitat and Restoration Division
333 Raspberry Road
Anchorage, Alaska 99518-1599

April 1997

PWSAC - PWS System Investigation - Experimental Fry Release

Restoration Project 96320K
Annual Report

Study History: In support of the needs of Sound Ecosystem Assessment (SEA) researchers, Prince William Sound Aquaculture Corporation (PWSAC) continued the late release of large pink salmon fry from Wally Noerenberg (WNH) and Armin F. Koernig (AFK) hatcheries. This procedure allows SEA researchers to target and quantify pink salmon fry migration and interaction with predators. The 1996 release project was the third in a series of four years of planned releases: 94320K, 95320K, 96320K and proposed 97320K.

SEA is an ongoing *Exxon Valdez* oil spill (EVOS) Trustee Council program which focuses on the processes and mechanisms that regulate losses of fry and juveniles to predators after emergence from nearshore natal habitats. Hatchery produced pink salmon fry and returning adults may provide a test of the influence of ocean-entry timing and of fry size at ocean entry on losses to predators.

Abstract: Prince William Sound Aquaculture Corporation released 11.39 million hatchery pink salmon fry in 1996 from the Wally Noerenberg Hatchery (WNH) which had been reared to an average 1.13 grams. The fry were coded wire tagged in known tagged to untagged ratios prior to release thereby making assessments of early marine growth, life stage mortality and migration patterns possible by other SEA researchers. Additionally, 12.46 million fry were released from the Armin F. Keornig Hatchery. These were smaller, released earlier and were not targeted for direct observation and sampling like those fry released from WNH. However, they too were coded wire tagged prior to release at known tagged to untagged ratios for later identification as adults and evaluation for marine survival.

Key Words: *Exxon Valdez*, hatchery, marine survival, *Oncorhyncus gorbuscha*, pink salmon, Prince William Sound, Prince William Sound Aquaculture Corporation, Sound Ecosystem Assessment (SEA).

Project Data: (will be addressed in the final report)

Citation:
Ferren, H., J. Milton. 1996. PWSAC - PWS system investigation - experimental fry release, *Exxon Valdez* Oil Spill Restoration Project Annual Report, (Restoration Project 96320K), Prince William Sound Aquaculture Corporation, Cordova, Alaska.

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EXECUTIVE SUMMARY

The Experimental Release Project is an integral component of the Prince William Sound (PWS) Ecosystem Assessment (SEA) studies. Identifiable pink salmon *Oncorhynchus gorbuscha* are an excellent tool to test a central SEA recruitment hypothesis concerning time at ocean entry and fry size at ocean entry. Consequently, SEA researchers requested very large and late fry, relative to typical size and timing upon ocean entry, from the PWS Aquaculture Corporation (PWSAC). Additionally, by utilizing two release sites for the subject salmon fry, an increase in the spatial difference at ocean entry point allows researchers insight into subtle locational differences within the Sound.

Approximately 11.39 million pink salmon fry nurtured at Wally Noerenberg Hatchery were released on June 1-2, 1996 at an average size of approximately 1.2 grams each. 19,686 large, pink salmon fry were marked and tagged, making assessments by other SEA researchers of early marine growth, life stage mortality and migration patterns possible at a highly reasonable cost. Only fry released from WNH were targeted for recapture. Due to unusually warm surface waters a minor outbreak of *Vibrio* sp. bacteria occurred at Armin F. Koernig Hatchery and resulted in 2% fry mortality. To reduce potential for bacterial spread and increased mortality in the net pens, fry were released early (May 24), prior to fry reaching the target weight. Approximately 12.46 million fry were released at an average weight of 0.70 grams each.

The justification for the late-large rearing and release strategy is evidence from Alaska and elsewhere which suggests that fry size is an important determinant of salmon fry survival during early marine residence (Kaeriyama, 1989; Parker, 1971). Faster growing juveniles are thought to enjoy better marine survivals than slower growing fish.

INTRODUCTION

The knowledge garnered by SEA researchers in evaluating the changes occurring in the PWS ecosystem subsequent to *Exxon Valdez* oil spill, is vital to evaluating and defining the best approaches to efficiently, and effectively restore the many damaged marine resources and associated services. The key to understanding the complex species interactions that occur during critical early marine life stages requires an immense amount of effort and team work by many institutions, agencies, groups, and private individuals. The ecosystem level information that is now being developed will aid the *Exxon Valdez* Oil Spill Trustee Council and others in their restorative tasks assisting injured pink salmon and herring populations in PWS, as well as forming predictive models which will benefit resource managers and harvesters on into the future.

Identifiable as to salt water entry point, time, and size, salmon fry are required by SEA researchers. Consequently, PWSAC has made available its facilities, personnel and expertise. Releases of restoration and enhancement facility-nurtured pink salmon fry is, as indicated by the full SEA proposal, providing "...a powerful test of the influence of ocean-entry timing and fry size at ocean entry on losses to predators".

OBJECTIVES

The goal of this project is, through collaboration with the SEA program, to assist "to develop an ecosystem level understanding of the natural and man-caused factors influencing the production of pink salmon in PWS".

Specific objectives are:

A. Rear approximately 12 million early emerging fry each at the Wally Noerenberg Hatchery (WNH) on Esther Island and Armin F. Koernig Hatchery (AFK) on Evans Island to 1.5 grams live weight for release in mid-June.

B. Release fry from WNH coincident with SEA sampling program to allow direct observation of fry migration and predator interaction.

C. Determine the marine survivals of fry in experimental releases from coded wire-tagged individuals recovered in corporate escapement and common property fishery the following year.

D. Compare the marine survivals of late-released, larger fry with other releases at these same facilities.

METHODS

Project 96320K took place in PWS at the AFK facility located on Evans Island and the WHN facility sited on Esther Island. Site work commenced in February 1996.

Project pink salmon fry were designated from early outmigrants and weighed on average 0.25 grams wet weight, each. Volitional outmigration from PWSAC NOPAD incubators insured osmocompetence and optimum developmental fitness. After passing a bank of electronic counters (+/- 1% accuracy), fry were conveyed via flexible hose to 12m x 12m x 3m (432m^3) saltwater rearing pens. Approximately three million fry were held in each of four pens at WNH, and four million fry in each of three pens at AFK Hatchery (Table).

Prior to release, 1/2mm Coded Wire Tags (CWT) were applied to approximately 1 out of every 600 fry. Each pen of fry contained a unique code (Table 1). The CWT fry are integral to identification thus allowing tracking migration patterns of pink salmon fry, and estimation of growth and mortality patterns.

All fry were fed a standard commercial diet of soft, semi-moist fish food for between 68-84 days at WNH and 53-66 days at AFK Hatchery prior to release. Releases occurred on June 1-2 at WNH Hatchery and May 24 at AFK Hatchery. One small release group was held at AFK Hatchery until June 12. Weights varied (Table) and were the maximum technically feasible given the release dates.

Close coordination and communication occurred between SEA researchers and the hatchery personnel during the field season to assure SEA's sampling efforts were closely timed to releases of facility pink salmon fry. Releases were done in concert with shipboard sampling carried out by SEA research teams. Fry release data from the hatcheries was communicated to biologists stationed on board trawl and purse seine vessels. Thus, near shore and open water sampling was targeted on released fry as deemed necessary by collaborating researchers' experimental designs and judgment.

RESULTS

Within the constraints of the state of the science and art of fish cultural technology, PWS pink salmon's genetically determined scope for growth, budgetary reality, and collaborating researchers' experimental designs/timing requirements, the results were as close to planned objectives as are currently feasible. Please see the Table for the exact dates, weights, numbers, number mark/tagged, codes, and untagged: tagged ratios.

DISCUSSION

PWSAC normally releases pink salmon fry in or near the peak of zooplankton biomass abundance after assisting with feeding and predator protection, thus closely emulating what PWS pink salmon fry do when unassisted. Consequently the test releases are not within the normal scope of PWSAC operational strategies. The project delineated herein, however, is intended to provide a tool for SEA researchers assisting increases in understanding of factors affecting survival of juvenile pink salmon fry in PWS.

CONCLUSIONS

Year to year variation in physical and biological oceanographic conditions in PWS are historically evidenced. That the saltwater entry of late, large-sized, marked and tagged pink salmon fry is of value to fellow SEA projects is evidenced by SEA researcher's requests that project 95320K be continued. Given the differences between inter-year PWS ecosystem comparisons, SEA projects require multi-years' data before reliable conclusions can be drawn concerning the many biotic and abiotic factors influencing PWS pink salmon survivals.

Hatchery produced pink salmon fry are a viable tool to test hypotheses regarding the causes of mortality in juvenile pink salmon in PWS.

The feasibility of releasing a 1.0-1.5 gram pink salmon fry using current technology has been ascertained by earlier work (94320K, 95320K) and 1996 work reported on in this annual report. The objectives appear to be attainable, particularly at the Esther Island facility, allowing that required additional resources are secured and employed.

Project 96320K should be continued as a necessary and important support function to other SEA projects as multiple years of data are needed before reliable conclusions can be drawn concerning factors affecting mortality in PWS pink salmon stocks. With the understanding of the theoretical underpinnings on the dynamics of pink salmon stocks and their interrelationships with abiotic and biotic factors, comes the promise of garnering the ability of enduring ecosystem management, thus assuring biodiversity, as well as economic security on into the future.

LITERATURE CITED

Kaeriyama, M. 1989. Aspects of salmon ranching in Japan. Physiol. Ecol. Japan, Spec. Vol. 1: 625-638. (1989).

Parker, R.R. 1971. Size selective predation among juvenile salmonid fishes in a British Columbia inlet. J. Fish. Res. Bd. Can. 28:1503-1510.

TABLE

Prince William Sound Aquaculture Corporation

BROOD YEAR 1995 PINK SALMON - Late/Large Rearing Strategy

Wally Noerenberg Hatchery

Pen Number	Release Date	Weights (gm)	Released Untagged	Released Tagged	Total Release	Tag Code	Tag Ratio 1:
2	6/2/96	1.29	2,846,911	4,958	2,851,869	13-01-03-12-02	574
4	6/2/96	1.36	2,991,257	5,052	2,996,309	13-01-03-12-03	592
6	6/2/96	1.06	2,845,340	4,731	2,850,071	13-01-03-12-04	601
8	6/1/96	0.81	2,684,345	4,945	2,689,290	13-01-03-12-05	543
		Totals	11,367,853	19,686	11,387,539		

Armin F. Koernig Hatchery

Pen Number	Release Date	Weights (gm)	Released Untagged	Released Tagged	Total Release	Tag Code	Tag Ratio 1:
2	5/24/96	0.79	4,214,839	4,810	2,756,287	13-01-03-14-12	573
2a	6/12/96	1.57		2,546	1,465,908	13-01-03-14-12	576
4	5/24/96	0.71	4,081,789	6,898	4,088,687	13-01-03-14-10	592
6	5/24/96	0.61	4,143,380	6,990	4,150,370	13-01-03-14-11	593
		Totals	12,440,008	21,244	12,461,252		586
		Grand Totals	23,807,861	40,930	23,848,791		

* Note: AFK released earlier than planned due to a Vibrio outbreak.

Chapter 8.

Observational Physical Oceanography (96320M)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Water Mass Variability and Circulation of PWS

Restoration Project 96320-M
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Shari L. Vaughan
Shelton M. Gay III
Loren B. Tuttle
Kenric E. Osgood

Prince William Sound Science Center
P. O. Box 705
Cordova, Alaska 99574

April 1996

Water Mass Variability and Circulation in PWS

Restoration Project 96320-M
Annual Report

Study History: Unexpectedly small Prince William Sound pink salmon runs in 1992 and 1993, and the almost complete collapse of the herring fishery in 1993, prompted the EVOS Trustee Council to initiate ecosystem-level studies of the region to investigate possible environmental reasons for these disasters. A collaborative effort involving the University of Alaska Fairbanks, the Prince William Sound Science Center, the Prince William Sound Aquaculture Corporation, and Alaska Department of Fish and Game resulted in the development of a coordinated plan in the fall of 1993. After substantial review, Sound Ecosystem Assessment (SEA) was approved for funding April 11, 1994. A scope of work for SEA was projected over 5-8 years at that time. Annual reports were issued in 1995 by D. K. Salmon entitiled Descriptive Physical Oceanography (project number 94320-M), and in 1996 by S. L Vaughan entitiled Observational Physical Oceanography in Prince William Sound and the Gulf of Alaska (project number 95320-M), both as chapter contributions to the single compiled report of all SEA FY94 and FY95 projects. Project results were presented in 1996 at one professional meeting (Vaughan, S.L. and D.K. Salmon, 1996: The Upper Layer Density Structure at the Entrance to Prince William Sound. Presented at the AGU Ocean Sciences Meeting, San Diego, CA). A journal article was submitted for publication in 1996 (Gay, S.M., 1996: Seasonal Changes in Hydrography of Embayments and Fjords of Prince William Sound, Alaska during Spring and Summer 1994, Fall 1995, and Late Winter 1996. In IAPSO Conference Proceedings).

Abstract: Hydrographic surveys and current velocity measurements in 1994 through 1996 show significant seasonal and interannual variability in water mass properties and circulation patterns in Prince William Sound (PWS). Cruises were conducted in April, June, September, and December 1996. Conditions are coldest and saltiest in April, and warmest and freshest in September. The upper 20 meter layer was warmer and saltier in 1996 than 1995. In April 1996, a small anticyclonic circulation seemed to form at Hinchinbrook Entrance. Outflow at Montague Straight is confined to a small surface jet in April. In June 1996, deep inflow appears to be present at Hinchinbrook Entrance. June outflow at Montague Straight is generally weak. In September at Montague Straight, the flow was southwestward except for a shallow layer of surface inflow. A cyclonic circulation in the central Sound appears in September of all years. In December at Hinchinbrook Entrance, there was inflow in the upper 150 m and outflow below. Physical data (temperature, salinity, density, and current velocity) will be correlated with phytoplankton, zooplankton, and nekton distibution and abundance. These data will also be incorporated into a numerical circulation model. The goal of this project is to identify physical factors that control the production of pink salmon and Pacific herring in PWS.

Key Words: physical oceanography, temperature, salinity, circulation, Prince William Sound.

Citation: Vaughan, S.L., S.M. Gay, L.B. Tuttle, and K.E. Osgood, 1997: Water Mass Variability and Circulation in Prince William Sound. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 96320-M), Prince William Sound Science Center, Cordova, Alaska, 99574.

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Executive Summary

Large scale hydrographic cruises were conducted in PWS in spring. summer, and fall months of 1994, 1995, and 1996. One winter cruise was conducted in 1996. Measurements of temperature (T), salinity (S), oxygen, current velocities, fluourescence, nutrient content. phytoplankton abundance, and zooplankton abundance were collected on nearly all cruises. Seasonal means of temperature and salinity were created and compared to the numerical model predictions. Dynamic height contours were created and used to infer the general circulation patterns. Profiles and vertical section contours were used to show the appearence of upper level stratification in the spring of each year, and differences in the deepening of the mixed layer. T/S diagrams were used to identify different water masses. and identify regions of mixing.

Horizontal current vectors calculated from towed acoustic Doppler current profiler (ADCP) measurements were plotted for each cruise at various depths. In 1996, repeat ADCP transects during periods of maximum flood and maximum ebb tide were made at critical transport regions in Hinchinbrook Entrance, Montague Straight, and Knight Island Passage. Velocities were averaged over both tide stages to remove the tidal contribution. Vertical sections of north/south and east/west velocities were created for each cruise.

To capture the physical processes that affect juvenile Pacific herring, measurements were taken on several nearshore research cruises conducted by the SEA herring project (320-T). Temperature, salinity, oxygen, current velocity, fluourescence, and zooplankton data were collected in several bays and fjords around PWS starting in October 1995. In 1996, the number of bays was reduced to 4: Whale Bay, Eaglek Bay, Simpson Bay, and Zaikof Bay. Vertical sections of temperature. salinity, density, and current velocity were created for each cruise. Horizontal contours of temperature, salinity, and density, and horizontal velocity vector plots were also created.

Throughout 1996, the upper 20 meter layer was both warmer and saltier than in 1995. Maximum differences occured in fall. The fall 1996 T/S properties were similar to fall 1994 (both warmer and saltier than 1995). Deeper layers showed less variability. The dynamic heights suggest that in 1996, the Sound was subject to greater flushing than in 1995. Dynamic height contours also reveal the existance of a closed cyclonic circulation in the fall of all three years. Vertical T/S sections show upper layer stratification in the spring of 1996, not present in spring of 1995. The water mass properties at Hinchinbrook Entrance are dependent on tide stage, resembling Gulf of Alaska (GOA) water during flood tide, and central Sound water during ebb tide.

The current velocity vector plots show that velocities at 100 meters were not negligable as assumed in previous work, but could be significant and opposite in direction to surface flows. Velocity sections in 1996 show weak flow below 20 meters in northern Montague Straight, previously thought to be a region of strong outflow. Sections averaged over both stages of the tide in 1996 show significant seasonal differences. In April the flow on the western side of Hinchinbrook Entrance was northward, while the flow on the east side was southward. This is consistant with the circulation of an anticyclonic eddy. Dynamic height contours suggest an anticyclonic eddy located in Hinchinbrook Entrance in April 1996. In June, a strong northward flow is present near the bottom at Hinchinbrook Entrance. In southern Montague Straight, the April averaged repeat sections show an intense southwestward jet down to about 50 meters on the western side. In June, the flow is more uniform. In

September, the mean flow in Montague Straight is actually northward in the upper 30 meter layer, and southwestward below. In December at Hinchinbrook Entrance the mean flow is northward in the upper 150 meters, and southward below.

The nearshore oceanographic data from the bays in PWS is just now starting to be compiled. Evidences of density fronts exist, along with horizontal current velocity shear. Large differences in temperature and salinity exist between bays at the same time of year. Vertical sections of velocity show the currents in these bays to be extremely complex and seasonally variable. Differences exist between the head and the mouth of the bay in nearly all cases. No anoxic deep layers were found.

Introduction

The Sound Ecosystem Assessment (SEA) is aimed at identifying the primary factors that control the production of pink salmon and Pacific herring in Prince William Sound (PWS). A main hypothesis of SEA is that physical conditions, such as ocean temperature and salinity, current velocities, and atmospheric forcing, primarily determine the survival of embryos and juvenile fish. Processes that control the physical environment include tidal motions, wind stress, seasonal heating and cooling, precipitation, river/glacial runoff, inflow and outflow of Gulf of Alaska (GOA) water, and longer term events like El Nino and the Southern Oscillation (ENSO). Time scales of these processes range from hours to decades, and space scales range from tens of meters to O(100 km). The purpose of this research is to identify the dominant physical processes that influence the distribution and abundance of pink salmon and Pacific herring in PWS.

Background

A great deal of work has been done on the GOA and the Alaska Coastal Current (ACC) since the 1970s. The seasonal variations of quantities such as dynamic height, baroclinic geostrophic transport, wind forcing, freshwater discharge, and coastal upwelling, have been described (e.g. Royer and Emery, 1987; Johnson et al, 1988; Royer, 1981a,b; Royer, 1979; Royer et al, 1990). Only one manuscript has been published dedicated to the physical oceanography of PWS (Niebauer et al (1994)). They focused on two periods: 1977-1979, and 1989, after the Exxon-Valdez oil spill. Hydrographic data were used to created dynamic topographies (0/100 meter). Monthly means of baroclinic geostrophic transport (relative to 100 m) were calculated at Hinchinbrook Entrance and Montague Straight. Current meter moorings deployed over 15 months from 1977 to 1979 in both Hinchinbrook Entrance and Montague Straight collected data from 4 or 5 depths. Current velocity shears (20 meter values minus 100 meter values) from acoustic Doppler current profiler (ADCP) transects made in 1989 were also presented. Based on estimates of transports in various pressure layers, and estimates of the total volume of the layer, Niebauer et al (1994) made estimates of flushing rates of PWS. They concluded that about 40% of PWS was flushed from May through September, and that the Sound was flushed two to four times from October to April.

Previous EVOS Work (FY94 and FY95)

Work in this and previous years has focused on seasonal and interannual variability. Large scale hydrographic cruises were conducted in PWS in spring, summer, and fall months of 1994, and 1995. Measurements of temperature (T), salinity (S), oxygen, current velocities, and fluourescence were made with simultaneous measurements of nutrient content, phytoplankton abundance, and zooplankton abundance. Seasonal means of temperature and salinity were created and compared to the numerical model predictions. Dynamic height contours were created and used to infer the general circulation patterns. Profiles and vertical section contours were used to show the appearence of upper level stratification in the spring of each year, and differences in the deepening of the mixed layer. Profiles and vertical section contours also showed the presence of a temperature minimum layer in spring, and the errosion of this layer in summer and fall. T/S diagrams were used to identify different water masses, and identify regions of mixing. Horizontal current vectors calculated from towed acoustic Doppler current profiler (ADCP) measurements were plotted for each cruise at various depths, and used to calculate the baroclinic component of the velocity.

In addition to the large scale hydrographic cruises, an ADCP mooring was deployed in Hinchinbrook Entrance from June 1995 to October 1995. Spectral analysis revealed a weak diurnal tidal component to the deep flow in addition to the strong semi-diurnal component present throughout the water column. Velocities filtered to remove the tidal component showed outflow from near the surface to about 120 meters depth, and inflow below.

Work in FY96

The large scale circulation patterns and water mass properties of PWS in spring, summer, fall, and winter of 1996 are described in this report. Basin scale hydrographic surveys, and ADCP transects were conducted on four cruises in 1996. An upward looking ADCP mooring was deployed in Hinchinbrook Entrance to collect current velocity data. Two satellite tracked drifting buoys were released to track upper layer currents. These data are used to describe the seasonal evolution of the water mass properties (temperature, salinity, and density) and general circulation of PWS.

Objectives

The fundamental premise of the SEA research program in Prince William Sound is that information describing how ecosystem-level processes control the production of pink salmon and Pacific herring is needed to effect an informed restoration of non-recovering species. The main objective of the Observational Physical Oceanography program is to identify the dominant physical processes (tides, storms, seasonal heating, exchange with the GOA, etc.) that influence pink salmon and Pacific herring production in PWS. Specific goals for FY96 listed in the FY96 DPD were:

1. Determine the seasonal and interannual variability of the large scale (O(50 km)) water mass properties (temperature, salinity, and potential density) of PWS.

2. Document the current velocities and transport through Hinchinbrook Entrance as a function of time and depth.

3. Document the current velocities and transport through Hinchinbrook Entrance and Montague Straight as a function of horizontal distance, and depth.

4. Document the variability of the large scale meteorological variables (atmospheric pressure, air temperature, wind speed, wind velocity, etc.).

5. Document mesoscale structures (<O(10km)), such as eddies and density fronts, and correlate with zooplankton and nekton distributions in PWS.

6. Document small scale structures (O(1km)) in the nearshore regions and correlate with fish distributions.

7. Characterize the herring overwintering environment.

8. Use large scale physical oceanographic measurements (hydrographic and current velocity) and meteorological data to characterize 'river' and 'lake' conditions.

9. Provide the large scale physical oceanographic data to validate the numerical circulation model, and later for assimilation into the model.

10. Use the model results to identify critical regions and time periods for data collection.

Nearly all of these objectives were met. Objectives that were not met, or only partially met are noted below. Work remains to be done correlating the biological and physical data, especially in the nearshore regions (tasks 5, 6, and 7). Model validation and hypothesis testing (8, 9) is ongoing. Identifying critical times and regions for data collection (10) is partially completed.

Methods

Large scale oceanographic cruises were conducted in April, June, September, and December of 1996. Station locations and transects for each cruise are shown in Figure 1 (a)-(d). Samples collected at each station for each cruise are in Tables 1-4. The cruise dates are listed below.

April	15 - 21
June	15 - 21
September	10 - 16
December	5 - 11

The hydrographic data was collected using a SeaBird 911 CTD. Conductivity, temperature, and oxygen as a function of pressure were recorded at 1 dbar intervals. Salinity was calculated from conductivity using standard SeaBird software. The CTD sensors were calibrated annually by SeaBird Electronics. The CTD salinities and oxygens were not calibrated with bottle samples because of minimal annual sensor drift rate. In December, XCTDs (expendable CTDs) were used when conditions were too rough to use the CTD. Potential density was calculated from temperature, pressure, and salinity.

Instantaneous current velocity transects were collected using an RDI 150 kHz broadband acoustic Doppler current profiler (ADCP) deployed from the stern of the ship in a towed body. Most transects were in water less than 400 m depth so that bottom tracking was available. The bin length was 8 m for most of the data. The ADCP generally measured flows from about 20 m depth to the bottom.

To calculate a coarse approximation of the mean flow without the tidal component, repeat ADCP transects were made during periods of maximum flood and maximum ebb tide at critical transport regions in Hinchinbrook Entrance, Montague Straight, and Knight Island Passage. The tidal component was assumed to be barotropic. Mean velocities were calculated by averaging over both tide stages. Vertical sections of north/south and east/west velocities were created for each cruise.

A time series of current velocities as a function of depth will be obtained from an upward looking ADCP mooring (RDI 150 kHz broadband) deployed in Hinchinbrook Entrance in September 1996. Velocities are recorded every 30 minutes using an 8 m bin length. The mooring is scheduled for retrieval in May 1997. Data from this mooring will not be presented in this report.

During the mooring deployment, 4 bottom pressure gauges were deployed in Hinchinbrook Entrance. Pressure gradients across the Entrance may be used to calculate coarse estimates of the transport through the Entrance. Bottom pressure gauges could be a cost effective monitoring tool if velocities calculated from the pressure differences agree with the ADCP velocities. The pressure gauges were retrieved in March 1997, but the data have not been analyzed at the time of this report. Pressure gauge data will not be presented in this report.

Two satelite tracked ARGOS drifting buoys were deployed in Hinchinbrook Entrance in August 1996. The buoys were drogued with an approximately 6 meter long canvas 'sock', extending from about 12 meters to 18 meters below the surface. The drifters followed currents at roughly 15 meters. The position of the drifters were tracked by a satellite (ARGOS) and transmitted to the lab.

Meteorological data from C-MAN stations in PWS is available from the National Data Buoy Center (NDBC). The stations are located at Bligh Reef, Potato Point, Seal Rocks, and Mid-Sound (in the central Sound). Wind speed, wind direction, wave height, barometric pressure, air temperature, water temperature, dew point temperature, and visibility are measured every 30 minutes. The buoys became operational in May 1995, and have collected mostly uninteruped data since then.

To capture the physical processes that affect juvenile Pacific herring, measurements were taken on several nearshore research cruises conducted by the SEA herring project (320-T). Temperature, salinity, oxygen, current velocity, fluourescence, and zooplankton data were collected in several bays and fjords around PWS starting in October 1995. In 1996, the number of bays was reduced to 4: Whale Bay, Eaglek Bay, Simpson Bay, and Zaikof Bay. Cruises took place in March, July, August, October, and November. Vertical profiles and sections of temperature, salinity, density, and current velocity were created for each cruise. Horizontal contours of temperature, salinity, and density, and horizontal velocity vector plots were also created.

To relate temperature and salinity to zooplankton distributions and fluorescence in mesoscale and small scale features, a combined instrument designed by Chelsea Instruments called an Aquashuttle was towed from the ship on both the large scale cruises and the nearshore herring cruises. The Aquashuttle consists of a Focal Technologies optical plankton counter (OPC), to measure zooplankton, and a Chelsea Instruments Aquapack, which measures temperature, salinity, and fluorescence. The Aquashuttle is raised and lowered vertically from the surface to about 50 meters as it is towed, sampling continuously.

Results

Large Scale Water Mass Properties

Temperature, salinity, and potential density collected at the stations listed in Tables 1-4, were averaged over depth layers of roughly 20 meters, and contoured using GMT Version 3 programs (Wessel and Smith, 1995). The upper 20 meter mean temperatures for each cruise are shown in Figure 2(a)-(d). Mean salinities are in Figure 3(a)-(d), and mean potential densities are in Figure 4(a)-(d).

The upper 20 meter layer is coldest and saltiest in April. September is the warmest and freshest month. Temperature, salinity, and potential density are fairly uniform in the upper 20 meters in April. In June, a cold, salty, dense layer is centered just north of Montague Island. Fresher, warmer water is present at the northern and eastern periphery of the Sound. Large gradients in temperature and salinity are present. In September, a dome of colder, saltier water appears in the central Sound. Large salinity gradients exist, but temperature is fairly uniform. In December, both temperature and salinity are more uniform, but not as cold and salty as in April.

Figure 5 shows a time series of the upper 20 meter mean temperatures and salinities averaged over all stations for each cruise in 1995 and 1996. The upper layer in 1996 was both warmer and saltier than in 1995. The differences are slight in April, but by September the mean temperatures differ by about $1.6^{o}C$, and salinities by about 1.8.

Vertical sections (0 to 100 m) of temperature, salinity, and potential density, from a north/south transect of the central Sound are shown for April, June, and September 1996 in Figures 6, 7, and 8. In April (Figure 6) a temperature minimum layer is centered at about 40 m. This layer was present throughout the Sound in April 1996, in various thicknesses and horizontal extent. A weak horizontal density front is present in April, separating fresher surface waters to the north of about NS4 (see Figure 1) from the well mixed southern half. In June (Figure 7), a doming of the deeper isopycnals is present, along with a density front at the surface. The sloping of the isopycnals is consistant with cyclonic circulation north of about CS12. By September (Figure 8), a homogeneous surface temperature layer has formed. The outcroping of the isopycnals is consistant with cyclonic circulation centered at about NS4.

The deepening of the mixed layer, and the appearance of vertical stratification with time is shown for one station in the central Sound (NS4) in Figure 9. During the winter and early spring months (December through April), the Sound is vertically homogeneous. December is very weakly stratified. By June a shallow mixed layer has formed. Stratification is maximum in September. The step patterns in the June and September profiles are remnants of mixing events.

Dynamic heights (0/100 m) for April, June, and September 1996 are shown in Figure 10(a)-(c). Dynamic heights contours indicate the sense and relative strength of the geostrophic current shear from 100 m to the surface. If velocities at 100 m are weak, the dynamic heights represent the sense and relative strength of the geostrophic current at the surface. Gradients are weak in April, but some suggestion of an anticyclonic circulation at Hinchinbrook Entrance is present (Figure 10(a)). In June, a pattern consistant with a basin scale cyclonic circulation appears, with inflow at Hinchinbrook Entrance and weak outflow at Montague Straight (Figure 10(b)). In September, strong inflow in Hinchinbrook Entrance is suggested, with a smaller, weaker cyclonic circulation in the central basin (Figure 10(c)). The contours in September show weak or no outflow at Montague Straight.

Large Scale Circulation

Actual current velocities were measured by a towed, downward looking 150 kHz ADCP. Velocity vectors at the 20 m level and the 100 m level for April, June, September, and December 1996 are shown in Figures 11-14. Only velocities calculated using bottom tracking are included. Tides have not been removed from these velocities. Interpretation of these figures is complicated by the tidal contribution, especially at Hinchinbrook Entrance and lower Montague Straight.

In the central Sound and in Hinchinbrook Entrance, the April (Figure 11) velocities are weaker at depth, but generally in the same direction as those at 20 m. The strongest velocities at both depths are at and just inside Hinchinbrook Entrance. Some suggestion of cyclonic curvature is present in the northern Sound. In June (Figure 12), except at Hinchinbrook Entrance and lower Montague Straight, velocities at 100 m are very weak. A current reversal is present along the north/south GOA transect. The flow in the central Sound at 20 m is generally northward. In September (Figure 13), the deep velocities in the central Sound are weak. Flow at Hinchinbrook Entrance and Montague Straight are still dominated by tides. A weak cyclonic circulation is present in the central Sound at 20 m. Flow in Knight Island Passage is northward at both depths. In December (Figure 14), the inflow at Hinchinbrook Entrance is very strong. At least part of the outflow in lower Montague straight comes from Knight Island Passage. The flow in the western half of the central Sound is mostly barotropic and to the west. These velocities require more careful analysis to separate tides from the mean flow.

The tidal contribution was removed at several locations in the Sound by averaging sections from repeat ADCP transects made during maximum flood and maximum ebb tide. Sections of mean north and east velocities, without the tidal component, from Hinchinbrook Entrance in April and December are shown in Figures 15(a) and (c). Velocity sections from the ebb tide only in June are shown in Figure 15(b) (no flood tide transect was made in June). No repeat transects were made in Hinchinbrook Entrance in September. Sections of mean north and east velocities from lower Montague Straight in April, June, and September are shown in Figures 16(a)-(c). Velocity sections from the ebb tide only in December are shown in Figure 16(d) (no flood tide transect was made in December). The sections for Hinchinbrook Entrance were from stations HE13 to HE11, and from stations SEA31 to SEA33 for the Montague Straight sections (see Figure 1).

At Hinchinbrook Entrance in April, the mean flow above about 100 m was northeastward on the western side of the Entrance, and southeastward on the eastern side (Figure 15(a)). This pattern is consistant with the circulation of an anticyclonic eddy centered just south of the transect line. The June velocities (Figure 15(b)) from the ebb tide only were mostly southwestward except near the bottom. The weaker southward flow near the bottom (and the stronger eastward component) on an ebb tide suggests that the deep mean flow is northward or into the Sound in June. The mean velocities in December (Figure 15(c)) show a northwestward upper layer flow (above 100 to 150 m), overlying a deep southwestward flow. The velocities are more uniform horizontally across the Entrance in December than in April and June. Magitudes are greater in December than in April.

At Montague Straight in April, a strong southwestward jet was present on the westward side of the Straight (Figure 16(a)). Velocities were weak elsewhere. By June, the jet had disappeared (Figure 16(b)). Velocities were weak southwestward everywhere, except for a shallow surface layer of northeastward flow. By September, the shallow northeastward surface layer had deepened and intensified (Figure 16(c)). Flow in the deeper layers was southward. The ebb tide velocities in December are southwestward everywhere except for a mid-depth northwestward flowing layer (Figure 16(d)). Southward velocities are intensified at the surface. The appearance of a northward flow during an ebb tide, and a weaker southward flow at depth could mean that the mean deep transport in Montague Straight in December is very weak outflow or perhaps inflow.

An attempt to document the large scale circulation of PWS using satellite tracked drifting buoys was made in August 1996. Two ARGOS tracked drogued drifters were released just inside Hinchinbrook Entrance, off Bear Cape, on August 2. The mean depth of the drogues was 15 m. Both drifters flowed north for about 2 days, then turned southward and exited the Sound on August 5. One drifter (25651) stopped transmitting soon afterward. Part of the path of the second drifter (25652) is shown in Figure 17. The drifter flowed south, then west past Montague Straight and Resurrection Bay. It finally stopped transmitting just east of Cook Inlet.

Meteorological Data

Wind speeds from the NDBC C-MAN Mid-Sound buoy for April, June, September, and December 1996, are shown in Figure 18(a)-(d). The julian hours for each cruise based on midnight of the first day of each month are listed below.

April:	336-504
June:	336-504
September:	216-384
December:	96-264

Except for December, the mid-Sound winds were light to moderate during all cruises. Winds during the April and June cruises were generally 5 m/s or less, which may account for the formation of surface stratification in those months (see Figures 6 and 7). In September, with sustained wind of around 10 m/s, a shallow surface mixed layer appeared (Figure 8). During the December cruise, periods of 10 - 15 m/s winds were not uncommon.

Nearshore Bay and Fjord Water Mass Properties and Circulation

Hydrographic measurements were made for 4 nearshore areas in March, July, August, October, and November 1996. Current velocity measurements were made in March, August, and October. Two areas, Whale Bay and Eaglek Bay, are fjords, and two, Simpson Bay and Zaikof Bay, are bays. Station locations are shown in Figures 19(a)-(d). To demonstrate the seasonal evolution of the water mass properties, temperature and salinity were averaged at each depth over the entire bay for each cruise. Profiles are shown in Figures 20 - 23. Unlike most of PWS, Eaglek Bay and Whale Bay (both fjords) retain their upper layer stratification throughout the year (Figures 20 and 21). In March, the stratification is weakened, but still present. The fresh, cold suface layer is never entirely mixed. Temperature maximum layers exist in the fjords in October and November. In contrast, Simpson Bay and Zaikof Bay (both bays) resemble the neutrally stratified majority of PWS in March (Figures 22 and 23). In October and November, Zaikof Bay is more thoroughly mixed than Simpson Bay.

Differences in March temperatures and salinities for a given bay between 1995 and 1996 were slight. Differences in October temperatures and salinities were also slight in all bays except Whale Bay. In October 1995, the upper 20 m of Whale Bay was both colder and fresher than in October 1996.

Magnitudes of temperature and salinity vary greatly between the bays and fjords. Figures 24 and 25 show mean March temperatures and salinities averaged over the upper 10 m for each of the 4 bays. Simpson Bay is the warmest, followed by Zaikof and Whale (Figure 24). Eaglek Bay is the coldest in this layer. Zaikof Bay is the saltiest, followed by Simpson and Eaglek (Figure 25). Whale Bay is the freshest. A temperature and salinity (and density) front is present at the mouth of Zaikof Bay (Figures 24(d) and 25(d)) in March 1996.

Current velocity vectors at the 10 m level for a flood tide in March and an ebb tide in October 1996 are shown in Figures 26 and 27 for each bay. Except for Eaglek Bay, the currents are generally weaker at the head than at the mouth of the bays. The currents at the mouths of the bays have a strong tidal component, especially Simpson and Zaikof Bay. The flow at the mouth of Whale Bay even during ebb tide is inward (Figures 27(b)). A strong current shear exists at the mouth of Zaikof Bay on both tides. These features at the mouths of the bays could be responsible for the retention of zooplankton and juvenile fish in the bay. An anticlyclonic eddy is present at the mouth of Zaikof Bay in October (Figure 27(d)), which could also act as a retention mechanism. These hydrographic features and circulation patterns will be compared to zooplankton and juvenile fish distribution and abundance (SEA project 320-T).

OPC and Aquapack Data

Results from a west to east transect in Orca Bay in May 1996 are shown in Figure 28(a)-(e). The transect starts at 60.58 N, 146.41 W and runs roughly 9 nm east to 60.58 N, 146.13 W. Temperature, salinity, and fluorescence (Figures 28(a)-(c)) were measured by the Aquapack. Total particles and *Neocalanus*-sized particles (Figures 28(d) and (e)) were measured by the OPC. *Neocalanus* spp copepods are a main food source for planktivorous fishes in PWS.

Figure 28(a) shows a deep (20 m) warm layer toward the western side (left side of Figure 28) of the transect, and a thermocline that rises from 20 m to about 10 m on the eastern side of the transect. Also in the eastern portion of the transect is a shallow low salinity layer (Figures 28(b)). The transect passes through a horizontal density front, going from a well mixed region in the west to a vertically stratified region in the east.

Figure 28(c) shows a layer of high fluorescence, or chlorophyll content, near the thermocline. The layer follows the thermocline, shoaling and becoming more concentrated going from west to east. The OPC total particle count Figure 28(d) has a similar pattern. Particles were deeper in the west, then shallower and more concentrated in the east. Total counts includes all size ranges, and probably includes some phytoplankton in addition to zooplankton. *Neocalanus*-sized counts (particles with equivalent spherical diameters between 1 and 4 mm) are also concentrated near the chlorophyll maximum (Figure 28(e)).

Discussion

The dynamic height (0/100m) contours from June 1996 (Figure 10(b)) are similar in pattern and magnitude to those calculated by Niebauer et al (1994) for June 1976. The Niebauer et al results suggested northward flow in June also. Values in 1976 ranged from 325 - 350 dyn-cm. Values in 1996 ranged from 310 to 340 dyn-cm. The September 1996 dynamic heights were lower than those found by Niebauer et al in September 1978. Values ranged from 380 - 420 dyn-cm in 1996, and from 420 - 450 dyn-cm in 1978. Dynamic heights from September 1995 were more similar to those in 1978. Values from Septmeber 1995 ranged from 420 -460 dyn-cm. The contours in September of all 3 years (1996, 1995, and 1978) suggested cyclonic circulation.

The dynamic height contours may be compared with the ADCP velocities even though the dynamic heights represent flow at the surface, and the most shallow ADCP velocity depth is 20 m. The dynamic height contours from April 1996 suggested an anticyclonic circulation at Hinchinbrook Entrance, and a weak outflow through Montague Straight (Figure 10(a)). Mean velocities (without tides) from repeat ADCP transects at Hinchinbrook Entrance (Figure 15(a)) were consistent with an anticyclonic circulation there. Mean velocities (without tides) from repeat ADCP transects at Montague Straight (Figure 16(a)) showed the presence of a shallow, narrow southward jet, with weaker velocities throughout most of the section.

The temperature minimum layer (T $< 4^oC$) present in April 1996 (Figure 6) was also present in April and May 1995, and to a lesser extend in June 1995. The layer was not present in June 1996. In March 1995, a cold layer with T $< 4^oC$ extended from the surface down to about 200 m.

In June 1996, vertical sections of potential density (Figure 7) suggested a cyclonic circulation in the central Sound. Dynamic height contours in June (Figure 10(b)) also indicated the presence of a cyclonic circulation. Figure 10(b) also indicated strong inflow at Hinchinbrook Entrance and weak outflow at Montague Straight. The towed ADCP velocities at 20 m showed strong northward flow on the eastern side of the central basin (Figure 12). Weak outflow at Montague Straight was confirmed by the mean ADCP velocities (Figure 16(b)) in June. In April through June 1978, Niebauer et al (1994) found the 30 meter flow at Montague Straight to be light and variable.

In June 1994 and 1995, dynamic heights did not indicate strong inflow at Hinchinbrook Entrance, or the existance of a cyclonic circulation. The dynamic height gradients were weak everywhere. The July 1994 dynamic heights did show northward flow in the central Sound.

The ARGOS satellite tracked drifting buoy released in August 1996, showed that the currents near Hinchinbrook Entrance in the 12 to 18 m depth range were southward. Southward flow at Hinchinbrook Entrance in August is consistant with the moored ADCP measurements in the summer of 1995, and with the measurements of Niebauer et al in summer 1978. Weak, often southward upper layer flow was found to overlie a strong northward deep flow (Niebauer et al, 1994).

In September 1996, vertical sections of potential density (Figure 8) suggested a weak cyclonic circulation in the central Sound. Dynamic height contours in September (Figure 10(c)) also indicated the presence of a weak cyclonic circulation, as did ADCP velocities at 20 m (Figure 13). The September 1994 and 1995 dynamic heights showed well defined cyclonic circulations in central PWS.

The 1996 dynamic heights showed strong inflow at Hinchinbrook Entrance in September. No mean ADCP velocities (without tides) were obtained for September, but the December mean ADCP velocity sections (Figure 15(c)) showed strong inflow above about 100 m. In September and December 1978, Niebauer et al (1994) found strong upper layer inflow (above 100m) at Hinchinbrook Entrance, overlying weak and variable deep flow.

Mean ADCP velocities at Montague Straight in September 1996 showed a shallow surface inflow overlying a deeper outflow. Niebauer et al (1994) found a similar pattern at Montague Straight in August and September 1978. The flow at 30m was northeastward, and southwestward below.

The observation that Eaglek Bay and Whale bay (both fjords) retain their upper layer stratification in March, while the majority of the Sound is homogeneous, may mean that these regions are less connected to the Sound than bays such as Simpson and Zaikof. Differences in temperature and salinity exist between the 4 bays in 1996, but differences between 1995 and 1996 for a single bay were small. Some evidence of potential retention mechanisms (fronts, eddies) exist, but these features need to be correlated with fish data before any conclusions can be made.

Conclusions

Conclusions are listed for each of the objectives listed previously.

1. Seasonal and interannual differences in the large scale water mass properties have been demonstrated. Vertical sections and horizontal contours of temperature and salinity illustrate the magnitude of the seasonal differences for April, June, September, and December 1996. The upper 20 m layer was warmer and saltier in 1996 than in 1995. Dynamic heights in June 1996 were similar to those in June 1976. Dynamic heights in September 1995 were similar to those in Septmeber 1978 (Niebauer et al. 1994).

2. The ADCP moored in Hinchinbrook Entrance will be retrieved in May 1997. Current velocities and transports through Hinchinbrook Entrance as a function of time and depth will be presented in a separate publication.

3. Mean current velocities in Hinchinbrook Entrance and Montague Straight, with the tidal component removed, were presented for April, June, September, and December 1996. At Hinchinbrook Entrace in April, half the transect shows inflow and half outflow. In June, a deep inflow may be present near the bottom. In December, the upper 100 m layer was flowing in, while deeper layer was flowing out. Niebauer et al (1994) found a similar December pattern in 1978. At Montague Straight, April outflow was confined to a narrow surface jet. June outflow was more uniform and weak. In September, the surface flow was into the Sound, and opposite to the deep flow. Niebauer et al (1994) found similar patterns in June and September 1978.

4. An example of one meteorological variable (wind) was presented. Other variables are available for comparison to the observed water mass and circulation changes.

5. Mesoscale features (eddies, fronts) are evident in the upper layer temperature and salinity contour plots (e.g. an eddy north of Montague Island in June), and in the ADCP current vector plots. An example of a correlation between the thermocline depth and plankton concentrations was shown for May 1996. The phytoplankton and zooplankton

were concentrated near the thermocline. The plankton were deeper on the mixed side of a density front, and rose with the thermocline. More rigorous correlation of physcial features with zooplankton and fish distributions remains to be done.

6. Small scale features (eddies, fronts) are evident in the nearshore temperature and salinity contours (the front at the mouth of Zaikof Bay), and in the ADCP current vector plots. Correlating these features with juvenile herring distributions remains to be done.

7. At least from 1995 to 1996, no large differences in the herring overwintering environment (in each bay) was observed. Further analysis is required to state conclusions confidently.

Work on the remaining objectives, characterizing 'river' and 'lake' conditions, validating the numerical circulation model, and identifing critical times and regions for data collection, is ongoing. Research in FY97 will focus on these tasks.

References

Johnson, W.R., T.C. Royer, and J.L. Luick, 1988: On the Seasonal Variability of the Alaska Coastal Current. *J. Geophy. Res.*, **93**, 12,423- 12,437.

Niebauer, H.J. T.C. Royer, and T.J. Weingartner, 1994: Circulation of Prince William Sound, Alaska. *J. Geophy. Res.*, **99**, 14,113-14,126.

Royer, T.C., 1979: On the Effects of Precipitation and Runoff on Coastal Circulation in the Gulf of Alaska. *J. Phys. Oceanog.*, **9**, 555-563.

Royer, T.C., 1981a: Baroclinic Transport in the Gulf of Alaska Part I. Seasonal Variations of the Alaska Current. *J. Mar. Res.*, **39**, 239-249.

Royer, T.C., 1981b: Baroclinic Transport in the Gulf of Alaska Part I. A Freshwater Driven Coastal Current. *J. Mar. Res.*, **39**, 251-265.

Royer, T.C. and W.J. Emery, 1987: Circulation in the Gulf of Alaska, 1981. *Deep Sea Res.*, **34**, 1361-1377.

Royer, T.C., J.A. Vermersch, T.J. Weingartner, H.J. Niebauer, and R.D. Muench, 1990: Ocean Circulation Influencing the *Exxon Valdez* Oil Spill. *Oceanography*, **3**, 3-10.

Wessel, P. and W.H.F. Smith, 1995: The Generic Mapping Tool (GMT) Version 3.0 Technical Reference and Cookbook. SOEST/NOAA.

Table 1: April 1996 Oceanography Cruise Stations

cast	stn	date	time	lat	long	samples
1	OB2	4/15/96	1445	60 35.20	146 24.60	CTD/phyto/zoop
2	CS9	4/15/96	1800	60 35.10	146 44.40	CTD/phyto/zoop
3	CFOS13	4/15/96	2015	60 35.07	146 55.68	CTD/phyto/zoop
4	CS6	4/16/96	0040	60 35.10	147 8.60	CTD
5	CFOSBY	4/16/96	0120	60 36.30	147 12.20	CTD/phyto/zoop
6	CS1	4/16/96	0355	60 34.50	147 21.90	CTD/phyto
7	NS5	4/16/96	0710	60 46.80	147 9.00	CTD/phyto
8	NWS4	4/16/96	0850	60 46.80	147 22.20	CTD/phyto/zoop
9	NWS4A	4/16/96	1230	60 50.00	147 22.20	CTD
10	SEA22C	4/16/96	1455	60 45.00	147 41.00	CTD
11	SEA22	4/16/96	1635	60 40.50	147 41.00	CTD/phyto/zoop
12	SEA22D	4/16/96	1837	60 36.00	147 41.00	CTD
13	SEA16	4/16/96	2130	60 31.10	147 54.50	CTD
14	SEA18	4/16/96	2220	60 31.10	147 50.00	CTD/phyto/zoop
15	SEA18B	4/17/96	0000	60 31.10	147 45.00	CTD
16	SEA25	4/17/96	0430	60 18.10	147 58.00	CTD/phyto/zoop
17	SEA26	4/17/96	0600	60 12.80	147 59.60	CTD
18	SEA27	4/17/96	0715	60 10.20	147 53.60	CTD/phyto/zoop
19	SEA39	4/17/96	1030	60 3.90	147 55.40	CTD/phyto
20	SEA28	4/17/96	1243	60 8.20	147 46.10	CTD/phyto
21	SEA29	4/17/96	1410	60 6.80	147 48.30	CTD/phyto
22	SEA31	4/17/96	1850	60 2.80	147 47.10	CTD/phyto
23	SEA32	4/17/96	1930	60 1.90	147 44.40	CTD/phyto/zoop
24	SEA33	4/17/96	2030	60 0.90	147 41.90	CTD/phyto
25	HE13	4/18/96	0750	60 15.70	146 53.50	CTD/phyto
26	HE12	4/18/96	0910	60 15.70	146 49.40	CTD/phyto/zoop
27	HE11	4/18/96	1015	60 15.70	146 45.30	CTD/phyto
28	GOA0	4/18/96	1445	60 13.00	146 40.00	CTD/phyto/rad
29	CS5	4/18/96	2020	60 22.50	146 47.50	CTD/phyto
30	CS12	4/18/96	2230	60 22.30	146 56.20	CTD/phyto
31	MS5	4/19/96	0600	60 8.40	147 30.60	CTD/phyto
32	MS5A	4/19/96	0700	60 10.00	147 36.00	CTD/phyto
33	MS5B	4/19/96	0830	60 11.50	147 41.00	CTD/phyto
34	MS7	4/19/96	2300	60 21.00	147 30.00	CTD/phyto
35	MS10	4/20/96	0115	60 30.00	147 30.00	CTD/phyto
36	MS9	4/20/96	0250	60 27.00	147 21.00	CTD/phyto
37	MS8	4/20/96	0455	60 24.00	147 12.00	CTD/phyto
38	NS4	4/20/96	1930	60 31.20	146 55.80	CTD/phyto
39	CFOS13	4/20/96	2100	60 35.07	146 55.68	CTD/phyto/zoop
40	NS3	4/20/96	2240	60 39.00	146 55.80	CTD/phyto
41	NS2	4/21/96	0005	60 43.20	146 55.80	CTD/phyto
42	NS1	4/21/96	0100	60 46.80	146 55.80	CTD/phyto/zoop

Table 2: June 1996 Oceanography Cruise Stations

cast	stn	date	time	lat	long	samples
1	OB2	6/15/96	1115	60 35.20	146 24.60	CTD/phyto/zoop1
2	CS9	6/15/96	2000	60 35.10	146 44.40	CTD/phyto/zoop1
3	CFOS13	6/15/96	2015	60 35.07	146 55.68	CTD/phyto/zoop1
4	CS6	6/16/96	0030	60 35.10	147 8.60	CTD/phyto
5	CFOSBY	6/16/96	0120	60 36.30	147 12.20	CTD/phyto/zoop1
6	CS1	6/16/96	0300	60 34.50	147 21.90	CTD/phyto
7	NS5	6/16/96	0710	60 46.80	147 9.00	CTD/phyto
8	NWS4	6/16/96	0925	60 46.80	147 22.20	CTD/phyto/zoop1/zoop2
9	NWS4A	6/16/96	1110	60 50.00	147 22.20	CTD/phyto
10	SEA4	6/16/96	1700	60 46.20	147 64.90	CTD/phyto/zoop1/zoop2
11	SEA22C	6/16/96	2130	60 45.00	147 41.00	CTD/nutr
12	SEA22	6/16/96	2315	60 40.50	147 41.00	CTD/phyto/zoop1/zoop2
13	SEA22D	6/17/96	0210	60 36.00	147 41.00	CTD
14	SEA18	6/17/96	0440	60 31.10	147 50.00	CTD/phyto/zoop1
15	SEA23D	6/17/96	0810	60 25.00	147 52.50	CTD/phyto
16	SEA23C	6/17/96	0845	60 25.00	147 54.50	CTD/phyto
17	SEA23B	6/17/96	0920	60 25.00	147 56.50	CTD
18	SEA25	6/17/96	1445	60 18.10	147 58.00	CTD/phyto/zoop1/zoop2
19	SEA26	6/17/96	1645	60 12.80	147 59.60	CTD/phyto
20	SEA27	6/17/96	1750	60 10.20	147 53.60	CTD/phyto/zoop1
21	SEA29	6/17/96	1930	60 6.80	147 48.30	CTD/phyto
22	SEA31	6/17/96	2105	60 2.80	147 47.10	CTD
23	SEA32	6/17/96	2140	60 1.90	147 44.40	CTD/phyto/zoop1/zoop2
24	SEA33	6/17/96	2250	60 0.90	147 41.90	CTD
25	MS5B	6/18/96	1444	60 11.50	147 41.00	CTD/phyto
26	MS5A	6/18/96	1535	60 10.00	147 36.00	CTD/phyto/zoop1
27	MS5	6/18/96	1630	60 8.40	147 30.60	CTD/phyto
28	MS7	6/18/96	2245	60 21.00	147 30.00	CTD/phyto/zoop1
29	MS10	6/19/96	0055	60 30.00	147 30.00	CTD/phyto
30	MS9	6/19/96	0250	60 27.00	147 21.00	CTD/phyto/zoop1/zoop2
31	MS8	6/19/96	0405	60 24.00	147 12.00	CTD/phyto
32	GOA0	6/19/96	2200	60 13.00	146 40.00	CTD/phyto
33	GOA3	6/20/96	0010	60 7.00	146 40.00	CTD/phyto
34	GOA6	6/20/96	0220	60 0.00	146 40.00	CTD/phyto/zoop1/zoop2
35	HE11	6/20/96	0900	60 15.70	146 45.30	CTD/phyto
36	HE12	6/20/96	1009	60 15.70	146 49.40	CTD/phyto/zoop1
37	HE13	6/20/96	1106	60 15.70	146 53.50	CTD/phyto
38	CS5	6/20/96	1245	60 22.50	146 47.50	CTD/phyto
39	CS12	6/20/96	1350	60 22.30	146 56.20	CTD/phyto
40	NS4	6/20/96	1545	60 31.20	146 55.80	CTD/phyto
41	CFOS13	6/20/96	1650	60 35.07	146 55.68	CTD/zoop1/zoop2
42	NS3	6/20/96	1840	60 39.00	146 55.80	CTD/phyto
43	NS2	6/20/96	2000	60 43.20	146 55.80	CTD/phyto
44	NS1	6/20/96	2140	60 46.80	146 55.80	CTD/phyto/zoop1
	OB2	6/21/96	0730	60 35.20	146 24.60	zoop2

Table 3: September 1996 Oceanography Cruise Stations

cast	stn	date	time	lat	long	samples
1	OB2	9/10/96	1935	60 35.20	146 24.60	CTD
2	CS9	9/10/96	2235	60 35.10	146 44.40	CTD
3	CFOS13	9/11/96	0003	60 35.07	146 55.68	CTD
4	CS6	9/11/96	0148	60 35.10	147 8.60	CTD
5	CFOSBY	9/11/96	0242	60 36.30	147 12.20	CTD
6	CS1	9/11/96	0440	60 34.50	147 21.90	CTD
7	NS5	9/11/96	0825	60 46.80	147 9.00	CTD
8	NWS4	9/11/96	0957	60 46.80	147 22.20	CTD
9	NWS4A	9/11/96	1143	60 50.00	147 22.20	CTD
10	SEA22C	9/11/96	1431	60 45.00	147 41.00	CTD
11	SEA22	9/11/96	1605	60 40.50	147 41.00	CTD/zoop
12	SEA22D	9/11/96	1956	60 36.00	147 41.00	CTD
13	SEA18	9/11/96	2208	60 31.10	147 50.00	CTD
14	SEA23D	9/11/96	2355	60 25.00	147 52.50	CTD
15	SEA23C	9/12/96	0019	60 25.00	147 54.50	CTD
16	SEA23B	9/12/96	0100	60 25.00	147 56.50	CTD
17	SEA25	9/12/96	1309	60 18.10	147 58.00	CTD/zoop
18	SEA26	9/12/96	1647	60 12.80	147 59.60	CTD
19	SEA27	9/12/96	1829	60 10.20	147 53.60	CTD
20	SEA29	9/12/96	1952	60 6.80	147 48.30	CTD
21	SEA31	9/12/96	2106	60 2.80	147 47.10	CTD
22	SEA32	9/12/96	2146	60 1.90	147 44.40	CTD
23	SEA33	9/12/96	2237	60 0.90	147 41.90	CTD
24	MS5B	9/13/96	1050	60 11.50	147 41.00	CTD
25	MS5A	9/13/96	1142	60 10.00	147 36.00	CTD
26	MS5	9/13/96	1228	60 8.40	147 30.60	CTD
27	MS7	9/13/96	1527	60 21.00	147 30.00	CTD
28	MS10	9/13/96	1759	60 30.00	147 30.00	CTD
29	MS9	9/13/96	1927	60 27.00	147 21.00	CTD
30	MS8	9/13/96	2054	60 24.00	147 12.00	CTD
31	NS1	9/14/96	0403	60 46.80	146 55.80	CTD
32	NS2	9/14/96	0458	60 43.20	146 55.80	CTD
33	NS3	9/14/96	0603	60 39.00	146 55.80	CTD
34	CFOS13	9/14/96	0707	60 35.07	146 55.68	CTD
35	NS4	9/14/96	0825	60 31.20	146 55.80	CTD
36	CS12	9/14/96	1142	60 22.30	146 56.20	CTD
37	CS5	9/14/96	1343	60 22.50	146 47.50	CTD
38	HE13	9/14/96	1600	60 15.70	146 53.50	CTD
39	HE12	9/14/96	1700	60 15.70	146 49.40	CTD
40	HE11	9/14/96	1749	60 15.70	146 45.30	CTD
41	GOA0	9/14/96	1854	60 13.00	146 40.00	CTD
42	GOA3	9/14/96	2013	60 7.00	146 40.00	CTD

Table 4: December 1996 Oceanography Cruise Stations

cast	stn	date	time	lat	long	samples
1	OB2	12/5/96	1640	60 35.20	146 24.60	CTD
2	CS9	12/5/96	2051	60 35.10	146 44.40	CTD/zoop50
3	SEA22	12/7/96	0913	60 40.50	147 41.00	CTD/XCTD/XBT/zoop50/zoop700/zoop400/zoop200
	SEA23C	12/7/96	1445	60 25.00	147 54.50	XBT
4	SEA25	12/7/96	1614	60 18.10	147 58.00	CTD/zoop50/zoop400/zoop200
5	SEA26	12/7/96	1902	60 12.80	147 59.60	CTD
6	SEA27	12/7/96	2029	60 10.20	147 53.60	CTD
7	SEA29	12/7/96	2204	60 6.80	147 48.30	CTD
8	SEA31	12/7/96	2323	60 2.80	147 47.10	CTD
9	SEA32	12/8/96	0011	60 1.90	147 44.40	CTD/zoop50
10	SEA33	12/8/96	0101	60 0.90	147 41.90	CTD
	HE12	12/10/96	0400	60 15.70	146 49.40	XCTD
11	CS5	12/10/96	1207	60 22.50	146 47.50	CTD
12	CS12	12/10/96	1340	60 22.30	146 56.20	CTD
13	NS4	12/10/96	1642	60 31.20	146 55.80	CTD
14	CFOS13	12/10/96	1841	60 35.07	146 55.68	CTD
15	NS3	12/10/96	2005	60 39.00	146 55.80	CTD
	NS2	12/10/96	2148	60 43.20	146 55.80	XCTD
	NS1	12/10/96	2249	60 46.80	146 55.80	XCTD/zoop50
	NS5	12/11/96	0100	60 46.80	147 9.00	XCTD
	CFOSBY	12/11/96	0320	60 36.30	147 12.20	XCTD

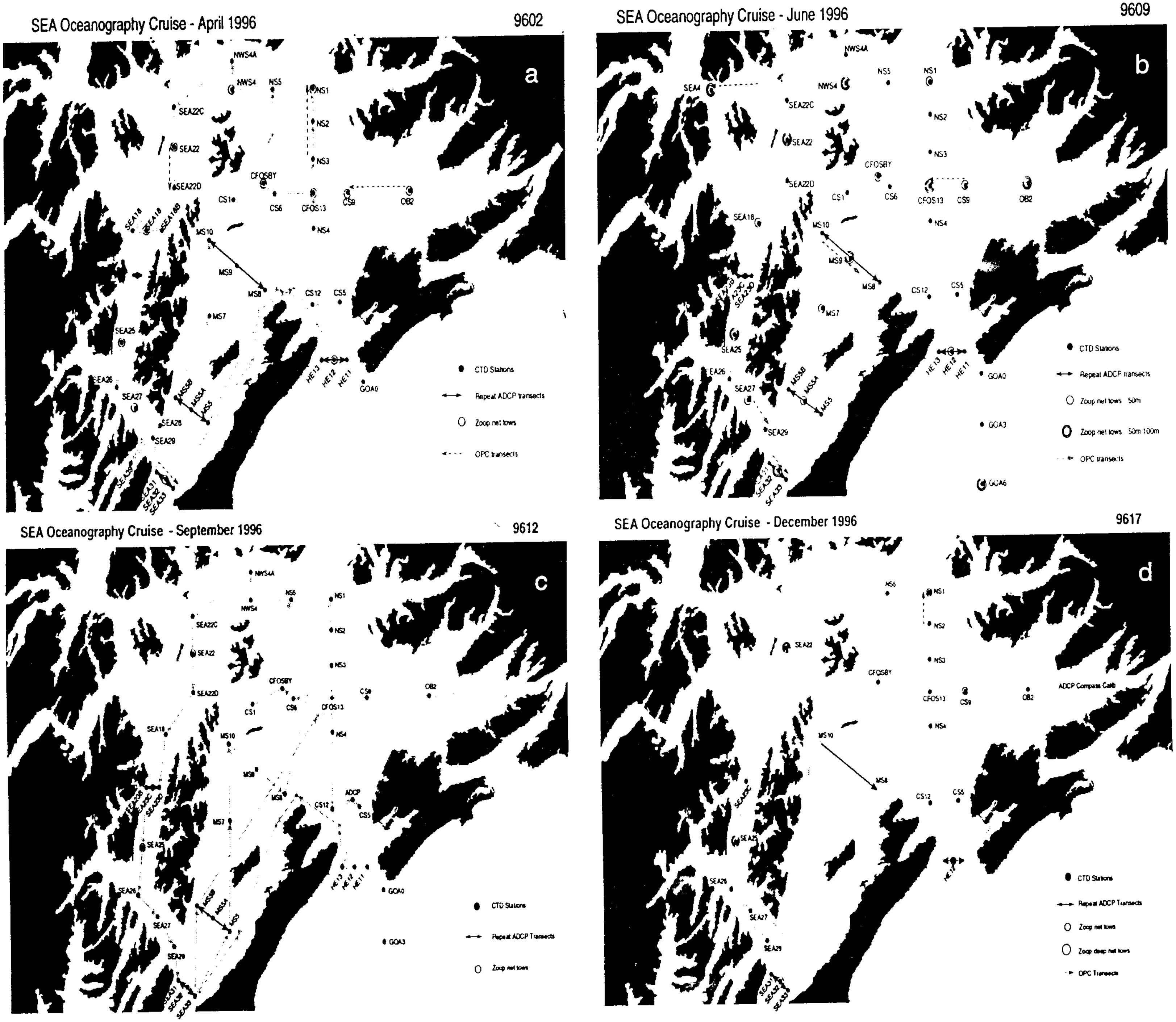

SEA Oceanography Cruise - April 1996
9602
a
NWS4A
NWS4
NS5
NS1
SEA22C
NS2
SEA22
NS3
CFOSBY
SEA22D
CS1
CS6
CFOS13
CS9
OB2
NS4
SEA18
SEA18
SEA18B
MS10
MS9
MS8
CS12
CS5
MS7
SEA25
SEA26
SEA27
MS5B
MS5A
MS5
HE13
HE12
HE11
GOA0
SEA28
SEA29
SEA30
SEA31
SEA32
SEA33
CTD Stations
Repeat ADCP transects
Zoop net tows
OPC transects
SEA Oceanography Cruise - June 1996
9609
b
SEA4
NWS4A
NWS4
NS5
NS1
SEA22C
NS2
SEA22
NS3
CFOSBY
SEA22D
CS1
CS6
CFOS13
CS9
OB2
SEA18
NS4
MS10
MS9
MS8
CS12
CS5
MS7
SEA25
SEA26
SEA27
MS5B
MS5A
MS5
HE13
HE12
HE11
GOA0
SEA29
GOA3
SEA32
SEA33
GOA6
CTD Stations
Repeat ADCP transects
Zoop net tows 50m
Zoop net tows 50m 100m
OPC transects
SEA Oceanography Cruise - September 1996
9612
c
NWS4A
NWS4
NS5
NS1
SEA22C
NS2
SEA22
NS3
CFOSBY
CS9
OB2
SEA22D
CS1
CS6
CFOS13
SEA18
MS10
NS4
MS9
MS8
CS12
ADCP
CS5
MS7
SEA25
SEA26
MS5B
MS5A
MS5
HE13
HE12
HE11
GOA0
SEA27
GOA3
SEA29
SEA31
SEA32
SEA33
CTD Stations
Repeat ADCP Transects
Zoop net tows
SEA Oceanography Cruise - December 1996
9617
d
NS5
NS1
NS2
SEA22
NS3
CFOSBY
CFOS13
CS9
OB2
ADCP Compass Calib
NS4
MS10
MS8
CS12
CS5
SEA25
HE12
SEA26
SEA27
SEA29
SEA31
SEA32
SEA33
CTD Stations
Repeat ADCP Transects
Zoop net tows
Zoop deep net tows
OPC Transects

Figure 1

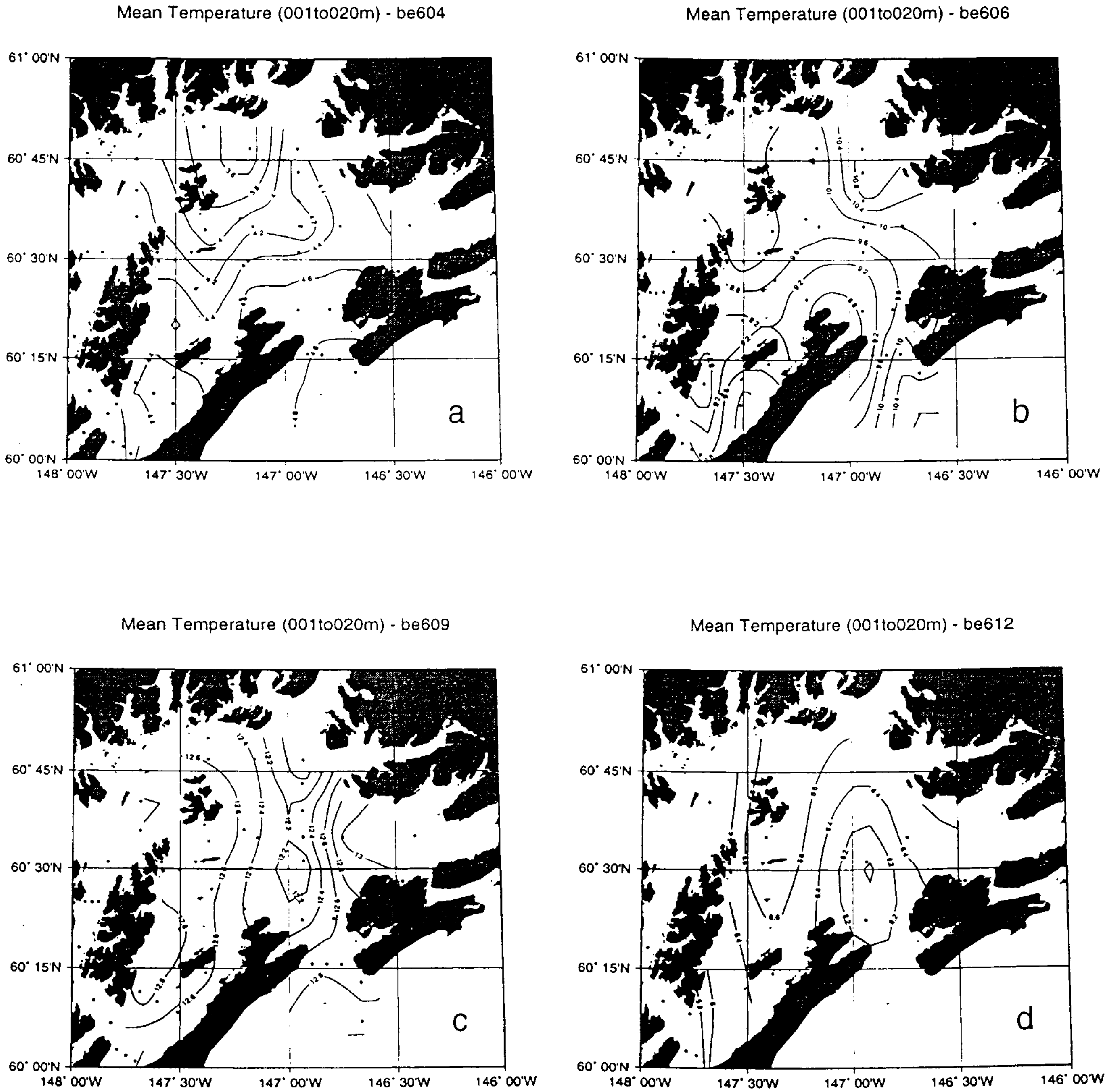


Figure 2: Upper 20m mean temperatures for (a) April, (b) June, (c) September, and (d) December, 1996.

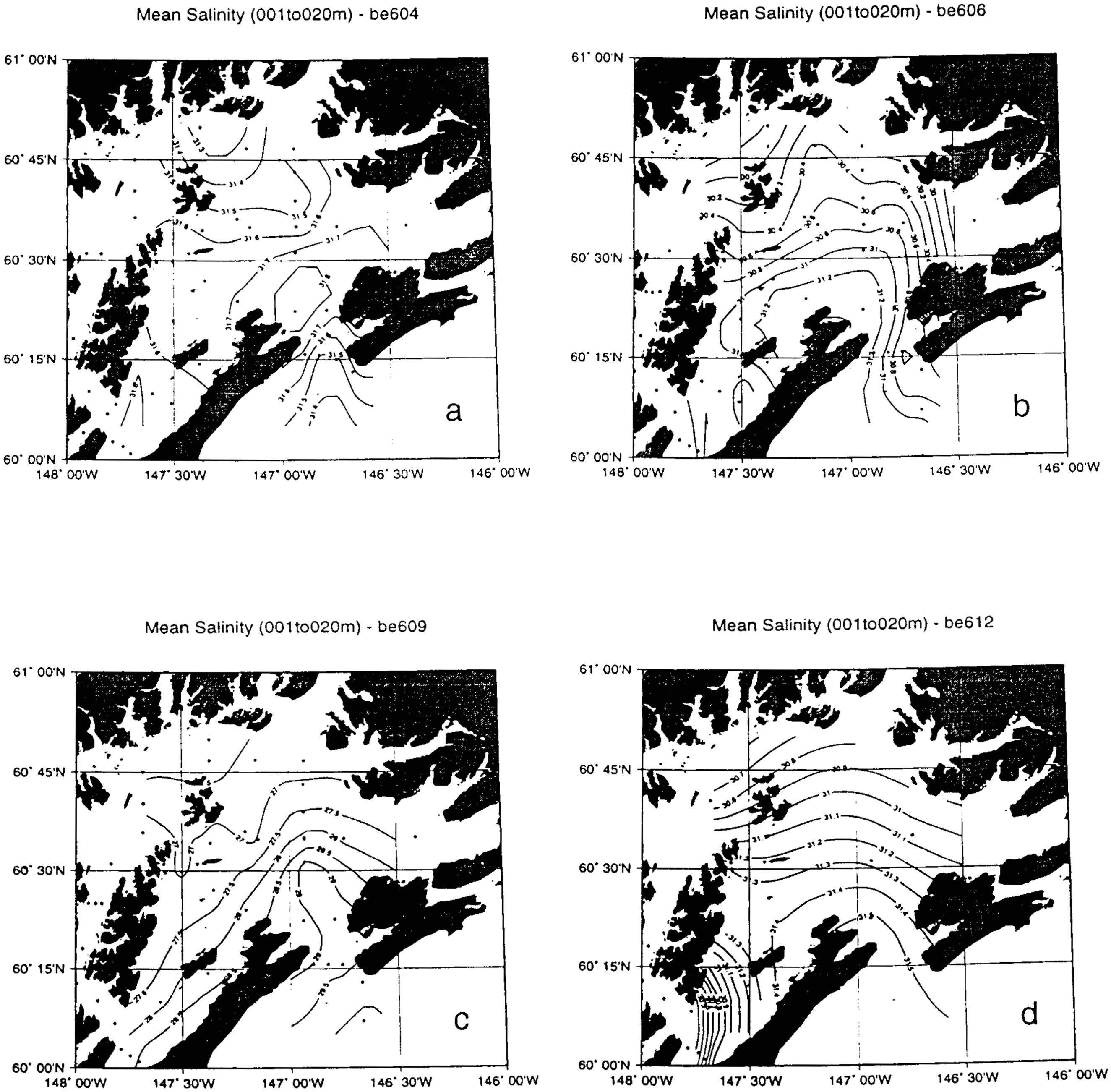


Figure 3: Upper 20m mean salinities for (a) April, (b) June, (c) September, and (d) December, 1996.

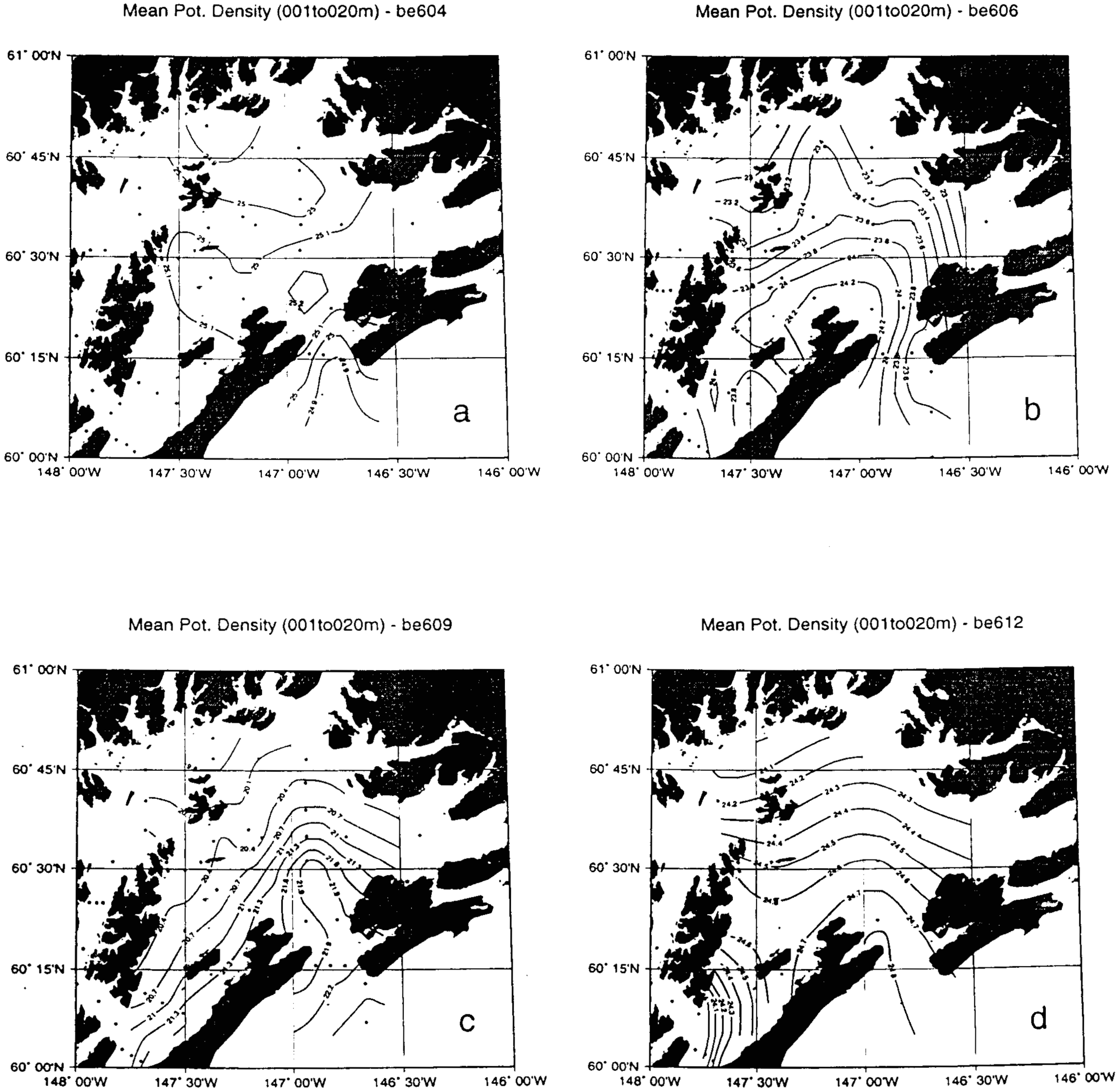


Figure 4: Upper 20m mean potential densities for (a) April, (b) June, (c) September, and (d) December, 1996.

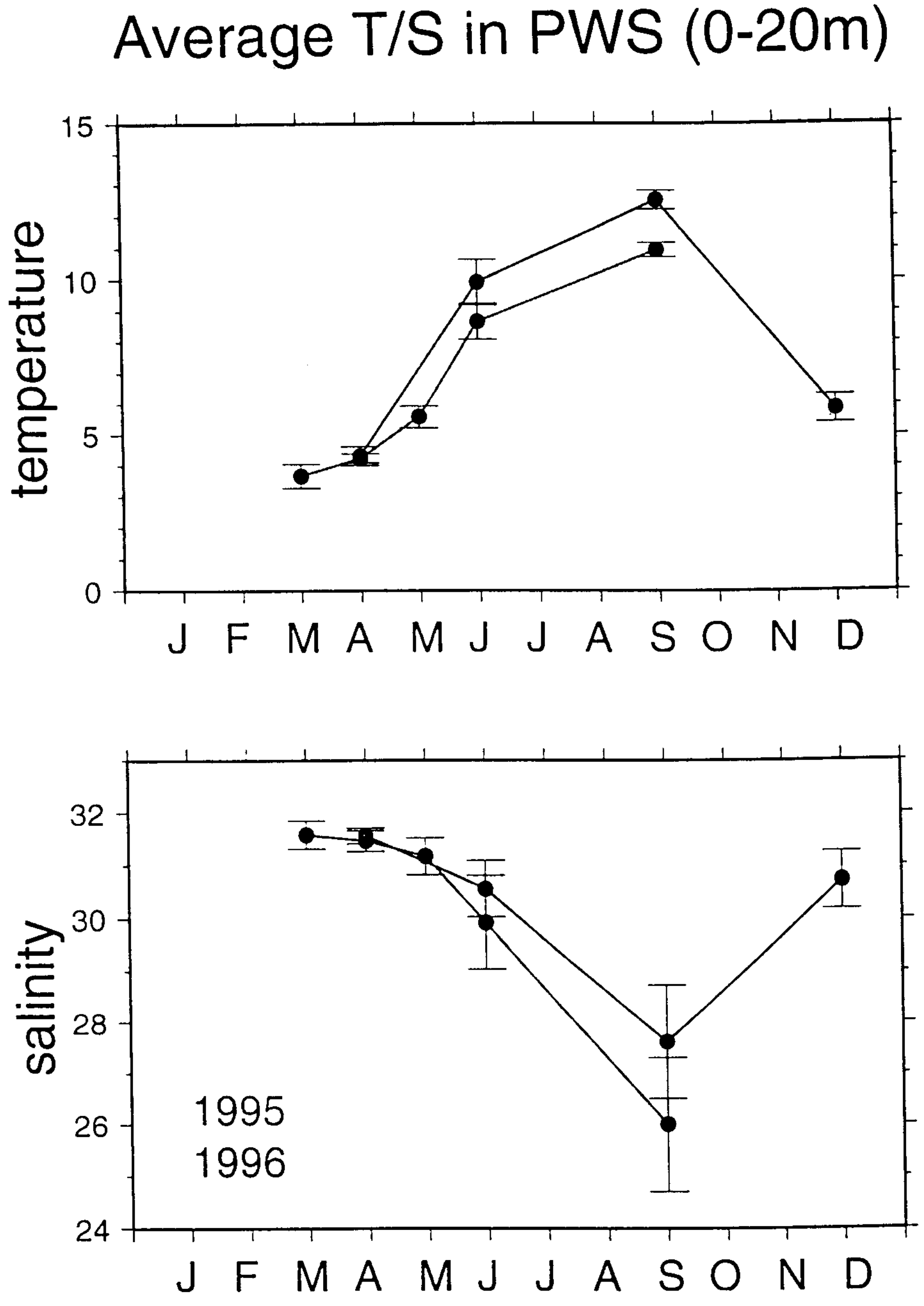


Figure 5: Time series of mean 0 to 20 m layer temperatures and salinities averaged over the entire Sound. Error bars are standard error.

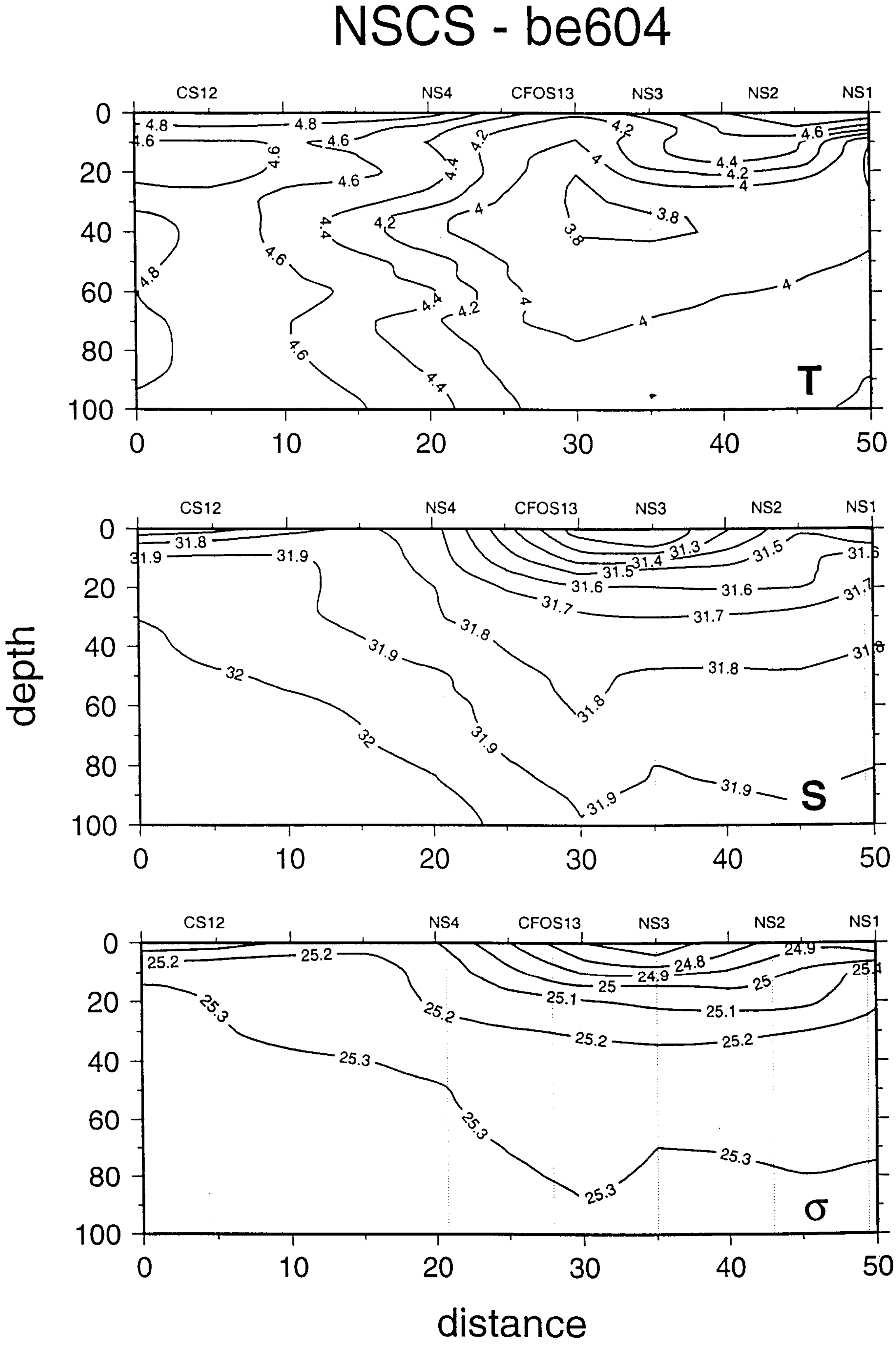


Figure 6: North/south sections of temperature, salinity, and potential density for April 1996.

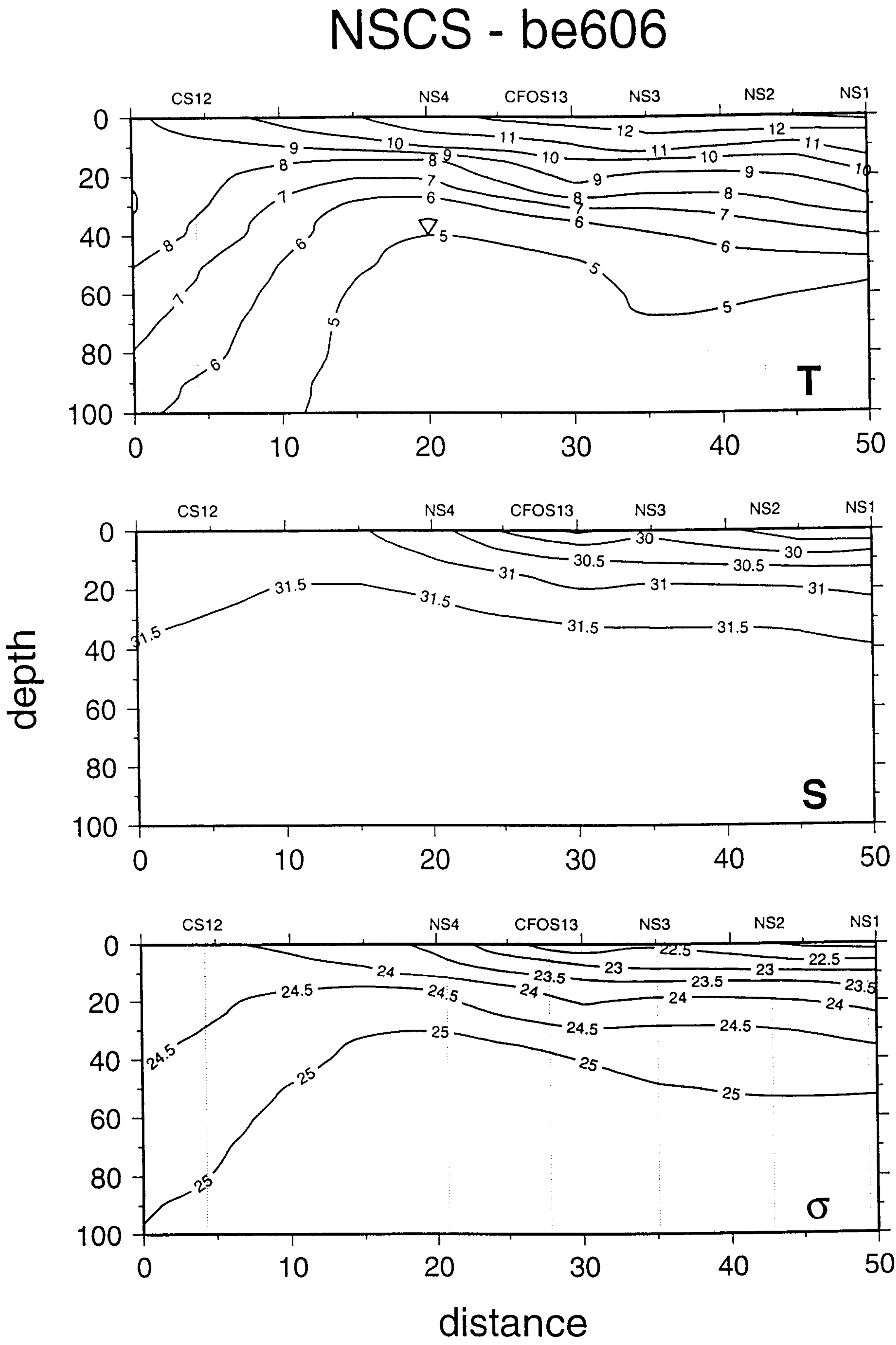


Figure 7: North/south sections of temperature, salinity, and potential density for June 1996.

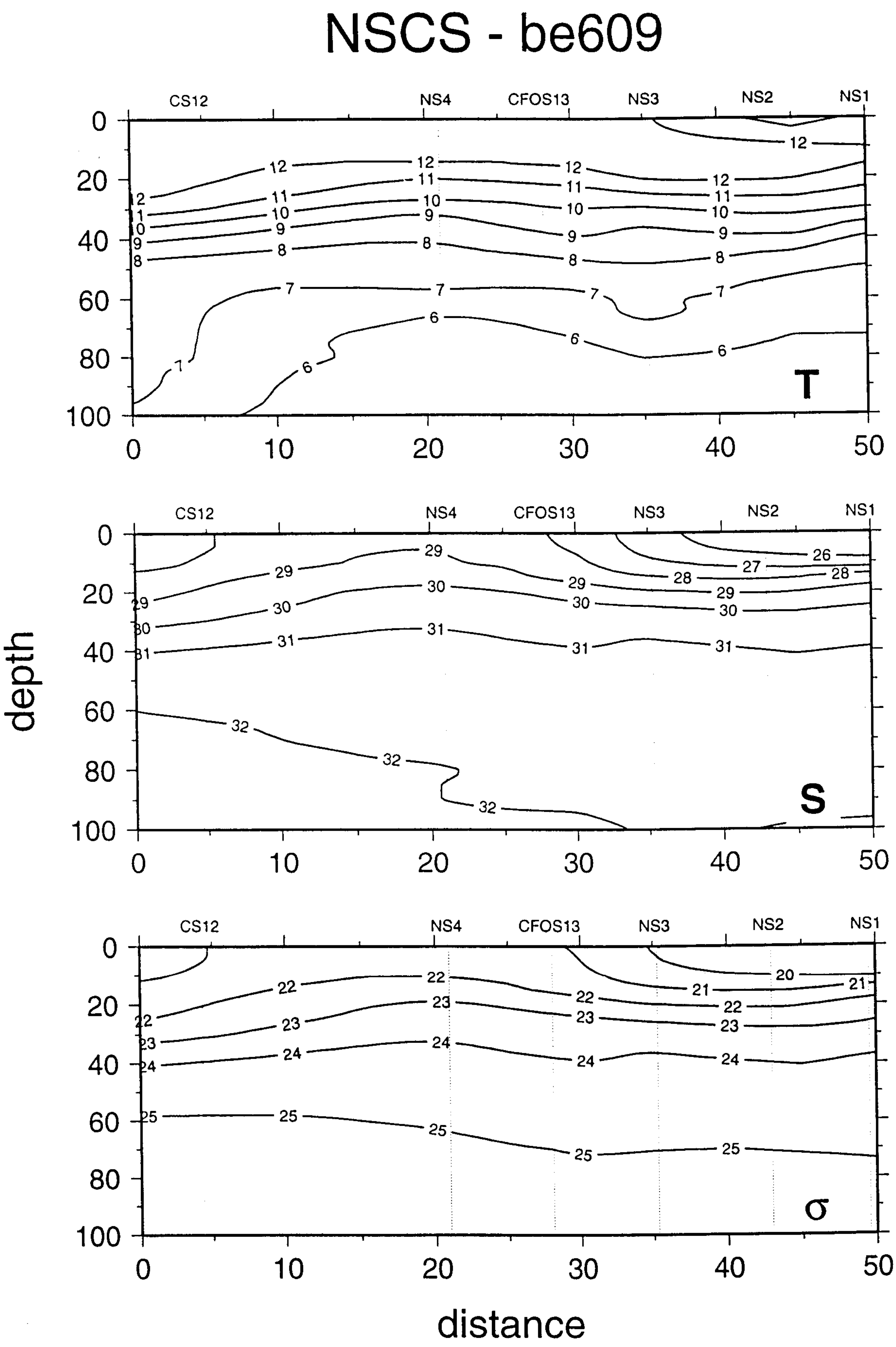


Figure 8: North/south sections of temperature, salinity, and potential density for September 1996.

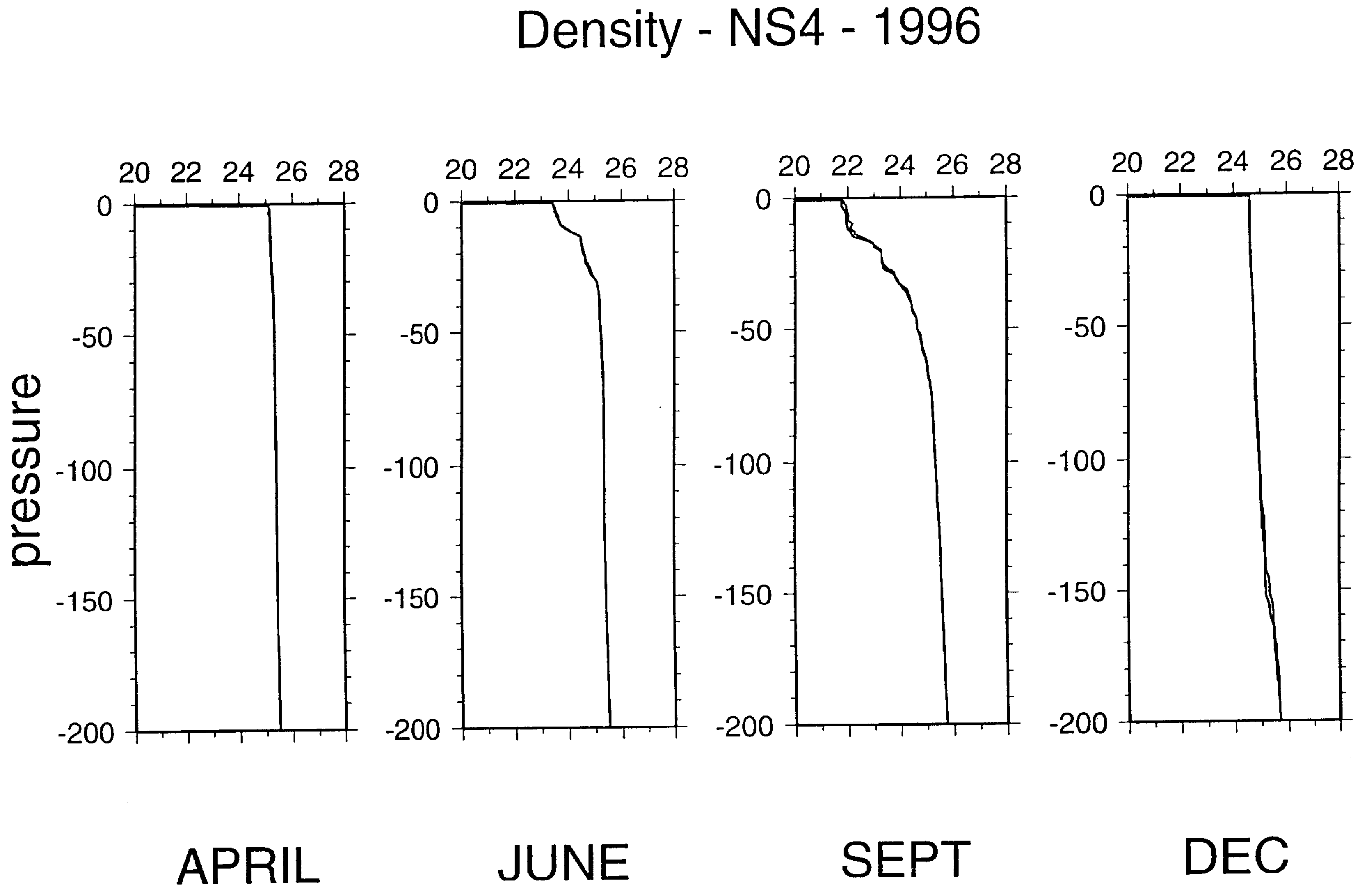
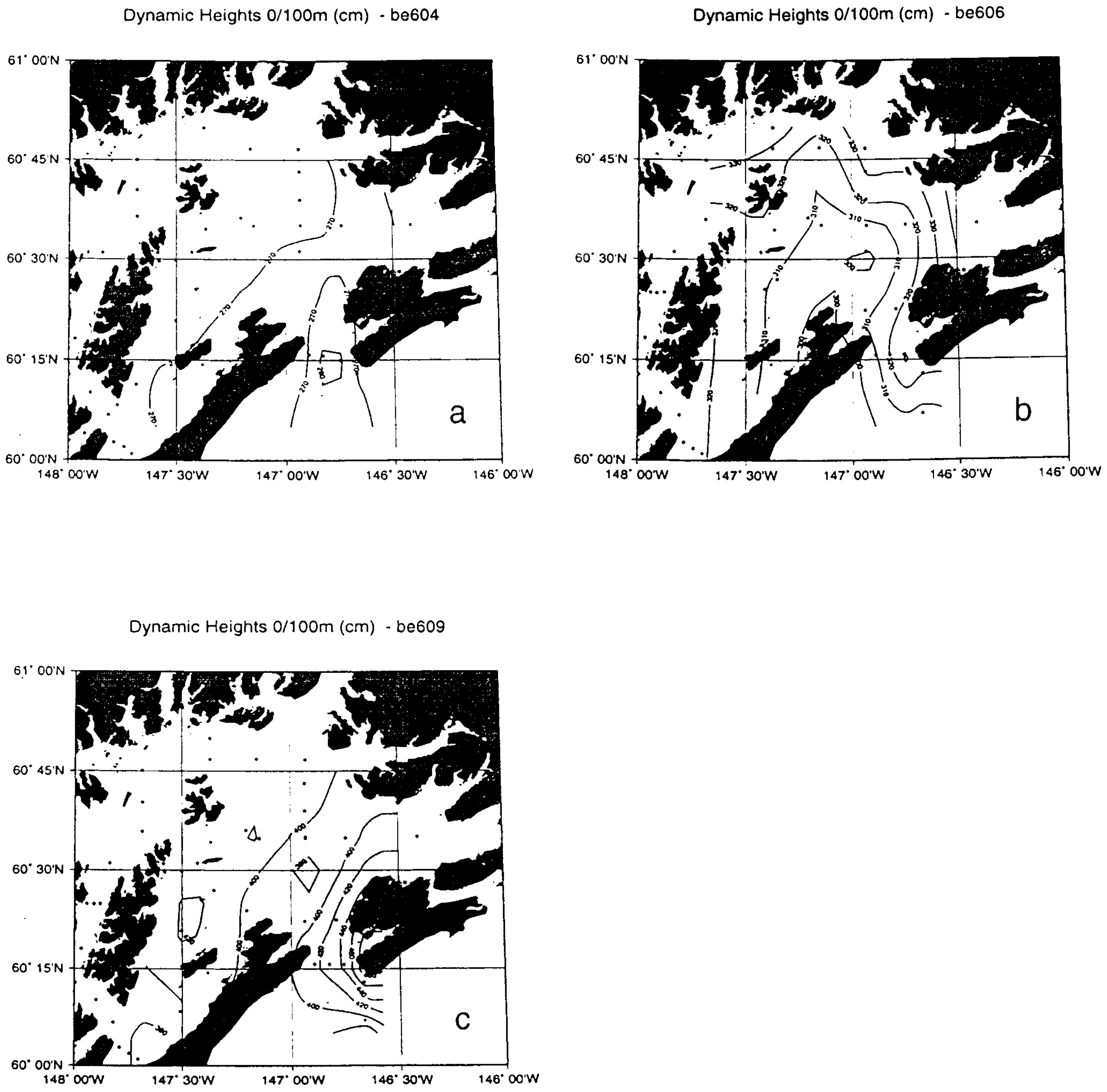


Figure 9: Vertical profiles of potential density.



Dynamic Heights 0/100m (cm) - be604

Dynamic Heights 0/100m (cm) - be606

Dynamic Heights 0/100m (cm) - be609

Figure 10: Dynamic heights 0/100 m (in cm) for (a) April, (b) June, and (c) September 1996.

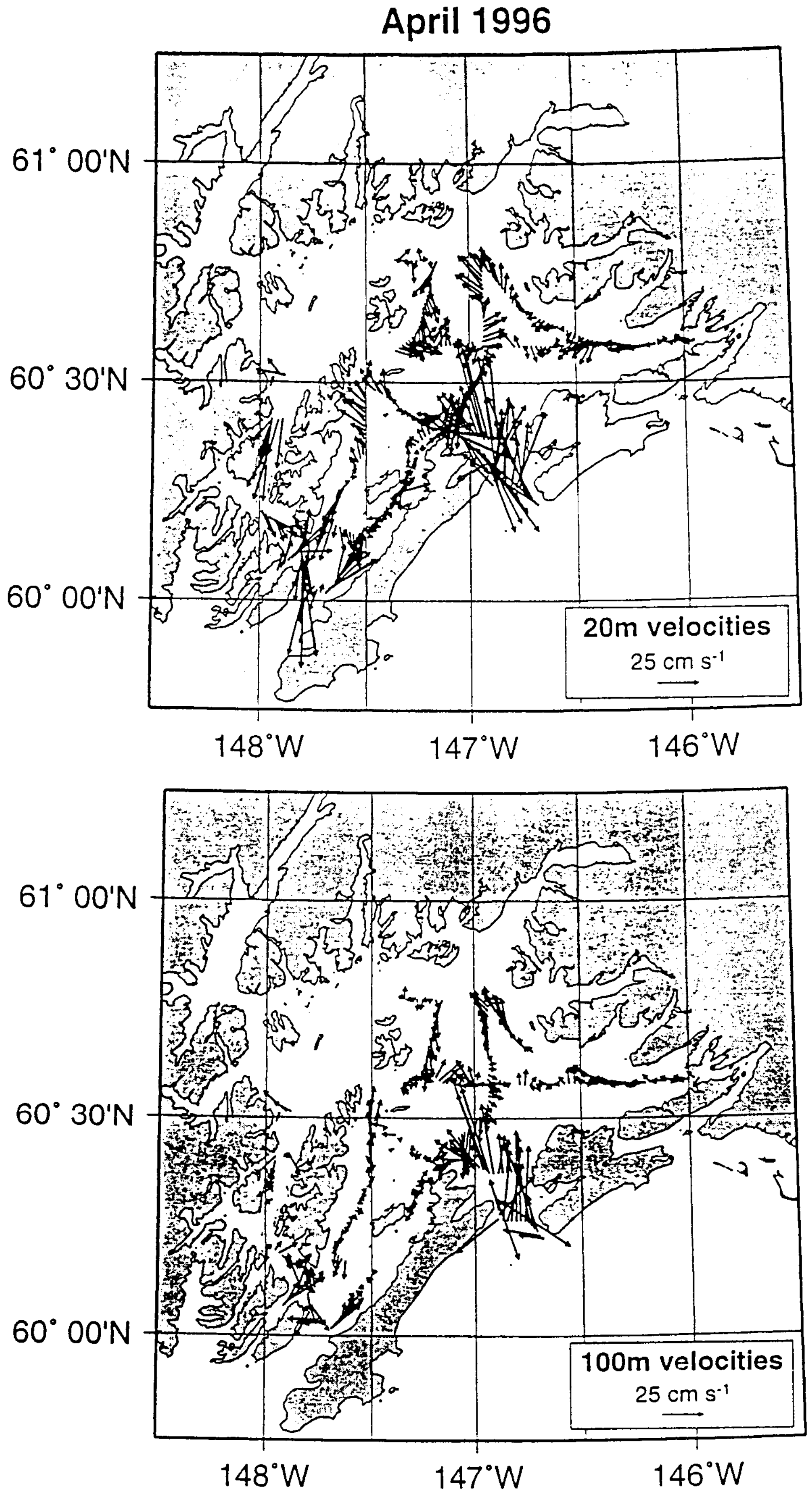


Figure 11: ADCP velocity vectors at 20 m and 100 m in April 1996.

June 1996

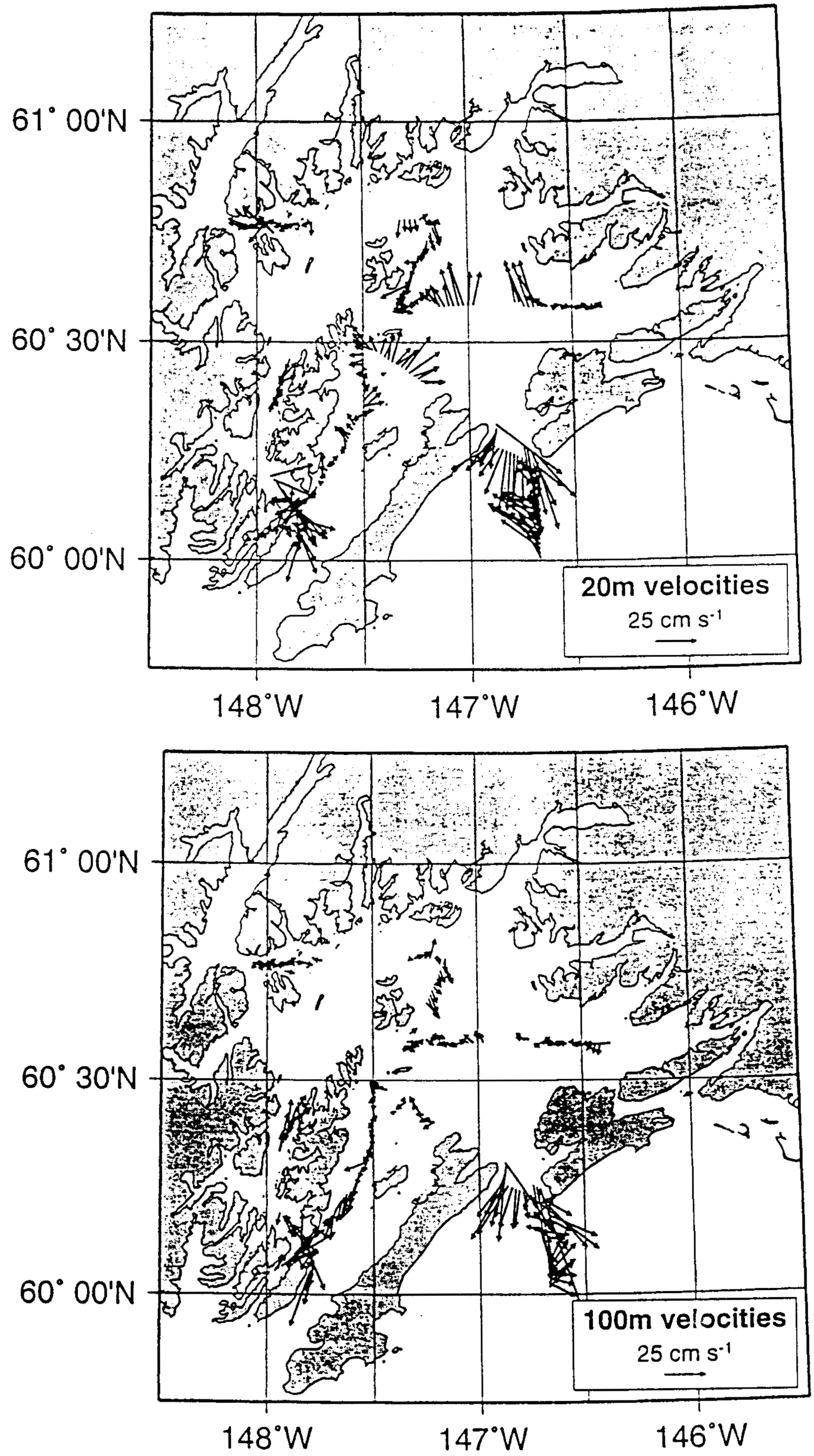


Figure 12: ADCP velocity vectors at 20 m and 100 m in June 1996.

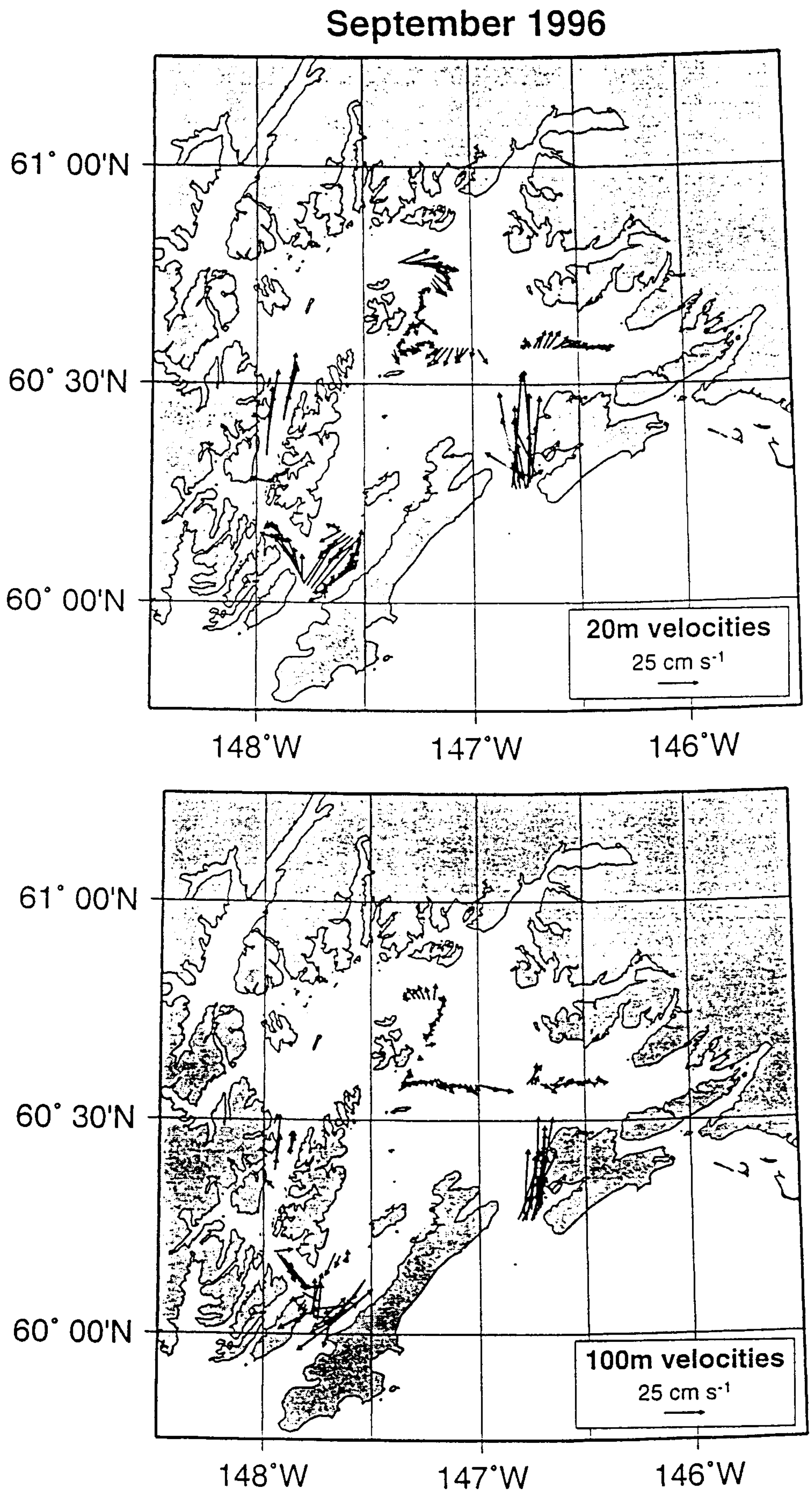
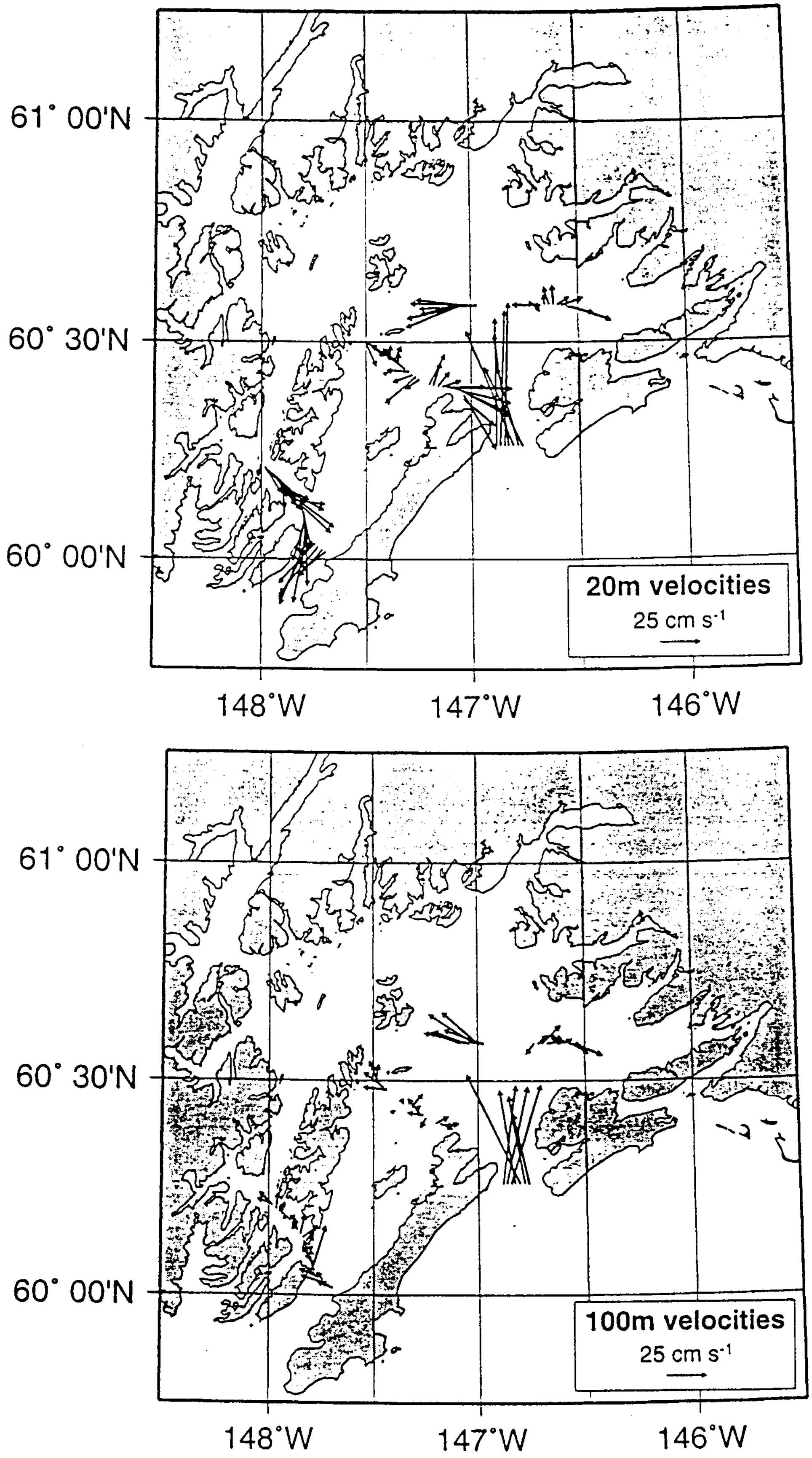
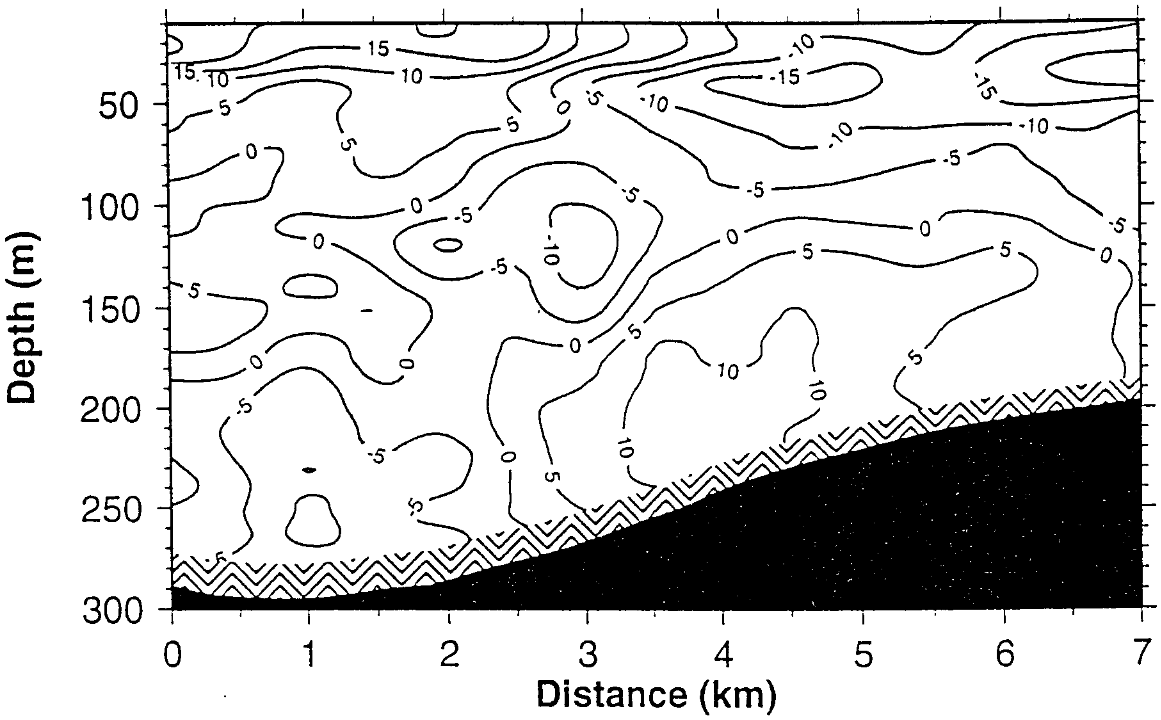


Figure 13: ADCP velocity vectors at 20 m and 100 m in September 1996.



December 1996

Figure 14: ADCP velocity vectors at 20 m and 100 m in December 1996.


HE13-HE11 April 1996 - North Velocities

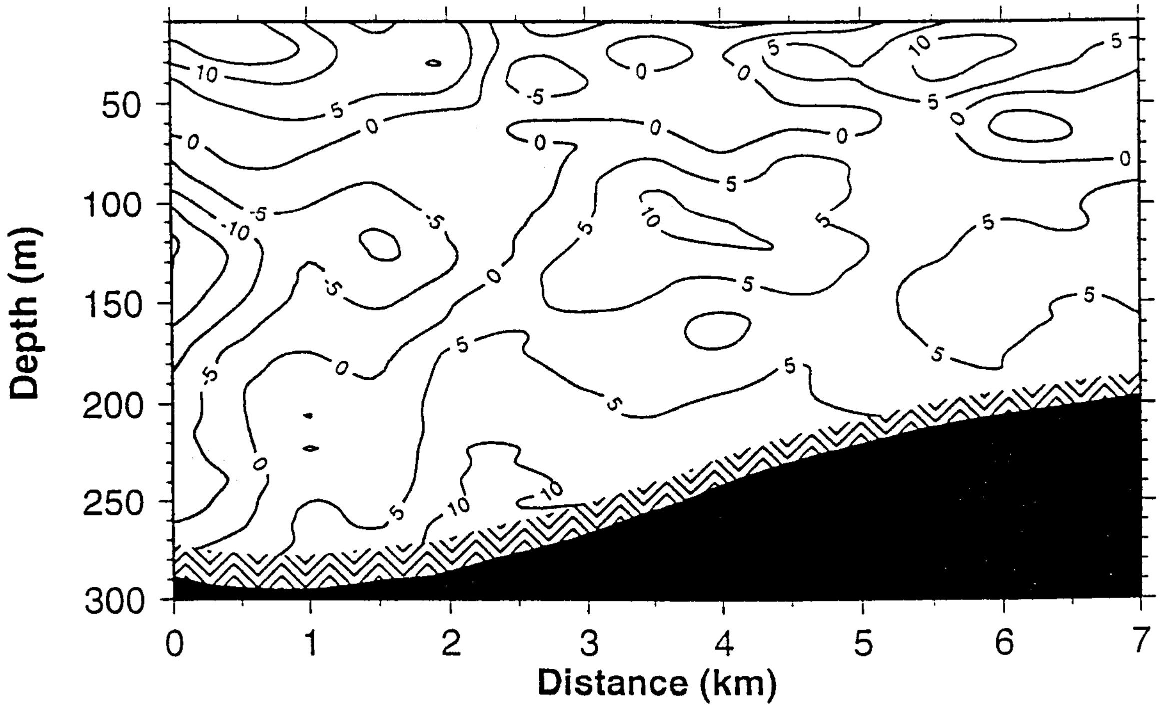
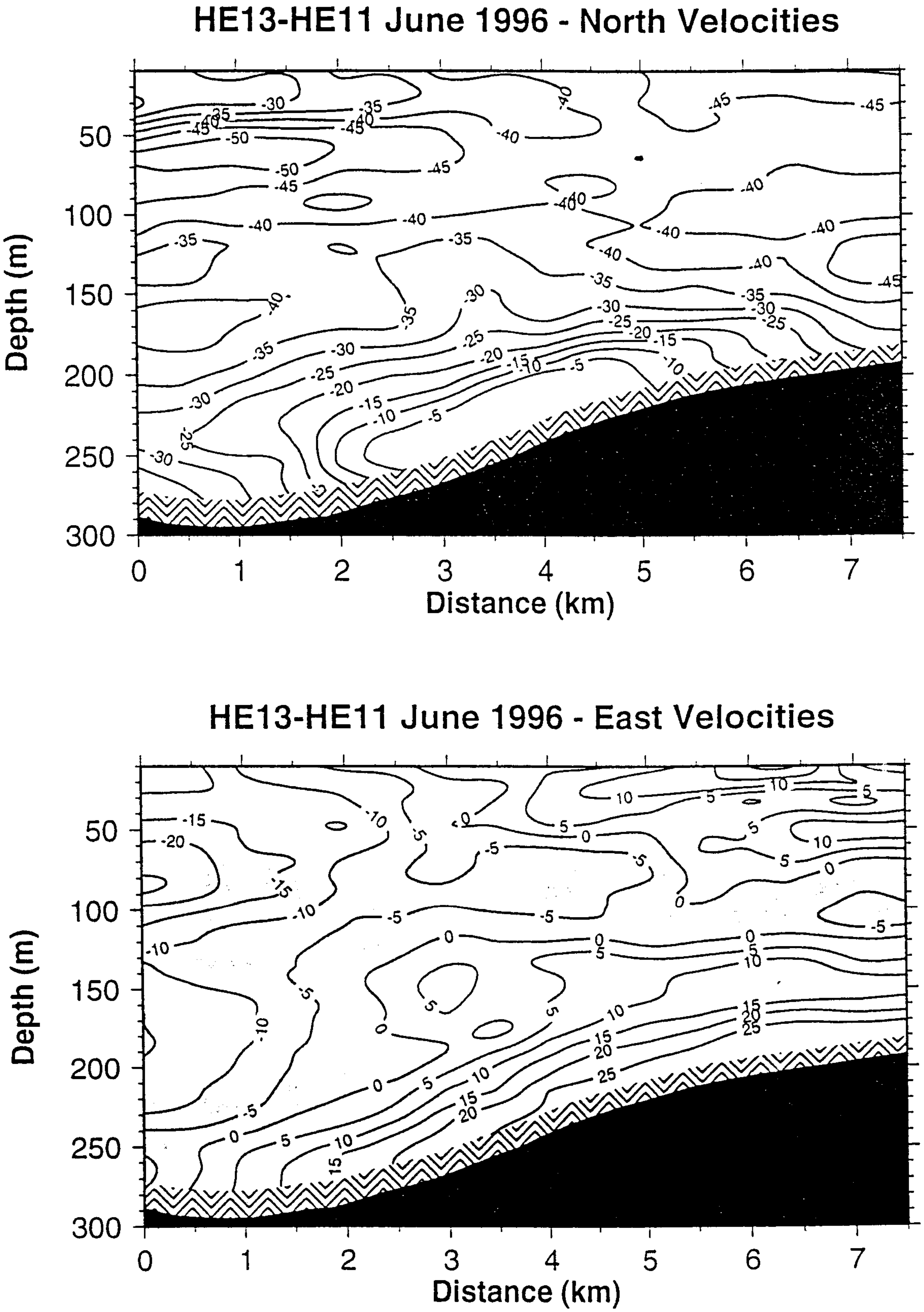

HE13-HE11 April 1996 - East Velocities

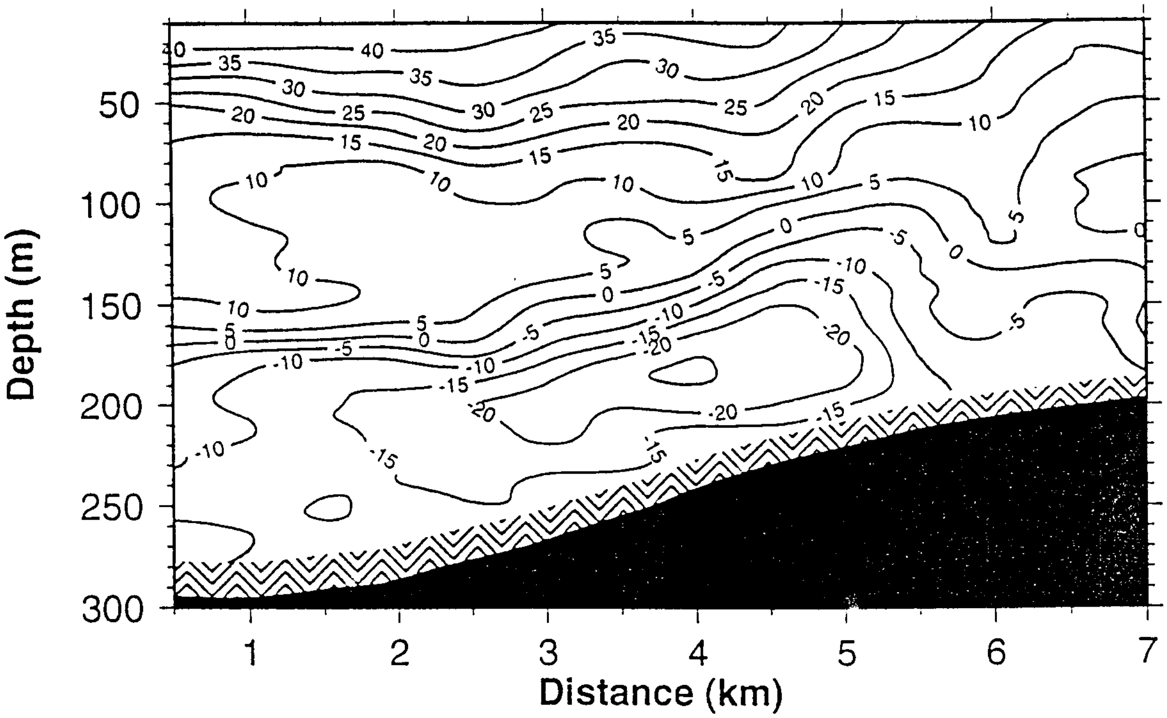
Figure 15(a): Mean ADCP velocities at Hinchinbrook Entrance in April 1996.


HE13-HE11 June 1996 - North Velocities

HE13-HE11 June 1996 - East Velocities

Figure 15(b): ADCP velocities for ebb tide at Hinchinbrook Entrance in June 1996.

HE13-HE11 December 1996 - North Velocities



HE13-HE11 December 1996 - East Velocities

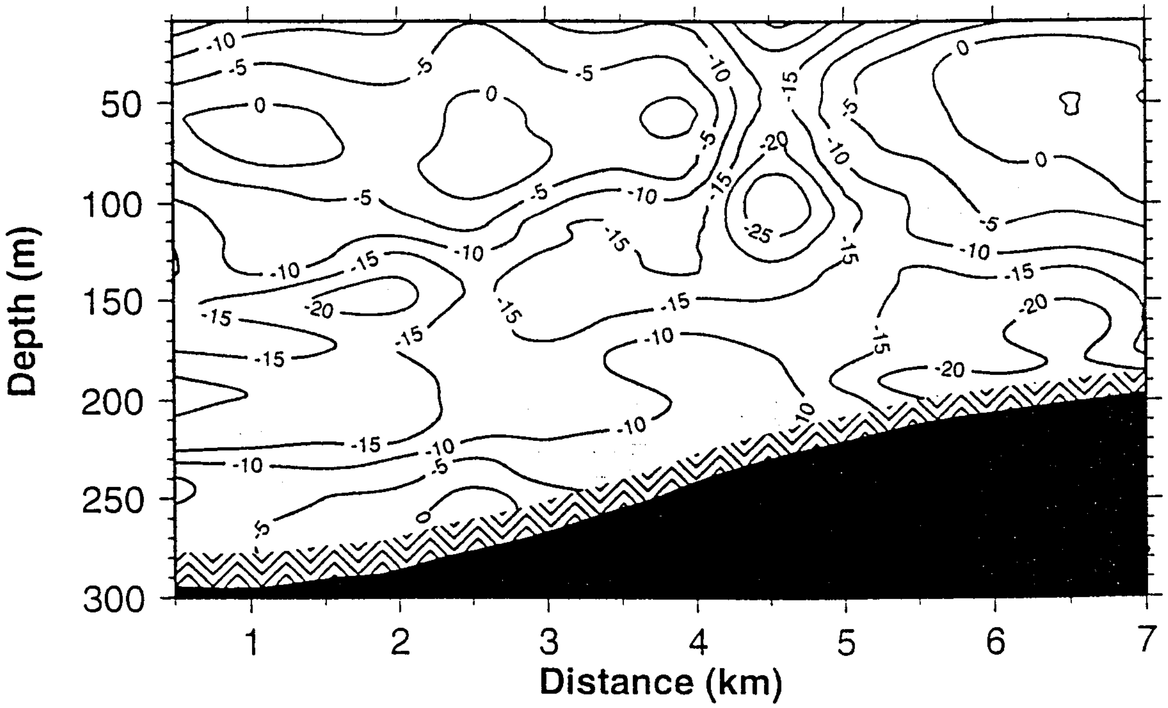
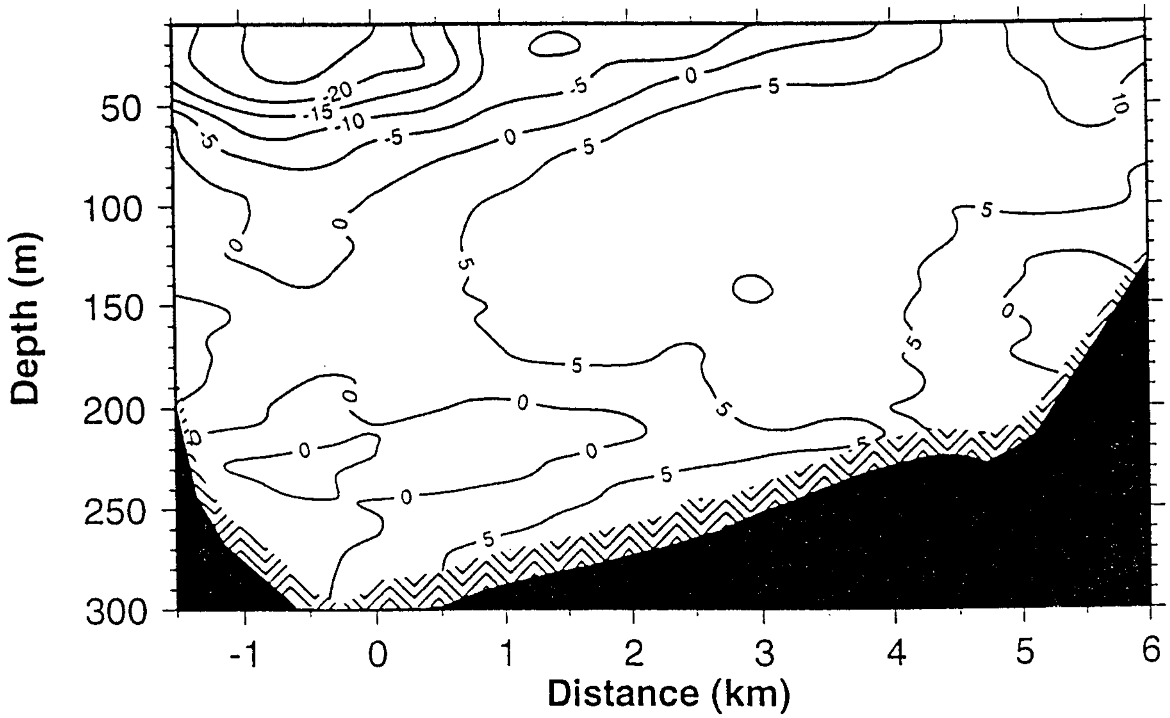


Figure 15(c): Mean ADCP velocities at Hinchinbrook Entrance in December 1996.

SEA31-SEA33 April 1996 - North Velocities



SEA31-SEA33 April 1996 - East Velocities

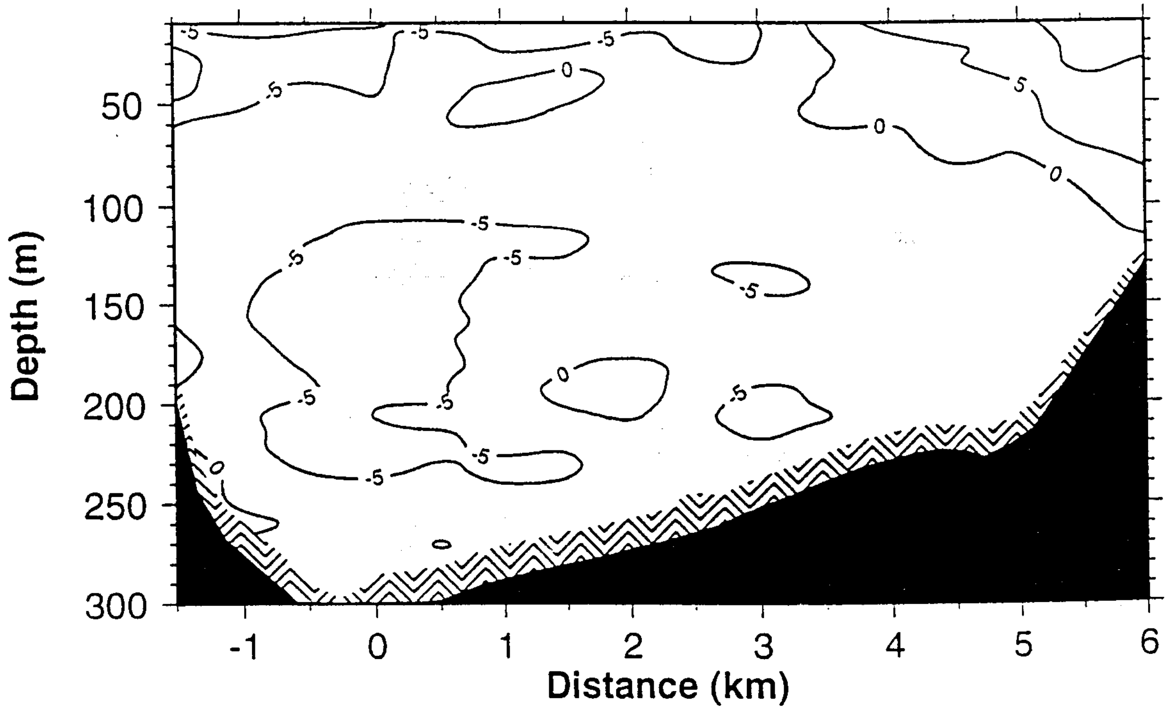
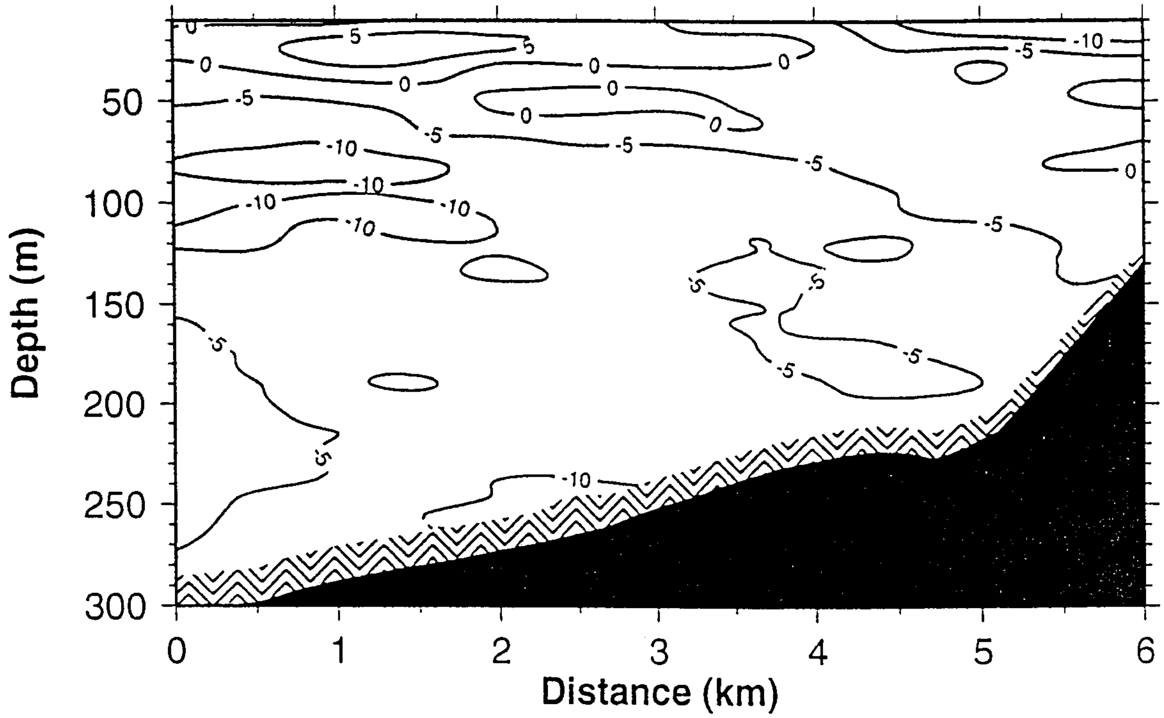


Figure 16(a): Mean ADCP velocities at Montague Straight in April 1996.

SEA31-SEA33 June 1996 - North Velocities



SEA31-SEA33 June 1996 - East Velocities

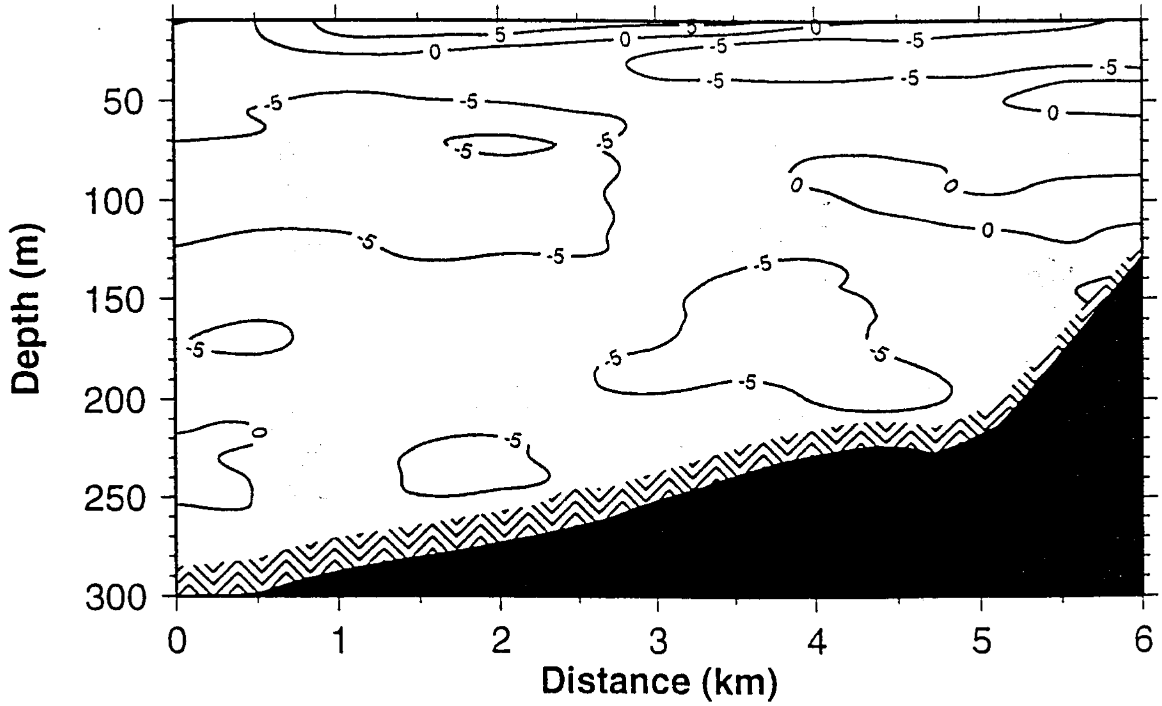
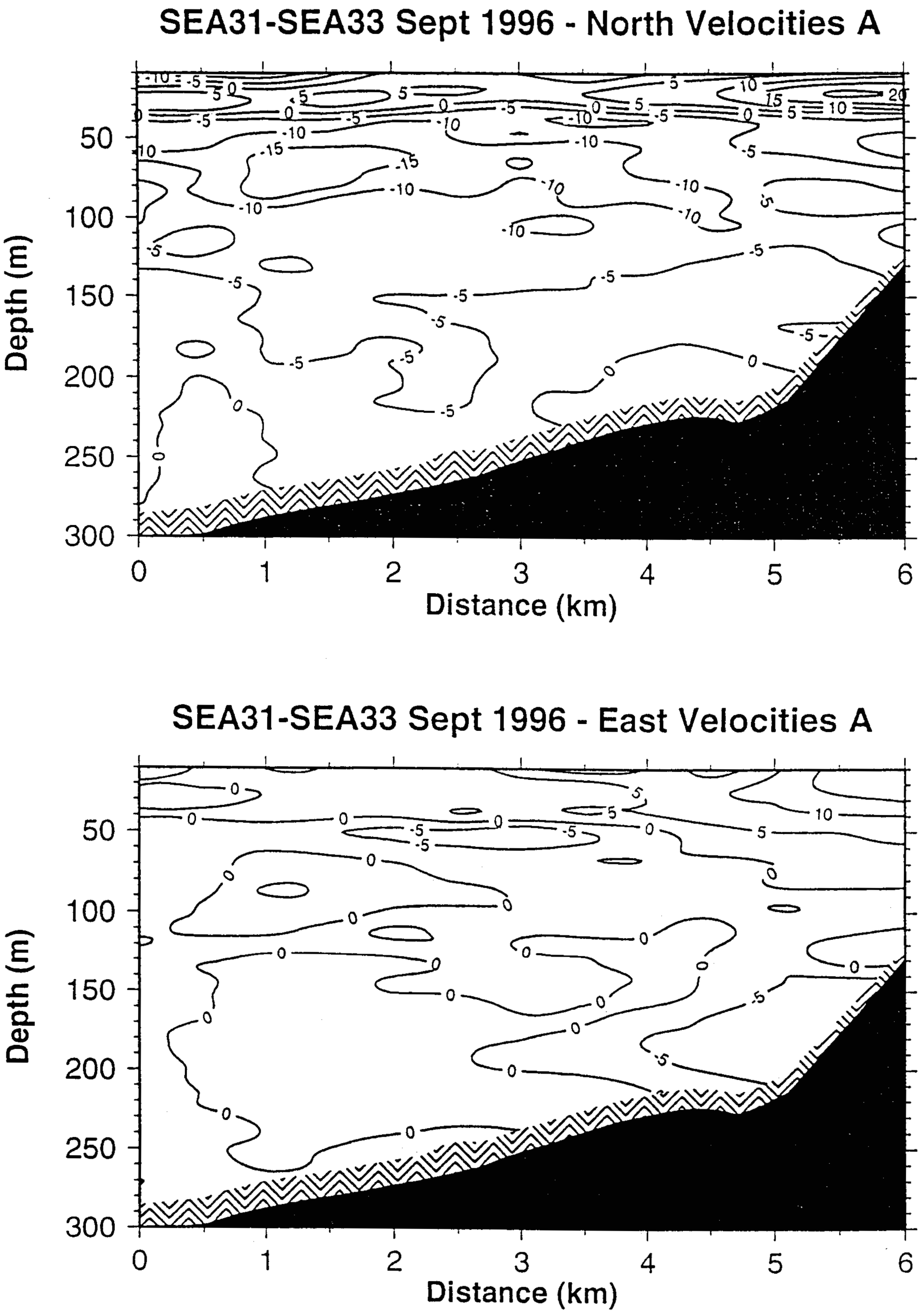


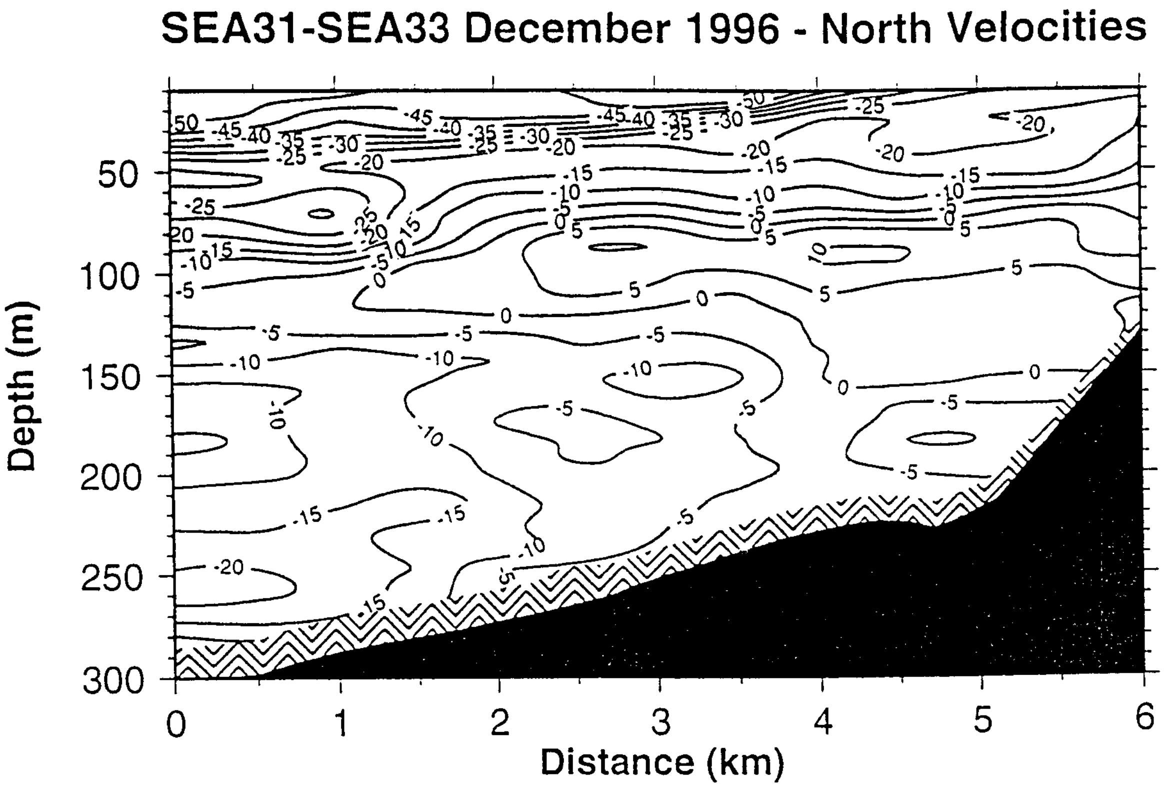
Figure 16(b): Mean ADCP velocities at Montague Straight in June 1996.



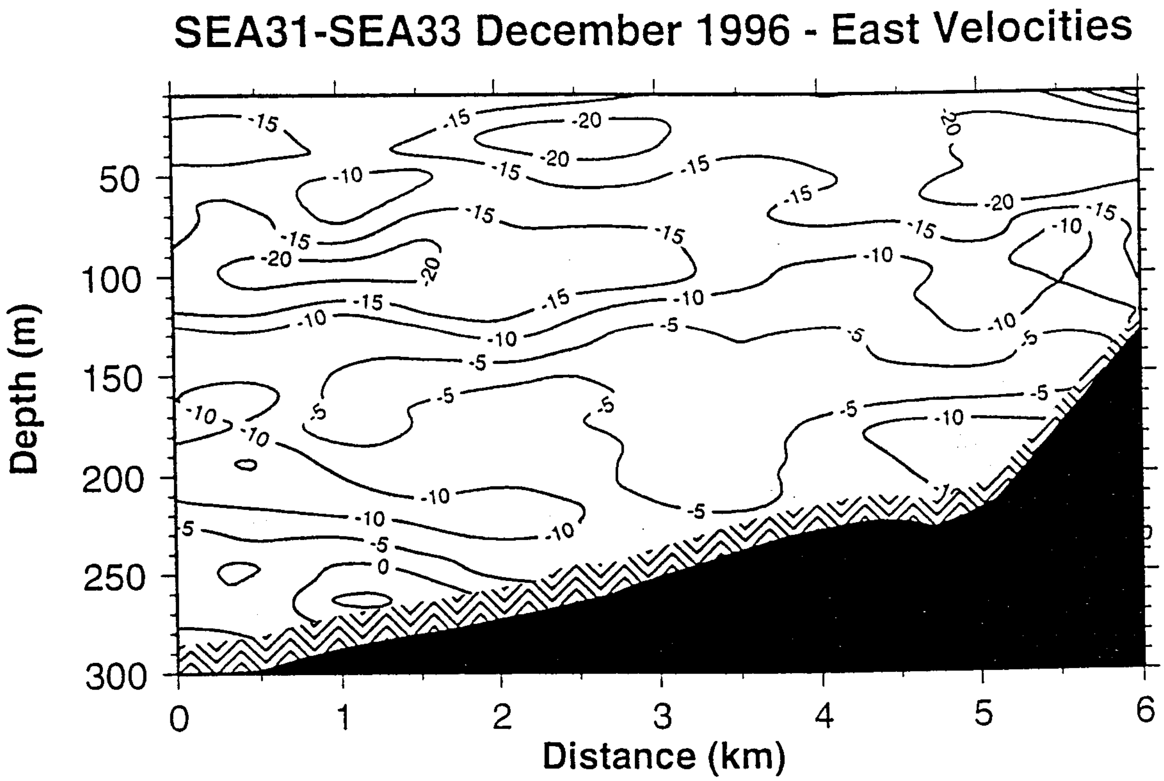
SEA31-SEA33 Sept 1996 - North Velocities A

SEA31-SEA33 Sept 1996 - East Velocities A

Figure 16(c): Mean ADCP velocities at Montague Straight in September 1996.



SEA31-SEA33 December 1996 - North Velocities



SEA31-SEA33 December 1996 - East Velocities

Figure 16(d): Mean ADCP velocities at Montague Straight in December 1996.

Drifter Track: 25652

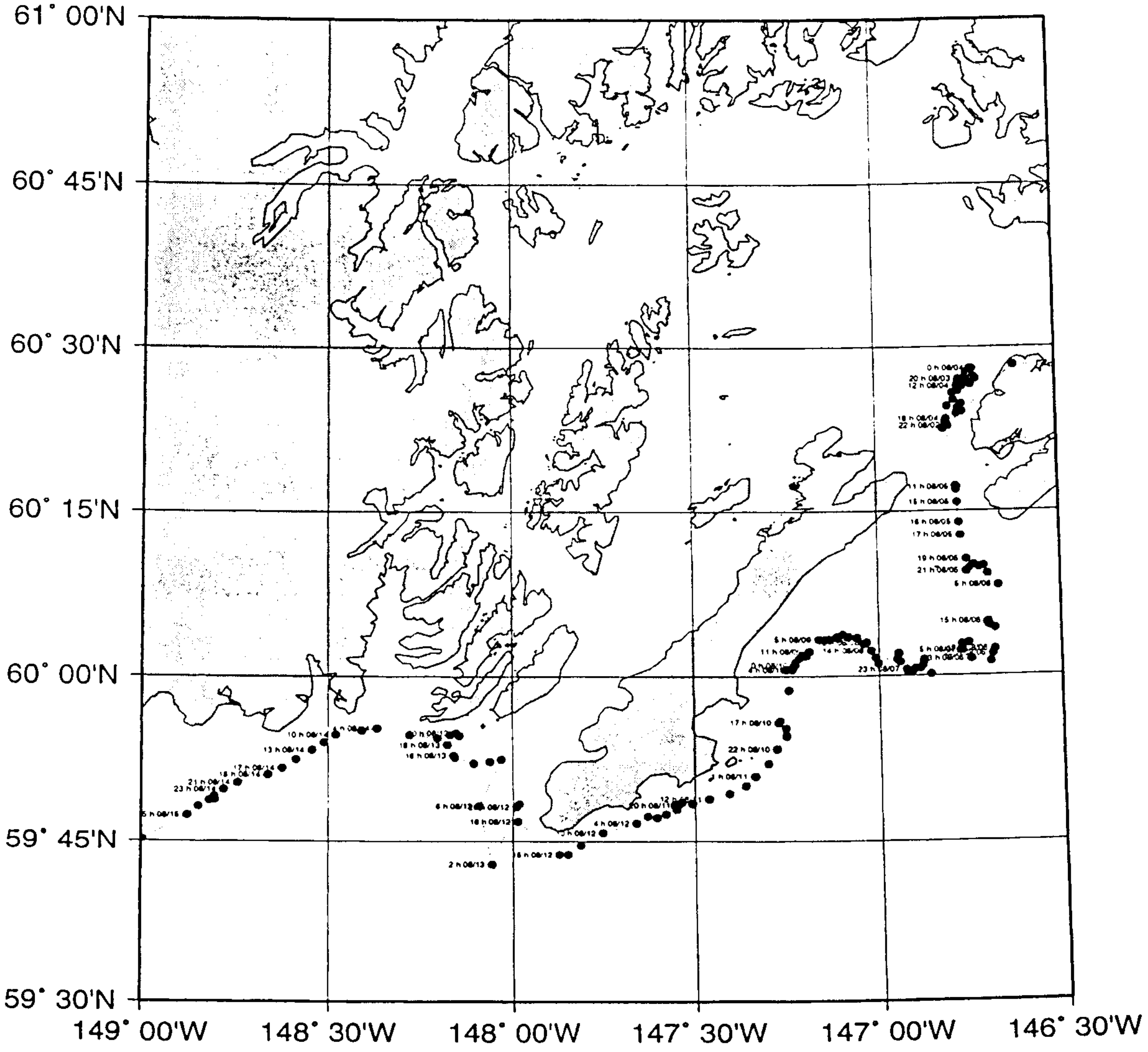


Figure 17: Path of ARGOS drifter drogued at 15 m released August 1996.

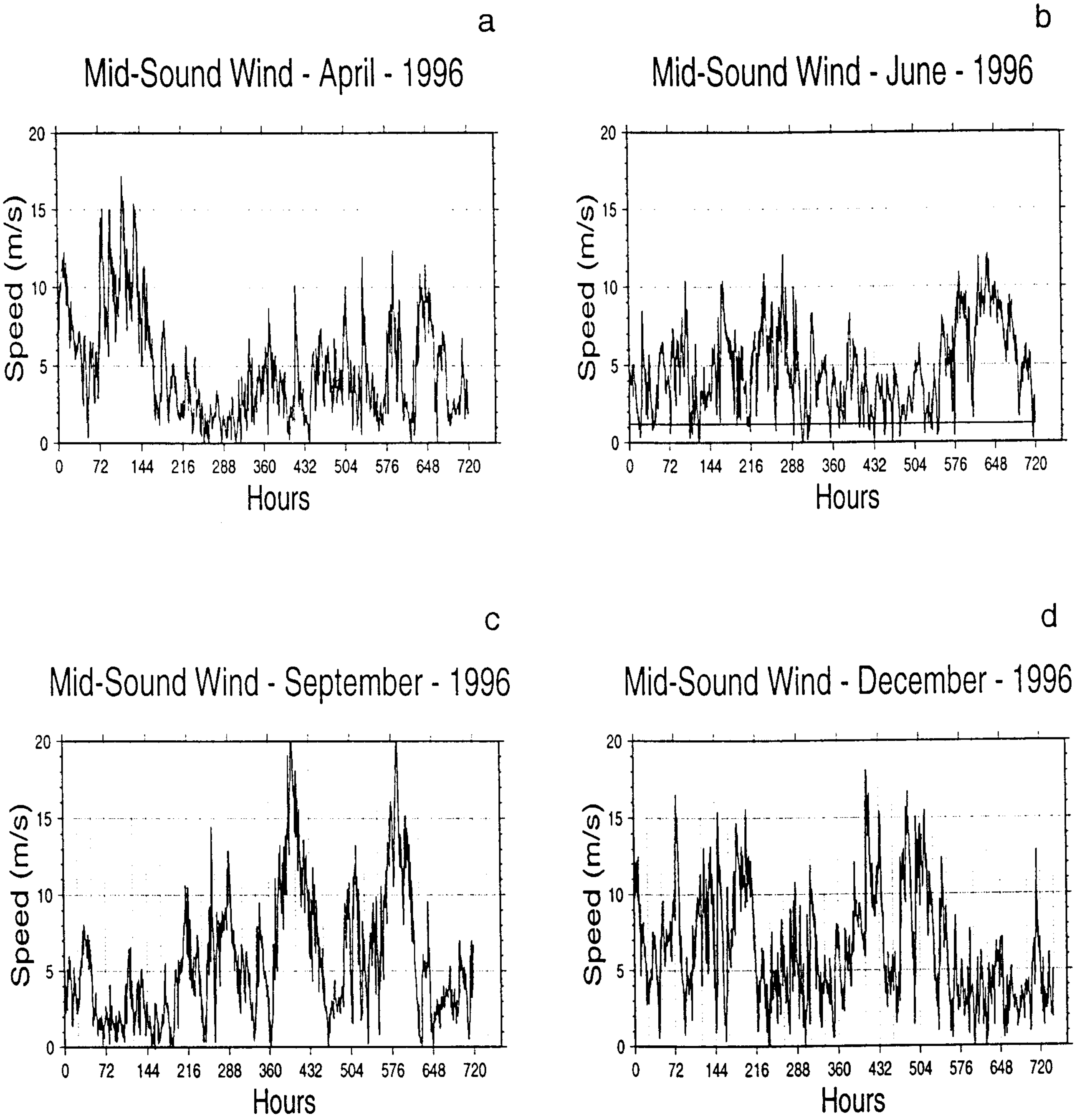


Figure 18: Wind speeds from NDBC Mid-Sound buoy for (a) April, (b) June, (c) September, (d) and December, 1996.

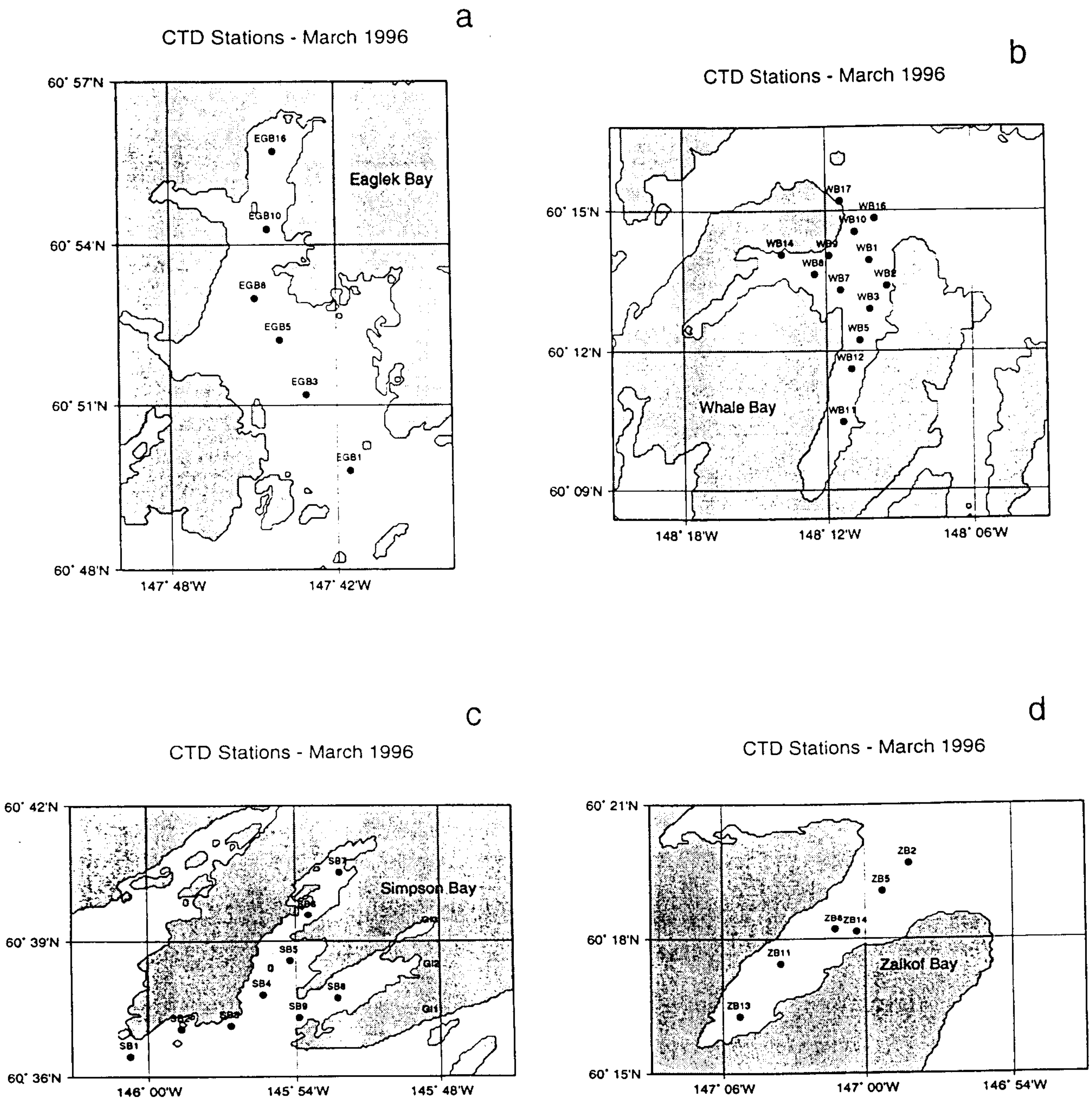


Figure 19: Station locations for (a) Eaglek Bay, (b) Whale Bay, (c) Simpson Bay, and (d) Zaikof Bay.

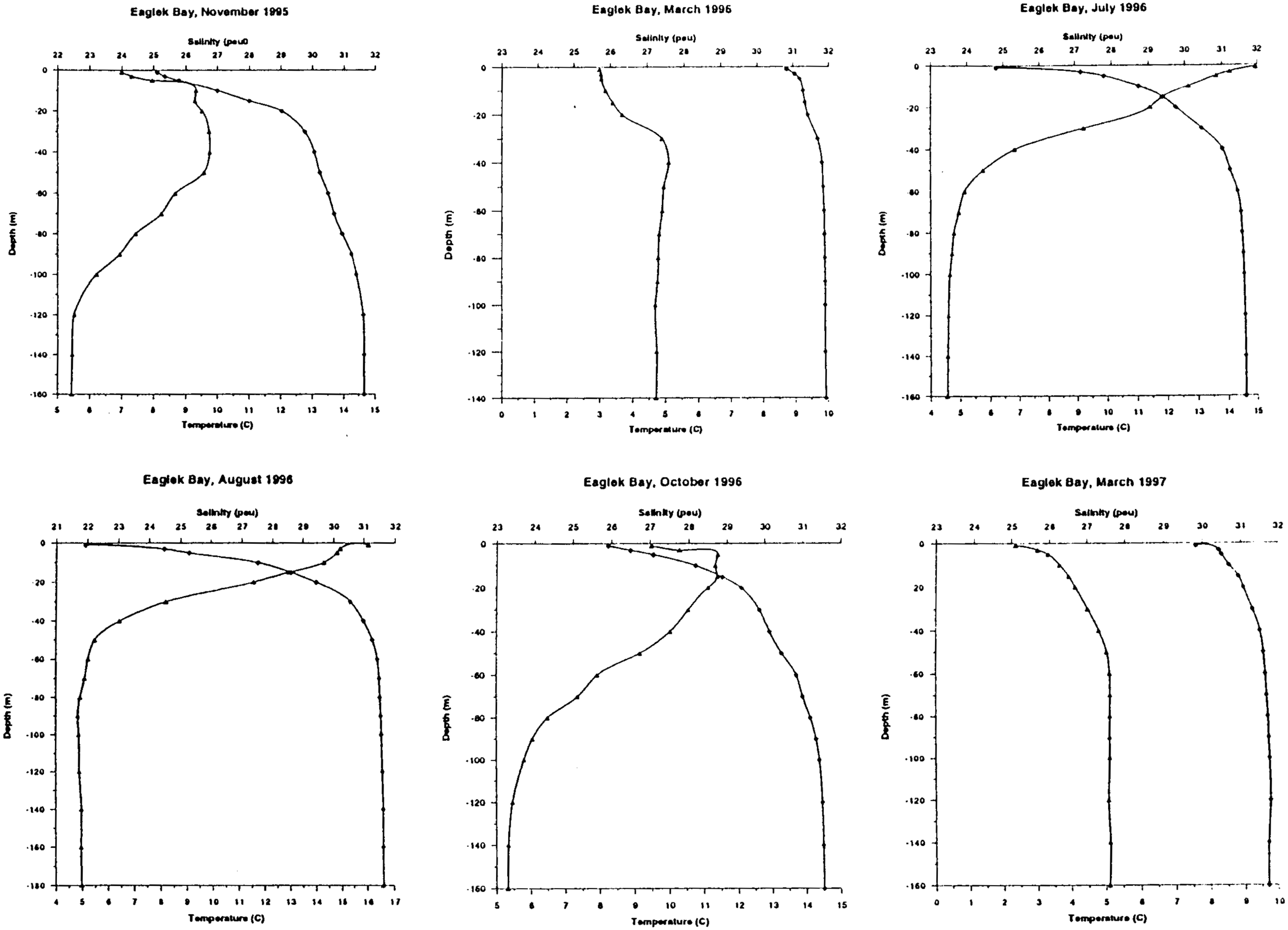


Figure 20: Mean temperature (triangles) and salinity (diamonds) of Eaglek Bay, Alaska from November 1995 to March 1997

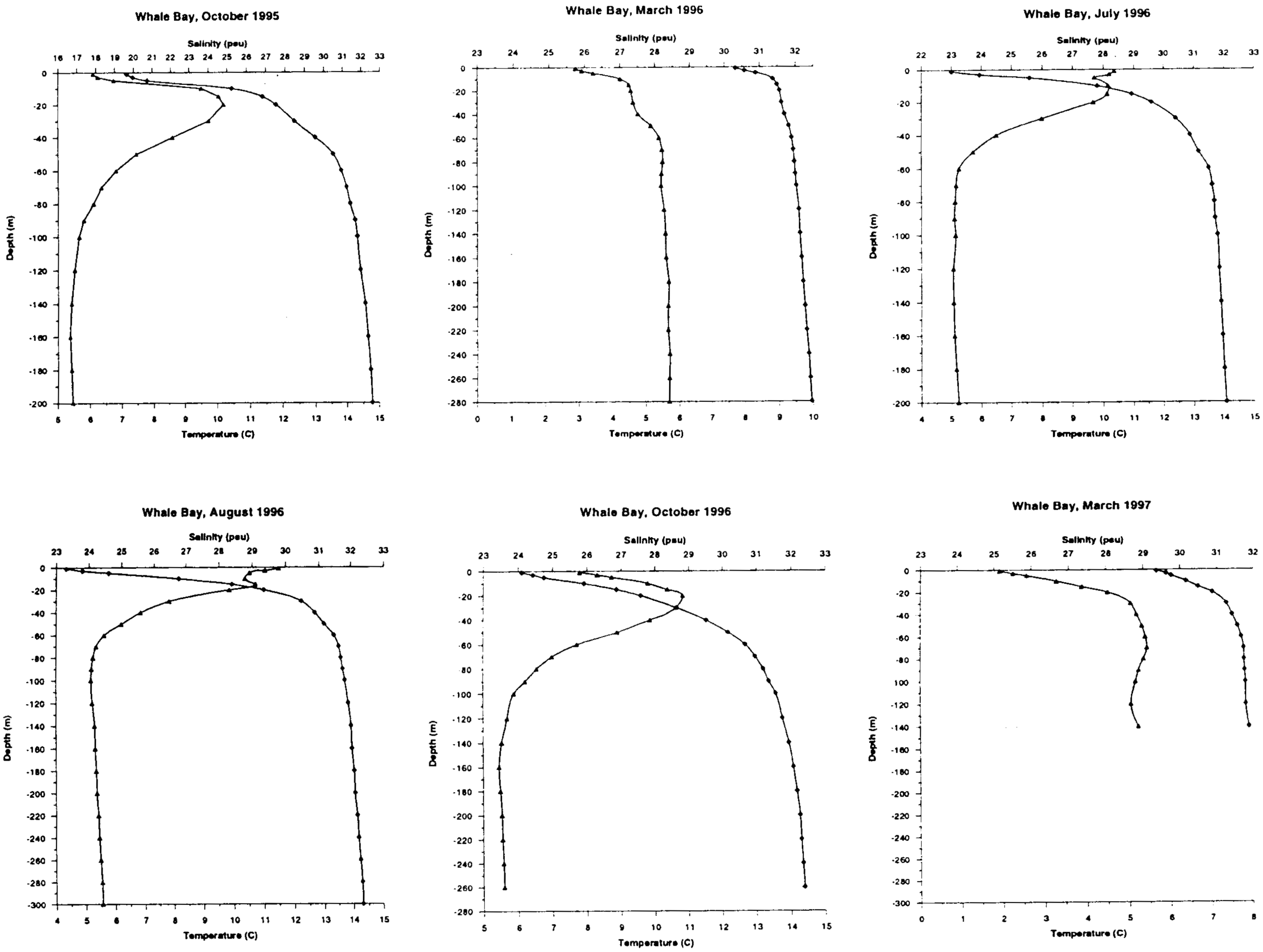


Figure 21: Means of temperature (triangles) and salinity (diamonds) for Whale Bay, Alaska from October 1995 to March 1997.

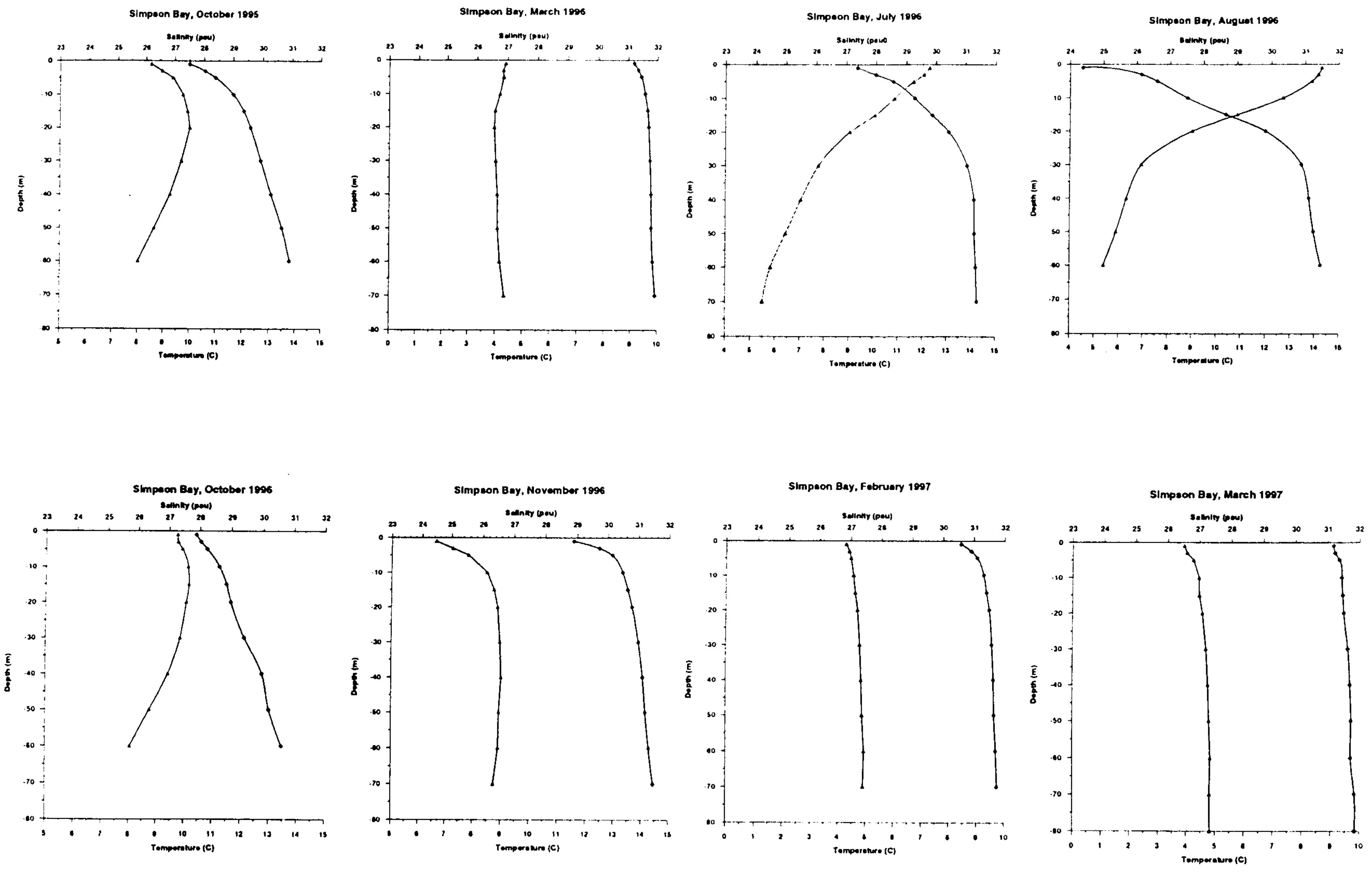


Figure 22: Means of temperature (triangles) and salinity (diamonds) for Simpson Bay, Alaska from October 1995 to March 1997.

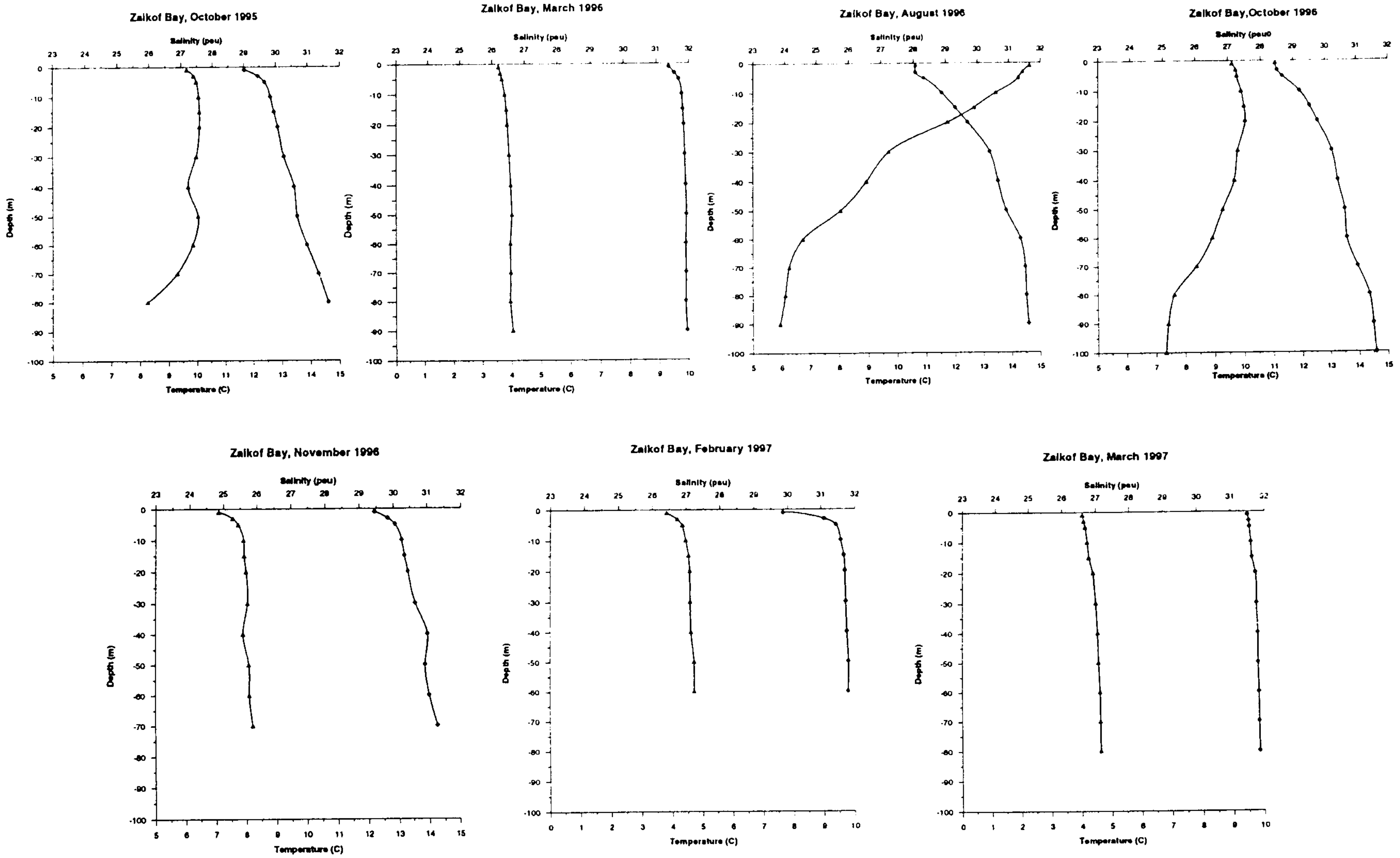
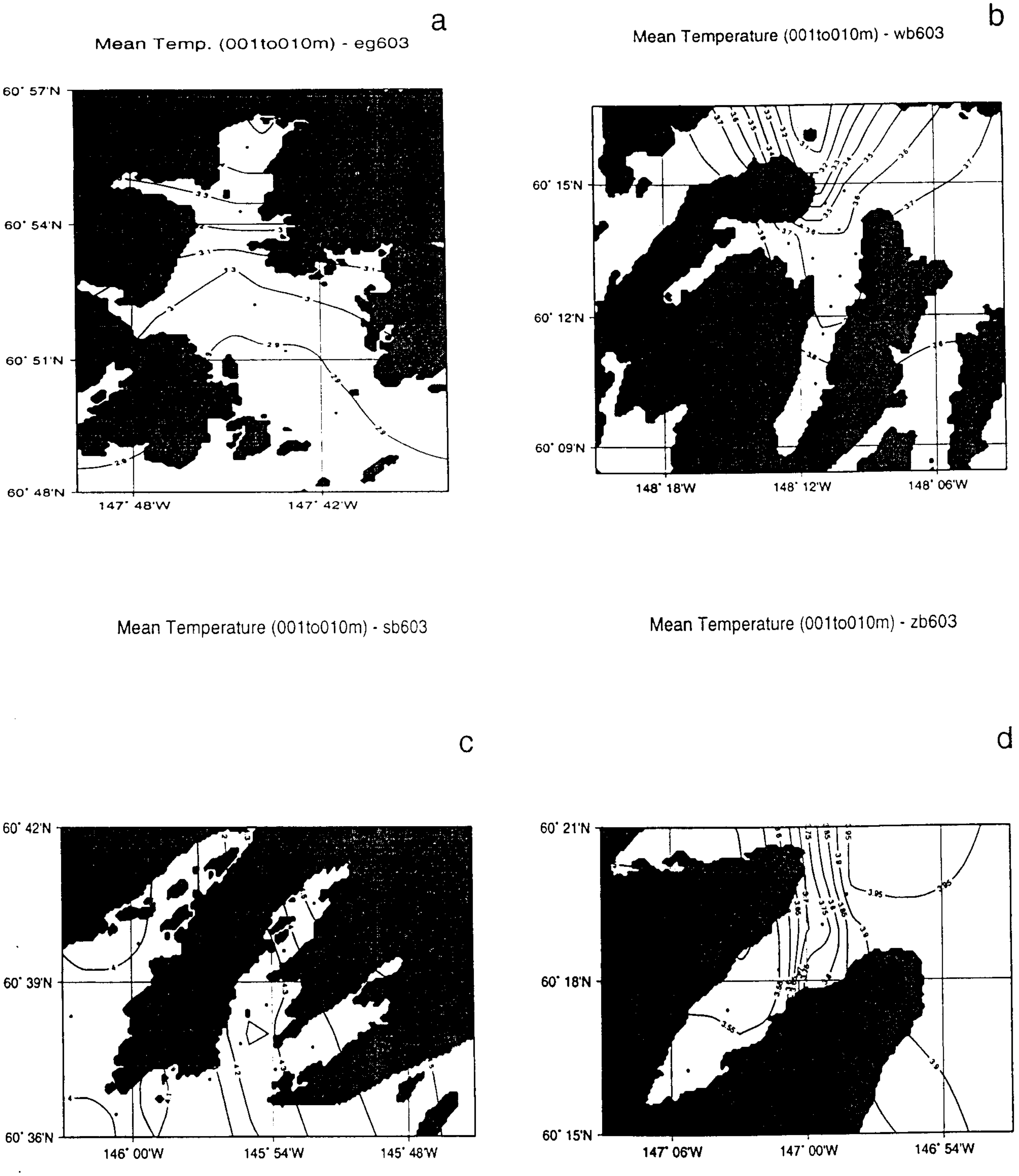


Figure23: Means of temperature (triangles) and salinity (diamonds) for Zaikof Bay, Alaska from October 1995 to march 1997.



Mean Temp. (001to010m) - eg603

Mean Temperature (001to010m) - wb603

Mean Temperature (001to010m) - sb603

Mean Temperature (001to010m) - zb603

Figure 24: Upper 10m mean temperatures in March for (a) Eaglek, (b) Whale, (c) Simpson, and (d) Zaikof Bay. Station locations are shown as dots.

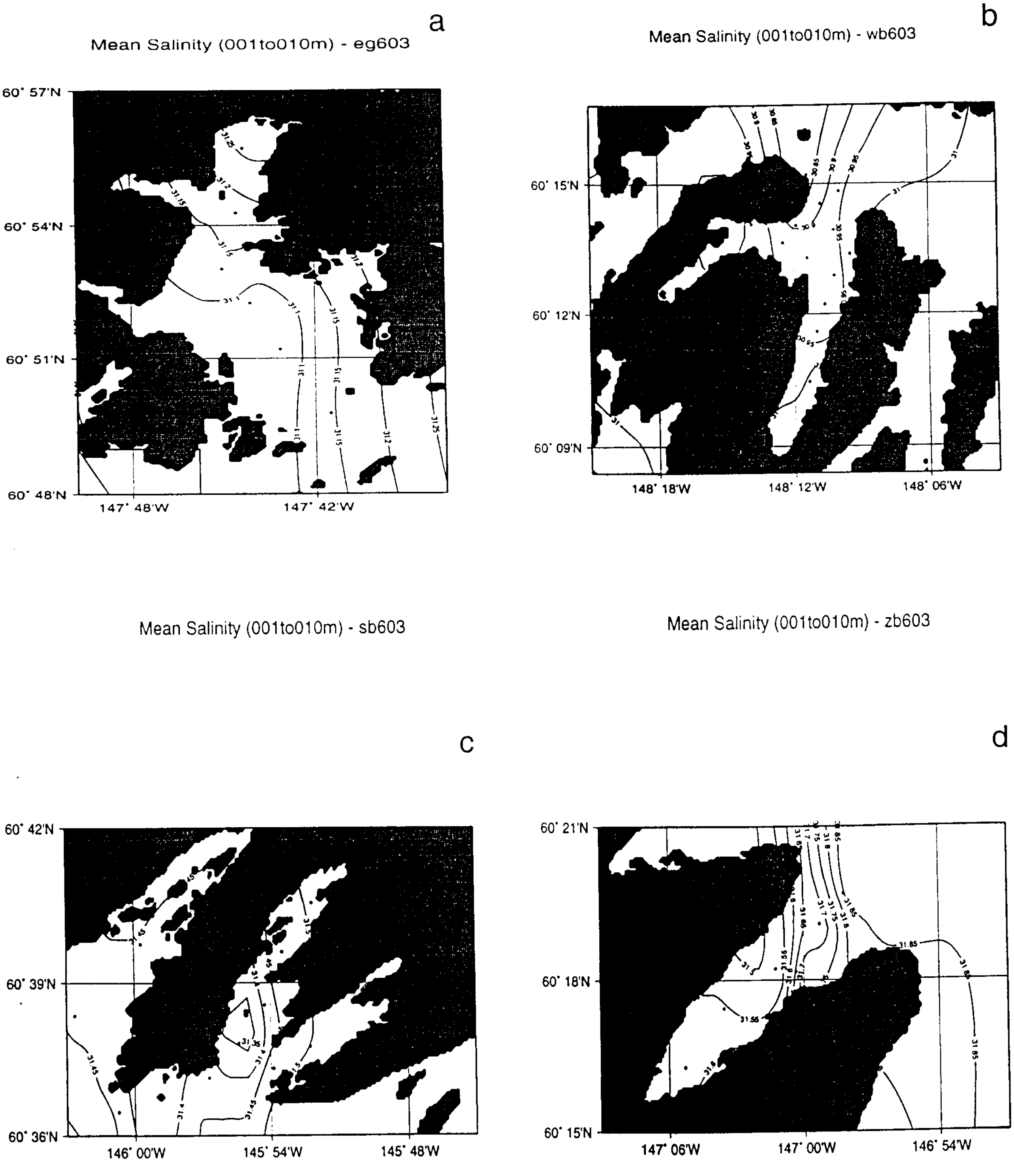


Figure 25: Upper 10m mean salinities in March for (a) Eaglek, (b) Whale, (c) Simpson, and (d) Zaikof Bay. Station locations are shown as dots.

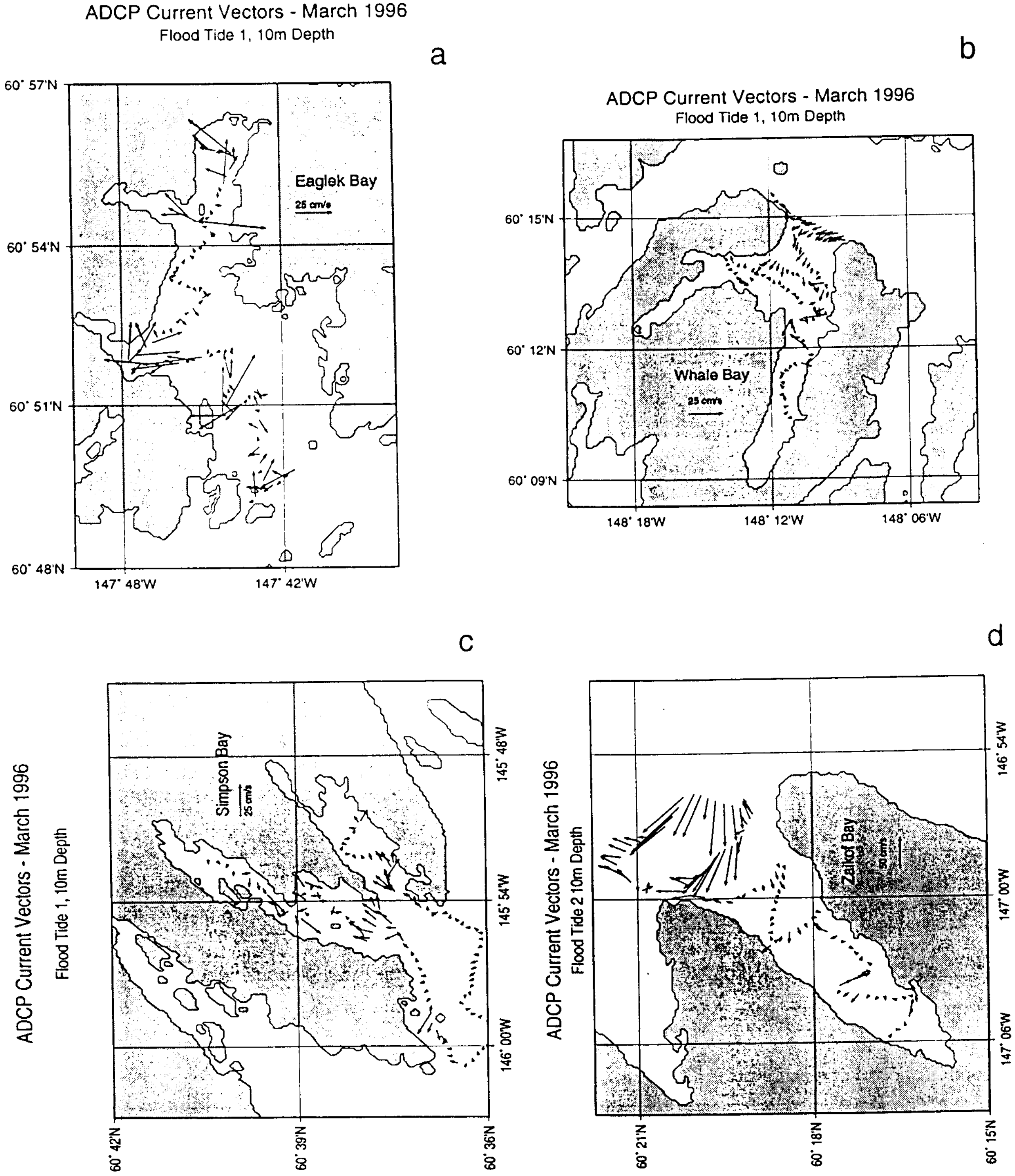


Figure 26: Velocity vectors at 10m for (a) Eaglek, (b) Whale, (c) Simpson, and (d) Zaikof Bay in March 1996 during flood tide.

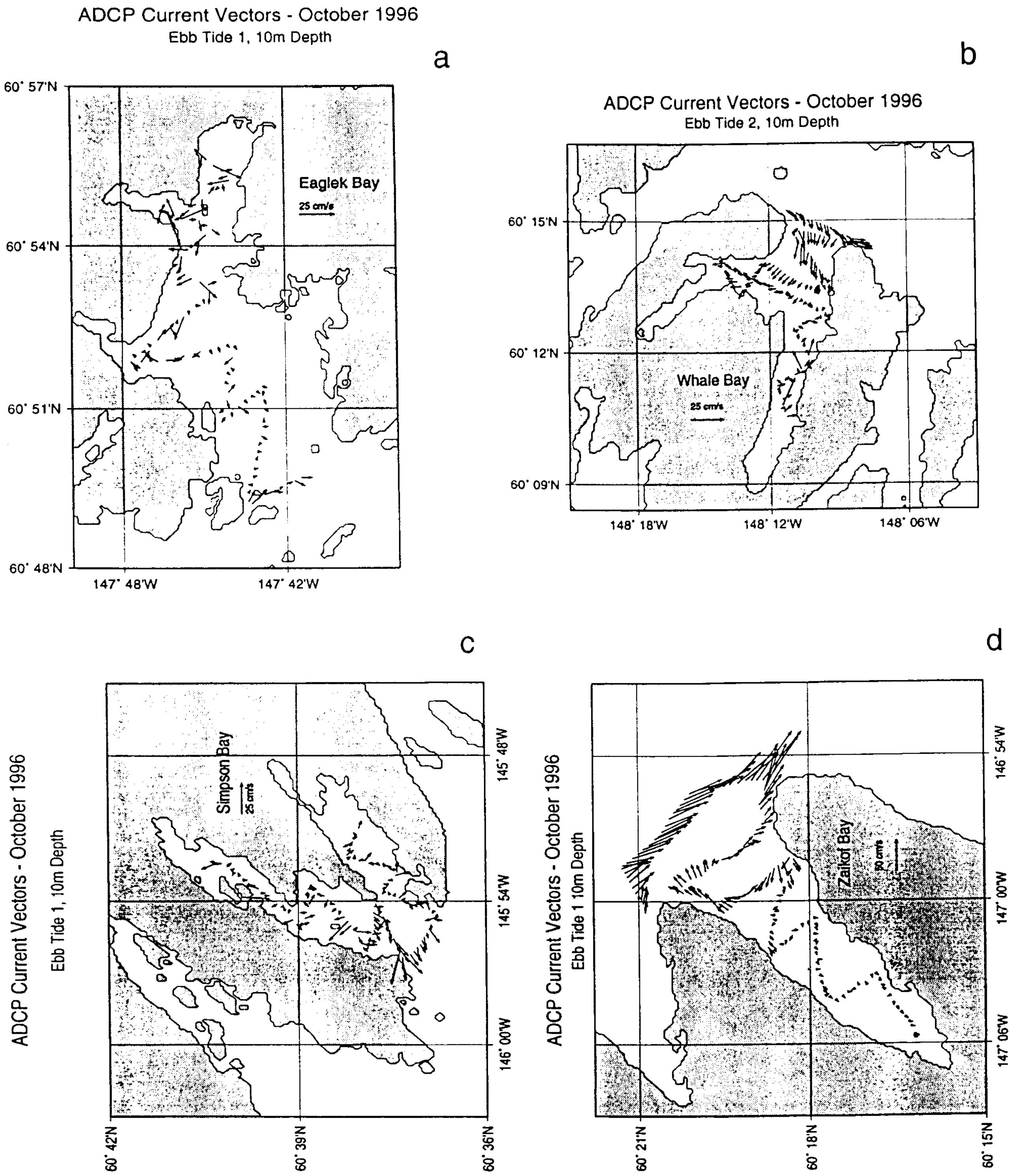


Figure 27: Velocity vectors at 10m for (a) Eaglek, (b) Whale, (c) Simpson, and (d) Zaikof Bay in October 1996 during ebb tide.

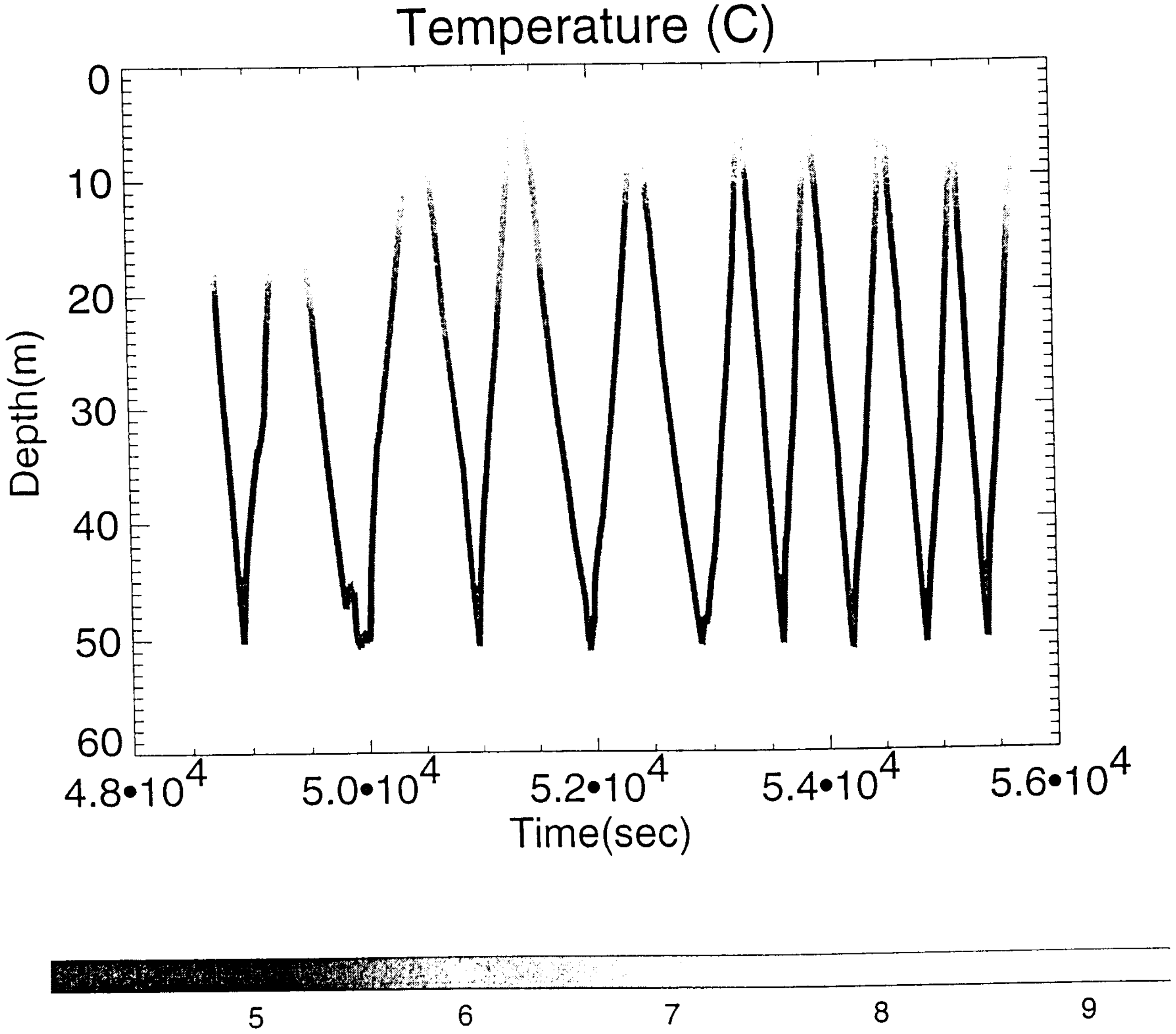


Figure 28(a): Temperature along west to east transect in Orca Inlet in May 1996.

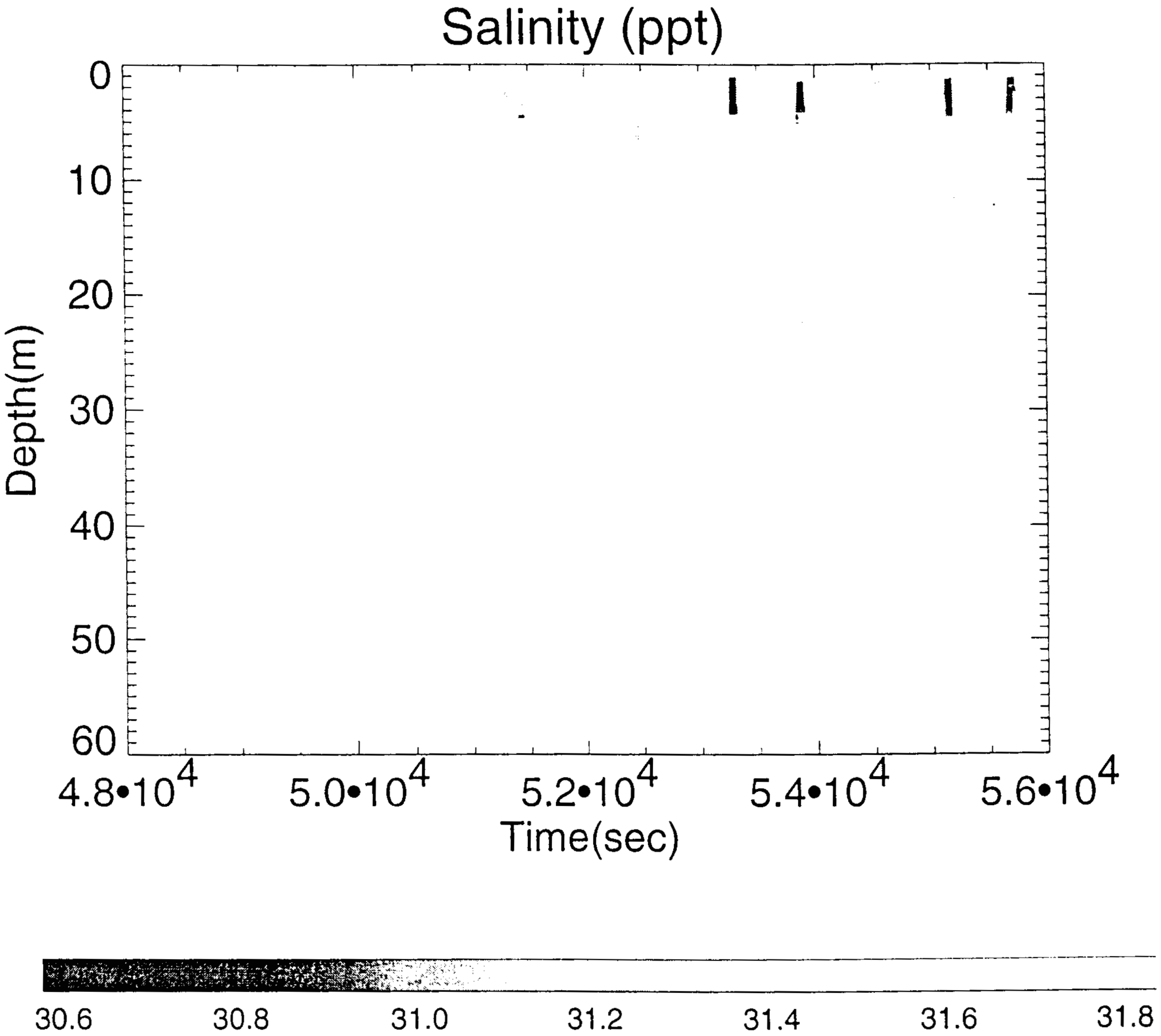


Figure 28(b): Salinity along west to east transect in Orca Inlet in May 1996.

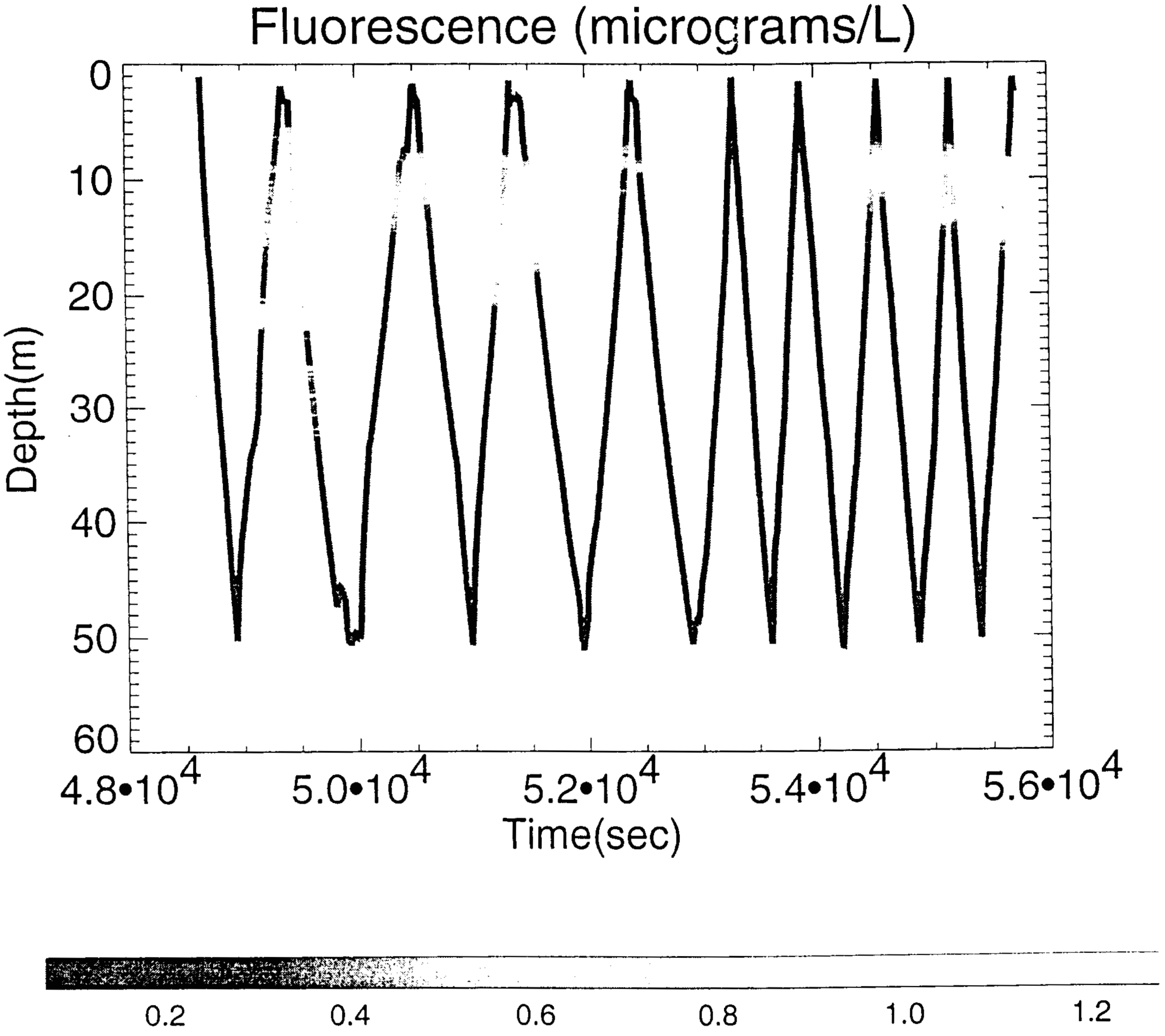


Figure 28(c): Fluorescence along west to east transect in Orca Inlet in May 1996.

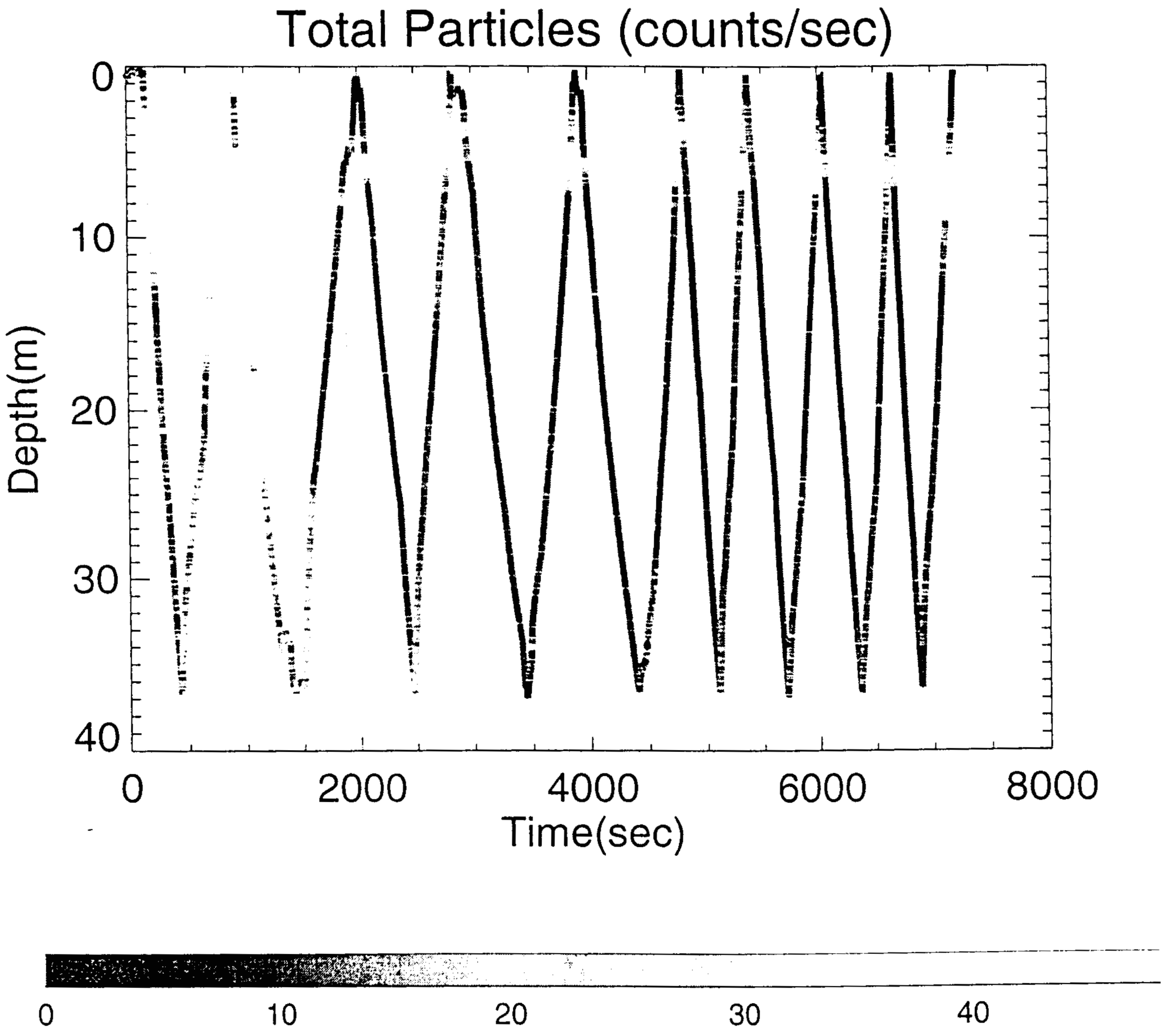


Figure 28(d): Total OPC counts along west to east transect in Orca Inlet in May 1996.

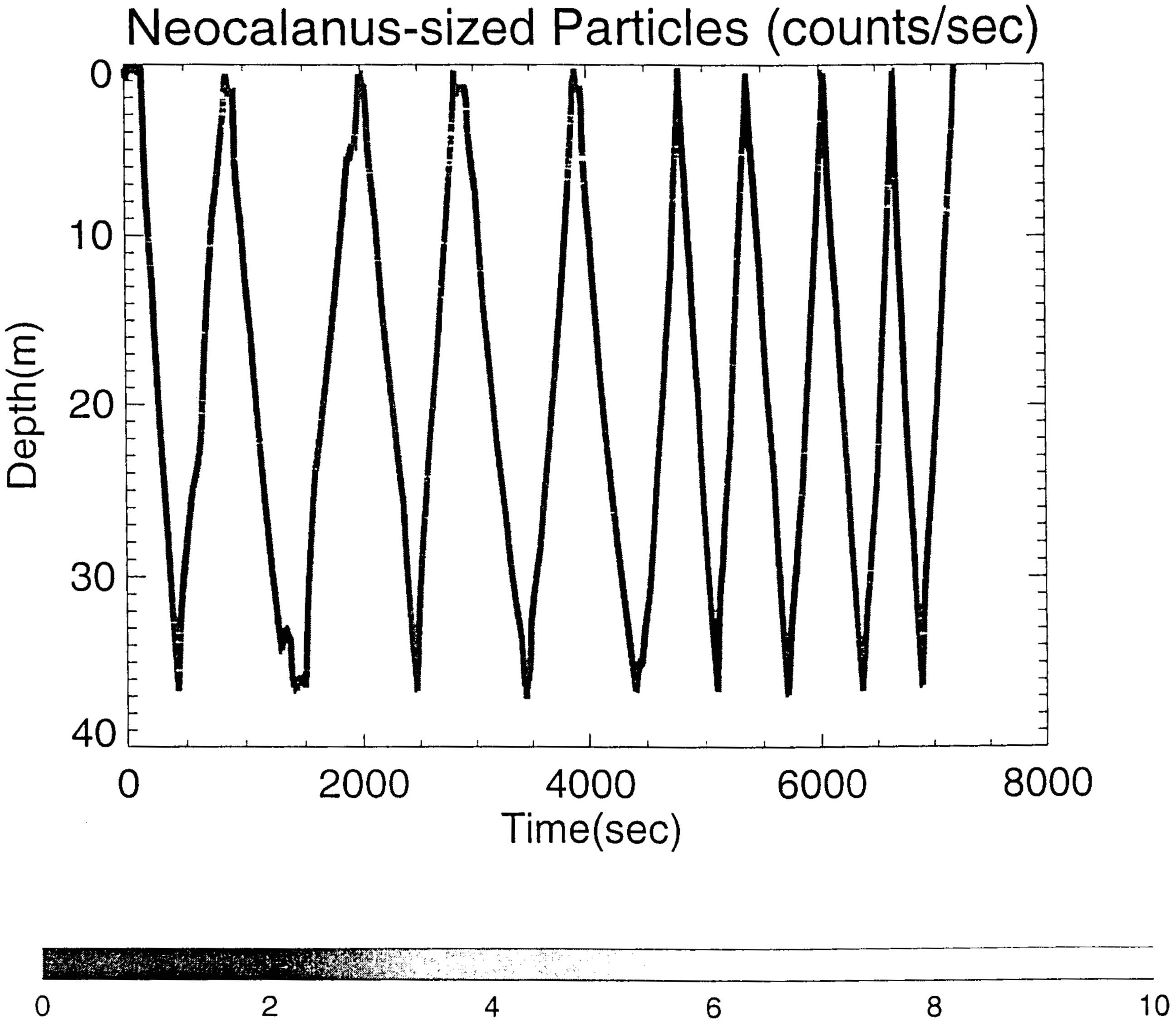


Figure 28(e): Neocalanus-sized particles along west to east transect in Orca Inlet in May 1996.

Chapter 9.

Plankton and Nekton Acoustics (96320N)

Exxon Valdez Oil Spill
Restoration Project Annual Report
Nekton-Plankton Acoustics Project 96320N

Nekton-Plankton Acoustics
Restoration Project 96320N
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

G.L. Thomas P.I., Jay Kirsch, P.L.
Geoff Steinhart and Nicholas Peters

Prince William Sound Science Center
P.O. Box 705
Cordova, AK 99574
Phone: (907)424-5800
Fax: (907)424-5820
e-mail: loon@grizzly.pwssc.gen.ak.us
April 15, 1997

Nekton-Plankton Acoustics (SEAFISH)

Restoration Project 96320N

Annual Report

Study History: The small runs of Prince William Sound pink salmon in 1992 and 1993, and the collapse of the herring population in 1993, prompted the EVOS Trustee Council to initiate the ecosystem-level studies to improve existing predictive tools. In 1993, the Sound Ecosystem Assessment science plan was developed using the GLOBEC program as a guide. Funding of research began in the spring of 1994. The Nekton-Plankton Acoustics project (SEAFISH) is evaluating and applying acoustic measurement technology to collect information on fish and macrozooplankton distribution and abundance.

This is the third annual report for the Nekton-Plankton Acoustic project. Four technical reports and five abstracts have been published to date, and the chapters in this report are being prepared for submission to journals this year. Upon implementation, the Sound Ecosystem Assessment program was recommended by peer reviewers to be a 8-10 year program. Funding from the EVOS Trustee Council is committed for five years. Funding for the fourth year is in place and preliminary budgets have been projected through FY99 (five years). We envision a transition from the intense observational oceanography and modeling program (SEA), into a model-based monitoring program in years four through six. This second phase will focus on the implementation of monitoring to collect the data needed to initialize the SEA numerical models and to verify the model predictions. Developments in the plankton-nekton acoustics are essential to the design of a cost-effective monitoring program.

Abstract: In the first three years, the primary contribution of the Nekton-Plankton Acoustics project is to develop accurate estimation procedures for animal abundance and distribution information. These data are used for testing of the river-lake and prey-switching hypotheses and the development of predictive numerical models. The results are spilt between preliminary and completed products. The preliminary products are the estimates of nekton predators and macrozooplankton prey along the outmigration corridor for the pink salmon in the spring, and the fall and winter density and distribution of the juvenile and adult herring, and pollock populations. The completed products are the stock assessments of adult pollock biomass in Feb-Mar 1995 and 1997 (37 and 36 thousand mt), and adult herring biomass in Sep 1993, Oct-Nov 1994, April 1995, Oct-Nov 1995, Mar-April 1996, and April 1997 (20, 13, 13, 24, 23, 40 thousand mt, respectively).

Key Words: *Clupea harengus*, *EXXON VALDEZ*, hydroacoustics, macrozooplankton assessment, salmon fry predators, *Oncorhynchus gorbuscha*, Pacific herring, pink salmon, population trends, stock assessment, *Theraga chalcogramma*, walleye pollock.

Citation: Thomas, G. L., Jay Kirsch, Geoff Steinhart and Nicholas Peters. 1997. SEA: Nekton-plankton acoustics second annual report, 1997. Restoration Project 96320N. *EXXON VALDEZ* Trustee Council. Anchorage, Alaska. 120 pp.

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1996 ANNUAL REPORT

Sound Ecosystem Assessment (SEA), Nekton-Plankton Acoustics

G.L. Thomas, Jay Kirsch, Geoff Steinhart and Nicholas Peters - PWS Science Center

EXECUTIVE SUMMARY

The Nekton-Plankton Acoustics Project (96320-N) is evaluating and applying acoustic measurement technology to collect accurate information on the distribution, density and size of specific animal populations. These data are essential for the development and operation of numerical models to improve the prediction of animal population change and the testing of the river-lake and prey switching hypotheses under the Sound Ecosystem Assessment Program (SEA). Improving the prediction of animal population change is a prerequisite for accurate assessment of anthropogenic influences and restoration from damage.

This is a multi-tasked project that relies on: (1) cooperative model development to assist in sampling design, data analysis, and interpretation, (2) shared vessel and facilities for data collection and logistical support, (3) data sharing with the agency, university, public and commercial interests, and (4) remote sensing with acoustical and optical technologies. We use the existing knowledge and skills of commercial fishers in the design and implementation of surveys. Salmon hatcheries in the region provide support for field crews and the hatchery releases of pink salmon are treated as an experimental manipulation of the marine ecosystem. Because of the multi-tasking nature of this project, we have relied on partnerships with other funding sources to accomplish tasks to fill in some of the gaps between SEA projects.

This annual report includes three chapters: (1) Seasonal and diel movements of walleye pollock (*Theragra chalcogramma*) in western Prince William Sound, (2) Acoustic estimates of macrozooplankton distribution in Prince William Sound, spring 1996 and (3) Juvenile herring assessment in Prince William Sound, winter-spring 1995-96. Predator and prey acoustic assessments are major components of the pink salmon investigations and incremental stock assessments are a primary part of the herring research.

Pink Salmon:

Predators (walleye pollock):

We have used acoustics to measure abundance and distribution of walleye pollock (*Theragra chalcogramma*) in western Prince William Sound since 1994. Although sampling protocol varied each year, we found trends in seasonal, and diel distributions of pollock. Pollock appeared to be most abundant in 1994, but densities in 1995 and 1996 were not much lower. Seasonally, pollock densities in the northwest portion of the Sound were lowest in early May, and generally increased throughout the sampling period. On a daily time scale, we did not see changes in pollock densities as a function of tide. During the night, pollock moved up in the water column, and at some sites pollock moved closer to shore at night than during the day. These changes in pollock distribution are important components of key hypotheses of the Sound Ecosystems Assessment project.

Prey (macrozooplankton):

A zooplankton survey was conducted in Prince William Sound in May 1996, using a 420 kHz digital sonar and a MOCNESS net. Data from the catch supplied us with zooplankton species, size, and density, which were applied to zooplankton scattering models, allowing us to predict volume backscatter. These predicted values are compared with measured acoustic backscatter to validate the measurement methods. Relative agreement in the two instruments is evident in the occurrence at the same depth of layers. However, more analysis of the catch information is needed for agreement of the absolute densities, since animal sizes are used to estimate the target strength that is used to scale the echo-square integration. The sources of error are discussed, with their potential solutions.

Pacific herring:

Juveniles:

A hydroacoustic-purse seine survey was conducted to examine the density and distribution of juvenile herring in Prince William Sound. We found the juvenile herring to be in a nearshore layer at the surface during the night. This layer included other scatters such as juvenile pollock, jelly plankton and larval fishes but the herring and pollock combined to represent the 95% or more of the backscatter and the juvenile pollock, the smaller component of the backscatter (0-17%) were separated by using purse seine catches. We show that the spatial distribution of juvenile herring is very contagious with a few locations supporting the majority of the herring population. We also have examined the density of the layer and found that it too is contagious but not directly related to where the bulk of the juvenile herring reside. From these results, we believe that it is possible to conduct broad-scale surveys of juvenile herring in the Sound to support development and verification of the herring overwintering model and allow the management agencies more information on future recruitment events. This capability also makes possible the building of an over-summer mortality model for herring. In 1994, the SEA program initially avoided this model building effort.

Multi-species management and restoration: SEA has shown that the pink salmon, herring and walleye pollock populations are dominant competitors and/or predators in the Sound. Since the EVOS Trustee Council is a unique entity in the fact that it represents the agencies that are responsible for establishing harvest strategies for pink salmon, Pacific herring and walleye pollock management, the continued investment in monitoring these populations creates an opportunity to evaluate the use of multi-species harvest strategies to assist the restoration of damaged species. The key to making multi-species management decisions is having reliable estimates of the abundance of each species and knowledge of how they interact[1]. The opportunity to evaluate a multiple-species approach to fisheries management in the Prince William Sound is unique and could be a major contribution to fisheries science by the EVOS Trustee Council.

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[1] Thomas, G.L., Vince Patrick, Jay Kirsch, and Jennifer Allen, 1997. Development of an ecosystem model for managing the fisheries resources of Prince William Sound. 2nd World Fisheries Congress (in press).

CHAPTER 1

SEASONAL AND DIEL MOVEMENTS OF WALLEYE POLLOCK (*THERAGRA CHALCOGRAMMA*) IN WESTERN PRINCE WILLIAM SOUND. G.B. Steinhart, G.L. Thomas, and Jay Kirsch.

ABSTRACT

We have used acoustics to measure abundance and distribution of walleye pollock (*Theragra chalcogramma*) in western Prince William Sound since 1994. We found trends in seasonal, and diel distributions of pollock. Seasonally, pollock densities in the Sound increased from May through July. This increase was greatest in the northwest passage where pollock numbers more than doubled in from May to June, 1995. On a daily time scale, we did not see changes in pollock densities as a function of tide. Pollock did undergo a diel vertical migration; at night, pollock moved up in the water column. In addition to a vertical migration, at some nearshore sites pollock were closer to shore at night than during the day. Where pollock were found, their density was highly correlated with plankton density. The observed patterns of pollock distribution and behavior are important to the testing of the prey-switching hypothesis.

INTRODUCTION

After the Exxon-Valdez oil spill, stocks of pink salmon in Prince William Sound had highly variable recruitment success. The roles of both the oil spill, and natural environmental fluctuations, on variable recruitment are still under debate. There is no doubt, however, that walleye pollock (*Theragra chalcogramma*) are one of the most abundant fish species in Prince William Sound. Not only are they important as a commercial fishery, but they play a large role in the food-web dynamics of the Sound. The goal of this research is to describe the seasonal and diel changes in pollock abundance and distribution in western Prince William Sound (PWS) in order to better understand their role as a predator of pink salmon fry.

Pollock may have both a direct and an indirect effect on juvenile salmon populations. A primary hypothesis of the Sound Ecosystem Assessment project (SEA) is the Lake/River hypothesis (Cooney 1993). This hypothesis states that in "river" years PWS experiences climatic conditions which lead to a relatively quick rate of flushing and increased turbulence in the Sound. This may result in lower zooplankton abundance, and fewer dense patches of zooplankton than during a "lake" year. During a "lake" year, slow flushing rates could result in high overall zooplankton abundance. In addition, in a "lake" year, low turbulence may facilitate the formation of large, dense plankton patches makes them more available as prey for both pink salmon fry and pollock. Since juvenile salmon feed on zooplankton, the abundance of zooplankton directly effects salmon survival. Walleye pollock also prey on zooplankton, and compete with juvenile salmon for this food resource (M. Willette, ADF&G, pers. comm.). Pollock not only compete with juvenile salmon, but they are also predators of salmon. The SEA Prey Switching hypothesis predicts that as zooplankton populations decrease, pollock will feed more heavily on juvenile salmon. Therefore, in order to predict salmon survival, it is essential to understand pollock behavior in PWS.

In this paper we present the results of three years of acoustic surveys in Prince William Sound. An assumption of SEA that was adapted from GLOBEC is that fish fry do not die by starvation, but that all mortality is the result of being eaten. Pollock, being the most abundant pelagic fish, are considered to be the primary predator of pink salmon fry in PWS (M. Willette, ADF&G, pers.comm.). By looking at how pollock abundance and distribution have changed over various time and spatial scales, we increase our knowledge of how this predator behaves. The first step in determining if pollock are feeding on zooplankton and/or salmon is to show that there is co-occurrence of pollock with either zooplankton or salmon. Since pollock are one of the most abundant fish species in PWS, understanding their ecology will aid us in efforts to restore and protect the valuable resources of the Sound.

METHODS

Study site

Prince William Sound (PWS) is located at the northern edge of the Gulf of Alaska (Figure 1). This large fjord/estuary covers an area of approximately 8800 km^2, and has about 3200 km of shoreline (Grant and Higgins 1910). Coastal rainforests, high mountains, and glaciers border the shoreline of PWS. The area receives seasonally intense storms moving up from the Gulf of Alaska, resulting in more than 7 m of annual rainfall.

Survey design

The survey designs differed during the three years of this project (Table 1). In 1994, offshore surveys were conducted during the day throughout western PWS (Figure 2). There were 88 different parallel transects in Wells, Perry, and Knight Island Passages, Montague Straight and the Southwest passages (Thomas et al. 1996). Data were collected with a BioSonics 101-120 kHz dual beam echosounder.

In 1995, acoustic surveys were concentrated in the northwest portion of PWS (Figure 3) and were designed to examine differences between nearshore, within 0.5 NM of the shoreline, and offshore (> 0.5 NM from shore) distributions of fish. Nearshore surveys were conducted from our boat, the R/V Orca Challenger, using a down-looking BioSonics 102-200 kHz dual beam echosounder. The nearshore surveys at each site consisted of 9 to 12 parallel transects perpendicular to the shoreline. Nearshore acoustic data were collected to a maximum depth of 125 m. The offshore surveys were conducted aboard the F/V Alaska Beauty using with a BioSonics 101-120 kHz dual beam echosounder, set to collect data to a depth of 250 m. At each site, the same transects were repeated both offshore and nearshore every 3 h for an entire 24 h diel cycle (Thomas et al. 1996).

In 1996, sampling was limited to Wells and Perry Passages, Esther Island, and Unakwik Inlet. Three cruises were conducted beginning in early May, and ending in early June. The surveys were conducted nearshore, and consisted of a long transect parallel to the shoreline, and 5 parallel transects perpendicular to the shoreline (Figure 4). The surveys were repeated 4 times a night: 2000, 2300, 0200, and 0500. Data were collected with a down-looking BioSonics 101-120 kHz dual beam echosounder.

For all surveys, transects were marked on paper and/or electronic charts to allow repetition of the same transect. At night, or during low tide, some transects were modified for safety purposes. Boat speed during transects was approximately 4-6 kn. The down-looking transducers were mounted on a fin towed alongside the boat at a depth of approximately 2 m.

Personnel from the Alaska Department of Fish and Game (ADF&G) collected numerous fish samples using a variety of fishing gear. Commercial seines and mid-water trawls were used for target verification of the acoustic data. In addition, small purse seines, pair trawls, bottom trawls, gillnets and longlines were used to collect fish. These fish were used for age/length/weight measurements and diet analyses.

Acoustic equipment

The acoustic data presented here was collected using either a BioSonics 101-120 kHz, or a 102-200/420 kHz echosounder. The data were processed in real-time using ESP software on a 486 laptop computer. The data were geo-referenced and time-coded by a connection to a Magellan DLX-10 GPS receiver with an external antenna. Echo-square integration, dual-beam target strength (TS), and GPS data were stored on the computer hard disk, and backed up on tape drives. Raw acoustic signals were stored on digital audio tape.

The acoustic systems were calibrated before each cruise (Table 2). The transducers were attached to a floating platform, and a tungsten-carbide standard target was carefully moved within the beam of the transducer until a large sample of target positions were collected. Using the known TS of the standard target, the peak target strength from the calibration was used to calculate the source level and receiver gains (Foote and MacLennan 1982).

Acoustic processing

Once the cruise was completed, the acoustic files were transferred to UNIX workstations where batch processing of files was performed. To facilitate reduction and processing of acoustic information, software was written in the Interactive Data Language (IDL) which corrected for physical parameters (temperature and salinity), and applied the acoustic calibrations. After initial processing, we wrote more IDL software to remove untracked bottom, to calculate biomass estimates, and to produce images (Figure 5).

Echo-square integration has been shown to be an effective tool for estimating fish biomass when densities are high (Ehrenberg and Lytle 1972); however, pollock densities are relatively low in PWS. Therefore, we used an echo-counting technique to estimate pollock density and biomass. Echo-counting has been used successfully in other studies (Traynor and Ehrenberg 1979; Burczynski and Johnson 1986). A test of our echo-counting technique was performed in 1995, and showed that for our data, echo-counting resulted in a small underestimate pollock density for most surveys (Thomas et al. 1996).

First, possible pollock targets were selected based on known biology and behavior of various fish in the Sound. These selections were made while looking at paper echograms, electronic target echograms, and catch data from that survey. Once unwanted targets were removed, a histogram of the selected target strengths was generated. On this histogram, usually biomodal, we manually selected the lower mode of target strengths, but included all target strengths that were pollock-sized.

Once the targets were selected, and a TS range chosen, the software counted all qualifying targets. These counts were then divided by the sample volume of the acoustic beam, and summed to the surface to yield densities in fish/m^2. Densities may also be converted to biomass using known weights of captured pollock, but since we hadn't received 1996 weight information from ADF&G at the time of this report, we only presented data on pollock numerical densities in this paper.

RESULTS

Seasonal variability

Pollock densities generally increased in Prince William Sound as the summer progressed, especially in the northwest region of PWS. Pollock densities peaked at nearly 0.006 pollock/m^2 in early July, 1994. Pollock densities also increased from May to June in both 1995 and 1996 (Figure 6). Compared with 1994, however, it appears that pollock may have moved into the northwest Sound later in 1995 and 1996 than in 1994. Since sampling ended in early July in both 1995 and 1996, it is possible we did not measure peak of pollock abundance in the northwest portion of the Sound. The increase in pollock numbers occurred in both the offshore and nearshore environments (Figure 7), although the offshore region usually had a higher areal biomass. The broadscale surveys in 1995 demonstrated that pollock densities increased throughout PWS from May to June (Figures 8, 9, and 10).

Diel variability

We found that pollock abundance and distribution changed on a daily cycle. However, we found no effect of tide height on pollock abundance (Figure 11). In addition, we saw no effect of current velocity or tide range on pollock density. It appeared that much of the diel variability was the result of the time of day, and probably was related to changing light intensities.

There appeared to be two layers of pollock during most surveys: A shallow layer (< 20 m deep) was present throughout the day, and a deep layer that migrated up and down in the water column. The depth of the deep layer was influenced by time of day. During the short nights, the pollock were shallower than during the day. At offshore sites, pollock were around 150 to 200 m deep during the day, but moved up to top 100 m at night (Figure 12). In nearshore areas, very few pollock were seen during the day, except an occasional shallow surface layer. At night, however, a deep layer of fish appeared around 2200 and migrated up to the top 100 m (Figure 13).

In addition to a diel vertical migration, at nearshore sites there was an occasional inshore migration of pollock. In 1995, the only data analyzed for horizontal migrations so far, pollock at most nearshore sites moved closer to the shore (Figure 14). We saw this pattern in approximately 50% of our 1995 nearshore diel surveys. We did not see changes in density between offshore and onshore sites.

We found a positive correlation between pollock density and relative zooplankton density in 1994 (Figure 15). In addition, echograms and computer visualizations have shown co-occurrence of pollock and plankton patches (Figure 16; Thomas et al. 1996). There results are preliminary due to sampling problems. Our acoustic equipment on the 1995 offshore cruises was limited to 120 kHz, so it was not ideal for measuring zooplankton.

DISCUSSION

Pollock in Prince William Sound display seasonal and diel changes in abundance and distribution. As a dominant predator in the Sound, the location, number, and behavior of pollock can have wide ranging effects on other populations. Pollock are predators of, and competitors with, juvenile salmon. Our data begin to show some insight into how pollock populations behave in PWS, and when combined with oceanography and zooplankton data, will help determine the validity of the Lake/River and Prey Switching hypotheses (Cooney 1993).

Pollock migrated northward into Prince William Sound as the year progressed. Commercial fisherman have long reported finding large concentrations of adult pollock in Port Bainbridge and the southwest Passages during winter (Thomas et al. 1996). These pollock probably begin migrating northward after the winter, eventually reaching as far north as Port Wells. Our data showed an increase in pollock densities in northwest PWS from May to June. Furthermore, in 1994, the increase in pollock in the northwest was accompanied by a decrease in pollock numbers in the southwest. This supports a hypothesis that the adult pollock migrate northward after the winter.

The reason for this migration is still unclear, but adult pollock are probably moving northward to feed on zooplankton. We did see a strong positive correlation of pollock biomass with zooplankton density, but we need to refine our methods for measuring and estimating zooplankton using acoustics (see Chapter 2). We also need to examine cases where pollock are not found with high zooplankton densities.

The Prey Switching hypothesis suggests that in the absence of abundant zooplankton, pollock will swtich to juvenile pink salmon. We did not see a relationship between pollock density and the density of small fish targets in 1994 or 1995. In 1994, however, the percent age-0 fish in pollock diets did increase in June (Figure 17), corresponding with the release and outmigration of juvenile salmon from the hatchery on Esther Island. In addition, the percentage of age-0 fish in the stomach were highest during nighttime hours (Figure 18). This suggests that pollock fed more heavily on juvenile fish as the year progressed, and that most of this feeding occurred at night.

We observed two layers of pollock during these surveys: a shallow layer that did not appear to vertically migrate, and a deep layer that did migrate. The presence of two layers of pollock presents many questions. It is possible that the upper layer represents a group of pollock feeding on plankton near the surface. In the offshore region, the deep layer migrates up at night and down during the day. Trawl catches showed a similar vertical migration of squid an euphausiids (Thomas et al. 1996). Therefore, the offshore vertical migration of the deep layer might be the result of pollock feeding on euphausiids, squid, or shrimp. In the nearshore region, the deep pollock layer moved up and close to shore at night, probably to feed on juvenile fish. The increase in % age-0 fish in the diet at night supports this hypothesis. The observed diel vertical migrations are to maximize feeding opportunities, but could be a combination of feeding rate, bioenergetic advantages and predator avoidance (Neilson and Perry 1990).

Although we found no diel changes in aerial densities between nearshore and offshore sites in 1995, this does not disprove a horizontal migration, but may be a problem of the correct spatial scale. If pollock are moving inshore to feed on juvenile salmon, it is likely that the offshore-onshore migration in occurring within our designated nearshore sites, and not between our nearshore and offshore sites. This is evident by the frequent reports of salmon fry schools that were closer to shore than we surveyed in our boat. It is unlikely, however, that a large portion of the pollock population is moving inshore to feed at night. If this were true, we would have seen a decrease in offshore densities at night.

The lack of tidal effects on pollock is not surprising given our sampling design. With many confounding variables, such as site, day, and time, it is difficult to isolate the tidal effects. Furthermore, tidal effects are likely to be acting on only a small spatial scale, since current velocities are highly variable. Our tidal data were from the Tides and Currents computer software (Nautical Software, Inc.). This information, especially the information on ocean currents, is highly variable based on a number of climatic and morphometric conditions. This does not mean that pollock don't react to changing tides: there may still be changes in behavior or distribution. But, the absolute abundance of pollock at our sample sites does not change over a given tidal cycle. When we get more accurate tidal information from ongoing oceanographic work, we may elaborate on these results.

Pollock in Prince William Sound feed heavily on zooplankton (M. Willette, ADF&G, pers. comm.), so the positive correlation we found between zooplankton and pollock density was not a surprise. Since zooplankton abundance and patch size are dependent on climate and oceanographic conditions, however, this relationship may be dependent on how many zooplankton are present. During "lake" years, high zooplankton numbers, and increased density of zooplankton patches may result in a higher correlation than during "river" years. When zooplankton are less abundant, or in less dense patches, pollock may prefer to feed on small fish, so the observed relationship may not hold true.

Our present results may be confounded by statistical problems. The small sample volume of the acoustic beam in shallow water, combined with relatively low overall fish densities, lead to high variability in our density estimates. The addition of one target in the top 10 m of a file can radically alter the predicted biomass for that site. In addition, target strengths of fish are highly variable and depend on many factors (Traynor and Williamson 1983; Mukai and Iida 1996). For example, a fish swimming up or down within the acoustic beam is tilted and thus presents a smaller cross-section to reflect the acoustic signal. The reduced acoustic return will lead to an underestimate of the total length of the fish, and therefore may result in that target being correctly classified as a pollock. Furthermore, an echo from a fish that is only partially within the acoustic beam will also underestimate the target's size. Coincident targets, which will occurr more frequently with depth, cause the target discriminator to omit targets. This will underestimate the number of targets in deep water.

To overcome these problems, we are planning on using both echo-square integration and echo-counting techniques to measure pollock. Due to corruption of the acoustic signal by dense scattering layers, the echo-counting technique is preferable to echo integration where dense layers of plankton or other species are present. Future work will focus on overcoming the statistical problems of a small sample volume near the surface to improve or echo-counting proceudre. For deep waters where scattering layers are not present, however, we will begin using echo-integration to more accurately assess pollock biomass.

ACKNOWLEDGMENTS

We would like to thank all the crews of our research vessels for helping us to collect these data. Without their knowledge and experience, this research would not have been possible. The Alaska Department of Fish and Game and the University of Alaska-Fairbanks were responsible for the daunting task of analyzing the catch data. A special thanks goes to Mark Willette (ADF&G) for sharing his data on pollock diets. This work is supported by the *Exxon Valdez* Trustee Council, Grant No. 96320-N.

LITERATURE CITED

Burczynski, J.J. and R.L. Johnson. 1986. Application of dual-beam acoustic survey techniques to limnetic populations of juvenile sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. **43**: 1776-1787.

Cooney, R.T. 1993. A theoretical evaluation of the carrying capacity of Prince William Sound, Alaska, for juvenile Pacific salmon. Fisheries Research, **18**: 77-88.

Ehrenberg, J.E. and D.W. Lytle. 1972. Acoustic techniques for estimating fish abundance. Trans. Geosci. Elec. GE-10: 138-145.

Foote, K.G. and D.N. MacLennan. 1982. Use of elastic spheres as calibration targets. p. 52-58. In O. Nakken and S.C. Venema [ed.], Symposium on fisheries acoustics. ICES/FAO. Bergen, Norway.

Grant, U.S. and K.F. Higgins. 1910. Reconnaissance of the geology and mineral resources of Prince William Sound, Alaska. U.S. Geological Survey Bulletin. No. 443. 89 pp.

Mukai, T. and K. Iida. 1996. Depth dependence of target strength of live kokanee salmon in accordance with Boyle's law. ICES J. of Marine Sci., **53**: 245-248.

Neilson, J.D. and R.I. Perry. 1990. Diel vertical migrations of marine fishes: an obligate or facultative process? Adv. Mar. Biol. **26**: 116-168.

Thomas, G.L, J. Kirsch, T. McLain. 1996. SEA: Nekton-plankton acoustics second annual report, 1996. Restoration Project 95320N. *EXXON VALDEZ* Trustee Council. Anchorage, Alaska. 120 pp.

Traynor, J.J. and J.E. Ehrenberg. 1979. Evaluation of the dual-beam acoustic fish target strength method. J. Fish. Res. Bd. Can. **36**: 1065-1071.

Traynor, J.J. and N.J. Williamson. 1983. Target strength measurements of walleye pollock (*Theragra chalcogramma*) and a simulation study of the dual-beam method. Proceedings of the Symposium on Fisheries Acoustics. FAO Fish. Rep. No. 300: 112-124.

Table 1. Survey location, design, and purpose for 1994-96 SEA Nekton-Plankton Acoustic cruises. Other cruises were conducted, and more data were collected, but this table describes the cruises where data presented in this report were collected.

Year	Surveys	Locations	Survey Design	Survey Purpose
1994	Offshore	Western PWS	Repeated same transects seasonally	Examined seasonal trends and patchiness of pollock distribution
1995	Offshore Broadscales	All PWS	Two repeated surveys covered vast distances	Examined seasonal trends and patchiness of pollock distribution
	Nearshore and offshore diels	NW PWS	Surveyed every 3 h for 24 h period at each site Seasonally repeated sampling at sites	Examined daily changes in pollock abundance and distribution between and within nearshore and offshore areas
1996	Nearshore	NW PWS	Surveyed each site four times at night Seasonaly repeated sampling at sites	Examined daily changes in pollock abundance and distribution in nearshore areas, and how diel changes vary seasonally

Table 2. Parameters of the acoustic equiptment used during sampling of Prince William Sound in 1996.

System	Frequency	Source Level	System Gain	Transducer Directivity	Pulse Duration
101	120 kHz	225.023	-159.282	0.0010718	0.4 ms
102	200 kHz	221.655	-155.765	0.0006515	0.4 ms

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Figure 2. Map of western Prince William Sound showing the offshore areas surveyed in 1994.

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Figure 7. Mean pollock per unit surface area (fish/m^2) for northwestern Prince William Sound for offshore and nearshore sites in 1995. Weighted means were calculated for each area.

Figure 8. Map of Prince William Sound showing mean pollock per unit surface area (fish/m^2) for transects surveyed in the May 1995. Darker grey indicates higher density than areas of light grey.

Figure 9. Map of Prince William Sound showing mean pollock per unit surface area (fish/m^2) for transects surveyed in the June 1995. Darker grey indicates higher density than areas of light grey.

Figure 10. Map of Prince William Sound showing mean pollock per unit surface area (fish/m^2) for general areas of the Sound surveyed in May (07a) and June (08a) broadscale surveys in 1995. Weighted means were calculated for each area.

Figure 11. Relative pollock densities (FPUSA) versus tide height for repeated nearshore and offshore surveys in 1995. Each point represents one survey. Relative FPUSA is calculated by dividing the FPUSA for a survey by the maximum FPUSA for all surveys at that site on the same date. This was done to avoid changes in pollock density between sites and between dates. Tide data are from Tide and Currents software (Nautical Software, Inc.).

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Figure 13. Changes in nearshore diel vertical distribution of pollock targets at Herring Point (site 509) on 14-15 June, 1995.. These data are representative of migrations seen at most nearshore sites in 1995.

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Figure 17. Mean percentage of age-0 fish in the diet of pollock during 1994 cruises. Error bars show the maximum value from each cruise and the numbers indicate the number of net sets used in the diet analyses. Data are from Mark Willette, ADF&G.

Figure 18. Percentage of age-0 fish in the diet of pollock versus time of day during 1994 sampling. Data are from Mark Willette, ADF&G.

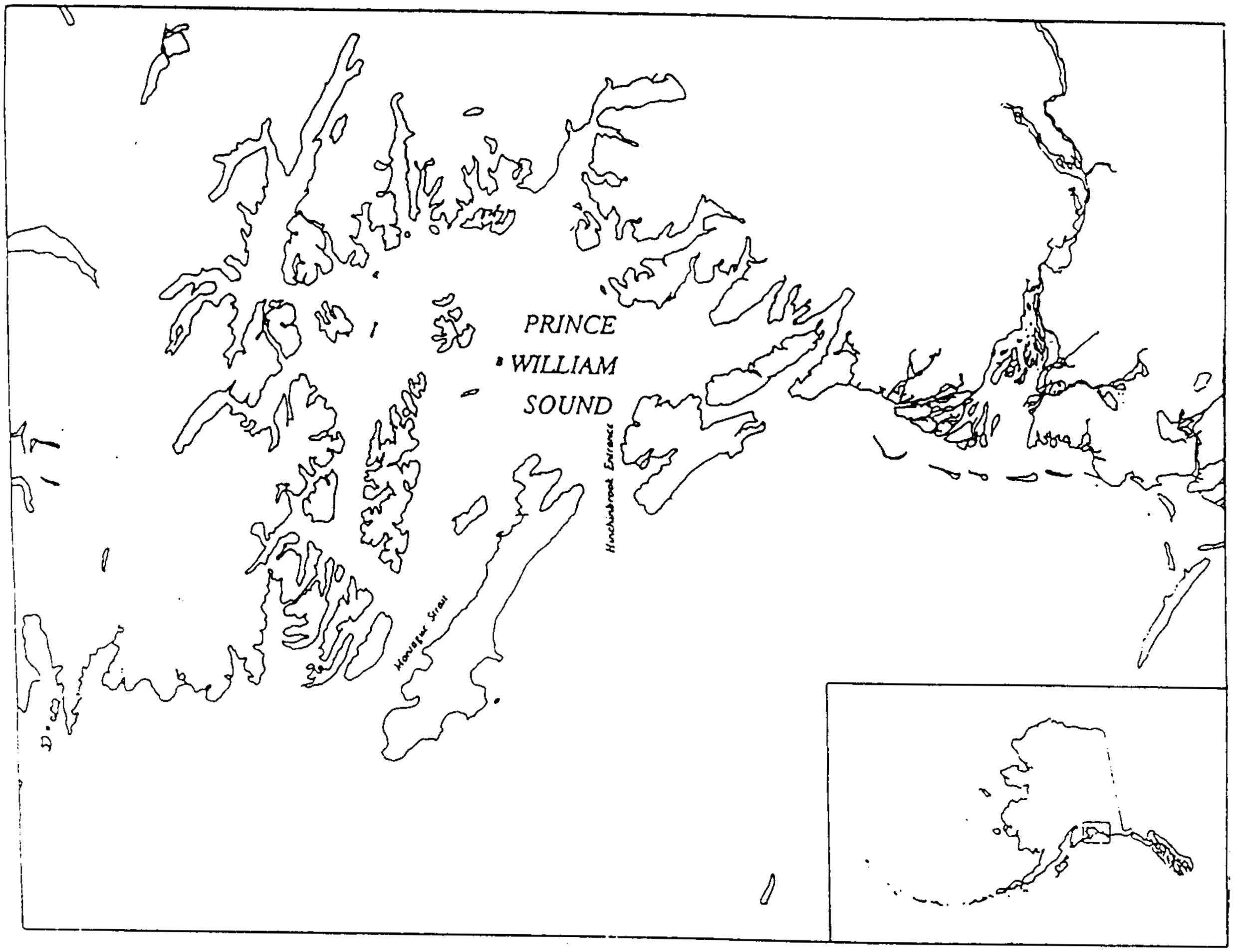
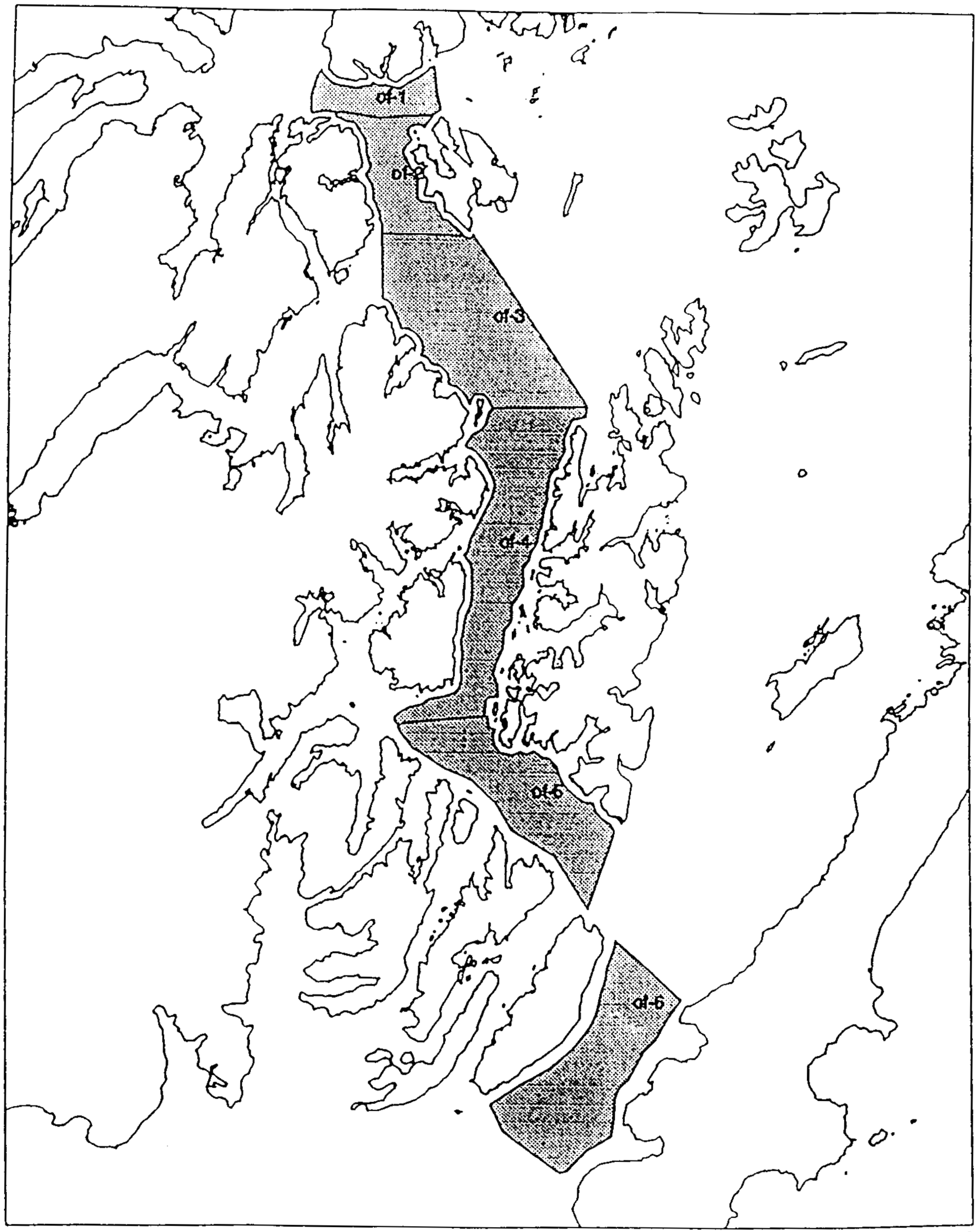
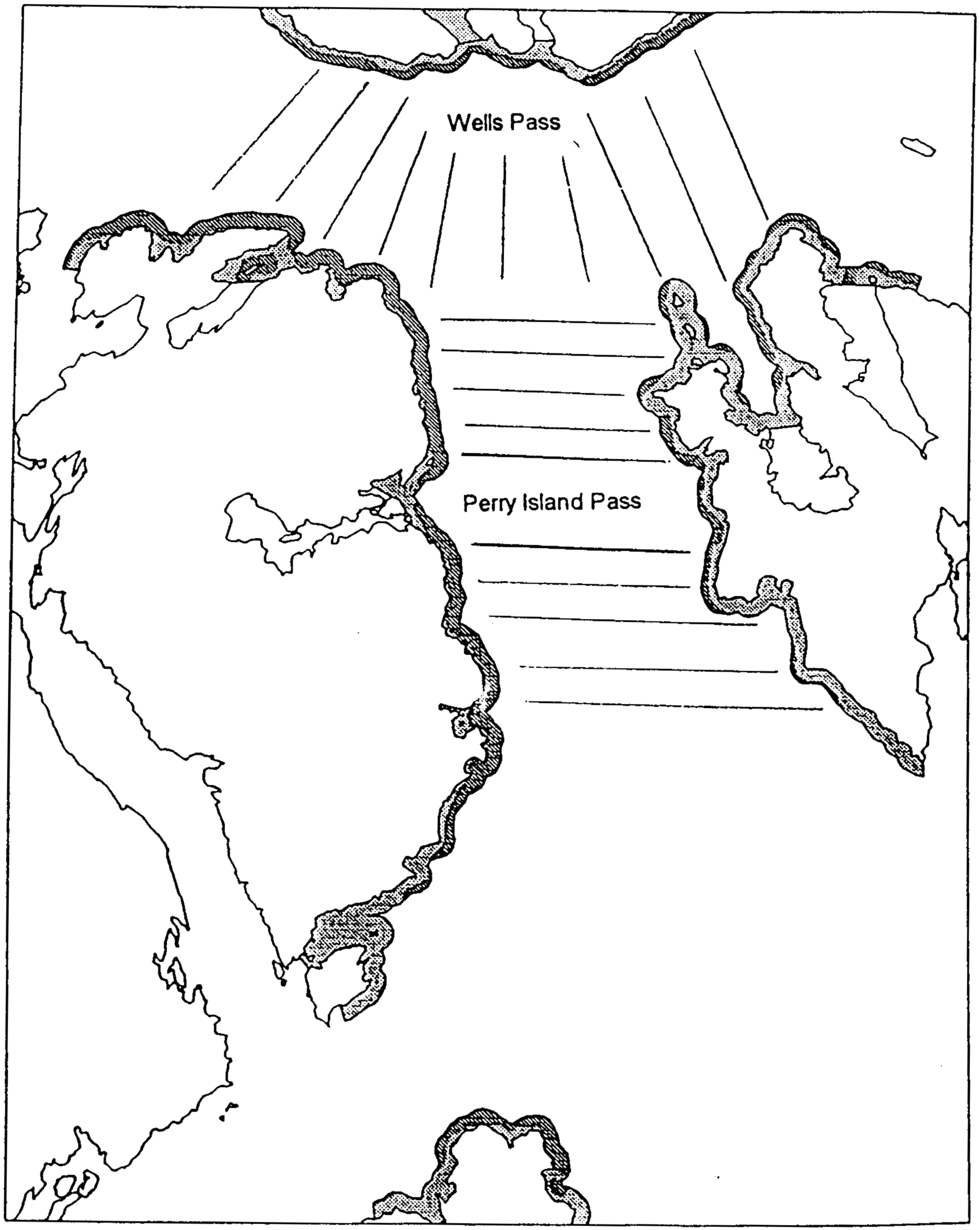


Figure 1. Map of Prince William Sound, Alaska, USA.



DLS, PWSSC 1995

Figure 2. Map of western Prince William Sound showing the offshore areas surveyed in 1994.



DLS, PWSSC 1996

Figure 3. Map of northwestern Prince William Sound showing where most of the sampling occurred in 1995 and 1996.

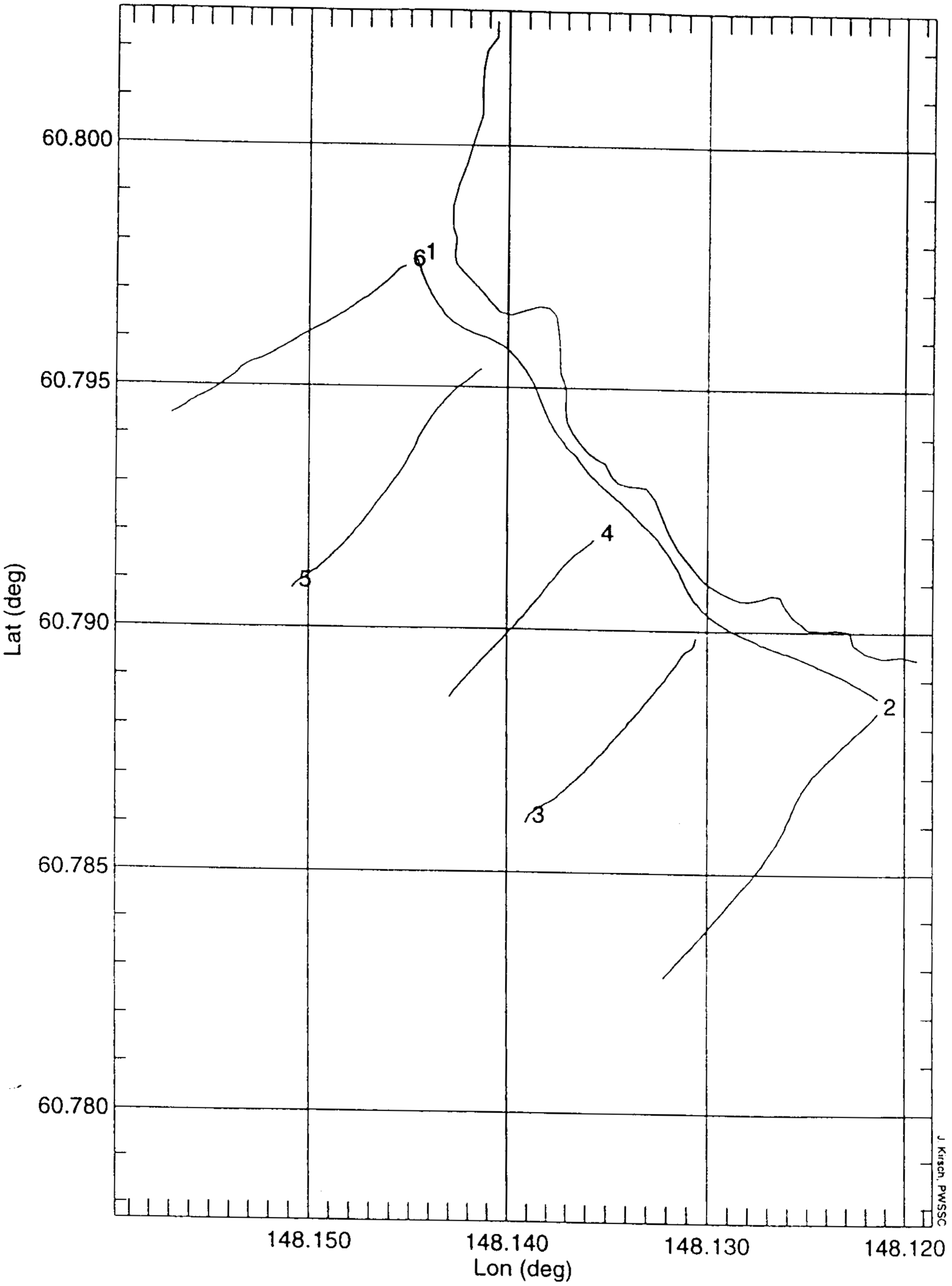


Figure 4. Map of transect design used during 1996 pollock sampling. Esther Island is located in northwest Prince William Sound.

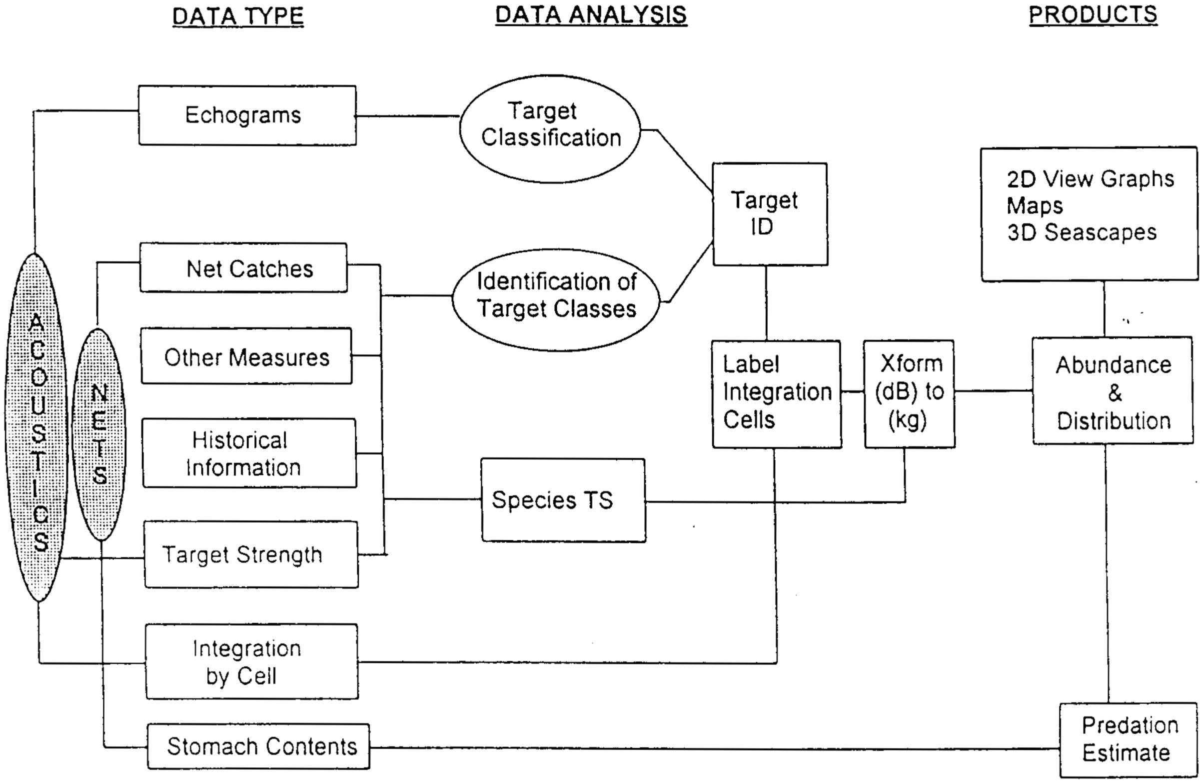


Figure 5. Flow chart of data processing steps used in analysis of SEA acoustic data collected in 1994-96.

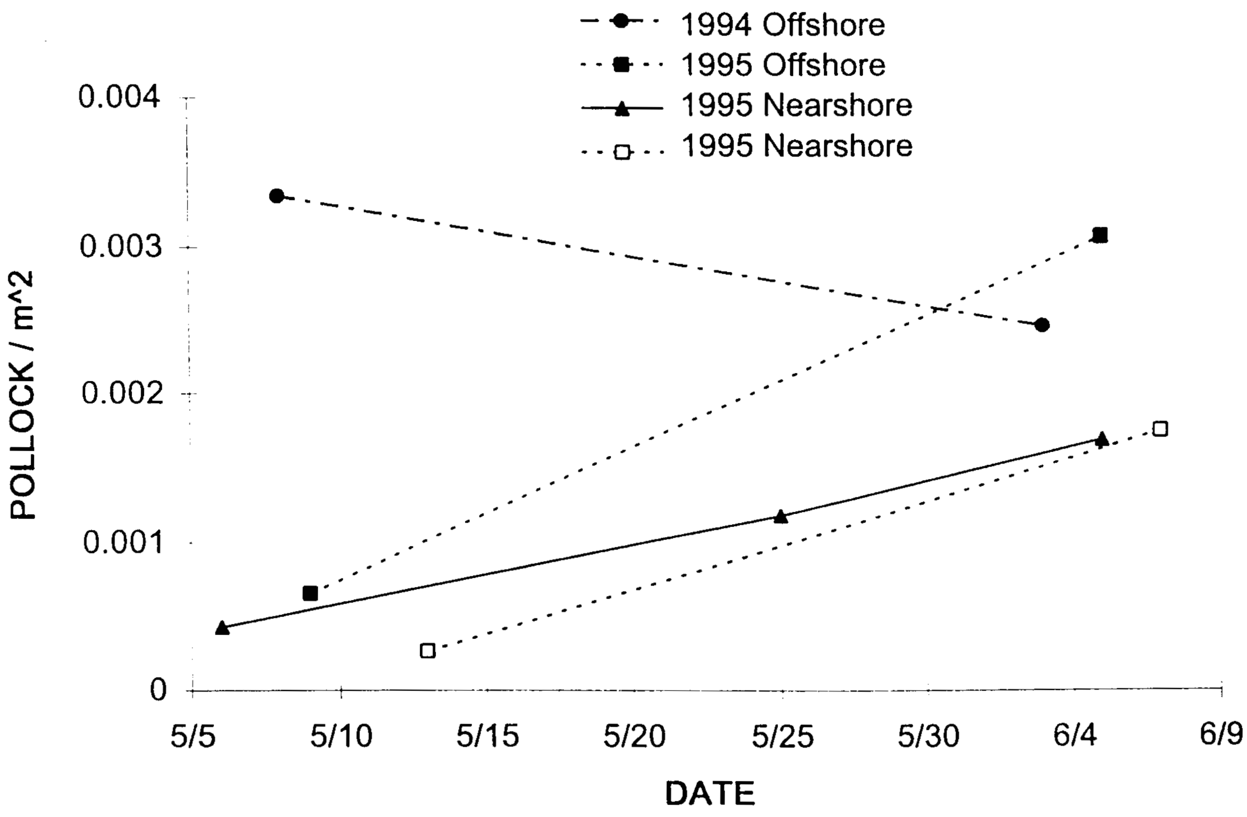


Figure 6. Mean pollock per unit surface area (fish/m^2) for northwestern Prince William Sound from 1994-96. Weighted means were calculated for all sites sampled during the different cruises.

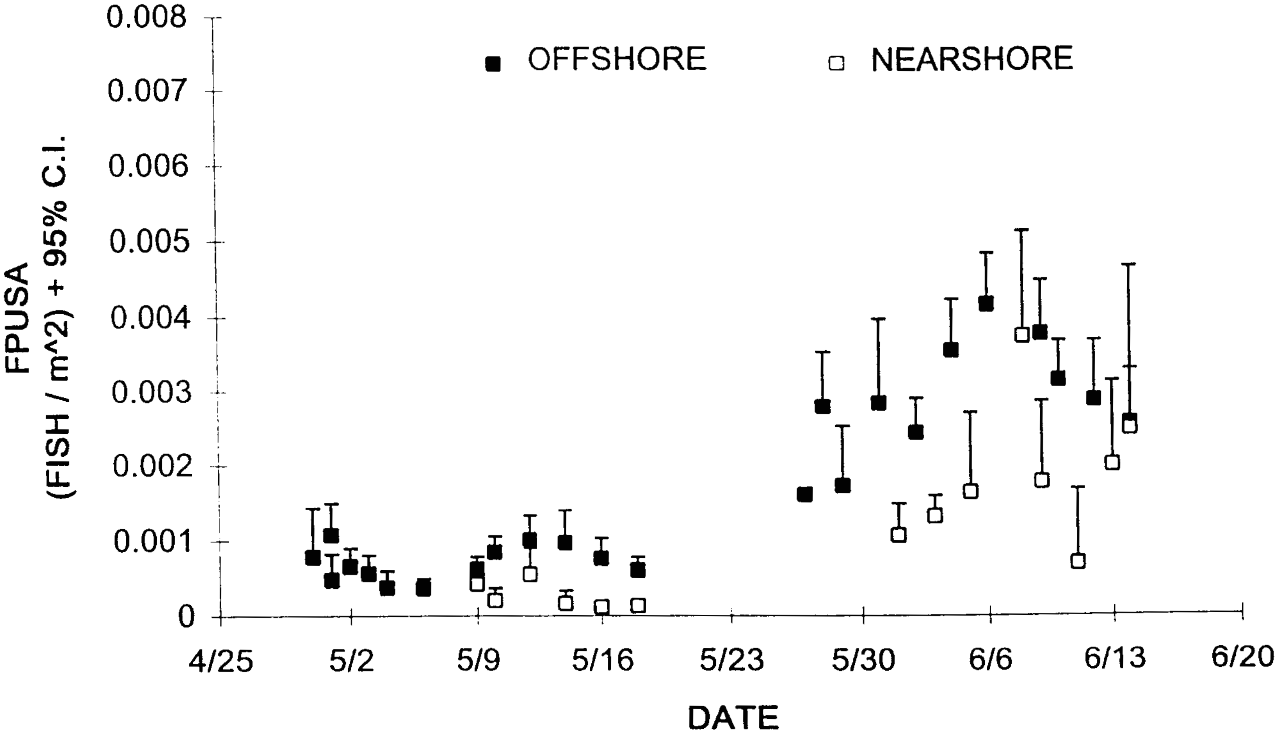


Figure 7. Mean pollock per unit surface area (fish/m^2) for northwestern Prince William Sound for offshore and nearshore sites in 1995. Weighted means were calculated for each area.

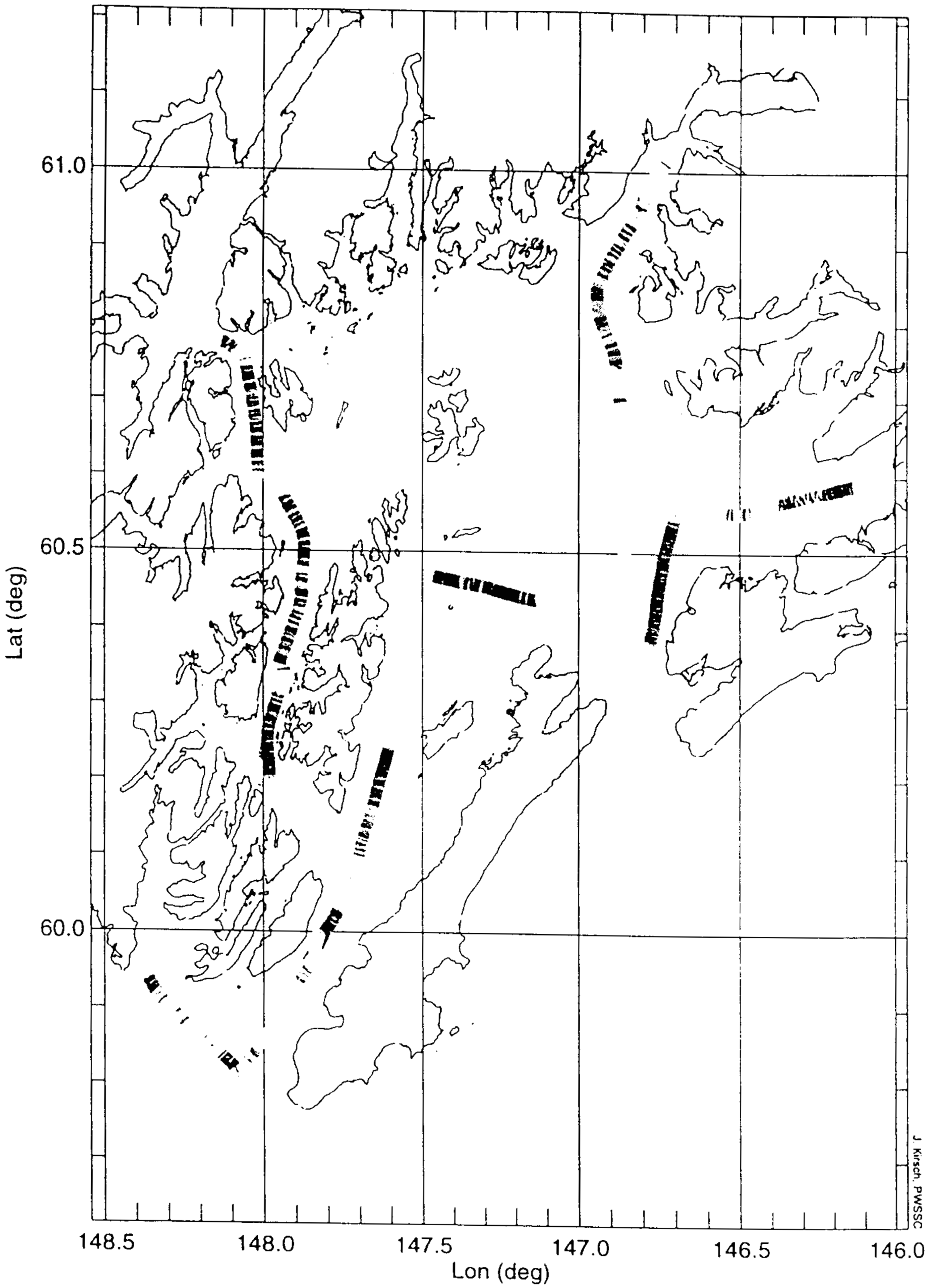


Figure 8. Map of Prince William Sound showing mean pollock per unit surface area (fish/m^2) for transects surveyed in the May 1995. Darker grey indicates higher density than areas of light grey.

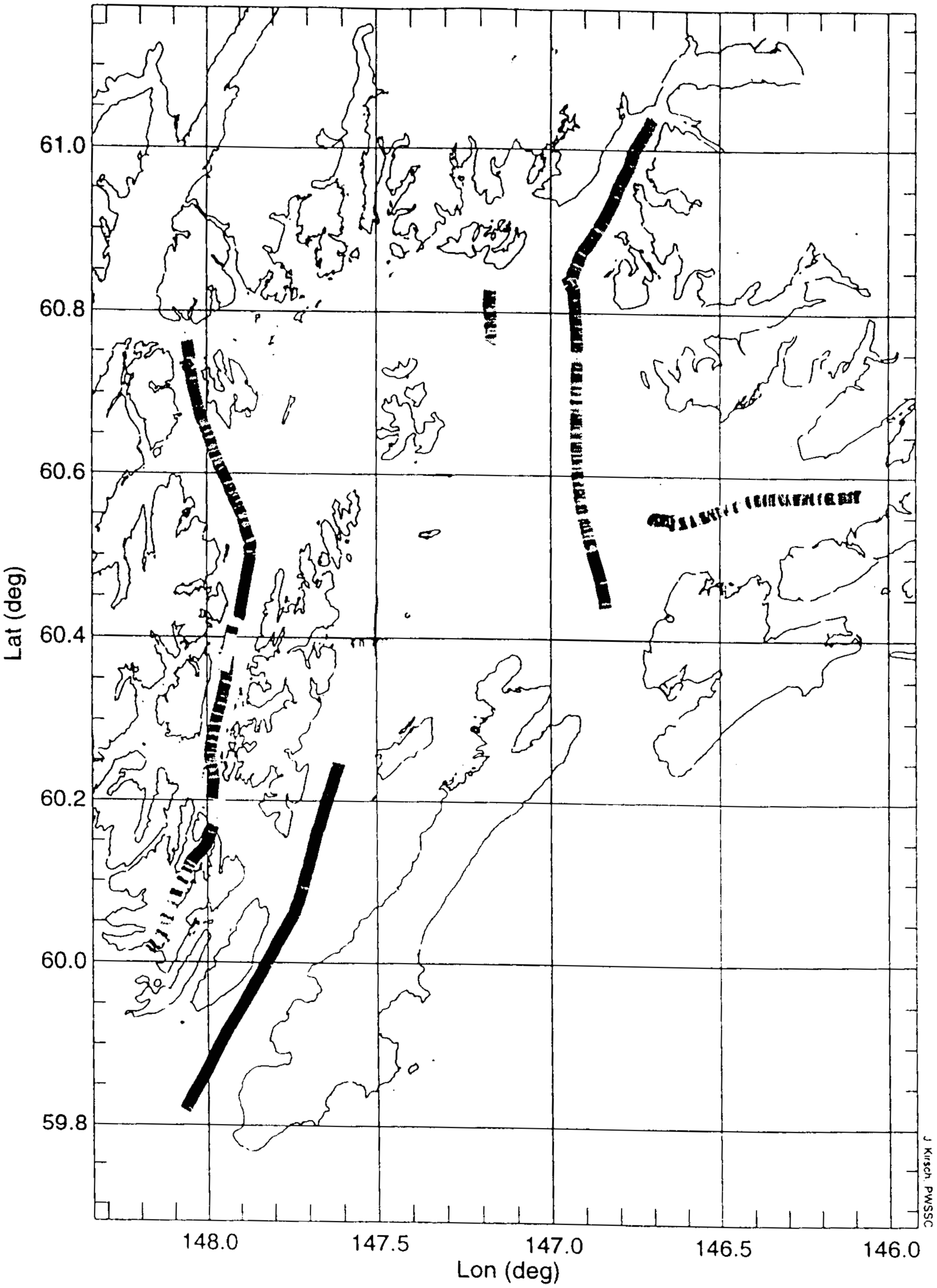


Figure 9. Map of Prince William Sound showing mean pollock per unit surface area (fish/m²) for transects surveyed in the June 1995. Darker grey indicates higher density than areas of light grey.

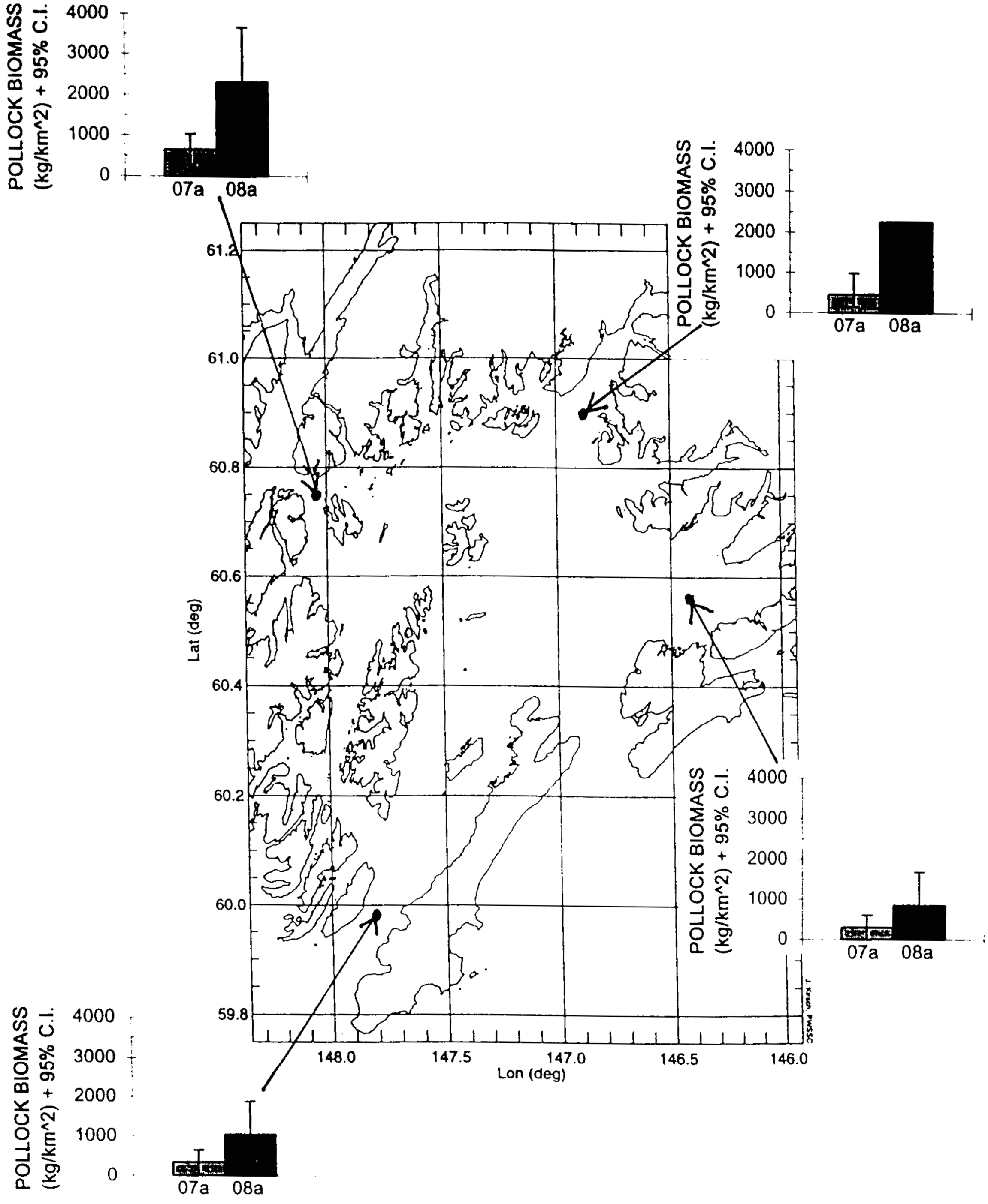


Figure 10. Map of Prince William Sound showing mean pollock per unit surface area (fish/m^2) for general areas of the Sound surveyed in May (07a) and June (08a) broadscale surveys in 1995. Weighted means were calculated for each area.

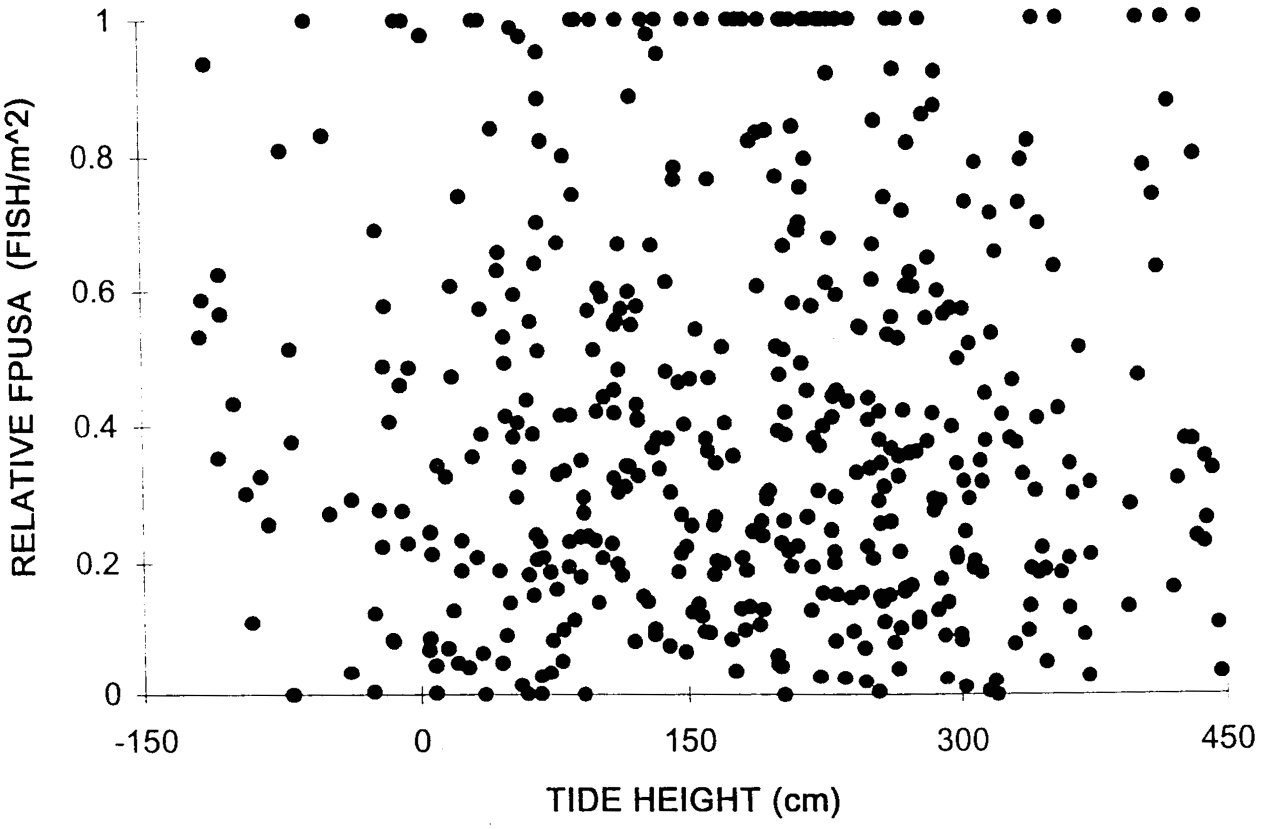


Figure 11. Relative pollock densities (FPUSA) versus tide height for repeated nearshore and offshore surveys in 1995. Each point represents one survey. Relative FPUSA is calculated by dividing the FPUSA for a survey by the maximum FPUSA for all surveys at that site on the same date. This was done to avoid changes in pollock density between sites and between dates. Tide data are from Tide and Currents software (Nautical Software, Inc.).

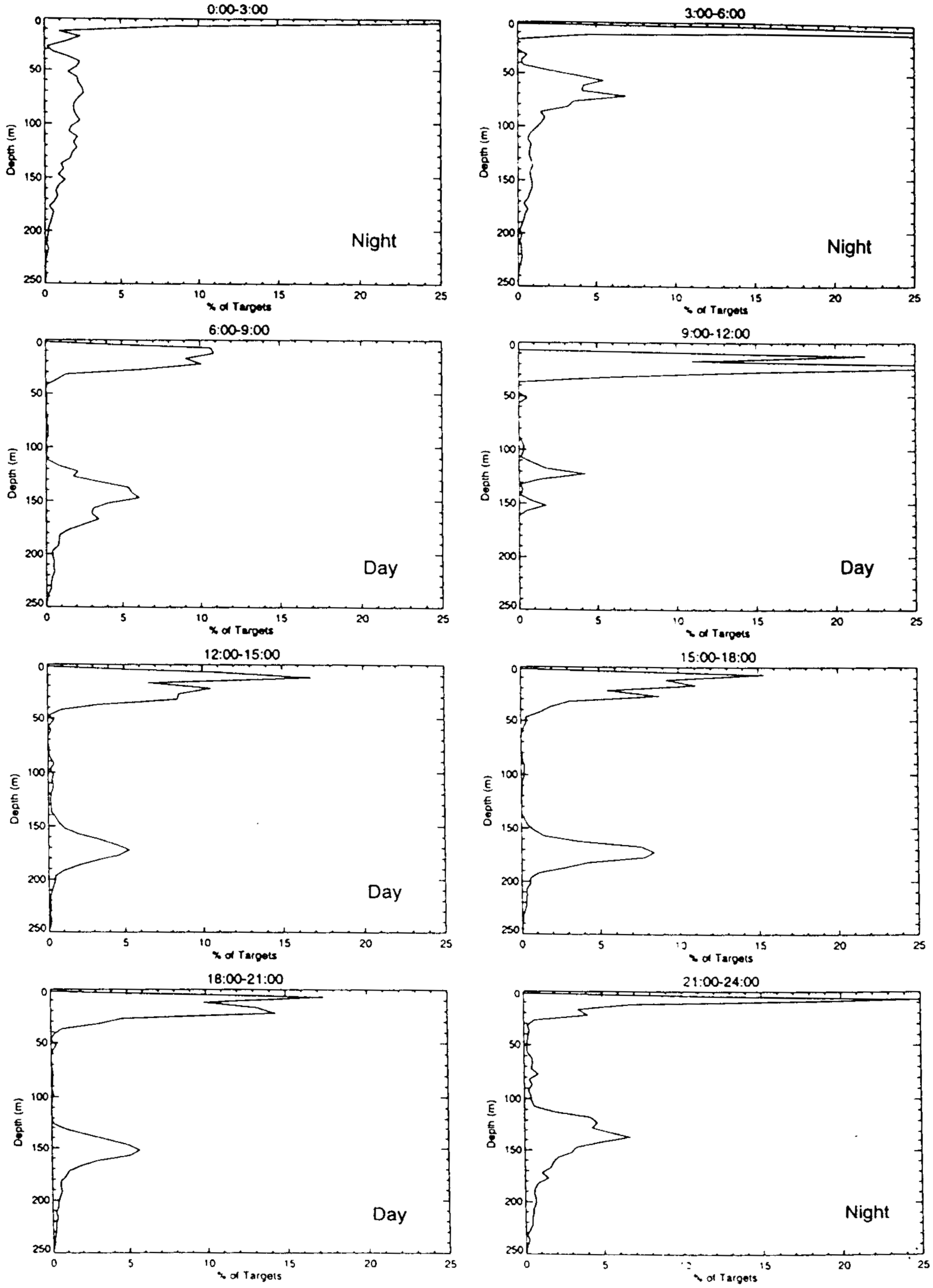


Figure 12. Changes in offshore diel vertical distribution of pollock targets at Herring Point (site 509) on 14-15 June, 1995. These data are representative of migrations seen at nearly all offshore sites in 1995.

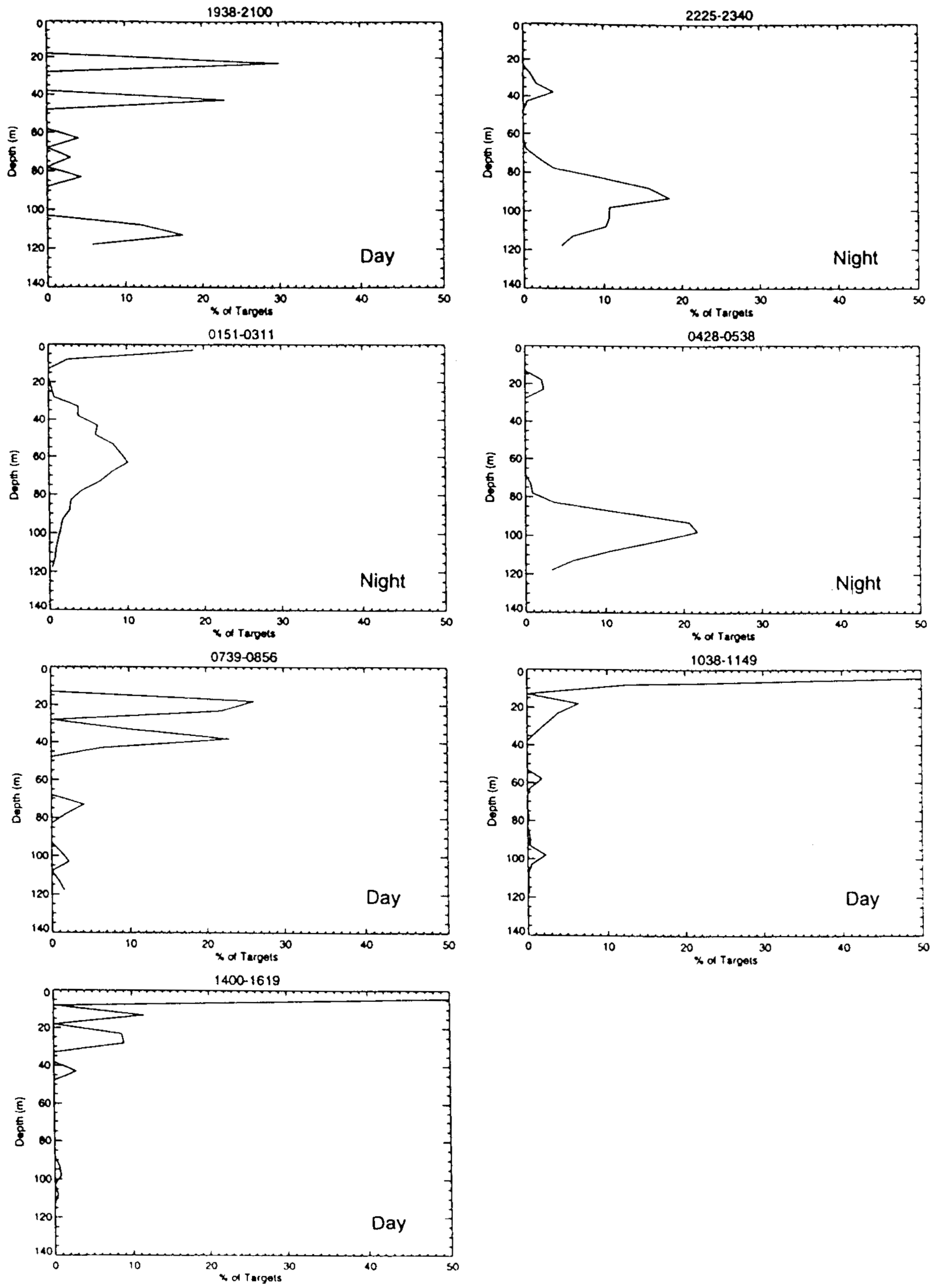


Figure 13. Changes in nearshore diel vertical distribution of pollock targets at Herring Point (site 509) on 14-15 June, 1995.. These data are representative of migrations seen at most nearshore sites in 1995.

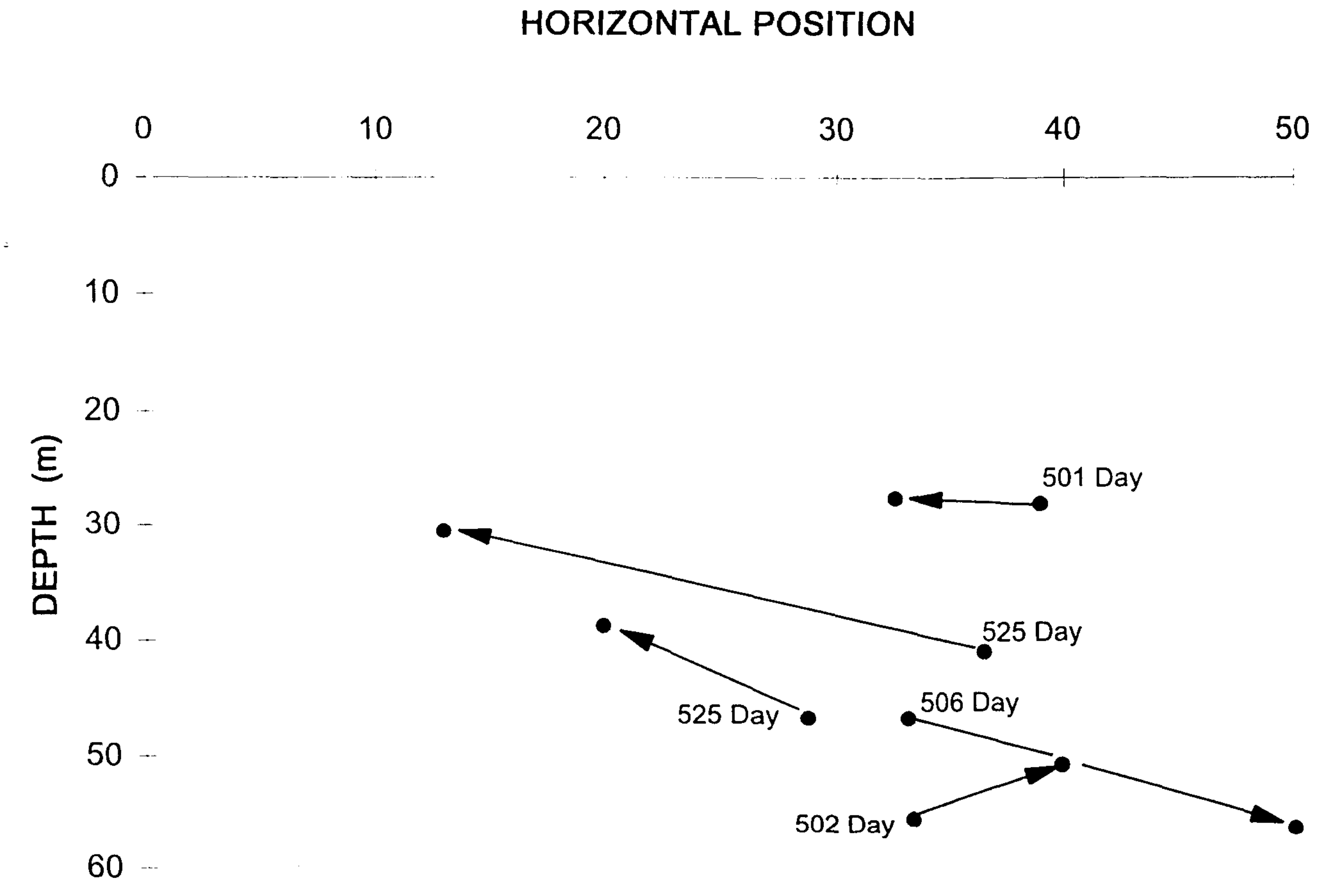


Figure 14. Changes in horizontal and vertical distribution of pollock during nearshore surveys conducted between 13-18 May, 1995. Each point represents the mean vertical and horizontal position of pollock targets during day or night for different sites (site number next to line). The arrows indicate movement from the daytime means to nighttime means. Horizontal position is relative distance from shore measured as the number of reports from the nearshore edge of the transect (8-12 m per report based on boat speed and ping rate).

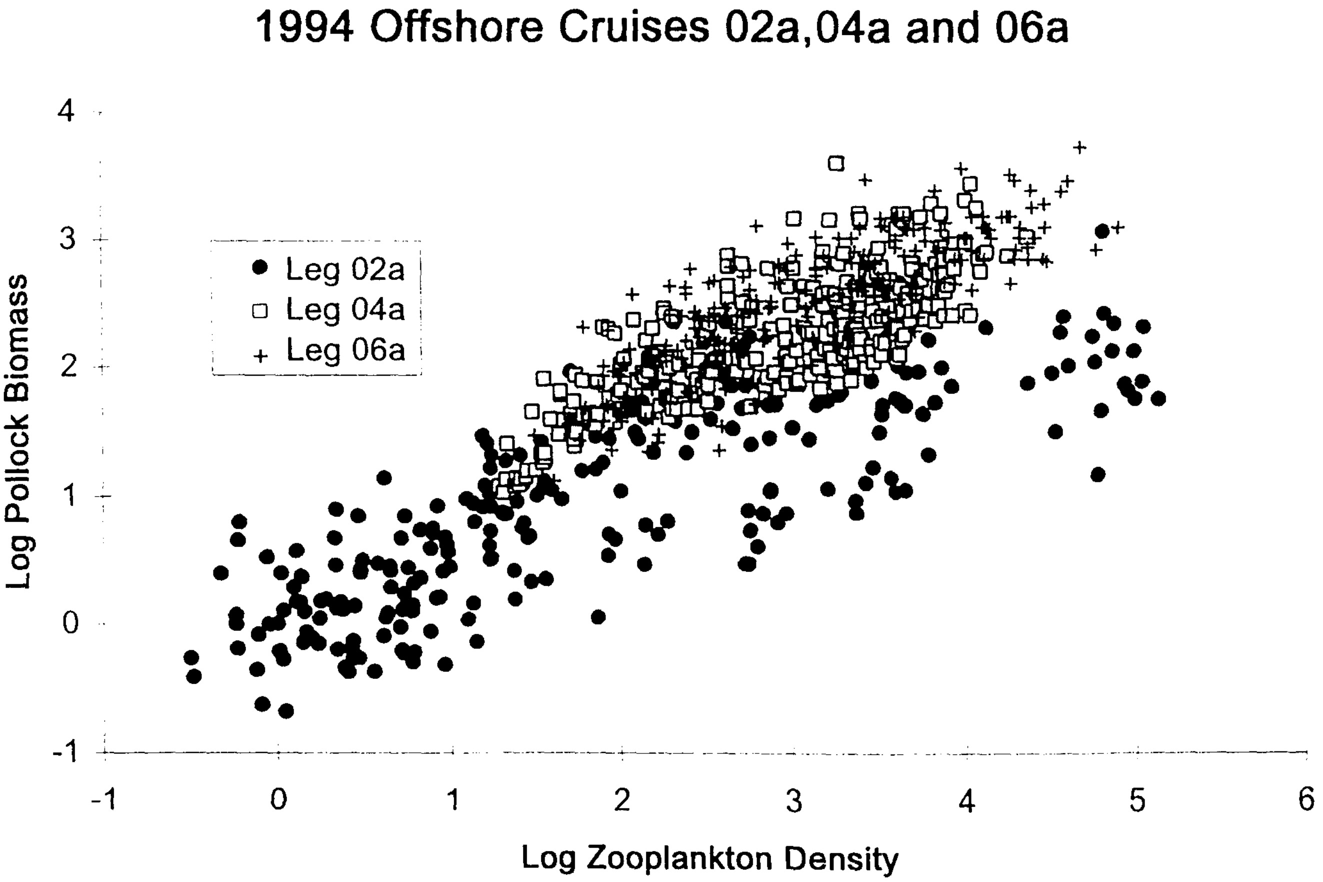


Figure 15. Relationship between pollock biomass and relative zooplankton density for offshore cruises in 1995. Data were log transformed, and the regression is for both cruises combined. Each point represents one cell 10 m deep, by one report (45 pings) in length. Only cells which contained both pollock and plankton were included on this graph. Note the logarithmic scale.

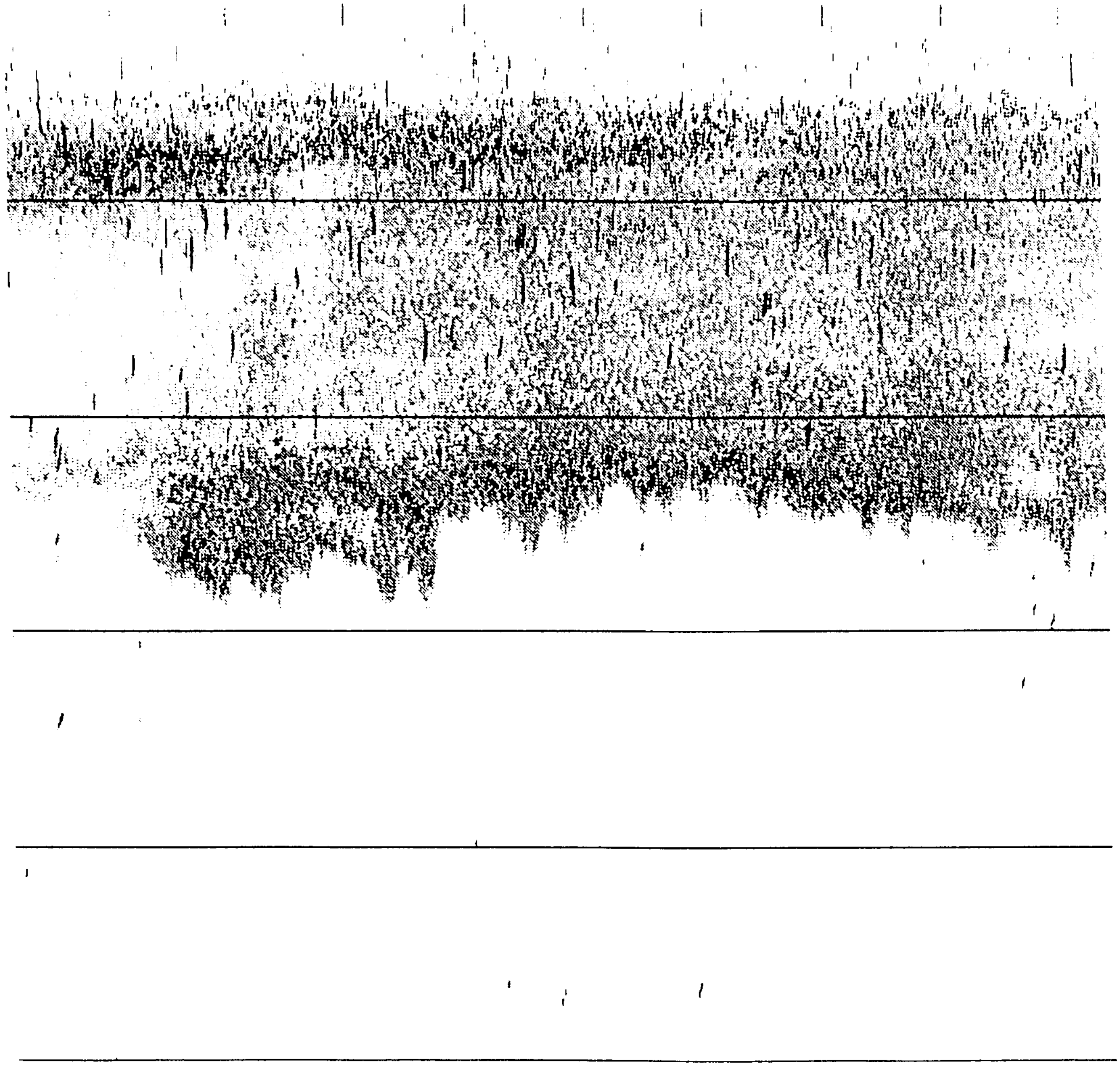


Figure 16. Echogram from Perry Passage in July 1994 showing high densities of pollock found in a dense plankton layer.

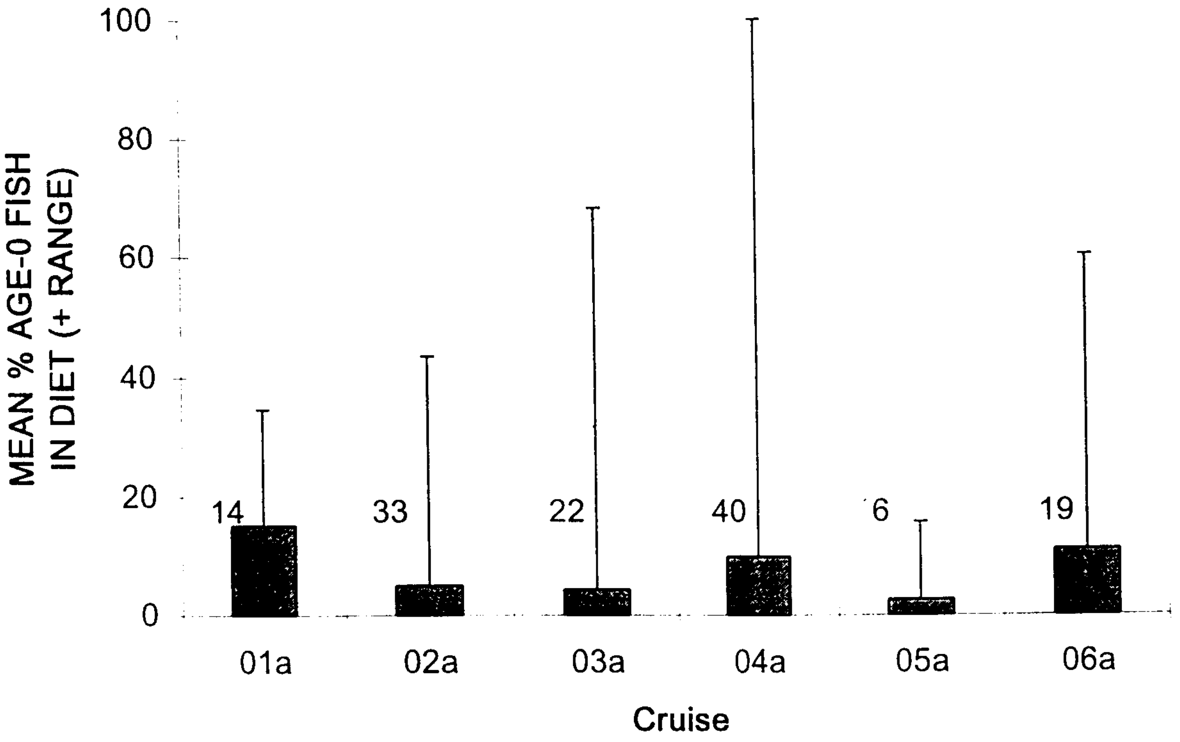


Figure 17. Mean percentage of age-0 fish in the diet of pollock during 1994 cruises. Error bars show the maximum value from each cruise and the numbers indicate the number of net sets used in the diet analyses. Data are from Mark Willette, ADF&G.

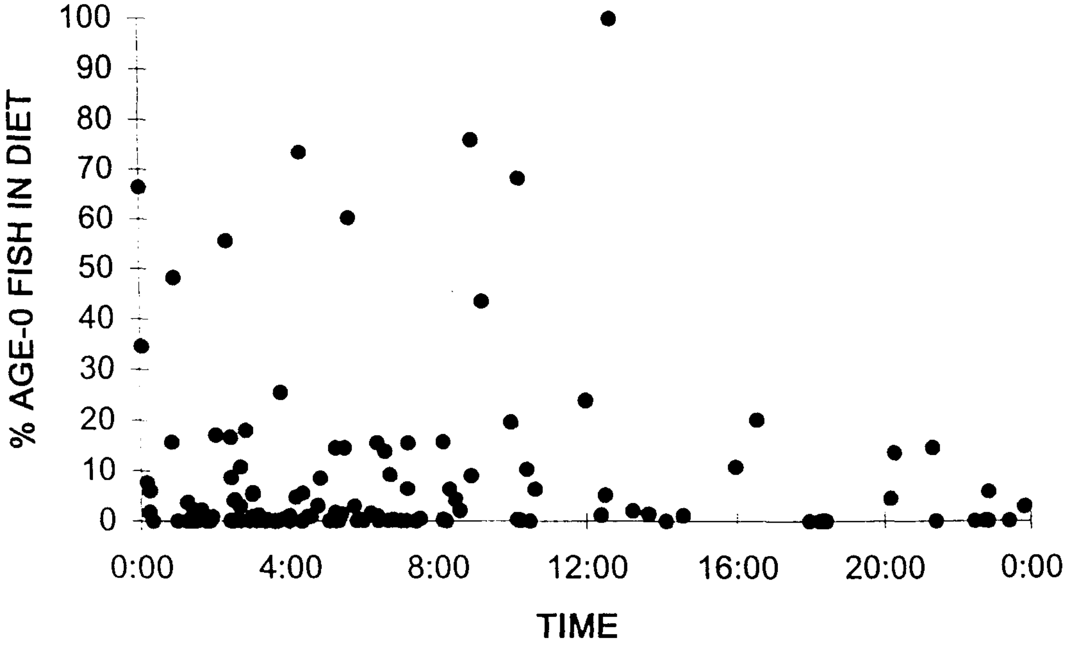


Figure 18. Percentage of age-0 fish in the diet of pollock versus time of day during 1994 sampling. Data are from Mark Willette, ADF&G.

CHAPTER 2.

ACOUSTIC ESTIMATE OF ZOOPLANKTON DISTRIBUTION IN PRINCE WILLIAM SOUND, SPRING 1996

Jay Kirsch[1], G.L. Thomas[1], and R. Ted Cooney[2]

[1]Prince William Sound Science Center
P.O. Box 705
Cordova, Alaska 99574
kirsch@grizzly.pwssc.gen.ak.us

[2]Institute of Marine Sciences
School of Fisheries and Ocean Sciences
University of Alaska Fairbanks
Fairbanks, AK 99775-1080
cooney@ims.alaska.edu

ABSTRACT

A zooplankton survey was conducted in Prince William Sound in May 1996, using a 420 kHz digital sonar and a MOCNESS net. Data from the catch supplied us with zooplankton species, size, and density, which were applied to zooplankton scattering models, allowing us to predict volume backscatter. These predicted values are compared with measured acoustic backscatter to validate the measurement methods. Relative agreement in the two instruments is evident in the occurrence at the same depth of layers. However, more analysis of the catch information is needed for agreement of the absolute densities, since animal sizes are used to estimate the target strength that is used to scale the echo-square integration. The sources of error are discussed, with their potential solutions.

INTRODUCTION

Acoustics has been used for zooplankton assessment since the early 1970's, but only until recent advances in target strength (TS) models has estimation of absolute density been attempted (Stanton et al. 1994). Density estimation through echo-square integration requires average target strengths of the individual organisms in order to scale the acoustic backscatter array. Measuring *in situ* target strength directly is problematic in that individual peaks need to be detected from the received electronic signal. This requires the infrequent case of low enough zooplankton densities to resolve individual echoes with a beam that spreads with range.

The objective of this survey was to estimate the biomass and distribution of calanoid copepods throughout Prince William Sound in spring of 1996. These zooplankton are a primary source of food for many fishes in Prince William Sound, including pollock, herring, and salmon.

MEASUREMENT METHODS

Acoustic surveys were conducted aboard the University of Alaska Research Vessel *Alpha Helix*. The acoustic system consisted of a 420 kHz BioSonics Digital Transducer scientific echosounder with a dual-beam transducer (although only the narrow beam was used for this analysis) mounted on a 3 meter long towing fin. Transducer signals were acquired on a NEC Versa personal computer via a PCMCIA cartridge, written to hard disk, and moved to a Bernoulli disk each day. Parameters of the acoustic system during the survey were: source level (SL) =+224.0 dB; receiver gain (RG) =-42.9 dB; transducer directivity (b^2) =.000274; and pulse duration=400μs. These parameters result in an echo integration constant of 6.61e+14. The trigger interval was set to .4 seconds (2.5 pings per second), but may have had some variability due to the computer's limited ability to acquire signals rapidly.

A nine day broad scale survey of Prince William Sound was conducted between May 2nd and 10th, 1996 (Figure 1). Knight Island Passage, Wells Passage, Unakwik Inlet, Montague Strait, and Orca Bay were surveyed in Prince William Sound. Another survey was conducted from Middleton Island in northern Gulf of Alaska through Hinchinbrook Entrance. The acoustic survey was conducted after the spring phytoplankton bloom when large calanoid copepod; Neocalanus spp., are found closest to the ocean surface. Measurements were performed in the daytime when many nocturnal organism migrate to deeper water, and contribute less to the acoustic signal.

A MOCNESS with nine 1 m^2, 0.505 mm mesh nets was used during the survey. There were 25 tows throughout the Sound. Each MOCNESS tow sampled from 50 meters to the surface in 5 meter increments. To measure temperature and salinity, a CTD was cast at the end of every net tow (as well as other stations), providing information on stratification in the water column.

Other sensors were operated during the cruise, but these output are not the focus of this paper. A Focal optical plankton counter with a Chelsea Instruments Aquapack (CTD, fluorometer) was towed on a Chelsea Aquashuttle during the acoustic surveys but not during MOCNESS tows. BioSonics 720kHz and 1MHz Digital Transducer systems were operated during the MOCNESS tows, which in the future could provide information for multifrequency inversion methods. Data were also collected by a hull-mounted Acoustic Doppler Current Profiler, and an on-deck weather station.

To facilitate batch processing, the data were processed using in-house software written in the Interactive Data Language (IDL). Our processing scheme included an echo-square integrator with a notch-gate (described later) to remove fish, a map generator for both survey plotting and visualization of geographical distributions, a database scheme to match acoustic files with MOCNESS files, and a program for MOCNESS volume backscatter prediction. The output files included echograms in GIF format, color maps in Postscript format, and ASCII tables.

Although daytime surveys provide the least corruption of the macrozooplankton signal due to reduced number of fishes in the surface water, it was still necessary to filter large fish from the signal. The BioSonics Digital Transceiver samples at 41667 samples per second, which at a speed of sound of 1470 meters per second, gives a sampling resolution of 17.6 mm. At this resolution, high zooplankton densities have smaller signals than a single fish. To remove large fish signals, we used the inverse of thresholding; notch-gating, where signals below a threshold are kept but larger ones are omitted. The echo-square integrator that was built into our processing scheme included a notch gate which removed echoes above a specified threshold of -60 dB, based on a histogram of signal values.

MEASUREMENT RESULTS

Figure 2 shows a digital echogram of a typical zooplankton layer. In the daytime, animals were layered typically around 10 to 20 meters. In the evening, there is suggestion of an upward migration, although zooplankton behavior will be the focus of a future paper.

Highest acoustic scattering levels were found in the Gulf of Alaska, Hinchinbrook Entrance, and southern Montague Strait. Other areas had significant scattering, but with values that were an order of magnitude lower (Figure 3).

Neocalanus flemingeri was the overall most abundant zooplankton species found in the MOCNESS tows. A pteropod species, Limacina Helicina was found throughout Prince William Sound, except in Wells Passage. Although these pteropods had low overall densities, their target strengths are higher (because of their hard shells) than target strengths of copepods (Stanton et al., 1996), so they will more easily contribute to the acoustic backscatter. We predict pteropods to be around 14 dB higher than copepods (see below), while Stanton et al. (1996) has predicted pteropods to be around 19 dB higher than copepods in the Atlantic Ocean. Moreover, the diameters of the pteropod shells varied throughout the Sound, causing more variability in the TS.

MODEL IMPLEMENTATION

In-situ TS measurement of small zooplankton is not typically feasible due to high densities of animals which cause target discriminators to fail in detection of individual echo peaks. Instead, a bent cylinder model was implemented for copepods, while an elastic sphere model was implemented for pteropods (Stanton et al., 1994). Material parameters (R) were assumed to be the same as used on the Georges Bank; 0.058 for copepods, and 0.5 for pteropods.

An alignment algorithm was used to partition the acoustic data into blocks that spatially overlap the same depths sampled by the MOCNESS. Horizontal alignment was more problematic due to the differences in tow point location. For each net in the MOCNESS, densities and species distributions were measured, but at the time of this writing, only a few individual lengths were available to be input to the scattering models. Stage V copepods Neocalanus flemingeri, Neocalanus plumchrus, and Neocalanus crisatus found in the MOCNESS samples had a unimodal length distribution, with a mean of 3.74 mm, and an average width/length ratio of 0.32. Given these data at 420 kHz, the fluid bent cylinder model predicts a TS of -86.2 dB (Figure 4). Catches of adult pteropods had a trimodal diameter distribution, with an overall mean of 1.68 mm. At 420 kHz, the elastic sphere predicts a TS of -72.1 dB (Figure 5). By multiplying σ (arithmetic equivalent of TS) by the catch density, then summing this factor from each species, an expected value of the volume backscatter (Sv) was calculated for each net.

Comparisons of acoustical measurements and MOCNESS samples indicate agreement of depth distributions (Figures 6-12) for cases of high neocalanus catch and low pteropod catch, but matching absolute densities will require more work. Figure 13 shows the comparison for each net. Note that the slope of the comparison is close to unity, however there is an offset of about an order of magnitude. Figure 14 shows a histogram of the ratio of the volume backscatters measured by the 420 kHz and predicted by the MOCNESS, which also indicates about an order of magnitude error.

The accuracy of the density estimates depends on the target strength scaling factor that is applied to the echo square integration, which is a function of the accuracy of the scattering models used, the quality and quantity of the net catch information, and the accuracy of the acoustic calibration, including beam pattern factor.

Comparison error comes from several sources. The animal lengths were available from only a few tows, which doesn't account for geographical variability in animal size. This causes error in the TS prediction. We plan to have the remainder of the animals measured later this year so that more complete TS distributions can be applied. Also, the flowmeter on the MOCNESS is sensitive to fluctuations in ocean currents, so that there will be some variability in the estimated sample volume and therefore the catch density estimates as well.

The comparison error appears to be worse in the deep net catches, labelled by a "2" in figure 13, where fewer animals were caught. This can be explained by thresholding. A flat threshold of -125 dB was used to eliminate noise. At 20 meters, 20logR=26 dB, $2\alpha R=4$, so a signal of -125+26+4 = -95 dB would be thresholded. At 50 meters, 20logR=34 dB, $2\alpha R=10$, so a signal of -125+34+10 = -81 dB would be thresholded. This signal thresholding will result in an underestimate in low densities since very low scattering values will be replaced by zeroes.

There is also significant error in the shallower catches, labelled by a "9" in figure 13. In the near future, we will look at the catches of these near-surface nets to determine if there is a species with significant TS that we have not accounted for.

Digital transducer systems are still in the development phase, which can be seen from problems in data acquisition speed. We attempted to ping every .4 seconds, however as the data bus becomes busy, it is difficult for it to accept more data. In this case the next ping will be delayed until the bus is ready for more data. This can also result in an underestimate, as higher densities result in more data to the bus, so ping delays and thus undersampling are more likely in higher densities. This problem is still under investigation.

There are several cases where the acoustics estimates a higher density than the catch. This is a result of not applying every species in the catch to this algorithm. Further work is needed to determine which species should be measured, modeled, and added to the predicted volume backscatter.

Another possible source of underestimation error is the tilt of the organism in situ, since it was not measured in this survey. Tilt of the animals can reduce the overall acoustic backscatter, as the TS models currently assume random orientation. Tilt would result in a smaller surface area as seen by the sonar, and therefore a lower target strength. Copepods may try to orient themselves vertically in the water column to optimize feeding (Peter Wiebe, personal communication). This error can be made worse by the exceptionally calm weather we experienced during the survey, since less ocean turbulence could result in more successful vertical orientation of the animals. The scattering models can be upgraded to include tilt, but an *a priori* knowledge of tilt is still needed.

In future cruises, video plankton recorders can be used to measure tilt as well as classify species, so that the probability density function (PDF) of tilt can be estimated for each species at each depth. Otherwise, a tilt PDF can be estimated which will adjust the acoustic scattering to match the predicted backscatter from the MOCNESS catches.

ACKNOWLEDGEMENTS

We would like to thank the crew of the R/V Alpha Helix for their assistance in operating gear. Geoff Steinhart, Nick Peters, and Loren Tuttle assisted with the acoustic calibration and review of the manuscript. This work is supported by the Exxon Valdez Oil Spill Trustee Council, through grant 96320-N.

FIGURE CAPTIONS

Figure 1. Cruise trackline, R/V Alpha Helix, May 1996.

Figure 2. Echogram of typical zooplankton layer, north of Perry Is, 5/3/96

Figure 3. Relative geographic distribution of zooplankton as measured by 420 kHz acoustics. Darker shades indicate higher density.

Figure 4. Length to TS transformation for bent cylinder model (R=.058), as used for copepods.

Figure 5. Diameter to TS transformation for elastic sphere model (R=.5), as used for pteropods.

Figures 6-12. Typical zooplankton depth distributions, as measured by both 420 kHz (solid line) and MOCNESS (dashed line).

Figure 13. Comparison of predicted Sa (MOCNESS and models) and measured Sa (420 kHz). The numbers indicate net number (depth). The dashed line is a linear fit to the data, which is an order of magnitude lower than the unity (dotted) line.

Figure 14. Histogram of ratio of measured Sv (420 kHz) and predicted Sv (MOCNESS+model). The dashed line indicates an ideal 0 dB shift.

REFERENCES

Ehrenberg, J.E. Calculation of the constants needed to scale the output of an echo integrator. Biomass Handbook 7

Exxon Valdez Trustee Council, Restoration Plan, 1995

Grant, U.S., and D.F. Higgins. 1910. Reconnaissance of the geology and mineral resources of Prince Williams Sound, Alaska. U.S. Geological Survey Bulletin. 443:1-89.

MacLennan, D.N. and E. John Simmonds. 1992. Fisheries Acoustics. Chapman & Hall. London. 325pp.

Schmidt, G.M. 1977. The exchange of water between Prince William Sound and the Gulf of Alaska. MS thesis. University of Alaska, Fairbanks. 116pp.

Thomas, G.L., E. Backus, H.H. Christensen, and J. Weigand. 1991. The Prince William Sound/Copper River Delta/Gulf of Alaska Ecosystem. Dobbin & Associates Press, Washington, D.C. 15 pages.

Stanton, T.K., 1989a. Sound scattering by cylinders of finite length. III. Deformed cylinders. Journal of the Acoustical Society of America, 86: 691-705.

Stanton, T.K., 1989b. Simple approxiamte formulas for backscattering of sound by spherical and elongated bodies. Journal of the Acoustical Society of America, 86: 1499-1510.

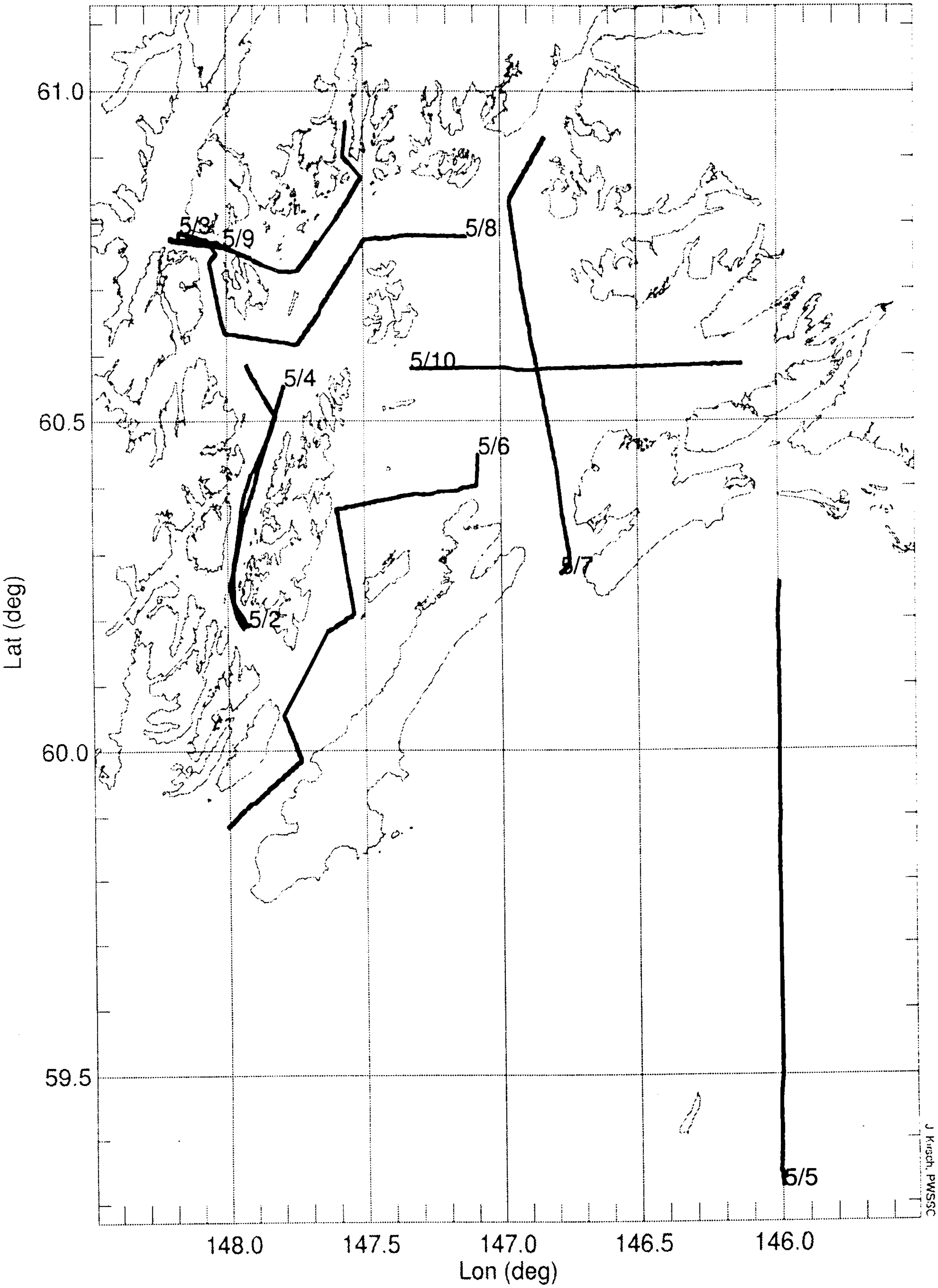
Stanton, T.K., 1990. Sound scattering by spherical and elongated shelled bodies. Journal of the Acoustical Society of America, 88: 1619-1633.

Stanton, T.K., Chu, D., Wiebe, P.H., and Clay, C.S. 1993. Average echoes from randomly oriented random-length finite cylinders: zooplankton models. Journal of the Acoustical Society of America, 94: 3463-3472.

Stanton, T.K., Wiebe, P.H., Chu, D., Benfield, M.C., Scanlon, L., Martin, L., and Eastwood, R.L. 1994. On acoustic estimates of zooplankton biomass. - ICES J. Mar. Sci., 51: 505-512

Stanton, T.K., Chu, D., and Wiebe, P.H. 1996. Acoustic scattering characteristics of several zooplankton groups. - ICES Journal of Marine Science, 53: 289-295

Urick, Robert J. 1967. Principles of underwater sound. McGraw Hill. New York. 384 pp.



61.0
60.5
60.0
59.5
Lat (deg)
148.0
147.5
147.0
146.5
146.0
Lon (deg)
5/3
5/9
5/8
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5/4
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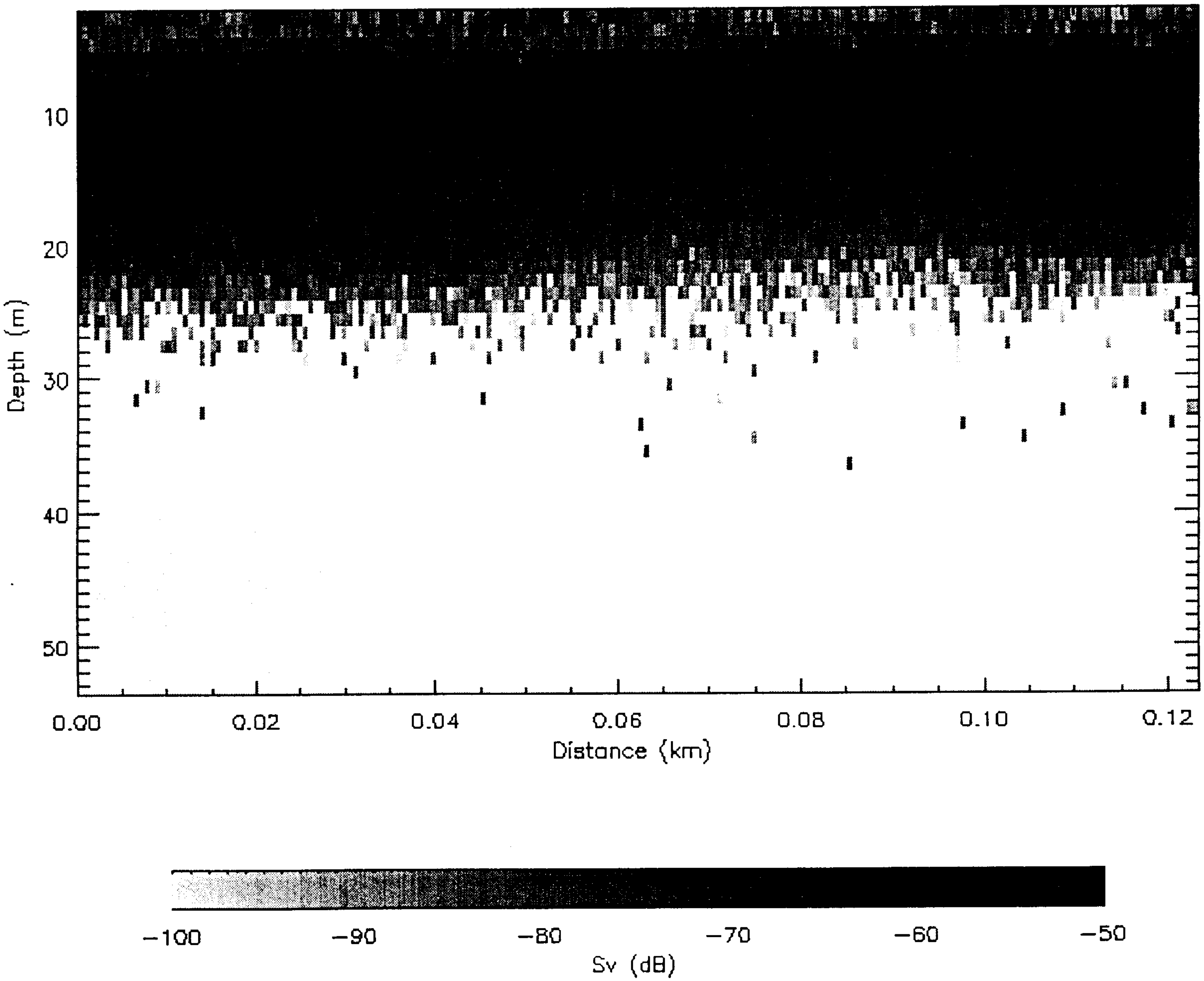
5/7
5/2
5/5
J Kirsch, PWSSC


Depth (m)
10
20
30
40
50
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Distance (km)
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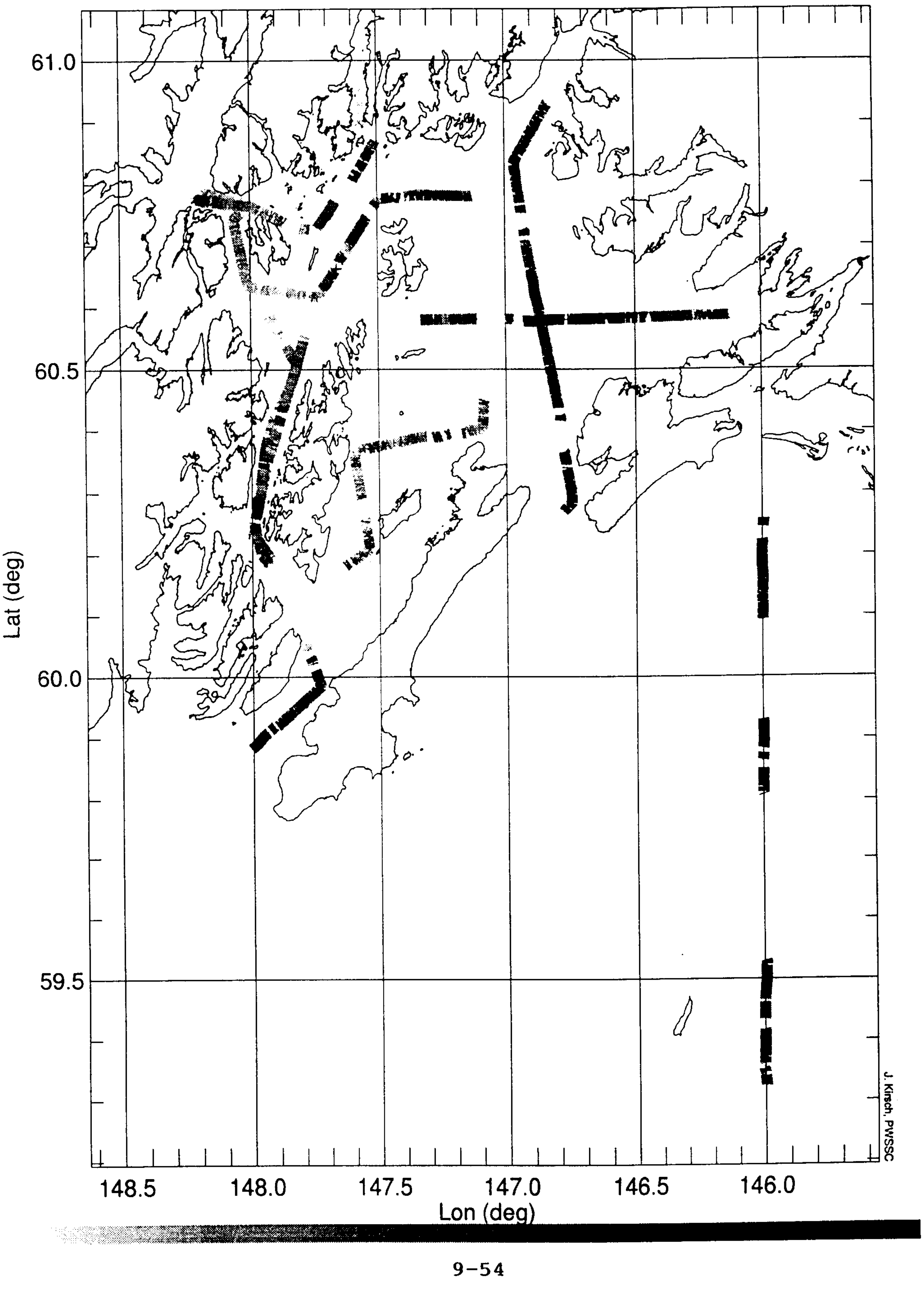
−90
−80
−70
−60
−50
Sv (dB)



61.0
60.5
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Lat (deg)
148.5
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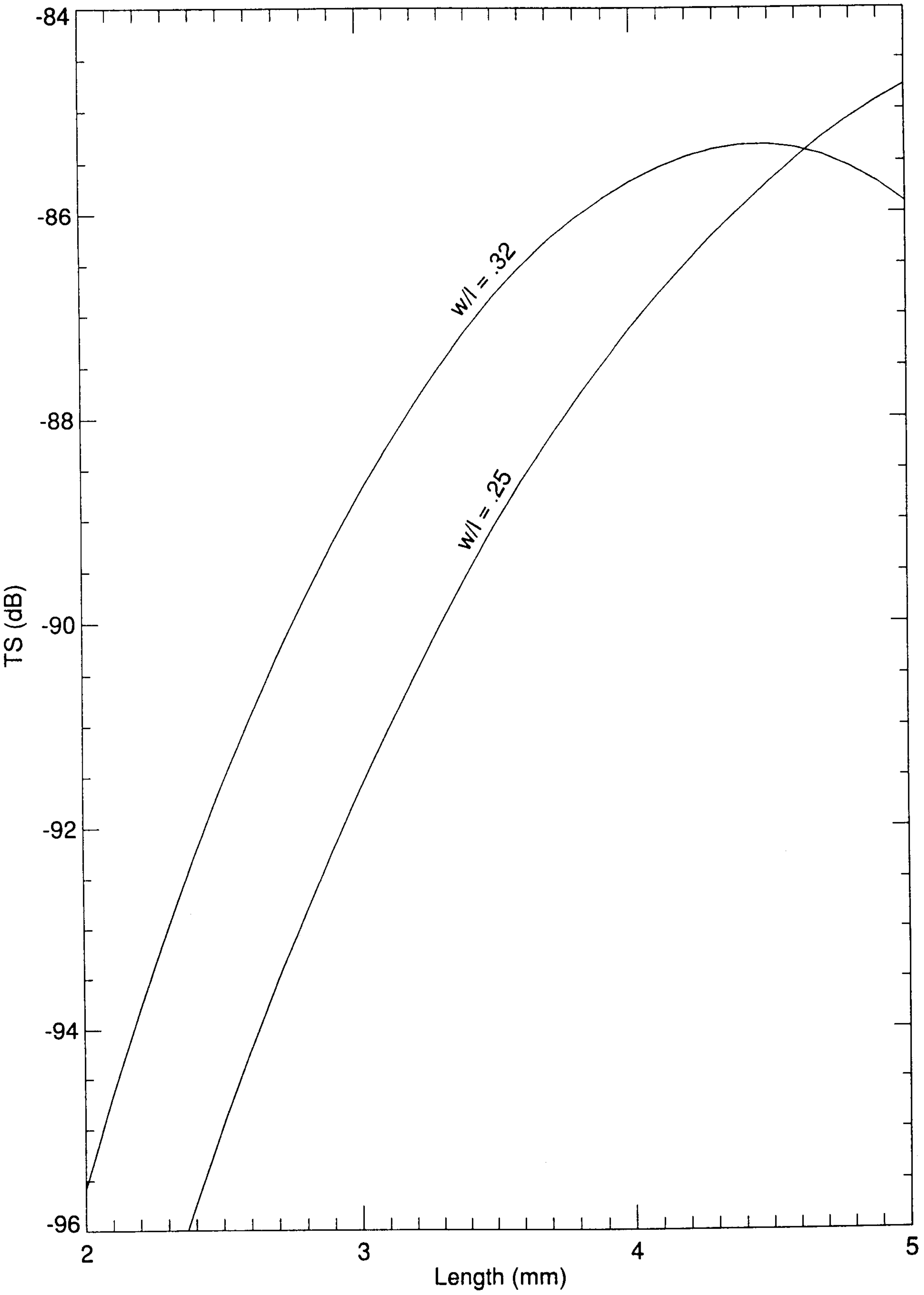
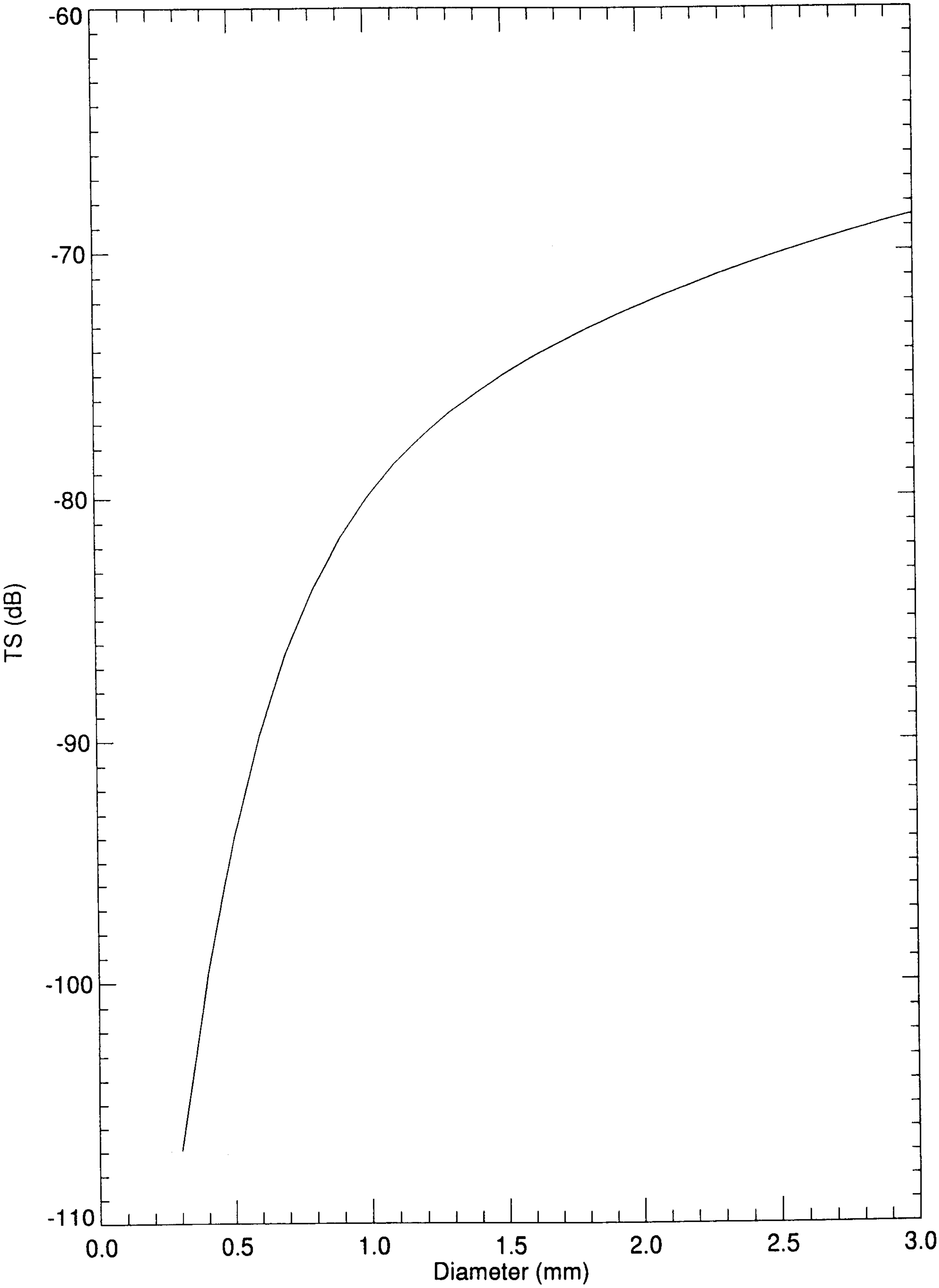
J. Kirsch, PWSSC


-84
-86
-88
-90
-92
-94
-96
TS (dB)
2
3
4
5
Length (mm)
w/l = .32
w/l = .25



-60
-70
-80
-90
-100
-110
TS (dB)
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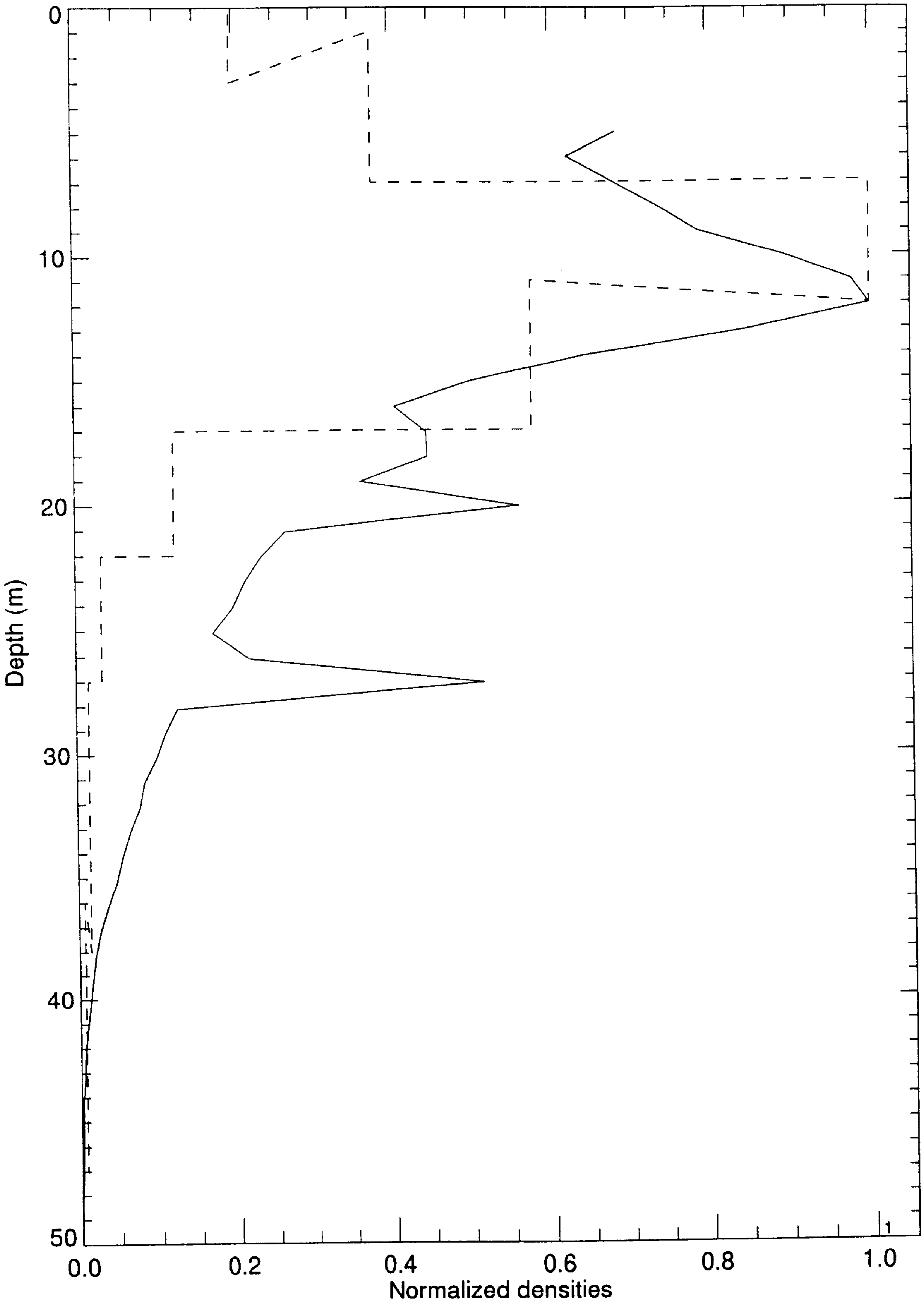
0.5
1.0
1.5
2.0
2.5
3.0
Diameter (mm)



0
10
20
30
40
50
Depth (m)
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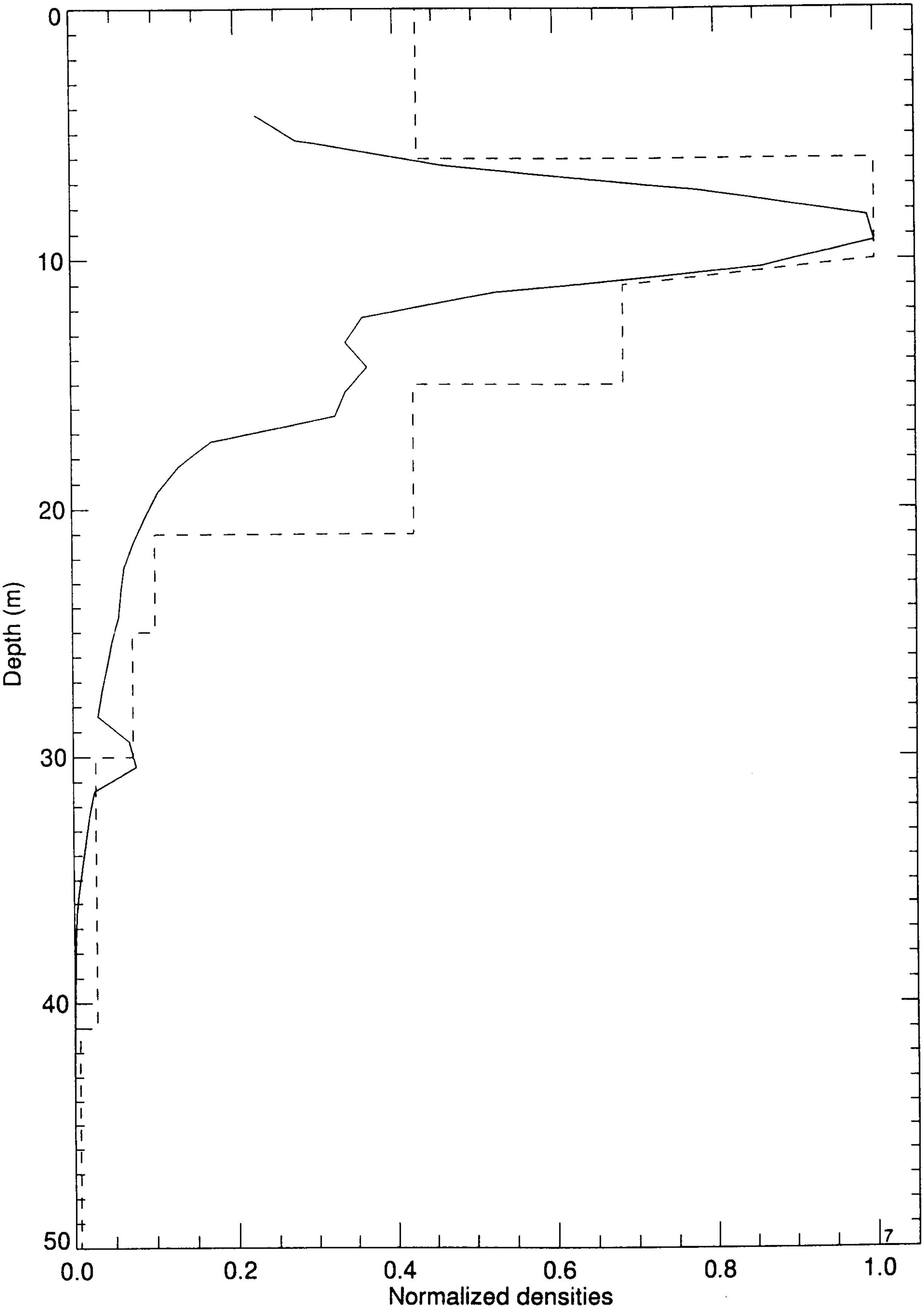
0.2
0.4
0.6
0.8
1.0
Normalized densities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10
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Depth (m)
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0.8
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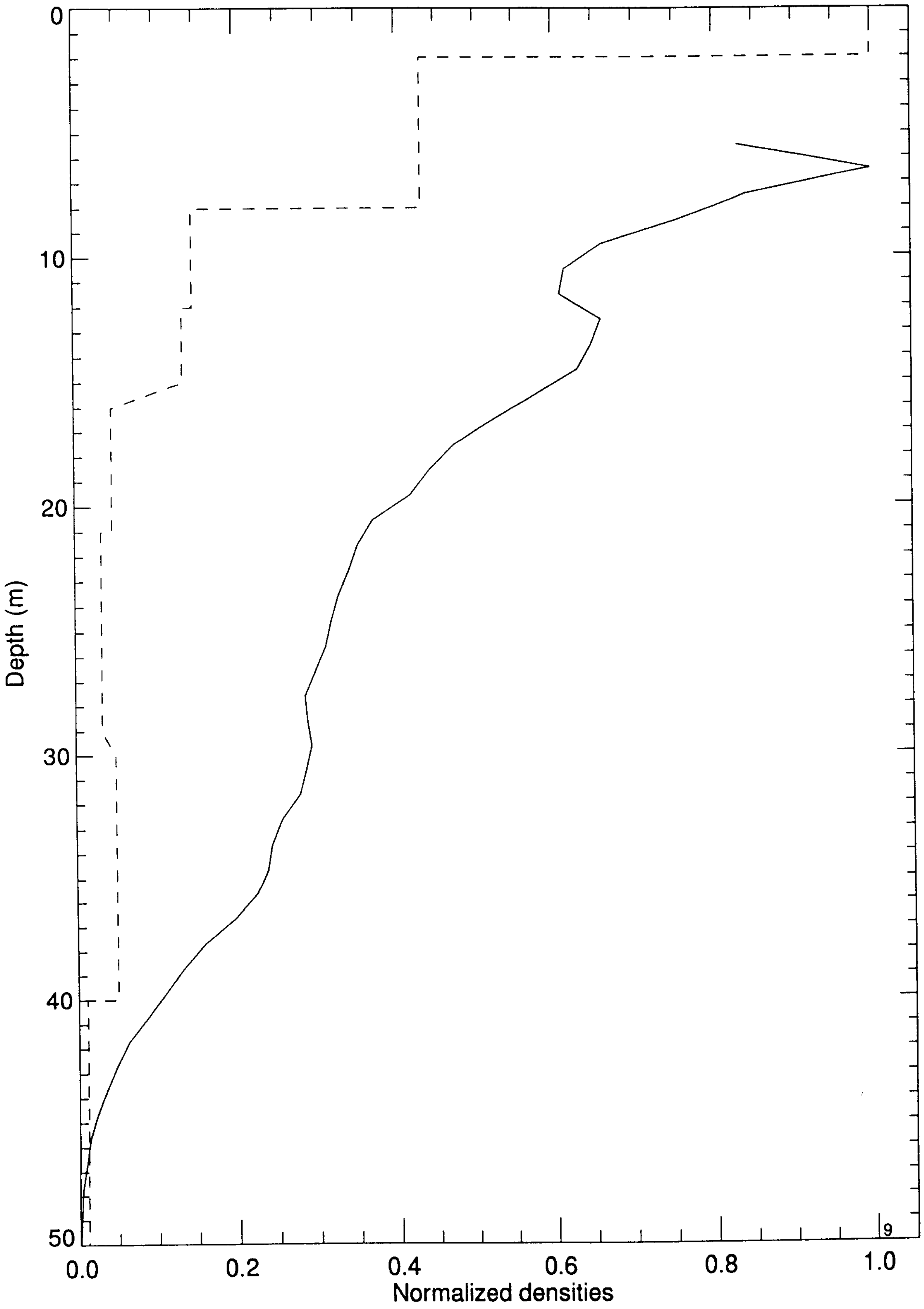
Normalized densities
7


0
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Depth (m)
0.0
0.2
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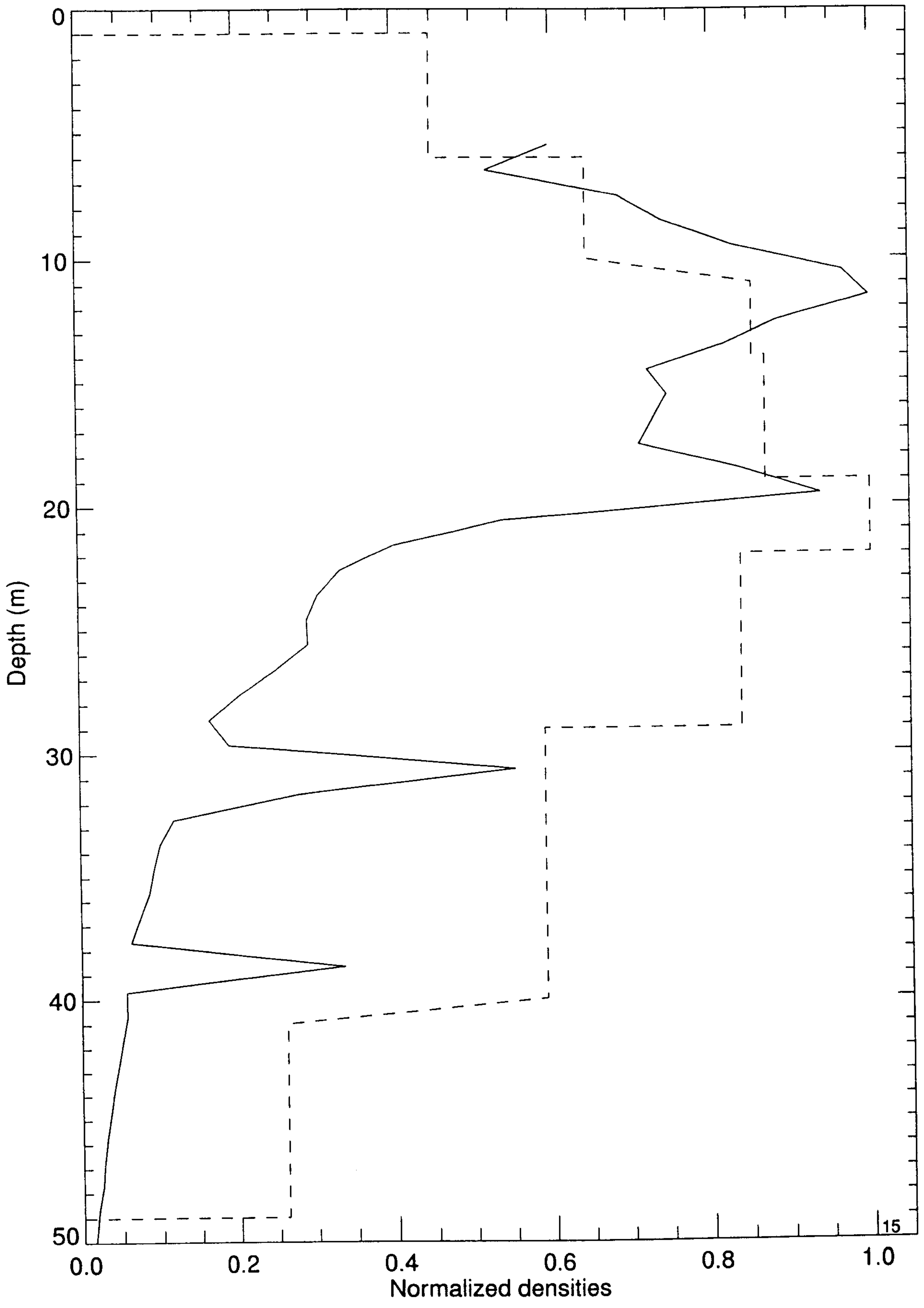
0.8
1.0
Normalized densities
9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40
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0.2
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0.8
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Normalized densities
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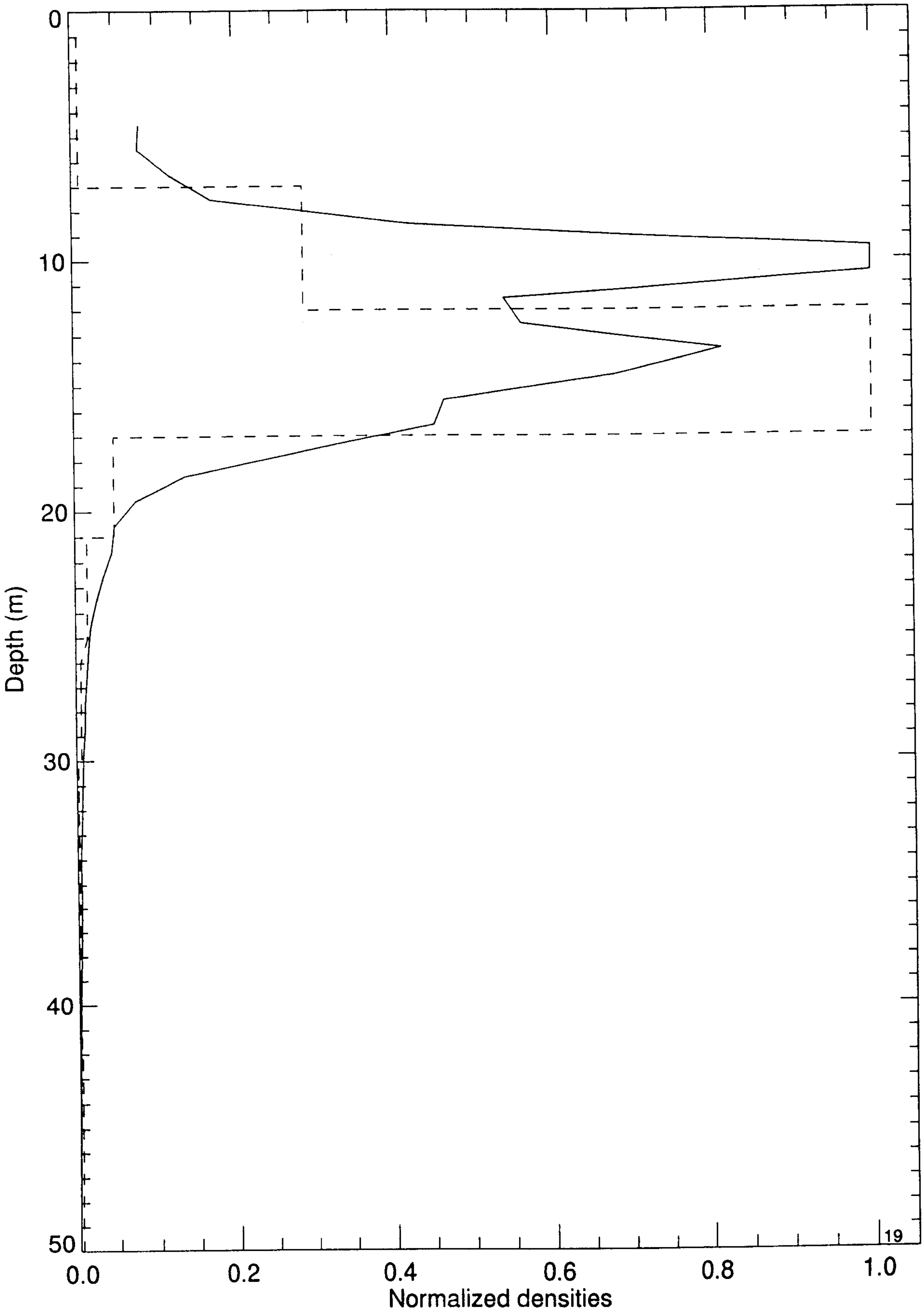
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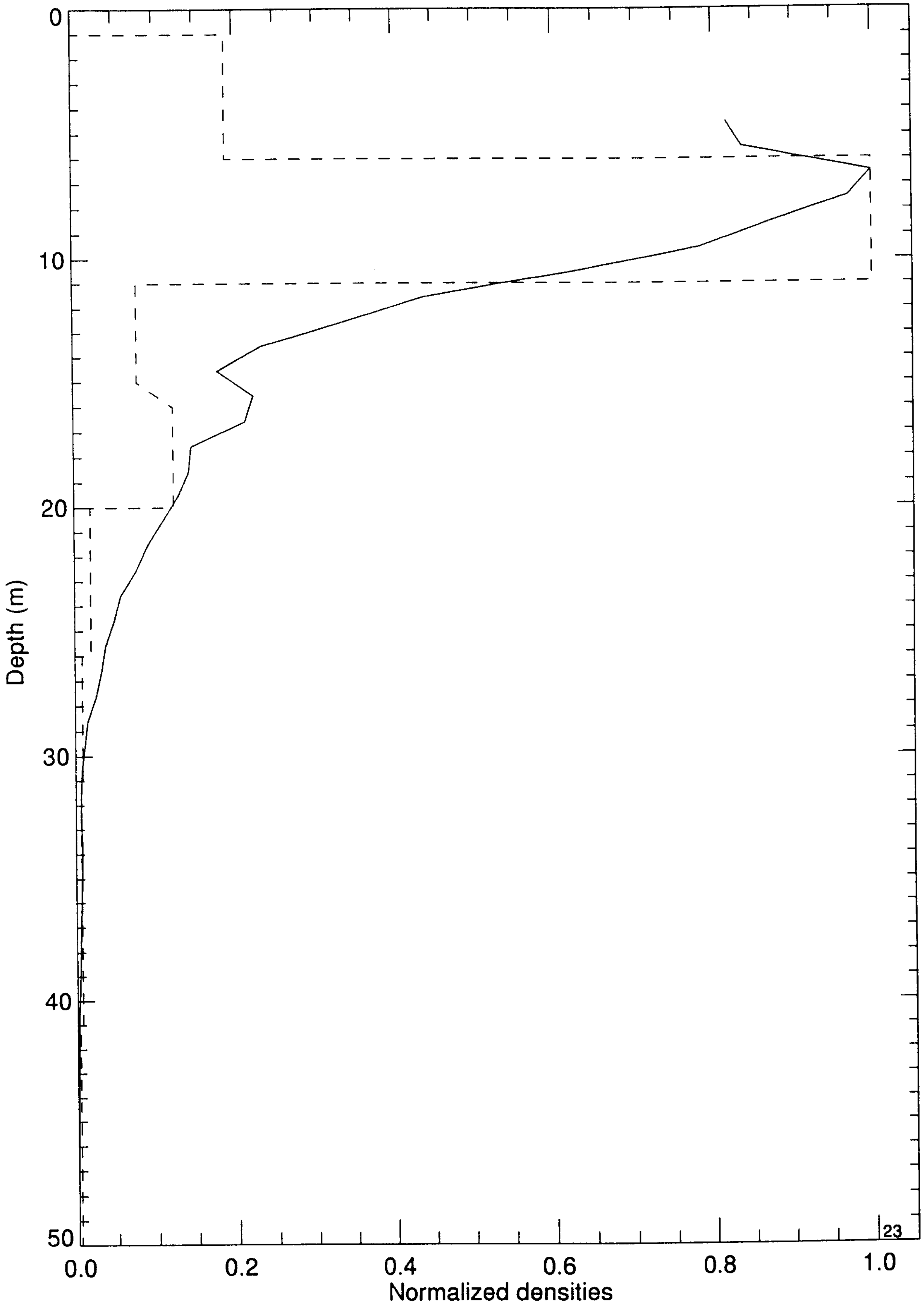
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Normalized densities
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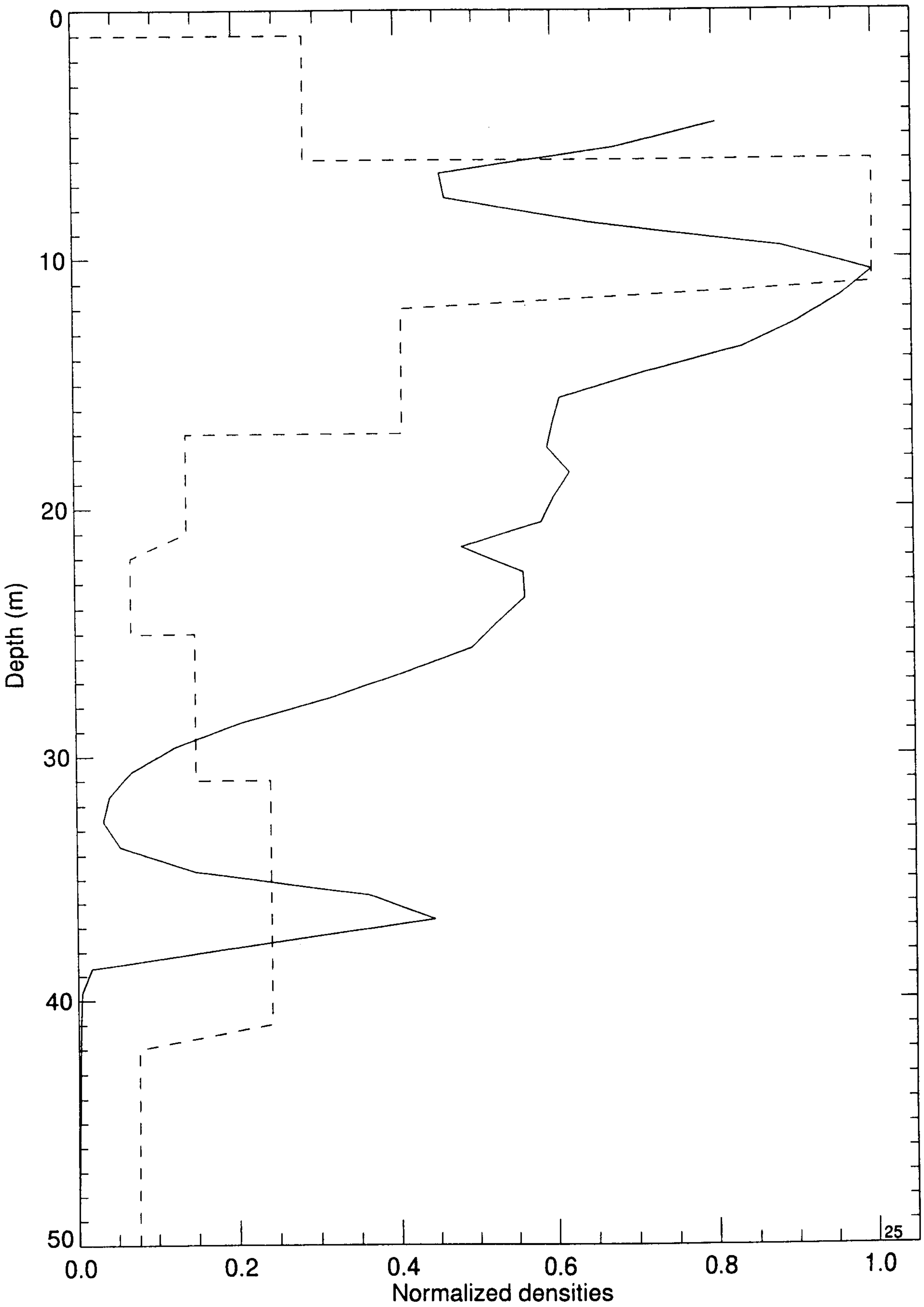
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Normalized densities
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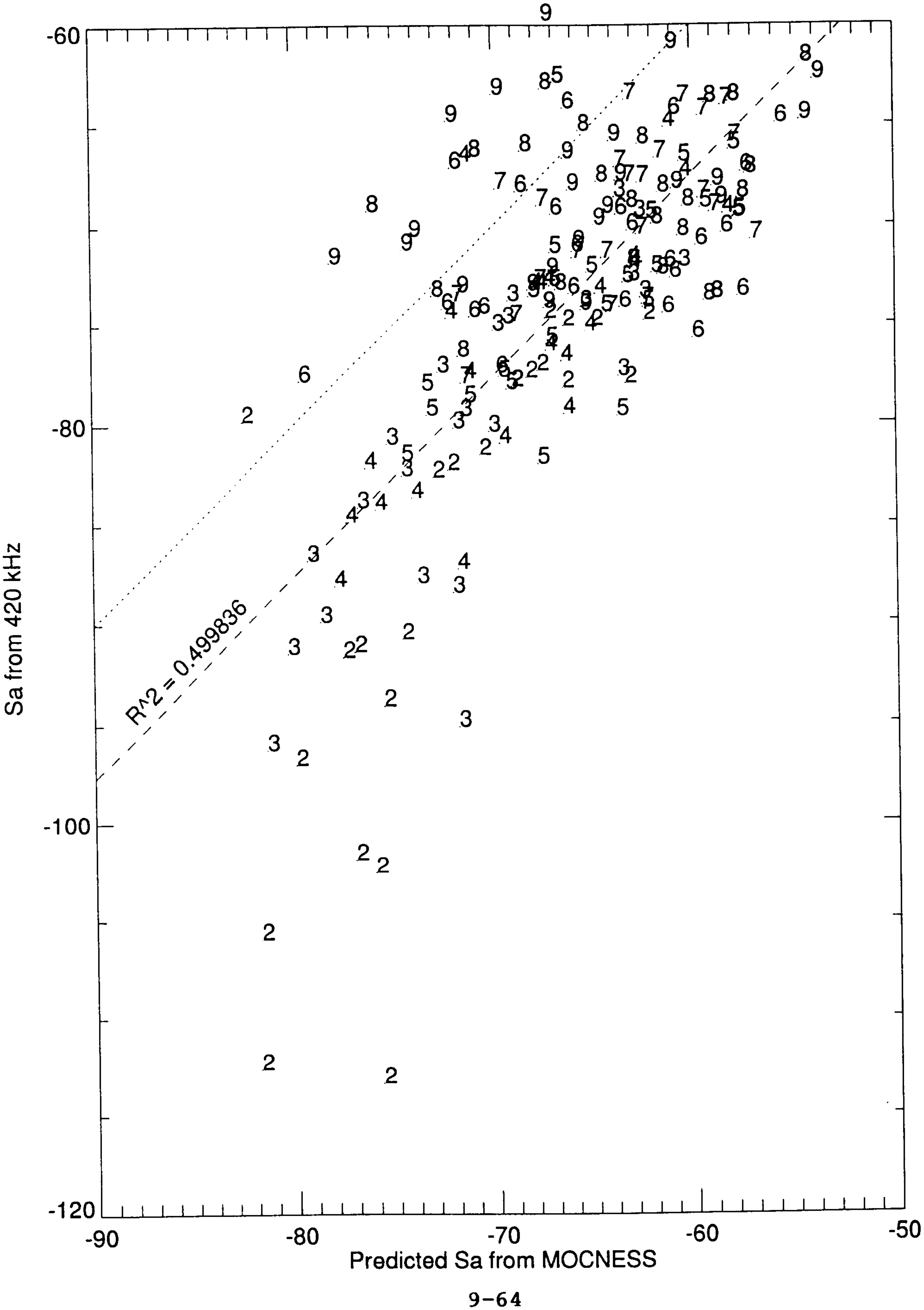
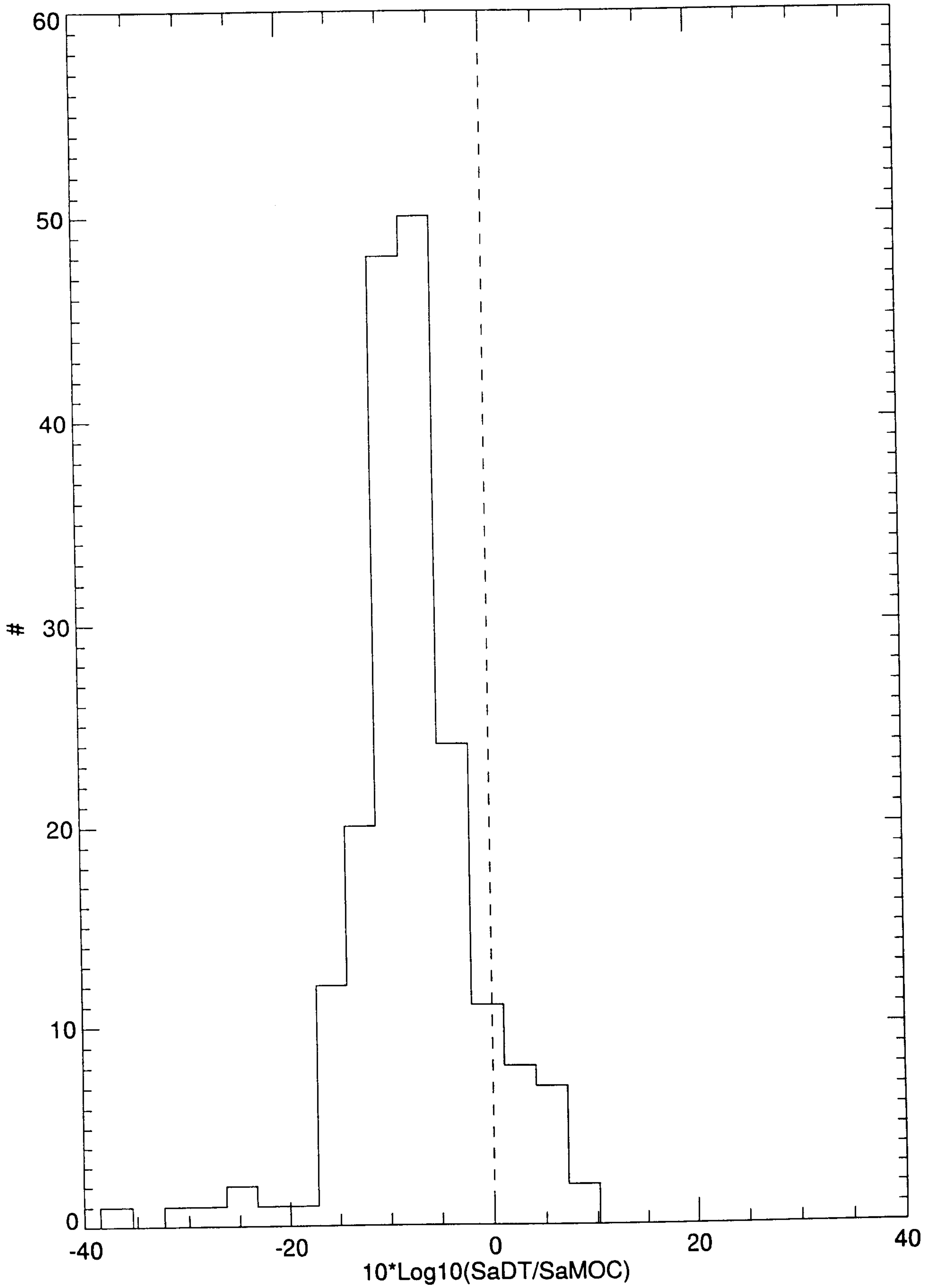

R^2 = 0.499836
Sa from 420 kHz
Predicted Sa from MOCNESS
-60
-80
-100
-120
-90
-80
-70
-60
-50


60
50
40
30
20
10
0
#
-40
-20
0
20
40
10*Log10(SaDT/SaMOC)

CHAPTER 3.

ACOUSTICALLY DETERMINED JUVENILE HERRING DISTRIBUTION IN PRINCE WILLIAM SOUND, FALL 1995

G.L. Thomas, Jay Kirsch, Nicholas Peters

ABSTRACT

A hydroacoustic/purse seine survey was conducted to examine the density and distribution of juvenile herring in Prince William Sound. We found the juvenile herring to be in a nearshore layer at the surface during the night. This layer included other scatters such as juvenile pollock, jelly, plankton and larval fishes, but the herring and pollock combined to represent the majority of the backscatter with the juvenile pollock the contributing the smaller component of the backscatter as separated by using purse seine catches. We show that the spatial distribution of juvenile herring is very contagious with a few locations supporting the majority of the herring population. We also have examined the density of the layer and found that it too is contagious but not directly related to where the bulk of the juvenile herring reside. From these results, we believe that it is possible to conduct broad-scale surveys of juvenile herring in the Sound to support development and verification of the SEA herring overwintering model and allow the management agencies more information on future recruitment events. This capability also makes possible the building of an over-summer mortality model for herring. In 1994, the SEA program

initially avoided this model building effort.

INTRODUCTION

Antidotal information gathered from local fishermen suggest that juvenile herring overwinter in the sheltered nearshore waters of Prince William Sound during the fall to winter months. It has been our observation that the younger year classes (ages 0, 1 and some 2) segregate from adult schools (some age 2 and ages 3+) at this time. Segregation of juvenile herring from adults in nearshore waters has been previously observed in British Columbia (Hourston 1956, 1957, Haegele 1995).

Acoustic-purse seine surveys conducted in falls of 1993 and 1994 to assess the biomass of adult herring provided us the insight to conduct a broad scale survey of juvenile herring throughout the Sound and adjacent waters in the fall of 1995. The fall 1995 survey was conducted as a multi-stage survey. The first stage was a broad scale acoustic survey to establish the areas of concentration of the juvenile herring. This stage consisted of a presence and absence search of nearshore waters for fish, and when fish were located a scientific hydroacoustic system that used GPS information to geo-reference the data was used to map the extent of the concentration and measure density. A second stage of the survey was to deploy a group of boats to areas of mapped fish concentrations to collect biological information and higher resolution information on the density structure of the aggregation. This report discusses the results of stage one of the survey.

METHODS

The broad scale survey consisted of a 10 knot zig-zag search pattern run along the coast of the Sound utilizing the fishing vessels' sonar. All transects started or ended as close to the shoreline that was safe to navigate. The distance offshore of the transects was about 1 km unless the fish concentrations extended further off the shoreline. This was common in areas with shallow shelfs (<50m). Once a concentration of juvenile herring was found, a tow-fin with the 120 kHz pre-amplified, dual-beam transducer was deployed to measure the fish density. Where concentrations were significant, a group of vessel were deployed to conduct intensive net and acoustical sampling. All surveys were conducted at night due to the nocturnal behavior of juvenile herring, who form a semi-discrete band near the surface making them easy to classify, insonify and capture.

The layer of juvenile herring generally ranges in depth from 0m to 20m but sometime to 60m. We assumed that most of the juvenile herring population is contained within this band, which was composed of other species as well as herring. An example of this can be seen on a echogram of a transect run in Sawmill Bay, November 7, 1995 (Figure 1). This figure illustrates the night-time separation of different species throughout the water column. The bottom echo is clearly seen. A layer of large targets just above the bottom is typical of adult and sub-adult pollock that were caught in the area with a mid-water trawl. Also the target strengths for this layer were near -34 dB, a typical value for adult-subadult pollock. The next feature is the pair of dense schools. Due to the discreetness of the school density, the depth (around 30m) and shape, this school was classified as adult herring based upon extensive acoustic-purse seine surveys in this region between fall 1993 and 1994. The surface layer which is much more diffuse, was found to consists of multiple species (juvenile herring and pollock, larval fishes, jelly, plankton and some juvenile salmon), but dominated by juvenile herring (Figure 2a). The purse seine catches were used to determine the size and relative abundance of species in this surface layer.

The lengths were used to estimate the target strength distribution of expected scatters and compared to the in-situ measurements. In-situ target strengths were used a supplemental information because in high densities, the target discriminator either fails or combined nearby fish and overestimates TS, a problem we term "target coincidence". Three seine sets for the Sawmill Bay caught a mix of juvenile herring (mean length = 94 mm), juvenile pollock (mean length = 104 mm), jellyfish, sculpin (mean length = 36 mm), and other miscellaneous fish. Thorne (1983) empirically derived the following equation relating TS to weight in dB per kilogram as a function of length.

$$TS_w = -5.98 * Log_{10}(l_{mm}) - 18.234 \qquad (\frac{dB}{Kg})$$

Target strengths of jellyfish have gone unmeasured during our surveys, so in summer 1996 we conducted an experiment where we measured *Cyanea* jellyfish with a 120 kHz transducer. We found the strongest return to be -60 dB. During the fall herring survey, however, these jellyfish are in an earlier life stage and are therefore smaller, and there are also other types of jellyfish in the water column in the fall which have less mass (and therefore a lower TS) to them. Therefore, -60 dB can be considered a maximum worst-case scenario for jellyfish target strength.

The calculated TS values from the net catch length data from target strength models based give herring; -49.7 dB, pollock; -45.6 dB (from Traynor 1979), jellyfish; -60 dB (field measurements) and sculpin; -56 dB (field measurements). Multiplying the relative catch densities by the modeled target strengths results in percentages of acoustic backscatter for each species present in the catch at the location of interest, as calculated by the following equation,

$$\%\ acoustic\ backscatter_1 = \frac{r_1 \sigma_1}{(r_1 \sigma_1 + r_2 \sigma_2 + \ldots + r_n \sigma_n)}$$

where r is the percentage of each species in the catch, and s is the arithmetic equivalent of the target strength. Figure 2a shows the purse seine catch percentages for Sawmill Bay, while Figure 2b shows the net catch percentages transformed into their respective acoustic backscatter. Note that the expected backscatter increased substantially for the juvenile herring. Upon inspection of the areas where purse seining conducted, Sawmill Bay was a worst case scenario. Figure 3 shows the juvenile herring represented 94% and 93% of the total net catch and total expected backscatter from the surface layer for entire survey. Biomass density is calculated by dividing the single species backscatter by the target strength s/w.

$$B_1 = \left(\frac{v^2}{k}\right)\left(\frac{r_1 \sigma_1}{(r_1 \sigma_1 + r_2 \sigma_2 + \ldots + r_n \sigma_n)}\right)\left(\frac{w}{\sigma}\right)_1$$

RESULTS AND DISCUSSION

The broad scale survey covered the many parts of the sound and adjacent waters of Port Bainbridge to Ressurection Bay (not shown). The areas where fish concentrations were sufficient to warrant slowing the vessel to sample with the scientific acoustic system are shown in Figure 4. The areas that were intensively surveyed, but not reported here, are shown in Figure 5. Figures 6 are juvenile densities for the top 50m, again for the broad. Figures 7 are biomass values for the top 50 m, calculated by multiplying the densities by the survey's surface area.

CONCLUSION

The depth of 50m was chosen as it predominately contained only the band of mixed targets seen at night, and so can be used as a relative comparison of the juvenile herring densities between bays. The net catch data used to extract the acoustic contributions of the different species must be closely associated in both time and space to the acoustically measured layer. This is to ensure an accurate species break down, and reduces the errors associated with a non homogeneous strata.

FIGURE CAPTIONS

Fig 1. Echogram from Sawmill Bay, showing both adult and juvenile herring

Fig 2. Species composition by count and by acoustic backscatter, Sawmill Bay.

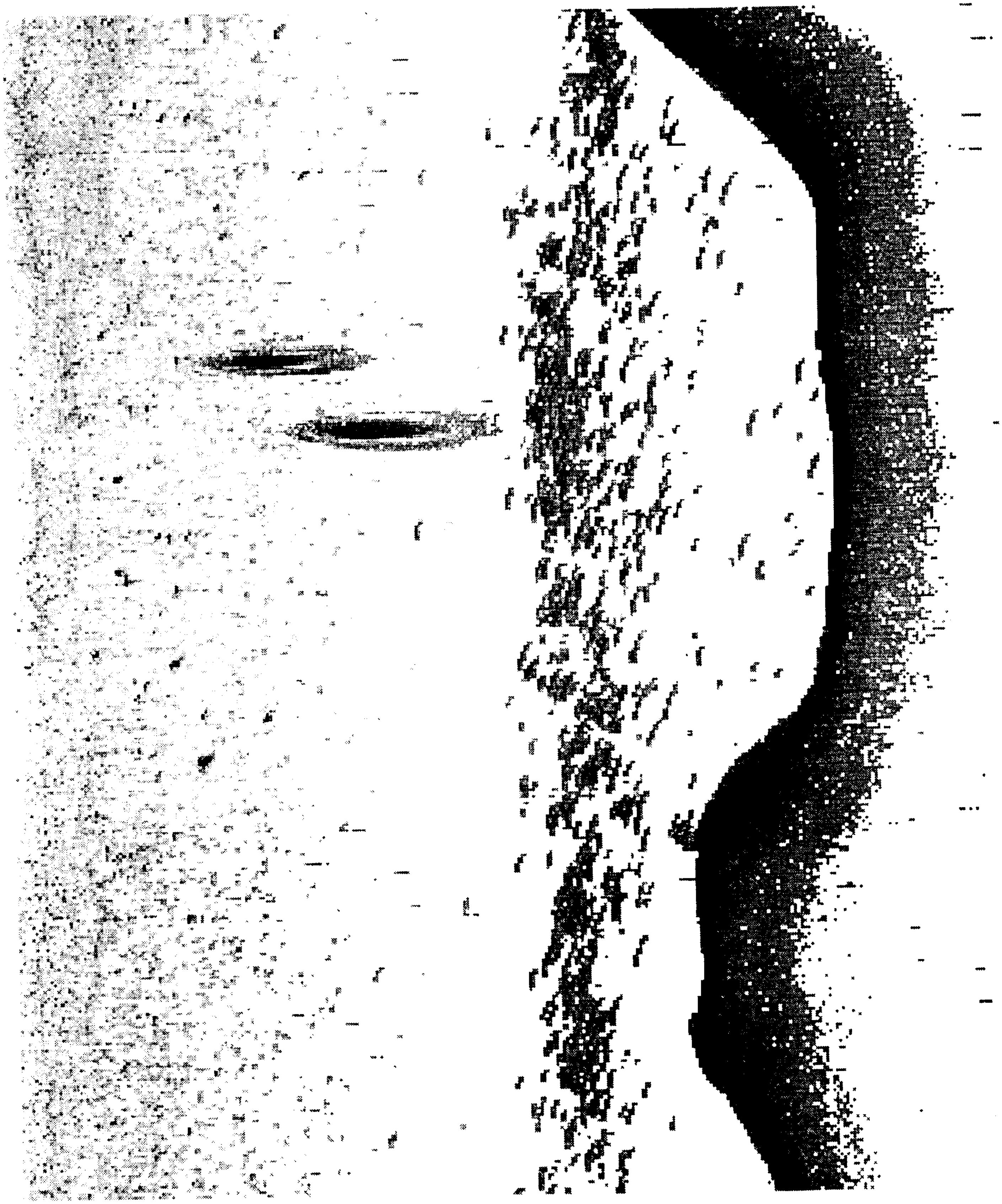
Fig 3. Species composition by count and by acoustic backscatter, all surveys.

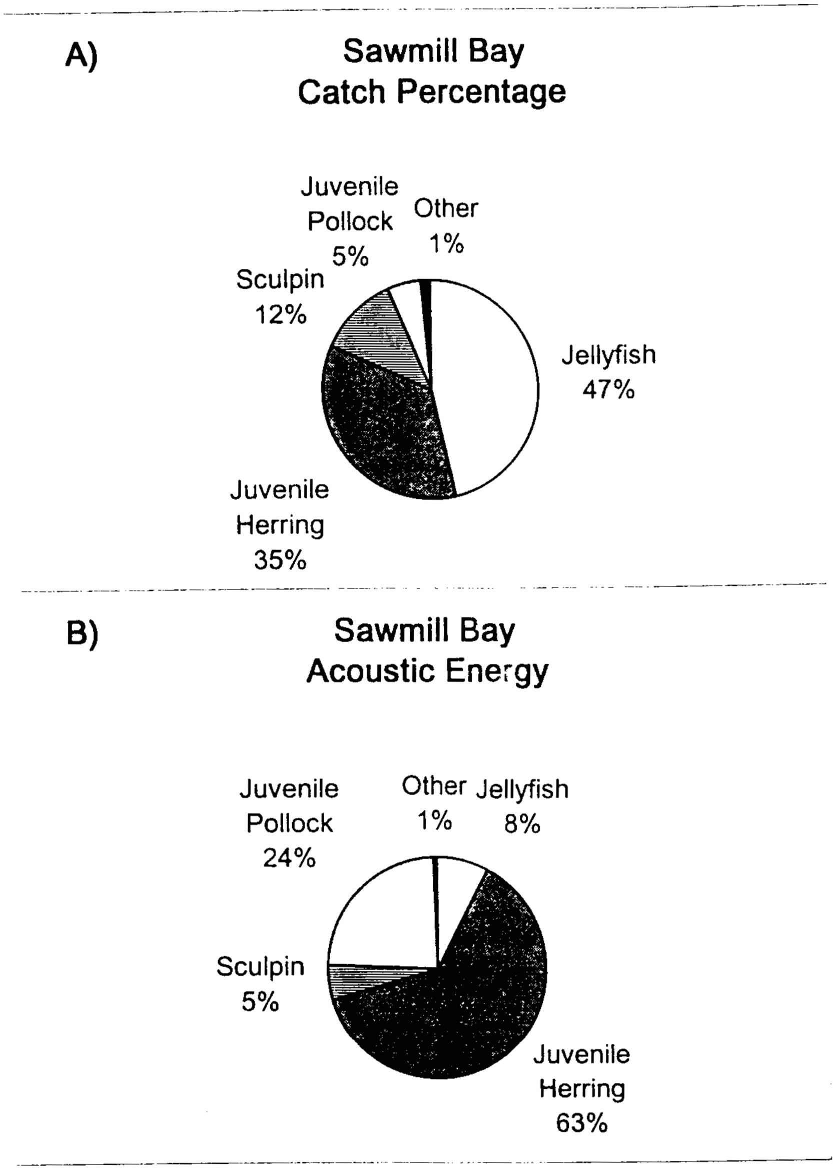
Fig 4. Area covered by broadscale (reconnaissance) survey.

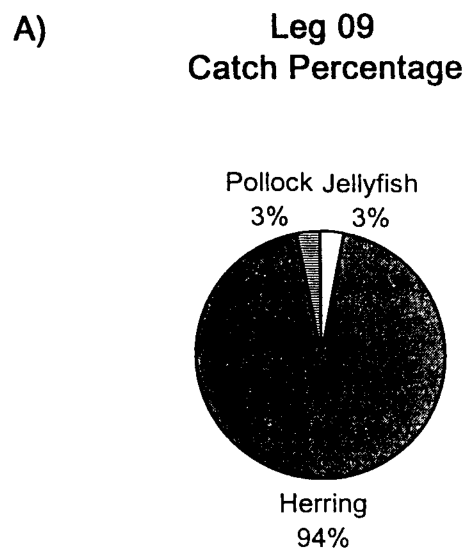
Fig 5. Areas covered by the intensive acoustic survey.

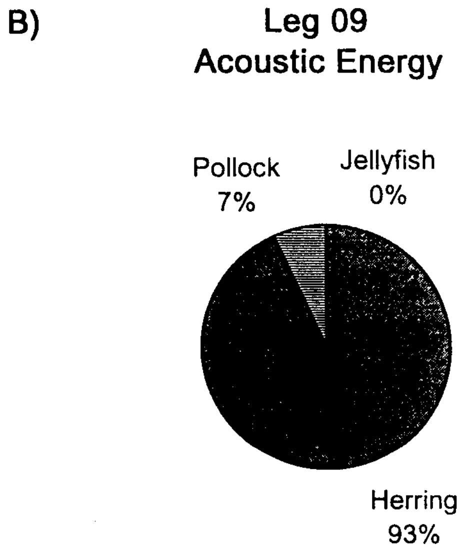
Fig 6. Densities for the top 50m for areas in the broad scale survey.

Fig 7. Biomass for the top 50m for areas in the broad scale survey.

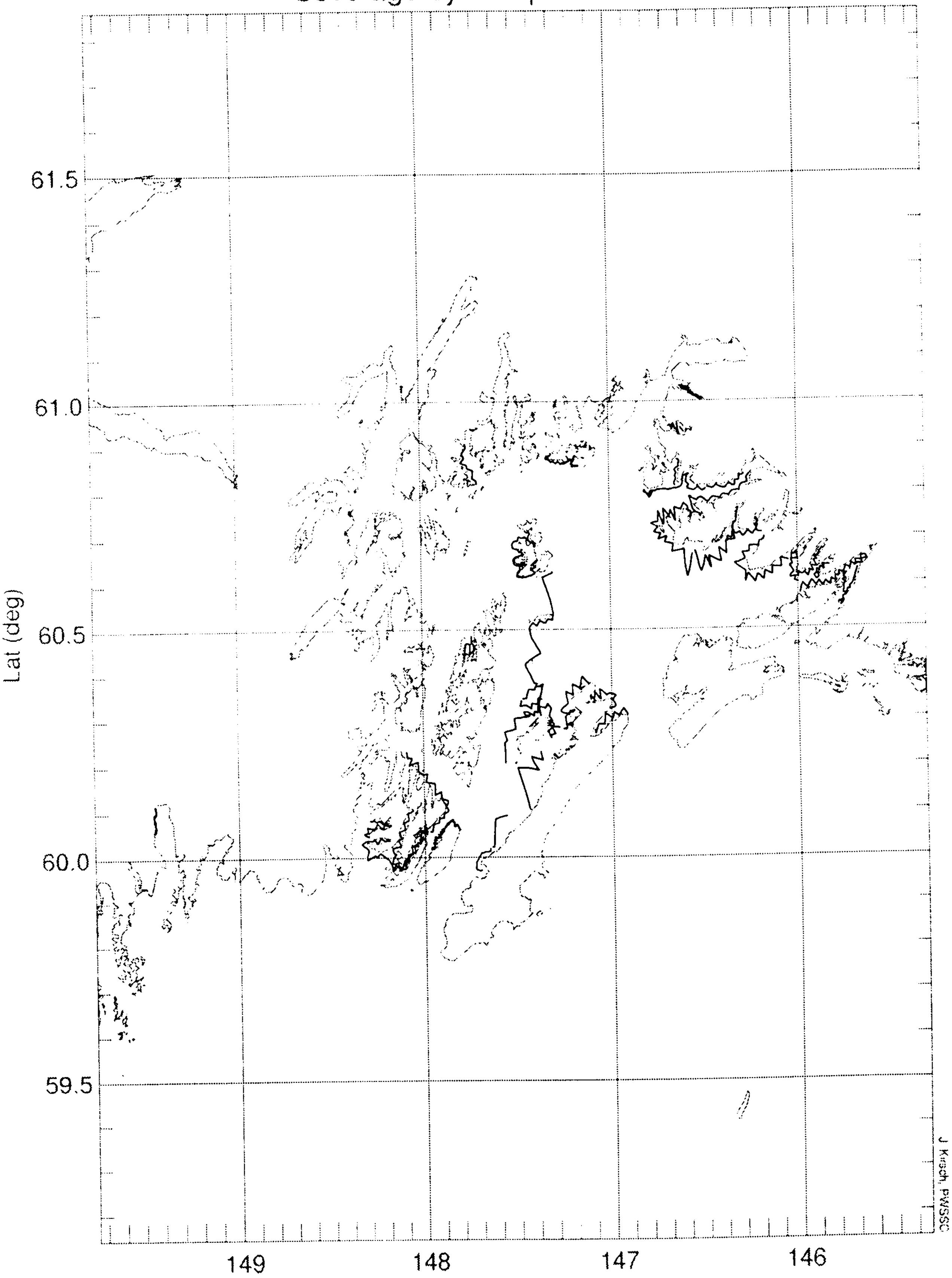


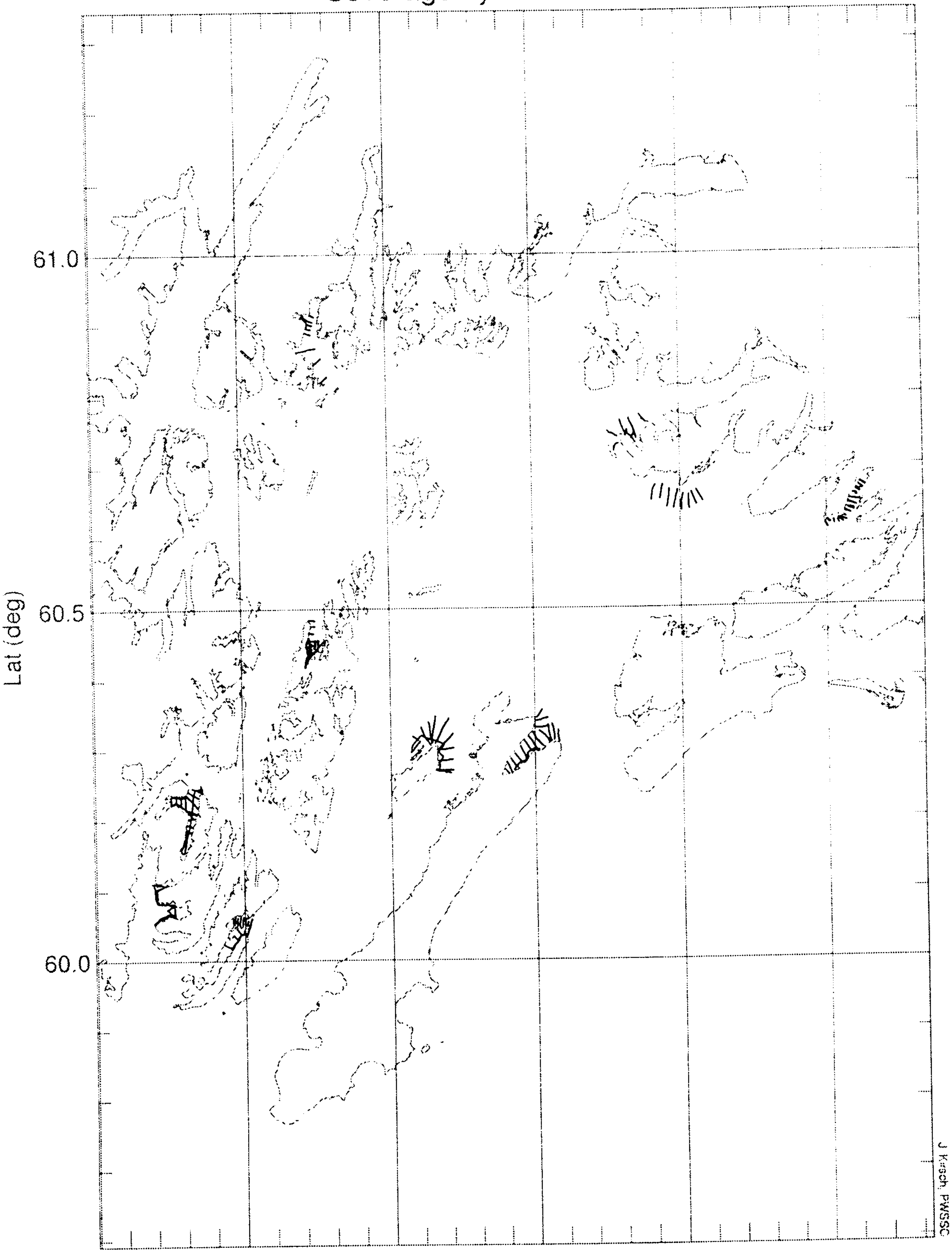

A)
Sawmill Bay
Catch Percentage
Juvenile Pollock 5%
Other 1%
Sculpin 12%
Jellyfish 47%
Juvenile Herring 35%
B)
Sawmill Bay
Acoustic Energy
Juvenile Pollock 24%
Other 1%
Jellyfish 8%
Sculpin 5%
Juvenile Herring 63%


A)
Leg 09
Catch Percentage
Pollock
3%
Jellyfish
3%
Herring
94%

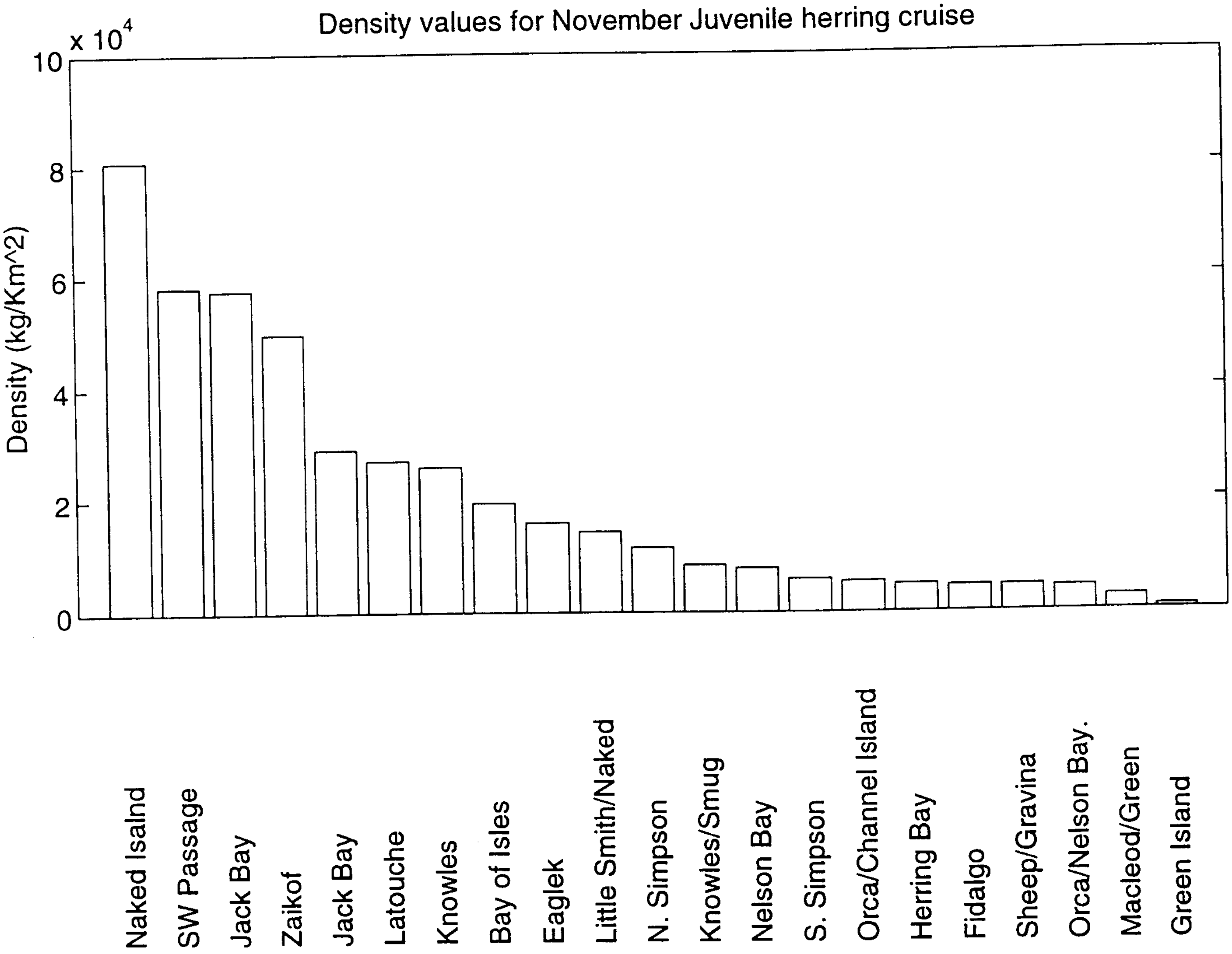

B)
Leg 09
Acoustic Energy
Pollock
7%
Jellyfish
0%
Herring
93%

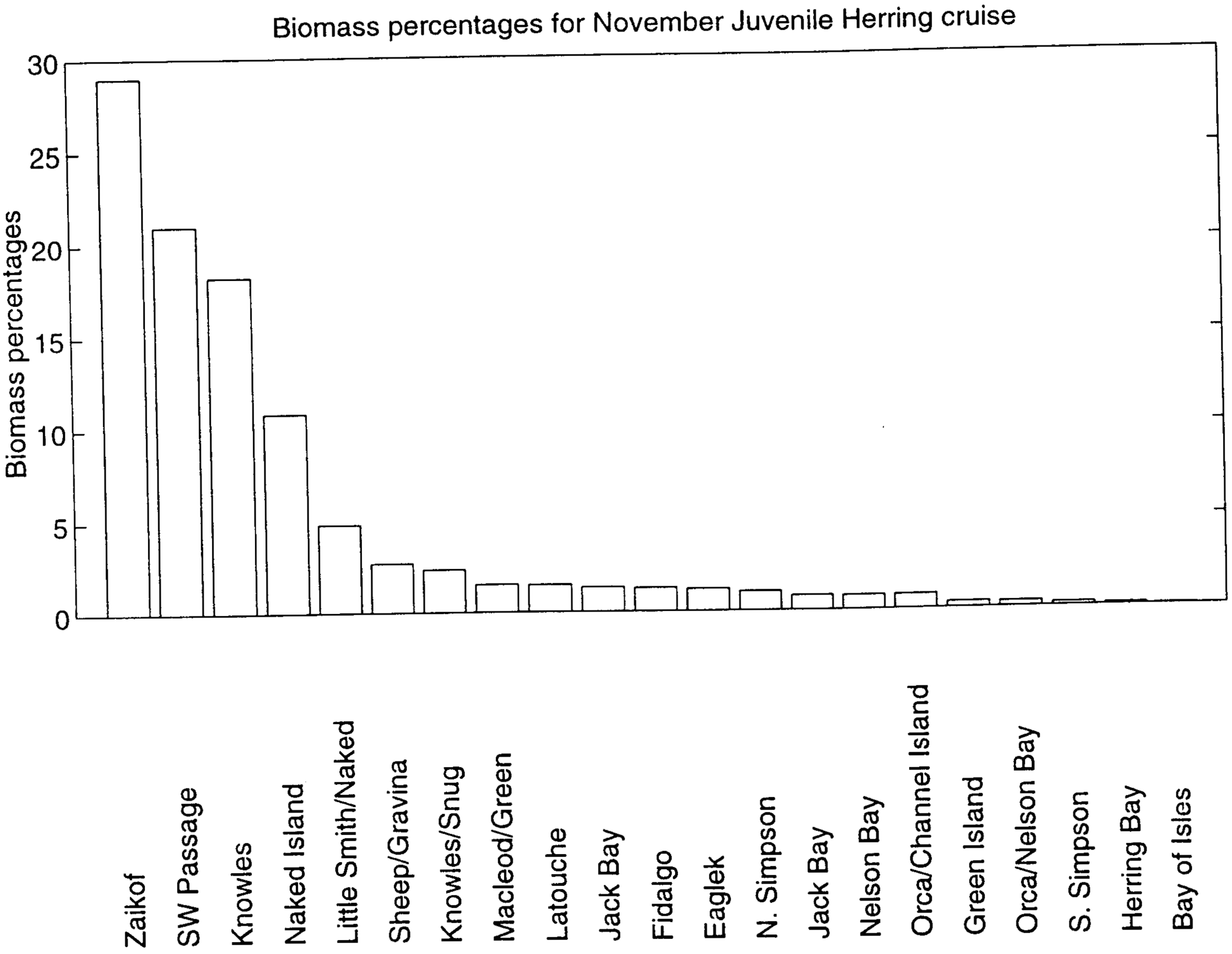
Coverage by Temptation fall 95





Coverage by Auklet fall 95

Density values for November Juvenile herring cruise
x 10^4
10
8
6
4
2
0
Density (kg/Km^2)
Naked Isalnd
SW Passage
Jack Bay
Zaikof
Jack Bay
Latouche
Knowles
Bay of Isles
Eaglek
Little Smith/Naked
N. Simpson
Knowles/Smug
Nelson Bay
S. Simpson
Orca/Channel Island
Herring Bay
Fidalgo
Sheep/Gravina
Orca/Nelson Bay.
Macleod/Green
Green Island


Biomass percentages for November Juvenile Herring cruise
Biomass percentages
0
5
10
15
20
25
30
Zaikof
SW Passage
Knowles
Naked Island
Little Smith/Naked
Sheep/Gravina
Knowles/Snug
Macleod/Green
Latouche
Jack Bay
Fidalgo
Eaglek
N. Simpson
Jack Bay
Nelson Bay
Orca/Channel Island
Green Island
Orca/Nelson Bay
S. Simpson
Herring Bay
Bay of Isles

AVIAN PREDATION ON HERRING SPAWN
EVOS 96320-Q

FY 96 Executive Summary

Principal Investigator: Mary Anne Bishop, Ph.D.
Copper River Delta Institute
Pacific Northwest Research Station, US Forest Service

Lead agency: USDA, U.S. Forest Service, Pacific Northwest Research Station

Authors: Mary Anne Bishop, Ph.D.
Larry Byrne
S. Patrick Green
Karen Hyer

Copper River Delta Institute
U.S. Forest Service
PO Box 1460
Cordova, Alaska 99574

Date Submitted: April 1996

EXECUTIVE SUMMARY

Avian predation on herring spawn was studied at northern Montague Island during spring 1994 and 1995. Final results will be presented in a separate, final report to the *EXXON Valdez* Oil Spill Trustees Council on 30 June 1996. What follows is an executive summary on results to date.

This project was designed to provide critical information to test the Sound Ecosystem Assessment's natal hypothesis #2: that recruitment success of Pacific herring (*Clupea pallasi*) populations in Prince William Sound is related to physical processes and predation during early life stages. Results from this study will be incorporated into a sound-wide embryo survival model being developed by scientists at University of Alaska-Juneau. Our estimates of avian consumption of herring spawn will also provide a management tool for Alaska Department of Fish and Game (ADF&G) whereby they can readjust their adult herring spawner biomass estimates.

The objectives of this study are to:

1) Determine the species composition, timing, and distribution of birds foraging in herring spawn areas in the rocky intertidal and subtidal habitats.
2) Estimate the amount of herring spawn consumed by avian predators.

Herring spawn deposition occurred from 18-25 April 1994 and from 27 April-2 May 1995 with hatch beginning approximately 23 days after initial deposition. Prior to spawn initiation, 1994 aerial surveys (n=3) recorded gull numbers ranging between 15,600-25,700, and 1995 boat surveys (n=2) recorded 9,350-10,100 gulls in the vicinity of the herring schools. Of the gulls, approximately 90% were glaucous-winged gulls (*Larus glaucescens*) and 10% mew gulls (*Larus canus*).

We documented avian abundance and distribution for all species by both date and location in relation to herring spawn. In 1994, three species accounted for >90% of all boat observations in spawn areas (n=178,581 birds, 12 surveys): glaucous-winged gulls (57.7%), mew gulls (14.2%), and surfbirds (*Aphriza virgata*) (18.6%). Both years, surfbirds, offshore diving ducks, harlequin ducks (*Histrionicus histrionicus*), and black turnstones (*Arenaria melanocephala*) comprised >93% of all non-gull species in spawn areas. Offshore diving ducks were principally surf scoters (*Melanitta perspicillata*) but also included oldsquaws (*Clangula hyemalis*), white-winged scoters (*Melanitta fusca*), and greater scaup (*Aythya marila*).

Populations of mew gulls and glaucous-winged gulls in Prince William Sound (PWS) consist of year-round PWS residents and spring-summer resident birds. Surf scoters winter in small numbers in PWS including at Montague Island, however, the largest numbers are observed in migrant flocks in spring. Surfbirds and black turnstones are transient spring migrants occurring in large numbers almost exclusively at Montague Island in April and May. Between 20-25 April both years, migrant flocks of surf scoters, surfbirds, and black turnstones appeared at

Montague Island. While in 1994 their arrival coincided shortly after spawn deposition, in 1995 their arrival occurred just prior to the 27 April spawn initiation. At the same time, despite a nine day difference between years in spawn hatch date, in both years surfbirds and black turnstones numbers decreased to negligible numbers after 12 May as they moved on to their more northerly breeding areas.

We tested the hypothesis that birds were attracted to areas of spawn. We calculated the likelihood that a species would occur in a spawn area as opposed to a non-spawn area for an 18km stretch of shoreline that included approximately even amounts of spawn and no spawn. We found that the birds more likely to occur in spawn areas were generally the most numerous: shorebirds, gulls, dabbling and offshore diving ducks as well as bald eagles. Except for the bald eagle, all of these birds are either known or suspected herring spawn consumers. Piscivorous birds (cormorants, mergansers, murrelets, grebes) along with inshore diving ducks and corvids (both omnivorous) and canada geese (herbivorous) were equally likely to occur in a spawn area as a non-spawn area.

We used generalized linear models to test the hypothesis that the distribution, timing and abundance of gulls, offshore diving ducks and shorebirds is positively correlated with the dispersion, timing, and abundance of herring spawn. We ran stepwise glm models to determine the relationship of total birds and total glaucous-winged gulls (dependent variables) and biomass variables at ADF&G spawn deposition transects. We included an additional suite of independent variables. For both models, the same two variables were significant: total eggs ($P<0.001$) and the number of days spawn was laid ($P<0.02$ for glaucous-winged gulls, and $P<0.01$ for all birds). The models were both significant and explained 84.7% and 82.7% of the variation in total numbers of glaucous-winged gulls and all birds, respectively.

We tested the hypothesis that herring spawn is a major component in the diet of birds species foraging in herring spawn areas. In spring 1995 we collected and analyzed stomach contents of the most abundant avian species foraging in spawn areas in northern Montague Island. Herring spawn occurred in 100% of the glaucous-winged gulls, mew gulls, and surf scoters stomachs and in 75% and 69% of the surfbirds and black turnstones, respectively. Based on the stomach contents, we estimated that glaucous-winged gulls, mew gulls, surf scoters, and black turnstones obtained between 99-100% of their total daily energy from spawn.

We applied a bioenergetics model to estimate the daily herring spawn consumption for each of these five species. Our model is based on field metabolic rates (kJ/day), energy content of spawn (kJ/g), assimilation efficiency of spawn, and the proportion of daily energy acquired from herring spawn. Glaucous-winged gulls, the most numerous and the largest predator, had the highest daily consumption rate at 1.27 kg/day per individual. For the other four species, rate of herring spawn consumption was calculated at 1.15 kg/day per surf scoter, 0.58 kg/day per mew gull, 0.19 kg/day per surfbird and 0.16 kg/day per black turnstone. These estimates are probably low due to the seasonal energetic demands of migration and breeding for all five species.

We performed a sensitivity analyses for each of the five major predator's models to examine the implications of parameter uncertainty on their predicted herring spawn consumption. Four parameters (body mass, assimilation efficiency, proportion of energy acquired from herring spawn, and field metabolic rate) were evaluated for their effect on total herring spawn ingestion estimates. The sensitivity analyses showed that for all five species, body mass was the most important model input. An increase in a bird's body mass of +20% affected total herring spawn consumption by +30%, whereas a -20% mass decrease affected total consumption by -28%. Assimilation had the second largest effect on ingestion rate. A -20% decrease in assimilation efficiency increased total consumption by +25%. The model was least sensitive to changes in the proportion of spawn in the diet and the estimated field metabolic rate.

We applied our bioenergetics model to determine avian consumption of spawn along a 6.4km shoreline at Montague Island during 1994. Using ADF&G diver survey data, total eggs in the area were calculated at 333.5 metric tons on 5 May. We estimated that 19.24% of these eggs were removed from 5 May through 13 May 1994. Although these losses occurred relatively late in the spawn cycle (days 16-24), daily percent egg loss rate ranged from -1.6 to -4.4, with an average of -2.5% loss/day ± 0.34%. Our estimate of egg removal is probably low because some of the ADF&G spawn deposition transects incorporated into our total egg calculation were conducted between 2-4 May when relatively large numbers of glaucous-winged gulls were in the area.

In an ADF&G study on spawn loss in Prince William Sound, Biggs-Brown and Baker (1993) estimated an average daily egg loss at -3.8% per day for all water depths. Based on our preliminary analysis, we believe their egg loss estimate is low because (1) they attribute the majority of eggs lost due to wave or tidal action, and (2), average daily egg loss due to bird predation alone is probably much higher during the first ten days of spawn, when glaucous-winged gull numbers are at their peak.

We were unable to test the hypothesis that birds preferred viable to nonviable spawn such as windrow. Scan samples at 100x300m plots indicated that, except for the surf scoters, gull and shorebirds follow the tidelines and could be taking viable spawn. We rarely observed birds foraging farther than 3m from the tideline. We also visually assessed esophagus contents for viable eggs consumed. For all birds (n=23, 4 species) there was little evidence of a correlation between viable spawn in the guts and the date of collection (r=0.363, Pearson's correlation coefficient),. When we calculated the same correlation by species, we found surf scoters and glaucous-winged gulls to be correlated; however, no correlation was found between viable spawn in the guts and date of collection for mew gulls.

Table 1. Ratios, total numbers, and significance of bird species and groups observed on boat shoreline surveys in spawn and non-spawn areas. Ratios indicate the relative odds of being observed in a spawn area as opposed to a non-spawn area. Significance levels refer to results from an odds ratio test.

SPECIES	RATIO	TOTAL OBSERVED	P-VALUE
POSITIVE ASSOCIATION			
BONAPARTE'S GULLS	85.1	1,880	$P < 0.001$
OFFSHORE DIVERS	43.3	6,700	$P < 0.001$
MEW GULLS	32.1	26,211	$P < 0.001$
GLAUCOUS-WINGED GULLS	15.5	110,736	$P < 0.001$
DABBLING DUCKS	12.3	187	$P < 0.001$
HARLEQUIN DUCKS	11.9	4,698	$P < 0.001$
SURFBIRDS	5.6	40,006	$P < 0.001$
CALIDRIS SHOREBIRDS	7.7	617	$P < 0.001$
BALD EAGLES	3,7	222	$P < 0.001$
BLACK TURNSTONES	2.8	3,331	$P < 0.001$
BLACK OYSTERCATCHERS	1.4	73	$P < 0.025$
NEUTRAL			
CORVIDS	1.1	401	$0.1 < P < 0.25$
CORMORANTS	1.0	648	$0.1 < P < 0.25$
CANADA GEESE	0.9	354	$0.1 < P < 0.25$
MERGANSERS	0.6	480	$0.1 < P < 0.25$
MURRELETS	0.4	234	$P > 0.25$
INSHORE DIVERS	0.3	234	$P > 0.25$
GREBES	0.1	30	$P > 0.25$
NEGATIVE ASSOCIATION			
PIGEON GUILLEMOTS	0.0	15	$P > 0.5$

Table 2. Aggregate weight (%) of prey items in the esophagus and proventriculus of Glaucous-winged Gulls, Mew Gulls, and Surf Scoters. Surfbird and Black Turnstone data include gizzard contents. All birds collected from herring spawn areas on northern Montague Island, Spring 1994-1995.

	Gulls			Shorebirds	
Prey Items	**Glaucous-winged** 1995, n = 12	**Mew** 1995, n = 8	**Surf Scoter** 1995, n = 7	**Surfbird** 1994-95, n = 20	**Black Turnstone** 1994-95, n = 16
Herring eggs	**98.6**	**88.9**	**99.4**	**69.0**	**70.4**
Mytilus edulis	**0**	**0**	**0**	**27.2**	**1.5**
Balanus sp.	**0**	**0**	**0**	**0.2**	**22.4**
Gastropod sp.	**0**	**0**	**0**	**1.3**	**0**
Other	**0.1**	**3.9**	**0**	**0.4**	**0.9**
Vegetation	**1.3**	**7.2**	**0.6**	**2.1**	**4.9**

Table 3. Estimated herring spawn consumption per individual by species based on a model incorporating body mass of bird, estimated field metabolic rate, proportion of energy derived from spawn, and assimilation efficiency of spawn.

Species	Mean Mass (kg)	Agg. Energy of Herring Eggs in Diet	Herring Eggs Ingested per Bird	
			Eggs / Day	Kg / Day
Glaucous-wgd. Gull	1.33	100	558,700	1.27
Mew Gull	0.45	100	255,900	0.58
Surf Scoter	1.16	100	507,000	1.15
Surfbird	0.20	92	83,900	0.19
Black Turnstone	0.14	99	69,149	0.16

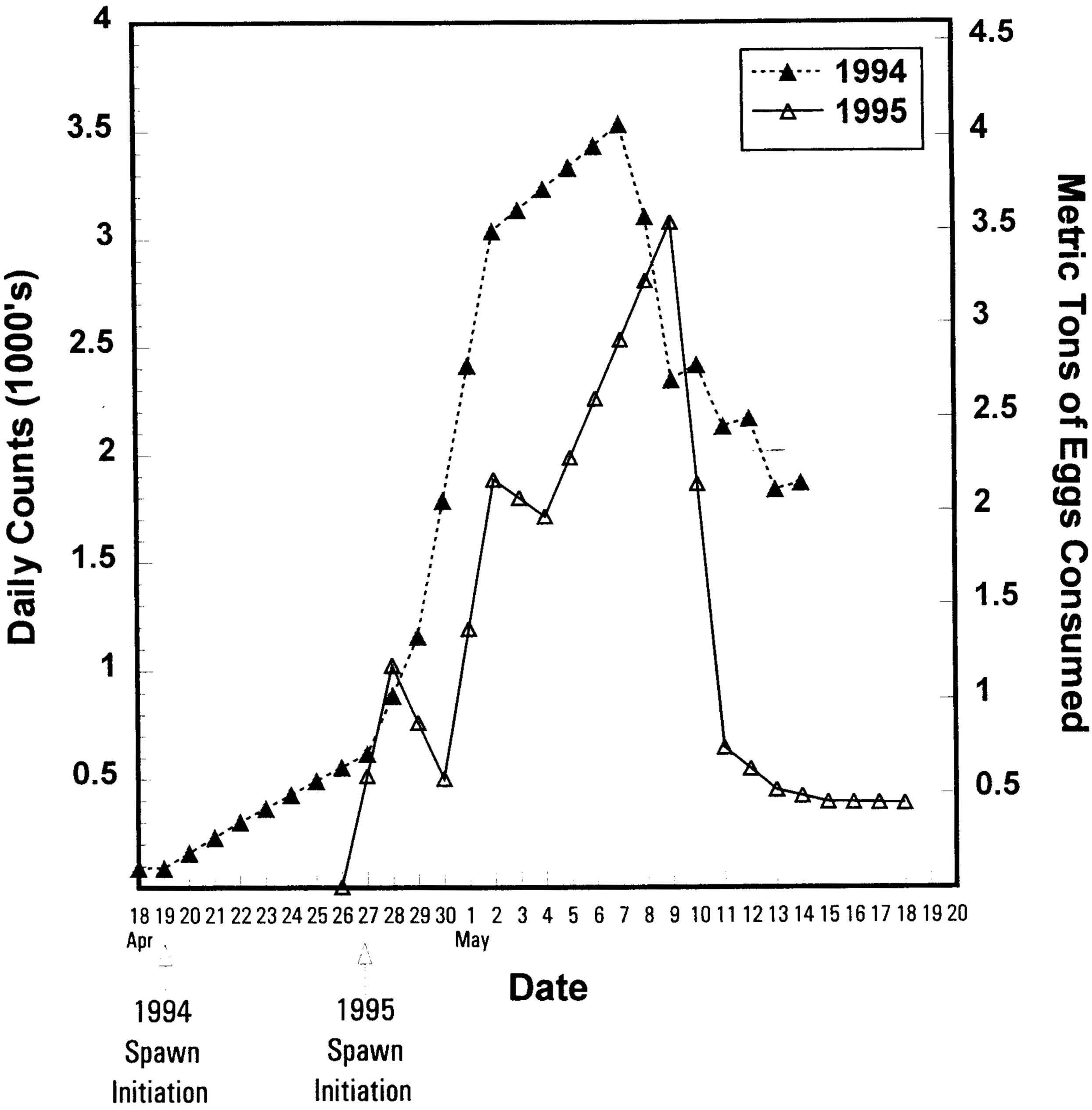


Figure 1. Surf Scoter abundance and herring spawn consumption at northern Montague Island, April-May 1994-95. Numbers determined from aerial surveys (1994) and boat surveys (1995). Grand totals: 1994 = 71.2 metric tons. 1995 = 31.7 metric tons.

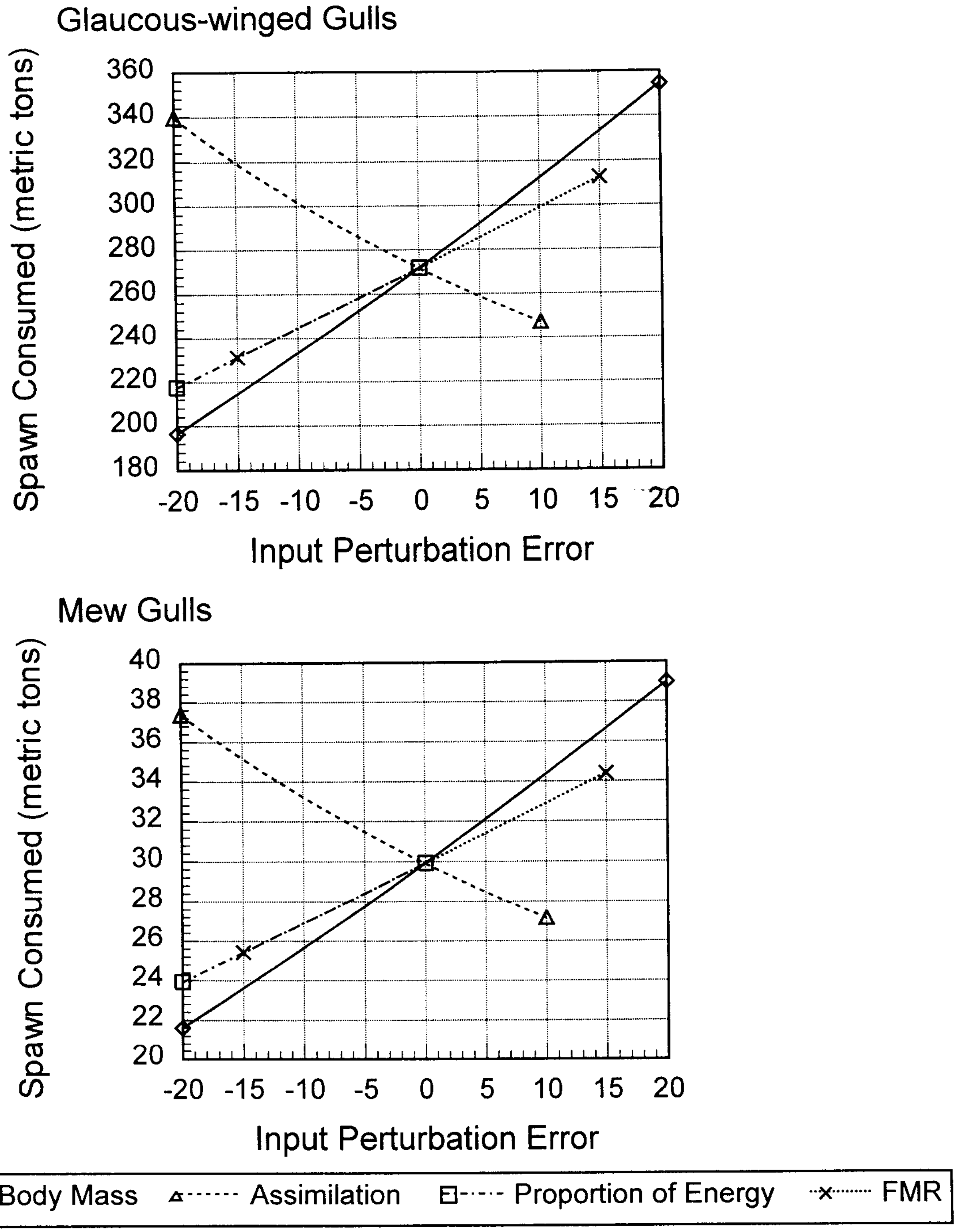


Figure 2. Sensitivity analyses estimate of spawn consumption model. Spawn consumed plotted as a function of possible errors (in %) in estimates of body mass, assimilation efficiency, proportion of energy derived from spawn, and field metabolic rate.

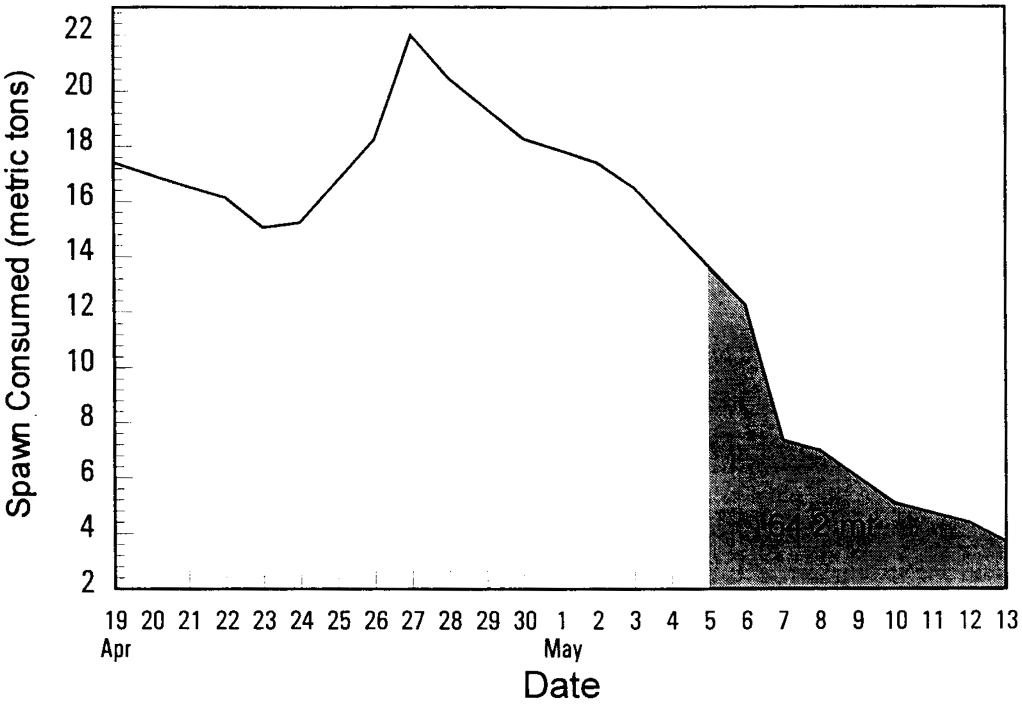


Figure 3. Total spawn consumption by glaucous-winged gulls, mew gulls, surfbirds, black turnstones, and surf scoter for a 6.4-km shoreline with spawn, Graveyard Point, Montague Island, Spring 1994. Area under curve after 5 May = 64.2 metric tons or 19.24% of an estimated 333.5 metric tons of eggs available on 5 May.

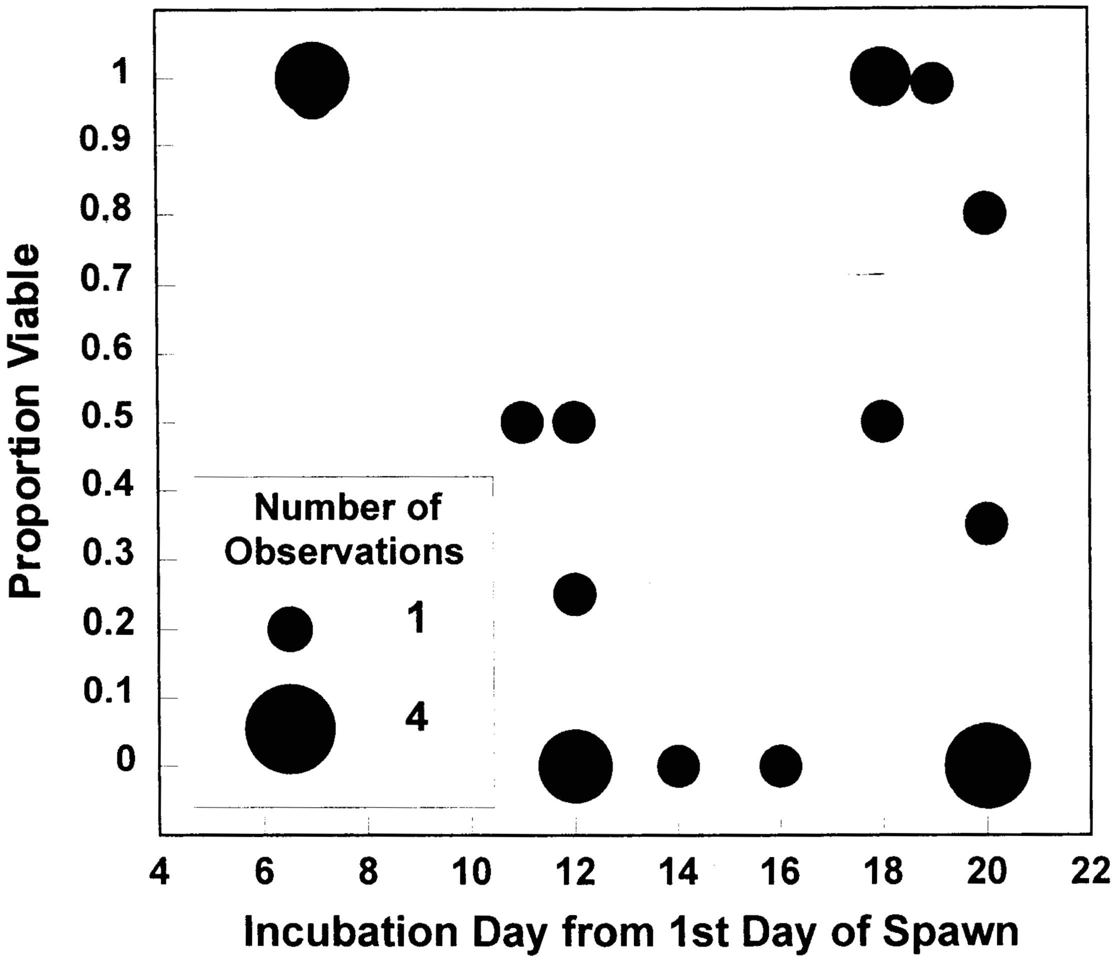


Figure 4. Proportion of viable spawn found in avian esophagi collected on northern Montague Island, Spring 1995. Species collected include glaucous-winged gulls (n = 7), mew gulls (n = 8), surf scoters (n = 6), and black turnstones (n = 2).

Chapter 10.

Biophysical Modeling and Remote Sensing (96320R)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Biophysical Modeling and Validation Through Remote Sensing

Restoration Project 96320-R
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

David L. Eslinger

University of Alaska Fairbanks
Institute of Marine Science
Fairbanks, Alaska 99775

April 1996

Biophysical Modeling and Validation Through Remote Sensing

Restoration Project 96320-R
Annual Report

Study History: This project is the result of an internal reorganization within the Sound Ecosystem Assessment (SEA) program.. Some of the work performed under SEA core projects 95320-G and 95320-J in FY-94 and FY-95 is to be done under this project in FY-96 and beyond. We are continuing the trophodynamic modeling of phytoplankton and zooplankton begun in FY-95 and adding modeling of ichthyoplankton, herring larvae in particular. We are evaluating and verifying the model against field data collected using a variety of remote sensing and *in situ* sampling platforms.

Abstract: Coupled physical and biological modeling of phytoplankton and zooplankton dynamics in Prince William Sound and the Gulf of Alaska have shown there to be two general scenarios of springtime dynamics. Warm, quiescent springs lead to brief intense phytoplankton blooms, whereas, colder, stormy springs lead to longer phytoplankton blooms. These two types of phytoplankton blooms produce substantially different zooplankton blooms. The brief intense blooms occur too quickly for much biomass to be transferred into the upper trophic levels. Therefore, the following zooplankton bloom is substantially lower. In contrast, the longer duration phytoplankton blooms allow time for the zooplankton to "catch up" and produce high zooplankton concentrations. In FY-96, we completed and validated a one-dimensional model that accurately simulated these dynamics. This model is being expanded into the full three-dimensional domain during FY-97 and FY-98.

Key Words: biophysical modeling, biological oceanography, physical oceanography, phytoplankton, Prince William Sound, spring bloom, zooplankton

Citation: Eslinger, David L, Biophysical Modeling and Validation Through Remote Sensing, *Exxon Valdez* Oil Spill Annual Report (Restoration Project 96320-R), Alaska Department of fish and Game, Anchorage, Alaska.

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Executive Summary:

Numerical modeling of phytoplankton and zooplankton, in combination with field data collected as part of 320-G and 320-H, shows that phytoplankton and zooplankton populations in Prince William Sound and the northern Gulf of Alaska are determined by the winds and air temperatures which occur over a relatively short, critical time period in early spring. Although this critical time period may be as short as two weeks, the meteorological conditions occurring during that time will play a dominant role in the dynamics of the phytoplankton and zooplankton populations for the rest of the summer. Changes in the amount of convective mixing, caused by cold air, and of wind mixing, caused by high winds, during the early part of the phytoplankton bloom change the timing and duration of the bloom, the total primary production occurring during the bloom, and the partitioning of that primary production between the upper water column food chain, and the benthic food chain.

The spring phytoplankton bloom occurs when mixing of the surface waters stops and there is sufficient light for phytoplankton growth to occur. In Prince William Sound and the Gulf of Alaska, this typically occurs in sometime in April. Blooms can be roughly categorized into two types, brief, intense blooms and longer, less intense blooms. The weather conditions during the initial part of the bloom determine what type of phytoplankton bloom will occur. If it is a relatively calm, warm spring, the water column stratifies and forms a shallow surface mixed layer. Phytoplankton and nutrients within this mixed layer are isolated from those deeper in the water column. With abundant light in the surface layer, phytoplankton quickly reproduce and build up their standing stocks to fairly high levels. As a consequence of this growth, nutrients are soon depleted and phytoplankton sink out of the surface layer. Because zooplankton reproduce at much slower rates than phytoplankton, the zooplankton populations cannot consume much of the phytoplankton production. The non-grazed phytoplankton slowly sinks out of the surface layer to deeper waters where it may be consumed by deeper pelagic organisms, or by the benthic fauna. Therefore, a relatively warm, quiescent spring produces a relatively short phytoplankton bloom, with high phytoplankton biomass, however, much of the phytoplankton biomass does not get passed on to the zooplankton populations. Zooplankton biomass therefore remains at fairly low levels for the rest of the summer.

In contrast to this, a cooler, stormier spring leads to higher zooplankton biomass. Although the cold stormy weather may delay the stratification of the water column somewhat, the major effect observed in field data and model simulations is due to the progression of the phytoplankton bloom, not the time at which it began. Storms typically pass through the PWS area at a frequency of about once a week during late winter. If they continue on into early spring, they become important to the biological dynamics. In a cold stormy spring, stratification typically occurs between storms, and when it does occur, the surface mixed layer may be somewhat deeper than in warm calm springs. The phytoplankton bloom begins in this surface layer, but is interrupted by a cold windy storm. This deepens the mixed layer, which reduces phytoplankton concentrations and increases nutrient concentrations. The bloom then takes off again. Subsequent storms may repeat the process, but at some point the stabilization of the upper water column, which has been increasing due to surface heating, becomes too strong and the seasonal mixed layer stabilizes. The phytoplankton bloom continues in this layer until nutrients are depleted. The net result of this type of spring weather is a deeper mixed layer, which took longer to become established. As a consequence of this, the phytoplankton bloom occurs over a longer period of time, and more nitrate is available for new primary production. In addition, the mixing of the surface layer has lengthened the total phytoplankton bloom period. During this longer period of high phytoplankton biomass, zooplankton increase in numbers and biomass and are thereby able to consume a higher proportion of the net production. Therefore, there is a transfer of more of the phytoplankton new production into the zooplankton population and zooplankton numbers and biomass remain high for the summer.

Both types of blooms have been observed in our four years of SEA field data. From the modeling work done as part of this project, we are able to determine the causes and interactions between the mixing regimes, phytoplankton, and zooplankton. This has allowed us to accurately simulate these processes. The zooplankton populations which have been modeled are of direct importance in the diet of juvenile pink salmon and larval and juvenile Pacific herring. Our understanding of the physical mechanisms that control the variable amounts of zooplankton (fish food, if you will) allows the SEA project to evaluate the effects of variability in the physical environment as it is propagated up through the phytoplankton and zooplankton, to the injured resources of Prince William Sound.

Introduction:

Pacific herring and pink salmon have been identified as non-recovering resources injured by the *Exxon Valdez* oil spill. An ecosystem approach has been recognized by the EVOS Trustee Council as being necessary to reaching an understanding of the underlying processes and variables which may be constraining recovery of these injured resources. The currently proposed work is critical to the ecosystem study being undertaken by the SEA program. The role of the physical environment in controlling phytoplankton, zooplankton, and ichthyoplankton populations, and the role of these populations in the life history of Pacific herring and pink salmon, must be understood for the intelligent, informed planning of successful restoration efforts.

This project directly addresses the SEA pink salmon and Pacific herring restoration objectives. The phytoplankton and zooplankton serve directly as food for both herring and pink salmon at various life stages. Two large calanoid copepod species, *Neocalanus cristatus* and *N. plumchrus*, in particular, are thought to be potentially important as both a dietary item and a refuge from predation for pink salmon. Larval and juvenile herring feed on different stages of calanoid copepods, which reproduce throughout the spring and summer. The reproductive effort of these copepods is dependent on the timing, magnitude, and duration of the phytoplankton primary production in the spring bloom period and throughout the summer. The interactions between the various types of phytoplankton (*e.g.*, diatoms, flagellates) and zooplankton (*e.g.*, oceanic copepods, neritic copepods) varies both between and within years. The timing of the major increase in biomass of phytoplankton or zooplankton, sometimes called the spring phytoplankton or zooplankton bloom, respectively, may be important to the first feeding and subsequent survival of the larval herring and juvenile herring and salmon, *e.g.* Cushing's match-mismatch hypothesis. This project examines these issues through the use of numerical models, remote sensing, and field observations.

Results through FY-96 indicate that physical forcing dominates the dynamics at the lower trophic levels. The physical signal propagates up through the food chain and has relevant consequences months after the physical interaction actually occurred. These effects are highly nonlinear, but can be accurately simulated using the present model.

Objectives:

The major objectives to be achieved over the life of this project as detailed in the FY-96 DPD were:

1. To construct a three-dimensional model of the physical/biological processes affecting phytoplankton, zooplankton, and ichthyoplankton dynamics in Prince William Sound.
2. To determine the relative roles of these processes in determining Pacific herring and pink salmon population levels.
3. To determine the spatial and temporal variability, both of the physical environment and of phytoplankton concentrations, using a combination of remote sensing techniques and field observations.

Additional minor objectives were:

4. To make laboratory measurements of the photosynthesis-irradiance parameters required to accurately model different phytoplankton populations.
5. To deploy and maintain an upgraded version of the CLAB buoy, which will provide high temporal resolution time series of wind velocity, air temperature, surface water temperature, and subsurface temperatures at 10 depths. This will be the primary data source for the development of the physical/biological dynamics portion of the model.

These objectives will enable us to test the following hypotheses:

1. That coupling between the physical environment and phytoplankton dynamics can be modeled reliably.
2. That phytoplankton dynamics drive zooplankton dynamics in a predictable manner, which can also be modeled.
3. That the survival of larval herring can be estimated by a combination of modeling and field work on eggs and 0-class juveniles.
4. That interactions between the physical environment, the zooplankton field, and juvenile pink salmon populations can be predicted using a coupled biological/physical 3-D model.
5. That the spatial variability of the SST and chlorophyll concentrations in Prince William Sound, observed in satellite remote sensing images, can be simulated by a 3-D model of physical and biological dynamics.

Methods:

We are using a combination of coupled biological and physical models and satellite remote sensing data sets to achieve the above objectives. We are continuing the development of a coupled biological-physical model of lower trophic level, i.e. phytoplankton and zooplankton, dynamics for the near-surface layers of Prince William Sound (PWS). We are expanding the one-dimensional, depth-time model developed in FY-95 to include herring larvae. The 1-D model will describes the biological and vertical processes that occur through time at a single location. The biological processes contained in the 1-D model are being integrated into a larger three-dimensional model with appropriate vertical resolution. This 3-D model will use the vector fields produced by the circulation model being constructed by V. Patrick and C. Mooers as part of 320-J. A detailed description of the methodology used in the one-dimensional bio-physical model is given in the Methods section of Appendix A.

Our remote sensing work entails reception and processing of National Oceanic and Atmospheric Administration (NOAA) Nimbus series satellite data in Fairbanks, AK. Data from the Nimbus Advanced Very High Resolution Radiometer (AVHRR) sensors are processed to produce sea surface temperature (SST) images of both the northern Gulf of Alaska (Figure 1) and a more detailed image of Prince William Sound (Figure 2). These images are archived and made available to the SEA project for comparison with model and field data. An additional type of satellite data should soon be available from the Japanese Ocean Color and Temperature Sensor (OCTS) which is being flown aboard the Japanese Advanced Earth Observation Satellite (ADEOS). D. Eslinger is and ADEOS/OCTS investigator and is pursuing the necessary international agreements to get access to the OCTS data and processing software. In addition, the SeaWiFS satellite is scheduled for launch in mid-1997. Within about 3 months after launch, we should have access to that data stream as well.

Results:

Detailed results from the one-dimensional modeling work are given in the Results section of Appendix A. Briefly, the 1-D model accurately simulates the timing and magnitude of the phytoplankton and zooplankton blooms in 3 out of the four years for which we have field data (Figures 3 and 4). The consistent differences in the timing which are observed in the 1994 simulation highlight the need for a spatial component in this model. The expansion of the 1-D model into 3-D space is the major goal of our FY-97 effort presently underway.

We have been processing and archiving AVHRR SST since 1994, and presently have an archive of over 17,000 SST images available to the SEA project. These images are stored on 8 mm tape, CD-ROM, and hard disk. In early FY-97, we delivered a subset of these images to the Prince William Sound Science Center (PWSSC) in CD-ROM format, for use by the PWSSC SEA investigators.

The measurable tasks which we proposed to perform in FY-96 and which were accomplished are listed below.

- Model phytoplankton and zooplankton using 1995 field data. Begin herring model literature search.
- Recover CLAB buoy deployed under 95320-G.
- Deploy CLAB buoy for 1996 field season.
- Begin herring model.
- Collect, process, and analyze AVHRR images for 1996 field season.
- Complete FY-96 field collection efforts.
- 1-D phytoplankton, zooplankton model complete.
- Complete analysis of AVHRR data from 1994-mid 1996.
- Annual report on FY-96 work.

The following tasks were not completed in FY-96. The reasons are given below.

- Collect remote-sensing reflectance as part of cruises. Incomplete: no funding available for the bio-optical instrumentation.
- Begin to collect, process and analyze ocean color from SeaWiFS and/or OCTS. Incomplete: satellites not launched during field season. SeaWiFS still not launched.
- Initial herring model complete. Incomplete: Although we have a preliminary ichthyoplankton model working, it is not complete. This was a typographical error. A meaningful model can not be constructed in the six months of time as stated. The correct time for the completion of the initial ichthyoplankton/larval herring model is September of FY-97.

Discussion:

A full discussion of the model results is presented in Appendix A.

Conclusions:

The coupled bio-physical model being developed as part of this project is able to simulate the phytoplankton and zooplankton dynamics in the upper waters of Prince William Sound. In most years, this model requires measurements of only air temperatures and winds to accurately model the timing and magnitude of the phytoplankton and zooplankton blooms. The year in which the model is significantly less accurate highlights the need for the continued work on developing the fully three-dimensional biological-physical model. The development of this model will enable us to simulate concentrations of zooplankton, the primary food source for pink salmon fry and larval and juvenile Pacific herring, based on relatively easily measured meteorological variables.

Appendix A

DRAFT

Modeling Phytoplankton and Zooplankton Variability in Prince William Sound, Alaska

David L. Eslinger and R. Ted Cooney
Institute of Marine Science
University of Alaska Fairbanks

Introduction

Prince William Sound is a deep, sub-arctic, semi-enclosed water body bordering the Gulf of Alaska, Figure 1. The Prince William Sound (PWS) region is the base for a large commercial fishing fleet. Phytoplankton and zooplankton in PWS are the main food sources for early life stages of several commercially important fishes, particularly Pacific herring and pink salmon. During the spring, phytoplankton and zooplankton biomass exhibit pronounced increases, often called spring blooms, within the Sound. These blooms vary in magnitude, timing, and duration both spatially and interannually. A well established theory for variations in the timing of the phytoplankton spring bloom was put forward by Sverdrup (1953), in which the relationship between the depth of water column mixing and the available light controlled the timing of the onset of the bloom. Eslinger and Iverson (*in press*) constructed a coupled biological-physical model for the spring phytoplankton bloom in the southeastern Bering Sea. That model replicated the initial spring diatom bloom over the Bering Sea shelf quite well. The accuracy of that model was due to the high vertical resolution, 2 meters, used. This high resolution enabled features such as self-shading and nutrient limitation to realistically interact with rapidly varying mixed layer depths. We have built upon the basic Eslinger and Iverson model (hereafter, the EI model) and constructed a model suitable for examining annual phytoplankton and zooplankton dynamics with a high temporal and vertical resolution.

In the following sections of this paper we will describe the physical and biological dynamics included in the model, compare model results to field data for four years and two locations, and discuss the conclusions that can be drawn from the model and field results.

Methods

Field Data

Model results were compared with field data collected as part of the Sound Ecosystem Assessment (SEA) project. Phytoplankton and zooplankton samples were collected during a series of cruises in 1994, 1995, and 1996, and daily at a field camp during 1995 and 1996. Chlorophyll concentrations were measured using standard fluorometric techniques (Strickland and Parsons, 1976) with extractions done in 90 percent acetone. Zooplankton settled volumes and biomass data were collected as part of 9x320-H. Techniques used are described in the annual report for that project. Data presented here are from tows made from depths less than 100 meters, generally 50 meters, to the surface.

Description of the Model

The coupled biophysical model used in this study is a major expansion of a spring diatom bloom model of Eslinger and Iverson (*in press*). The significant features of the EI model retained in our model are the high vertical resolution, 2 meters, and the realistic mixed-layer dynamics. We modified the EI model to apply to annual time periods by increasing the number and complexity of the chemical and biological processes included in the model. We have added ammonium and silicon dynamics; a flagellate component; three types of zooplankton: large *Neocalanus*-type copepods, smaller *Pseudocalanus*-type copepods, and euphausiids; and an unspecified carnivorous nekton component which preys upon the zooplankton. Details of the model are given below.

Physical Model and Forcing Variables:

The physical domain is the upper 100 meters of a significantly deeper water column. Therefore, there are no bottom boundary layer or tidally mixed layer effects. The physical model was a 50-layer, one-dimensional mixed-layer model based on the model of Pollard, *et al.* (1973) as modified by Thompson (1976). Meteorological forcing (due to wind mixing, solar heating, ocean-atmosphere heat fluxes) is applied at the surface and the water column mixes downward until there is a balance between the kinetic energy available for additional mixing and the potential energy cost of overcoming the existing stratification. This balance is determined by examining the Fruode number of the mixed layer. A full description of the 1-D physical model can be found in Eslinger (1990). Vertical grid resolution is 2 meters (a 50 layer model), and the time step is two hours. The model was run to examine interannual and spatial variability. When run in an interannual mode, the model was run beginning in late February or early March, depending on the availability of forcing data, and was run through approximately the middle of November for 1993, 1994, 1995, and 1996. Although the model was run for the greater part of the year, we will limit the remainder of this discussion to the spring and summer periods, when the planktonic dynamics are greatest. Meteorological forcing data were obtained from the Continuous-Linked Automated Buoy (C-LAB) moored buoy system initiated by Dr. Ted Cooney as part of the Cooperative Fisheries and Oceanographic Studies program. In 1995, buoy data were unavailable for the early portion of the year, so meteorological data from a National Weather Service (NWS) unmanned station on Middleton Island, Alaska, were used. The 1995 spatial variability analysis was performed using forcing data from two NWS stations: the Middleton Island, AK NWS station, and a NWS station located at Whittier, AK. For 1996, spatially varying winds were taken form two NOAA buoys in Prince William Sound. Locations at which all forcing data were collected are shown in Figure 1. Insolation data required by the model was calculated using the radiation model of Frouin *et al.* (1989).

Biological Dynamics:

Both diatoms and flagellates are included in the model. Maximum possible daily growth rates of both species were determined by temperature (Eppley, 1972), and were reduced by light or nutrient limitation. Nitrate, ammonium, and silicon are considered as potentially biologically limiting nutrients, and nutrient uptake rate is assumed to follow a Michaelis-Menten relationship (Dugdale, 1967). Ammonium inhibition of nitrate uptake is included (Wroblewski, 1977). Both phytoplankton species compete for the nitrogen nutrients; silicon is utilized only by the diatoms. Photosynthesis is calculated as a function of light intensity, with potential photoinhibition (Platt *et al.,* 1980). Maximum growth rate for each species was calculated by multiplying the temperature dependent growth rate by a non-dimensional value that was the minimum of the relative amount of limitation by nutrients or light. At very low nutrient concentrations, the uptake rate for the phytoplankton species with the slowest uptake rate was calculated based on the amount of nutrient available after uptake by the phytoplankton species with the fastest uptake rate.

Copepods dominate the spring and early summer zooplankton biomass in Prince William Sound and euphausiids are a significant fraction of the remaining biomass. The copepods can generally be broken down into two types. There is a group of larger species composed of *Neocalanus flemingeri, N. plumchrus, N. cristatus, Calanus marshallae, Eucalanus bungii,* and *Metridia ochotensis.* We will hereafter refer to these as the neocalanus-type copepods, or as just neocalanus. In contrast, there is a group of generally smaller species composed primarily of *Pseudocalanus spp., Acartia spp., Oithona spp.,* and *Metridia spp.* aside from *M. ochotensis.* We will hereafter refer to these as the pseudocalanus-type copepods, or as just pseudocalanus. These two groups make up approximately 90% of the springtime zooplankton biomass. In addition to size, these two types of calanoid copepods have dramatically different reproductive strategies. The neocalanus-type copepods undergo a dramatic ontogenetic migration, descending in late summer as stage copepidite V (hereafter, CV's) to a depth of 200-400 meters, where they overwinter. The following spring they mature, reproduce and die. Their eggs hatch at depth and the nauplii begin to ascend towards the surface, which they reach at about the time they mature to the CI stage. This is generally prior to the spring phytoplankton bloom. They feed and grow in the surface waters for approximately 65-75 days, after which they begin to descend again, as CV's (Fulton, 1973). In contrast, the pseudocalanus-type copepods spend the majority of their life cycle in the upper water column, and overwinter as adult, fertilized females. These females must feed on the spring phytoplankton bloom to begin reproducing, and can reproduce up to 10 times at approximately 5 day intervals (Corkett and McLaren, 1978). The life history descriptions given are representative and are a simplification for the purposes of creating this model. Several species of euphausiids occur in Prince William Sound. The most abundant genera are *Euphausia* and *Thysanoessa*. Euphausiid life history was also simplified in the model. Total euphausiid biomass was modeled and reproduction was included in the increases in population biomass.

Three types of zooplankton are included in the model: neocalanus-, and pseudocalanus-type copepods, and euphausiids. In the model, Neocalanus arrive in the surface (enter the model domain), as three groups of CI's, spaced over a 30 day time period, with the middle group containing one-half of the total biomass the other two groups containing one-quarter total biomass each. Both pseudocalanus and euphausiids were present in the model at the start of the run. Life history dynamics of both populations were simplified in the model by simulating total biomass for each population, with no attempt made at keeping track of life stages. This simplification introduced some errors, *e.g.*, individual weight-specific parameters, such as grazing rate, were constant for all life stages; and that egg biomass is included in total biomass when calculating population biomass-specific effects, *e.g.* zooplankton grazing. As will be seen, these assumptions did not prevent the model from accurately simulated the zooplankton populations. The model dynamics for all zooplankton include modified Ivlev-type grazing (Ivlev, 1945; Magley, 1990) on both diatoms and flagellates; fecal pellet production, excretion of ammonium, and natural mortality (6%/day). Actual rates of the various parameters differed between the three zooplankton types.

Results

The model results showed that small differences in the meteorological forcing over a short critical time early in the spring phytoplankton bloom could create order of magnitude variations in the standing stock of zooplankton later in the summer. These small changes had similar effects when they occurred at a single location due to interannual variation in meteorological conditions, and when they occurred at different locations in the same year due to fairly small horizontal gradients in meteorological conditions.

Interannual Variability

The model was run for 1993, 1994, 1995, and 1996. The simulations began with identical initial temperature and nutrient fields and initial concentrations of phytoplankton and zooplankton. The only differences were in the meteorological forcing data sets. Figure 2 shows winds speeds, air temperatures and simulated chlorophyll concentrations for the four years. In all years, the model phytoplankton blooms began during the first period of calm winds after the last cold storm event. Model chlorophyll concentrations are compared with C-LAB buoy fluorescence in Figure 3. In 1993, the model simulated the timing, magnitude, and duration of the spring phytoplankton bloom extremely well. The bloom was fairly short in duration, approximately 20 days, and maximum chlorophyll concentrations were reached approximately 5 days after the onset of the bloom (Figure 3 a). In 1994, the model bloom began approximately 10 days earlier than the bloom observed in the fluorescence data. The magnitude of the true bloom was correctly estimated in the modeled bloom, but the timing of the peak was off. In both the model results and field data, the chlorophyll initially increased rapidly in 1994, however, a number of strong cooling events occurred in the middle of the bloom and led to a more protracted phytoplankton bloom (Figures 2 b, 3 b). In the 1995 simulation, the initial chlorophyll increase began near day 90, but occurred over a much longer time than in previous years, due to periodic strong wind mixing events during the initial phase of the bloom (Figures 2 c, 3 c). In 1996, the bloom onset again was well modeled, with a very rapid small increase in chlorophyll, which decreased due to wind and convective mixing and a subsequent rapid increase to peak chlorophyll concentrations (Figure 2 d, 3 d). The model bloom was approximately ten days shorter than the bloom observed in the field.

Total modeled copepod biomass is compared with settled volumes in Figure 4. Euphausiids are not included because the field data are from the upper 20 m where there are no euphausiids. It is immediately apparent that in 1993 and 1996, zooplankton populations were much lower than in 1994 and 1995, in both the model and the field data. In addition, the model did a very good job of simulating the timing and duration of increases in the zooplankton populations. Figure 5 shows the simulated zooplankton by species. The most dramatic interannual differences occur in the pseudocalanus, which were able to fully utilize the longer phytoplankton blooms of 1994 and 1995. Maximum pseudocalanus biomass in 1994 and 1995 was about twice as high as that in 1993 and 1996. This large biomass persisted throughout the model run, with final pseudocalanus biomass 3 to 4 times higher in years with lengthy blooms than in years with very short blooms. Neocalanus and euphausiid populations also show differences, but not as large as those of the pseudocalanus. Recall that neocalanus are only within the upper water column for part of the year and begin to descend on day 135, completely leaving the upper 100 meters by approximately day 175. Therefore the biomass differences do not persist in the upper layer. Euphausiids also show persisting differences in biomass, but they are not as great as in the pseudocalanus because euphausiids are distributed throughout the water column, whereas pseudocalanus were only distributed within the upper 40 meters. This difference means that euphausiids have access to sinking phytoplankton, which provided them with additional food resources in 1993 and 1996 to which pseudocalanus did not have access. Therefore, the relative interannual differences between euphausiid biomass are not as great as for pseudocalanus.

Spatial Variability

For the analysis of spatial variability, simulations were run in 1995 using meteorological forcing data from Whittier, AK, located in northwestern Prince William Sound, and from Middleton Island, AK, located at the edge of the continental shelf, south of Prince William Sound (PWS). The Middleton Island data is assumed to be representative of the conditions over the Gulf of Alaska (GOA) shelf, which may impact the Sound. For the 1996 runs, meteorological data was available from two NOAA buoys, 46060 and 46061 located in Prince William Sound, and just outside of the Sound. See Figure 1 for locations. The model simulations presented below all began with identical initial concentrations of phytoplankton and zooplankton, temperature and nutrient fields. Figure 6 shows the wind and air temperature data sets used. Winds in the Gulf were generally slightly higher, and air temperatures slightly lower, than in the Sound. These small spatial differences produced pronounced differences in the phytoplankton and zooplankton. Figures 7 and 8 show the results of the spatial-variability model runs for phytoplankton and zooplankton respectively. Notice the dramatic differences in the phytoplankton and zooplankton populations caused by the small gradients in actual measured wind fields and air temperatures. Although field data at all locations are not presently available to compare to these results, as part of the SEA hypotheses, it was thought that Gulf of Alaska waters entering Prince William Sound determine phytoplankton and zooplankton concentrations at the AFK hatchery. Figure 9 shows field data from AFK compared to the Gulf model simulations. The model fit is extremely good, indicating that the SEA hypothesis is likely correct, and that the model is accurate.

Discussion

In both interannual and spatial simulations, meteorological factors were responsible for controlling both the timing of the initiation of the spring phytoplankton bloom, and the **character or nature** of the bloom. By character, we mean whether the bloom was a brief, intense event, or whether it was a more protracted event with a slower increase to, and duration of, maximal chlorophyll values. In cases when the bloom was brief and intense, *i.e.*, 1993, 1996 and the PWS spatial simulations, winds calmed, and remained relatively calm, for approximately 10 days (Figures 2, 6). This allowed a strong thermocline to develop, and the phytoplankton community responded with a rapid increase in biomass. This increase soon stripped the near surface, stratified layer of nutrients. and the phytoplankton spring bloom ceased (Figures 3, 7). Continued production in the near-surface layer was driven by recycling through the zooplankton. Zooplankton, whose grazing is a function of biomass, could not take full advantage of these brief intense blooms. Therefore, zooplankton biomass, and pseudocalanus biomass in particular, remained relatively low (Figures 6, 8).

In contrast, when the initial stratification of the water column was periodically interrupted during the bloom period, either by convective cooling, as in the 1994 and GOA 1996 simulations, or by intermittent strong wind mixing, as in 1995 and GOA 1995 simulations (*c.f.* Figures 2, 6), the phytoplankton bloom occurred over a longer period of time due to deeper mixing of the upper water column. This deeper mixing increased the total amount of nutrients available to phytoplankton in the euphotic zone, causing a longer phytoplankton bloom with more new primary production. The increased new production could support a higher zooplankton biomass, and the slower, more gradual phytoplankton bloom gave zooplankton time to increase their biomass at a rate more similar to that of the phytoplankton. This, in turn, lead to zooplankton biomass as much as five times greater than those found when the phytoplankton bloom was brief and shallow.

These differences in bloom dynamics lead to difference in the timing of, and mechanisms of, export of fixed organic carbon to the aphotic zone and/or benthos which are summarized in Table 1. In general, approximately 75 percent of the new production was exported out of the near-surface waters. When the phytoplankton spring bloom was short and intense, *e.g.*, in the 1993 and 1995 PWS spatial simulations, the new primary production during the bloom was low, and, due to the poor coupling between the phytoplankton and zooplankton populations, over 80 percent of the carbon flux was due to sinking of senescent phytoplankton cells, rather than due to zooplankton fecal material. In contrast, in the 1994 and 1995 simulations, when the phytoplankton bloom was protracted due to continued mixing, new production was high and the fecal flux contributed over 30 percent. Different springtime mixing regimes control both the total amount of new production which occurs and the partitioning of that production throughout the ecosystem. Differences in the timing of, and type of carbon sinking out of the surface waters has implications for the relative success or failure of benthic and mesopelagic species.

Table 1. Primary production and particle flux from surface waters

Simulation	New Production (g C/m^2)	Phyto flux (g C/m^2)	Phyto flux (%)	Fecal flux (g C/m^2)	Fecal flux (%)	Total Flux (g C/m^2)	Total Flux (percent)
1993	49.	29.	60	6.	12	35	72
1994	63.	31.	49	14.	22	45	72
1995	60	32.	53	12.	21	44	74
1996	48.	25.	53	6.	13	32	65
PWS, 1995	39.	26.	66	4.	10	30	76
GOA, 1995	60.	32.	53	12.	21	44	74
PWS, 1996	51.	27.	53	8.	16	35	68
GOA, 1996	62.	34.	55	9.	14	42	69

Conclusions

Numerical modeling of phytoplankton and zooplankton, in combination with field data collected as part of 320-G and 320-H, shows that phytoplankton and zooplankton populations in Prince William Sound and the northern Gulf of Alaska are determined by the winds and air temperatures which occur over a relatively short, critical time period in early spring. Although this critical time period may be as short as two weeks, the meteorological conditions occurring during that time will play a dominant role in the dynamics of the phytoplankton and zooplankton populations for the rest of the summer. Changes in the amount of convective mixing, caused by cold air, and of wind mixing, caused by high winds, during the early part of the phytoplankton bloom change the timing and duration of the bloom, the total primary production occurring during the bloom, and the partitioning of that primary production between the upper water column food chain, and the benthic food chain.

The spring phytoplankton bloom occurs when mixing of the surface waters ceases and there is sufficient light for phytoplankton growth to occur. In Prince William Sound and the Gulf of Alaska, this typically occurs in sometime in April. Blooms can be roughly categorized into two types, brief, intense blooms and longer, less intense blooms. The weather conditions during the initial part of the bloom determine what type of phytoplankton bloom will occur. If it is a relatively calm, warm spring, the water column stratifies and forms a shallow surface mixed layer. Phytoplankton and nutrients within this mixed layer are isolated from those deeper in the water column. With abundant light in the surface layer, phytoplankton quickly reproduce and build up their standing stocks to fairly high levels. As a consequence of this growth, nutrients are soon depleted and phytoplankton sink out of the surface layer. Because zooplankton reproduce at much slower rates than phytoplankton, the zooplankton populations cannot consume much of the phytoplankton production. The non-grazed phytoplankton slowly sinks out of the surface layer to deeper waters where it may be consumed by deeper pelagic organisms, or by the benthic fauna. Therefore, a relatively warm, quiescent spring produces a relatively short phytoplankton bloom, with high phytoplankton biomass, however, much of the phytoplankton biomass does not get passed on to the zooplankton populations. Zooplankton biomass therefore remains at fairly low levels for the rest of the summer.

In contrast to this, a cooler, stormier spring leads to higher zooplankton biomass. Although the cold stormy weather may delay the stratification of the water column somewhat, the major effect observed in field data and model simulations is due to the progression of the phytoplankton bloom, not the time at which it began. Storms typically pass through the PWS area at a frequency of about once a week during late winter. If they continue on into early spring, they become important to the biological dynamics. In a cold stormy spring, stratification typically occurs between storms, and when it does occur, the surface mixed layer may be somewhat deeper than in warm calm springs. The phytoplankton bloom begins in this surface layer, but is interrupted by a cold windy storm. This deepens the mixed layer, which reduces phytoplankton concentrations and increases nutrient concentrations. The bloom then takes off again. Subsequent storms may repeat the process, but at some point the stabilization of the upper water column, which has been increasing due to surface heating, becomes too strong and the seasonal mixed layer stabilizes. The phytoplankton bloom continues in this layer until nutrients are depleted. The net result of this type of spring weather is a deeper mixed layer, which took longer to become established. As a consequence of this, the phytoplankton bloom occurs over a longer period of time, and more nitrate is available for new primary production. In addition, the mixing of the surface layer has lengthened the total phytoplankton bloom period. During this longer period of high phytoplankton biomass, zooplankton increase in numbers and biomass and are thereby able to consume a higher proportion of the net production. Therefore, there is a transfer of more of the phytoplankton new production into the zooplankton population and zooplankton numbers and biomass remain high for the summer.

Both types of blooms have been observed in our four years of SEA field data. From the modeling work done as part of this project, we are able to determine the causes and interactions between the mixing regimes, phytoplankton, and zooplankton. This has allowed us to accurately simulate these processes. The zooplankton populations which have been modeled are of direct importance in the diet of juvenile pink salmon and larval and juvenile Pacific herring. Our understanding of the physical mechanisms that control the variable amounts of zooplankton (fish food, if you will) allows the SEA project to evaluate the effects of variability in the physical environment as it is propagated up through the phytoplankton and zooplankton, to the injured resources of Prince William Sound.

References

Corkett, C. J. and I. A. McLaren, 1978, The biology of *Pseudocalanus. Adv. Mar. Biol.,* 15:1-23.

Dugdale, R. C., 1967, Nutrient limitation in the sea: dynamics, identification, and significance, *Limnology and Oceanography,* 12:685-695.

Eslinger, D.L., 1990, *The Effects of Convective and Wind-driven Mixing on Springtime Phytoplankton Dynamics as Simulated by a Mixed-layer Model.* Ph.D. Dissertation, Florida State University, Tallahassee, FL.

Eslinger, D.L. and R. L. Iverson, 1996, The effects of convective and wind mixing on springtime phytoplankton dynamics in the southeastern Bering Sea shelf. *Accepted, Continental Shelf Research.*

Fulton, J., 1973, Some aspects of the life history of *Calanus plumchrus* in the Strait of Georgia, *J. Fish. Res. Bd. Canada,* 30:811-815.

Frouin, R., D. W. Lingner, C. Gautier, K. S. Baker, and R. C. Smith, 1989, A simple analytical formula to compute clear sky total and photosynthetically available solar irradiance at the ocean surface, *Journal of Geophysical Research,* 94:9731-9742.

Ivlev, V. S., 1945, The biological productivity of waters, *Usp. Sovrem. Biol.,* 19:98-120.

Magley, W.C., 1990, *A Phytoplankton-Zooplankton Model of the Middle and Outer Shelf Domains of the Southeast Bering Sea Shelf During Spring Bloom Conditions,* Ph.D. Dissertation, Florida State University, 1990.

Platt, T., C.L. Gallegos, and W.G. Harrison, 1980, Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton, *Journal of Marine Research,* 38:687-701.

Pollard, R.T., P.B. Rhines, and R. O. R. Y. Thompson, 1973, The deepening of the wind-mixed layer. *Geophysical Fluid Dynamics,* 4:381-404.

Strickland and Parsons, 1976 A Practical Handbook of Seawater Analysis.

Thompson, R. O. R. Y., 1976, Climatological numerical models of the surface mixed layer of the ocean, *Journal of Physical Oceanography,* 6:496-503.

Wroblewski, J. S., 1977, A model of phytoplankton plume formation during variable Oregon upwelling, *J. Marine Res.,* 35:357-394.

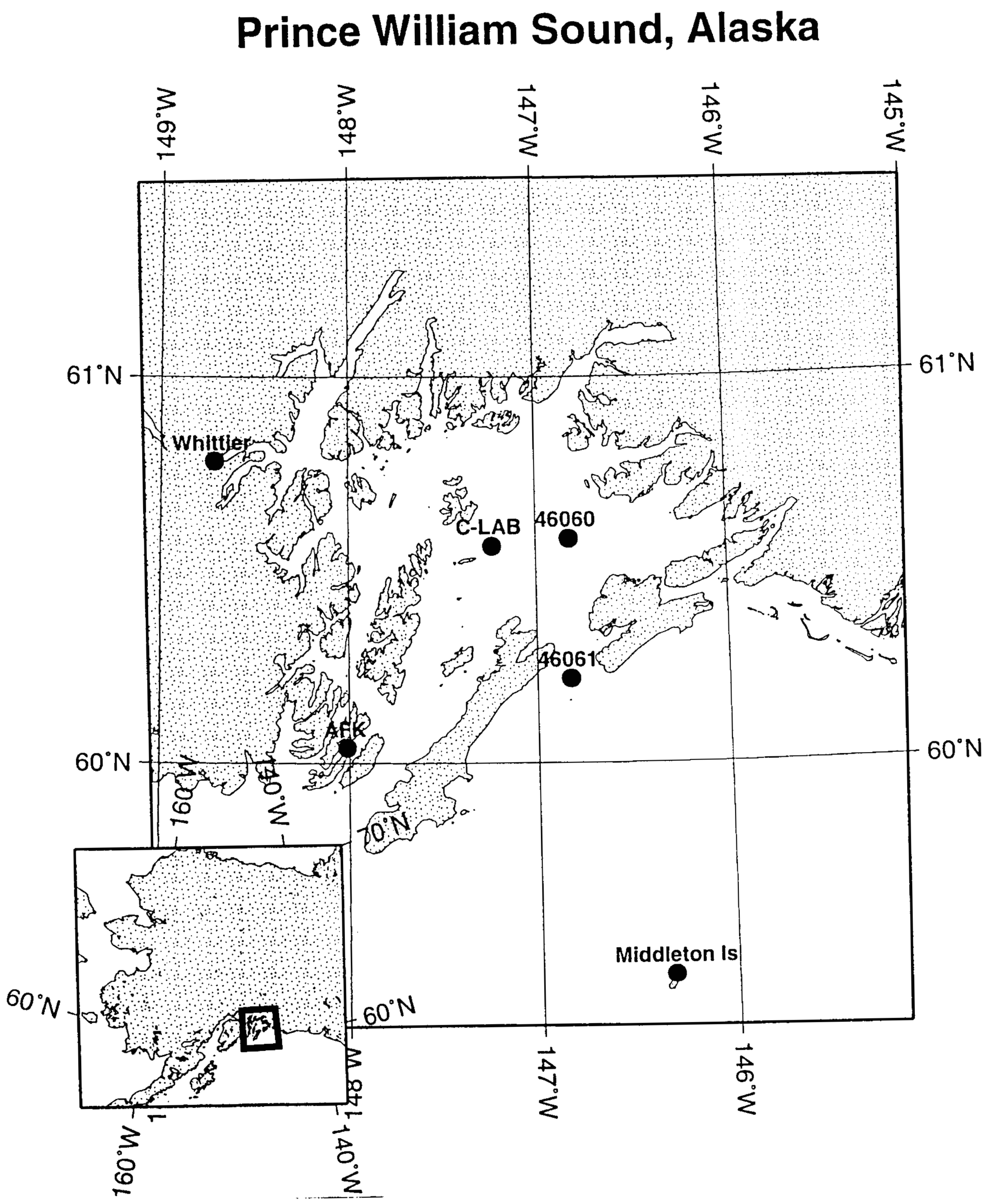


Figure 1. Prince William Sound, Alaska. Locations at which forcing data sets and field data were collected are shown by the dots. Meteorological data from Whittier and Middleton Island came from the National Weather Service. 46060 and 46061 are NDBC weather mooring. C-LAB is a mooring maintained by this project. AFK stand is a Prince William Sound Aquaculture Corporation hatchery at which phytoplankton and zooplankton data were collected.

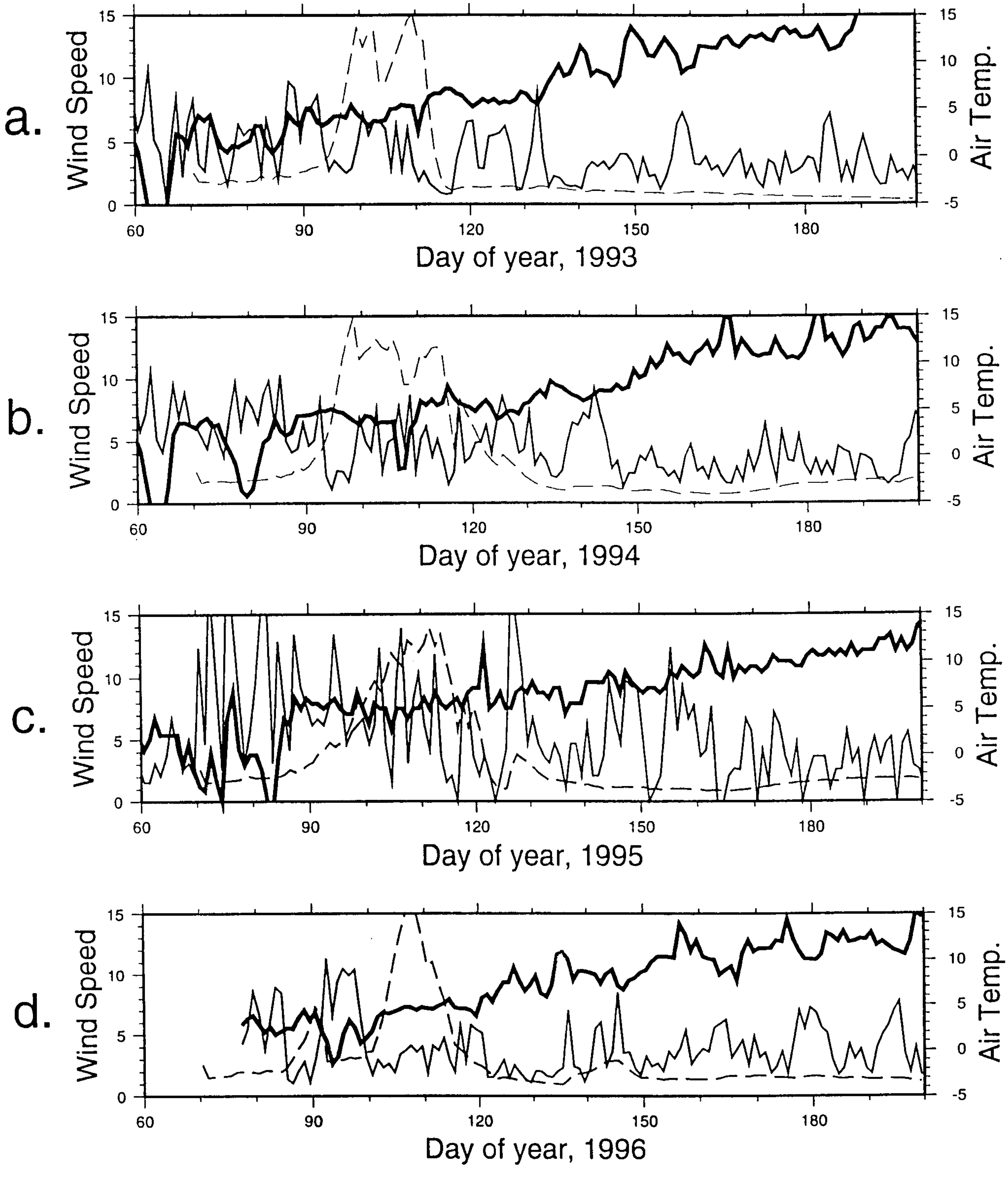


Figure 2. Wind speed (m s^{-1}; thin solid line), air temperature (°C; thick solid line), and modeled chlorophyll (mg Chl m^{-3}; thin dashed line) for a) 1993, b) 1994, c) 1995, and d) 1996.

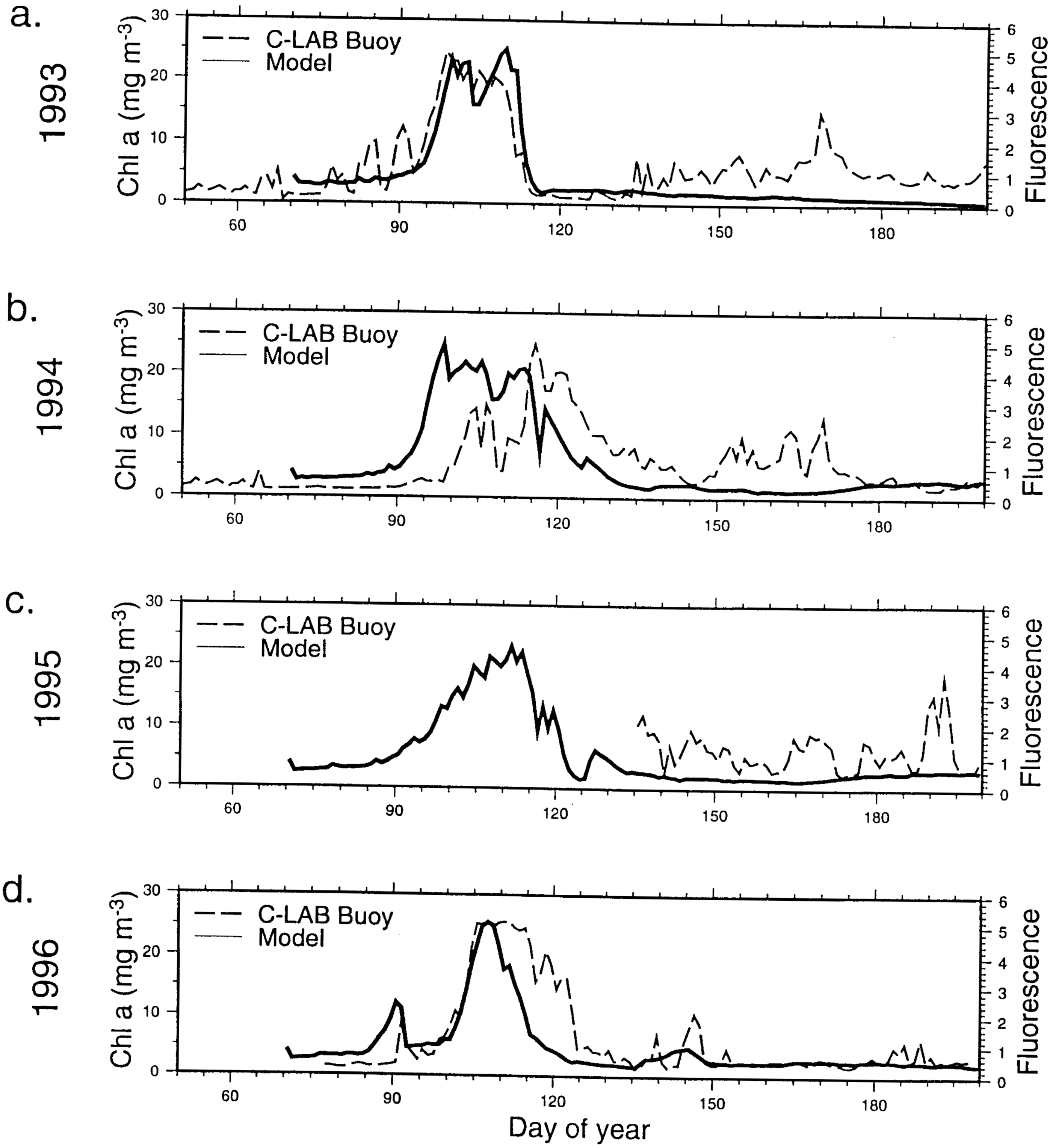


Figure 3. Model chlorophyll concentration (mg Chl m^{-3}) and C-LAB measured fluorescence (Volts) ,both measured at 10 m, for a) 1993, b) 1994, c) 1995, and d) 1996.

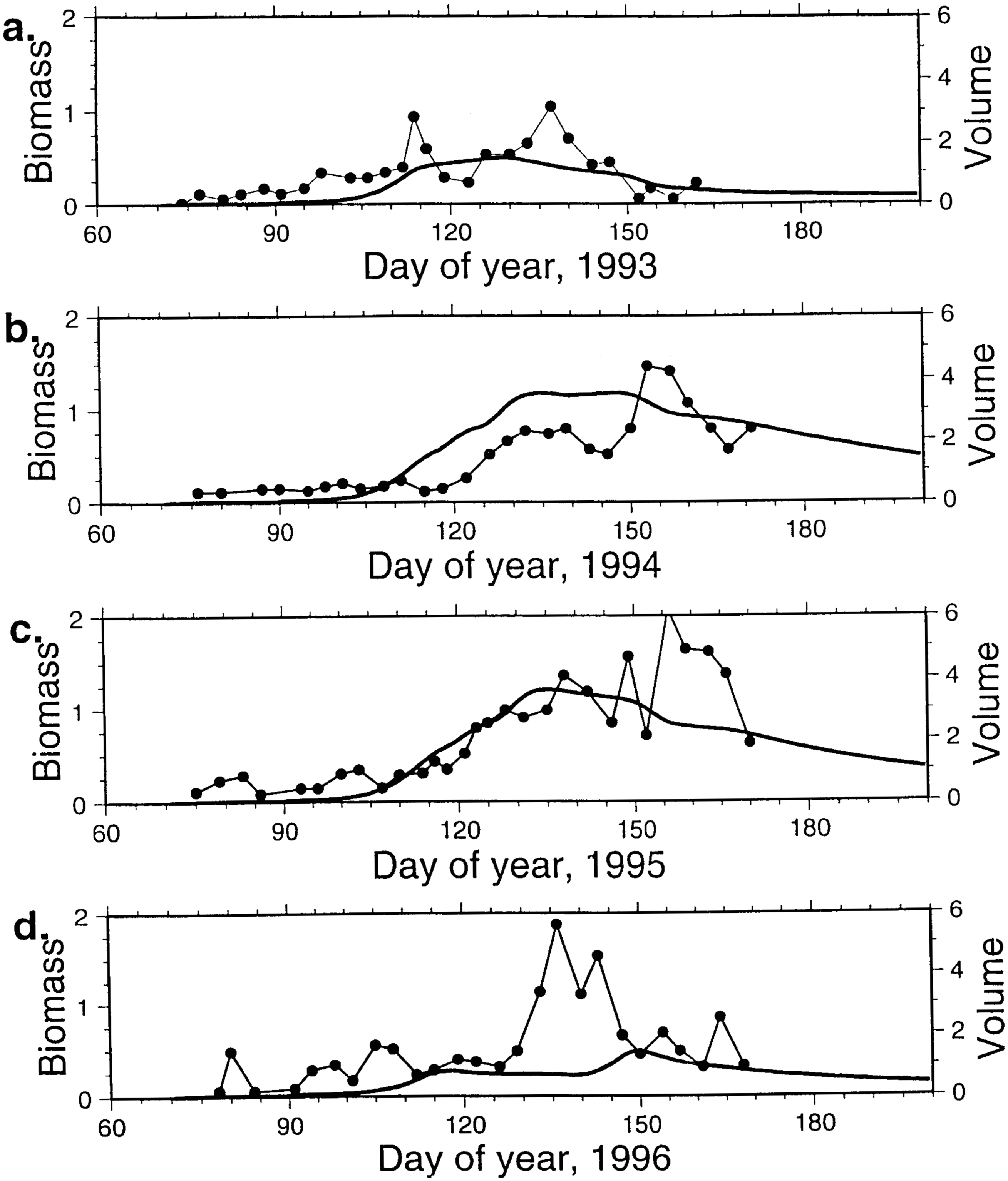


Figure 4. Model copepod biomass (g wet weight m^{-2}; thick solid line) and settled volume (; thin line with symbols) from the AFK hatchery for a) 1993, b) 1994, c) 1995, and d) 1996.

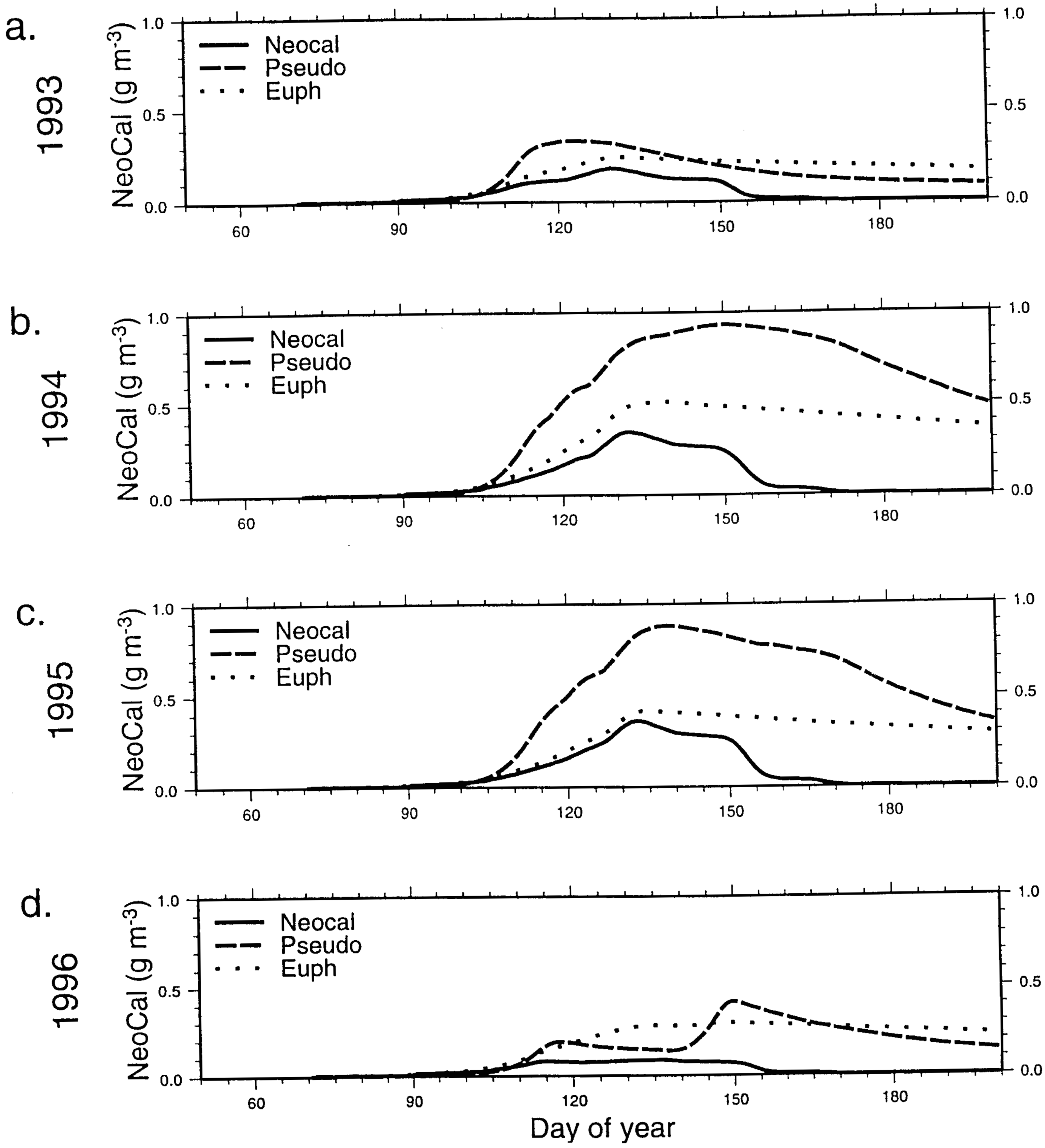


Figure 5. Model zooplankton biomass (g wet weight m^{-2}) by group for a) 1993, b) 1994, c) 1995, and d) 1996.

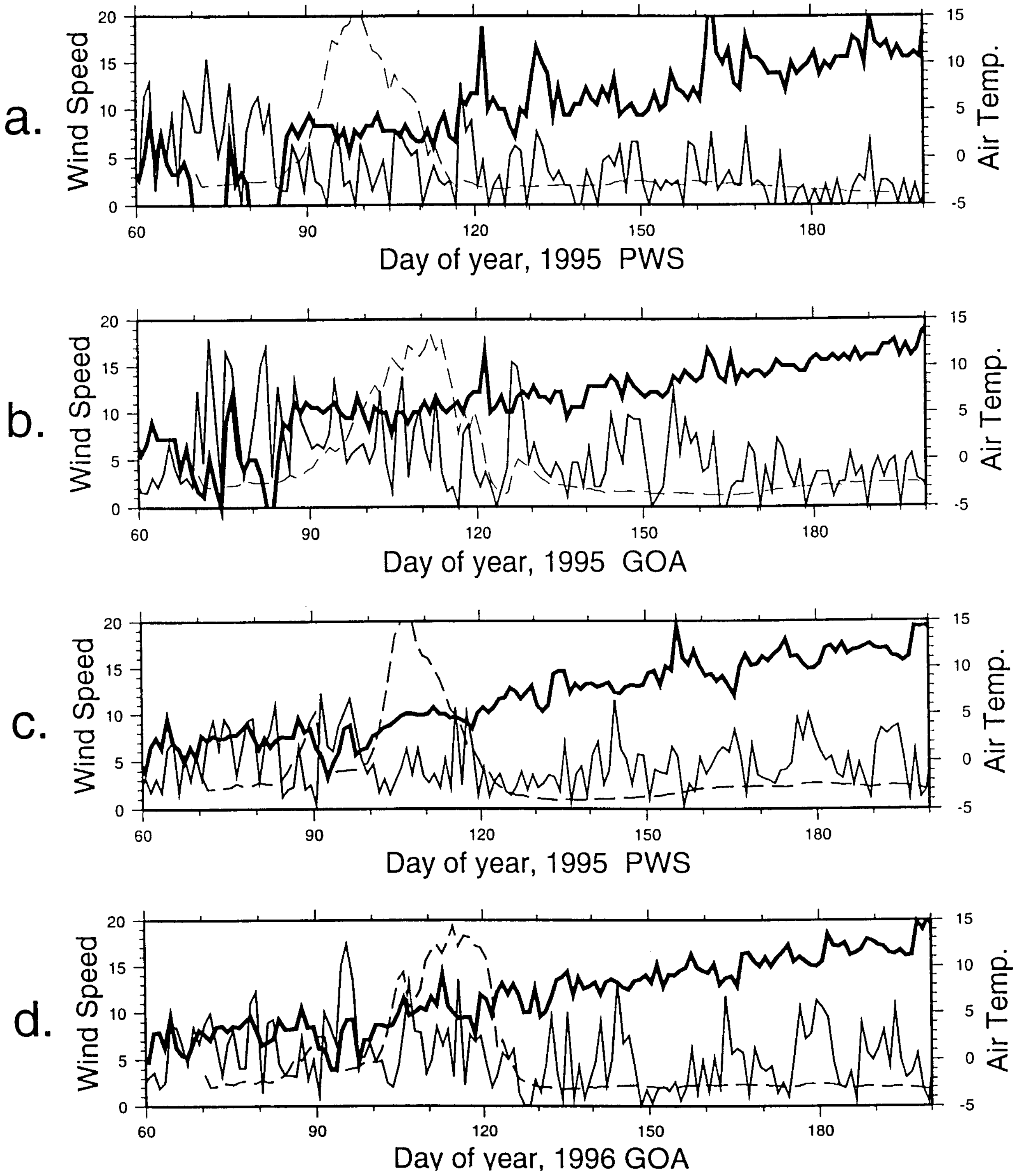


Figure 6. Wind speed (m s^{-1}; thin solid line), air temperature (°C; thick solid line), and modeled chlorophyll (mg Chl m^{-3}; thin dashed line) for a) Prince William Sound, 1995; b) Gulf of Alaska, 1995; c) Prince William Sound, 1996; and d) Gulf of Alaska, 1996.

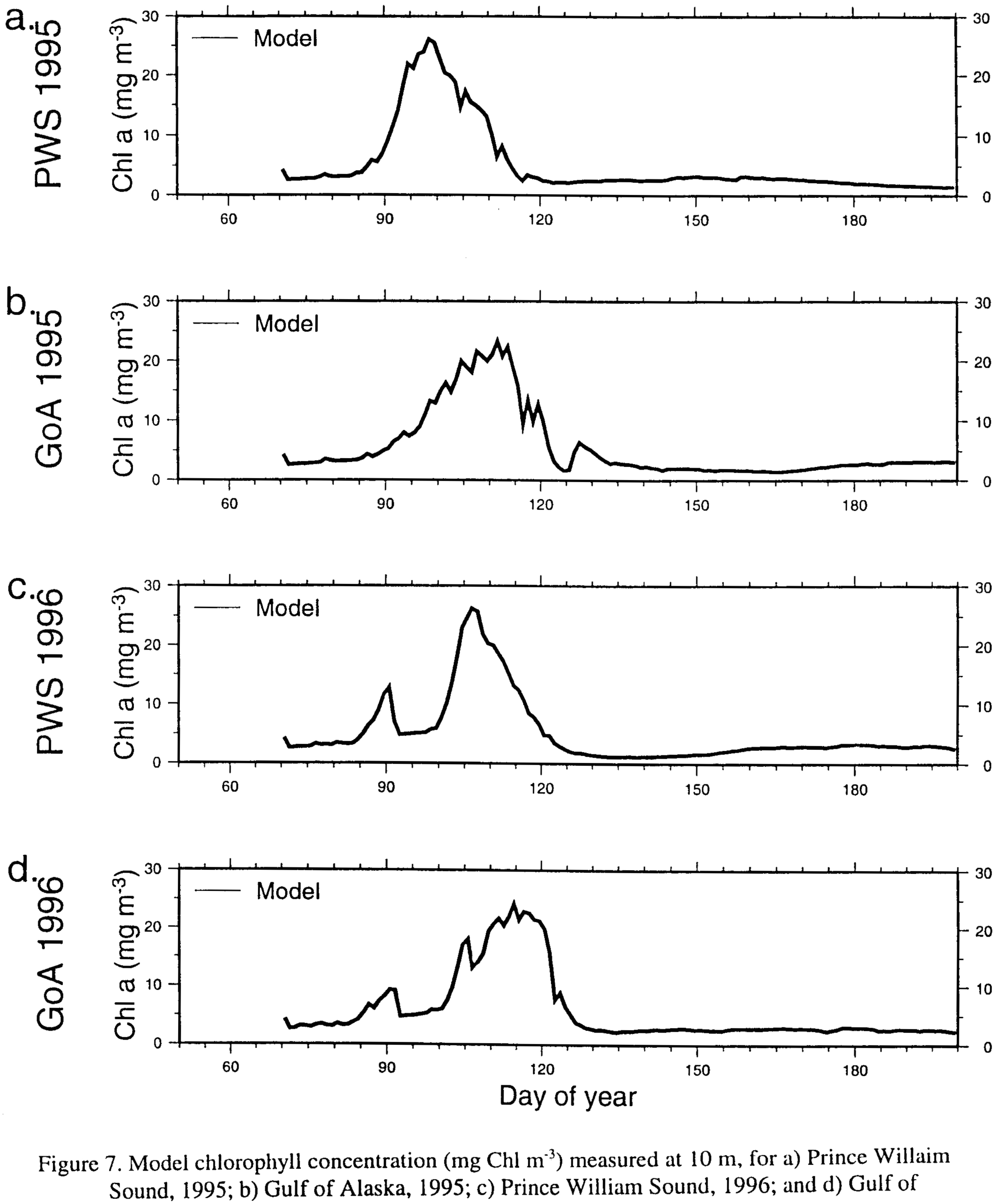


Figure 7. Model chlorophyll concentration (mg Chl m^{-3}) measured at 10 m, for a) Prince Willaim Sound, 1995; b) Gulf of Alaska, 1995; c) Prince William Sound, 1996; and d) Gulf of Alaska, 1996.

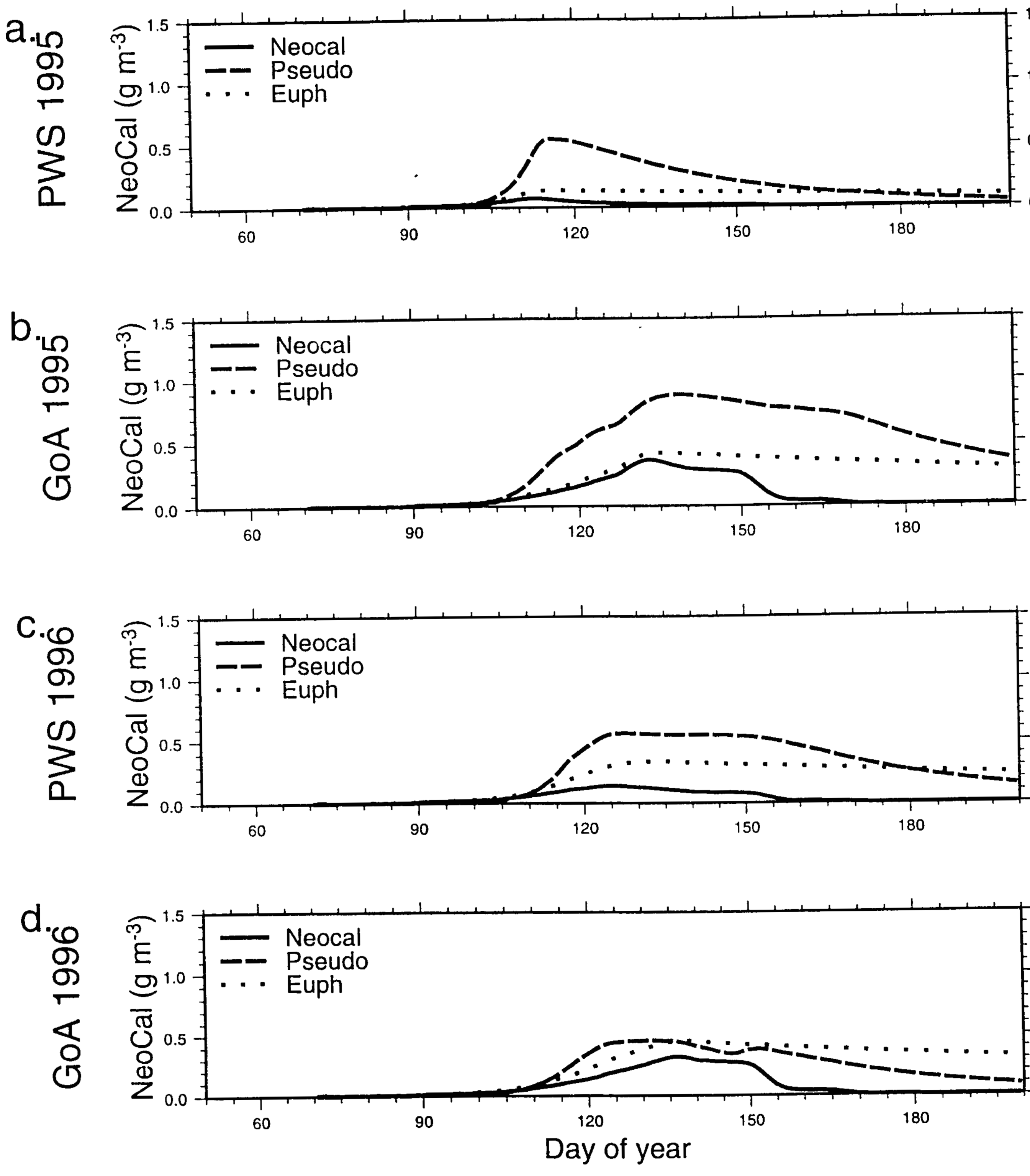


Figure 8. Model zooplankton biomass (g wet weight m^{-2}) by group for a) Prince William Sound, 1995; b) Gulf of Alaska, 1995; c) Prince William Sound, 1996; and d) Gulf of Alaska, 1996.

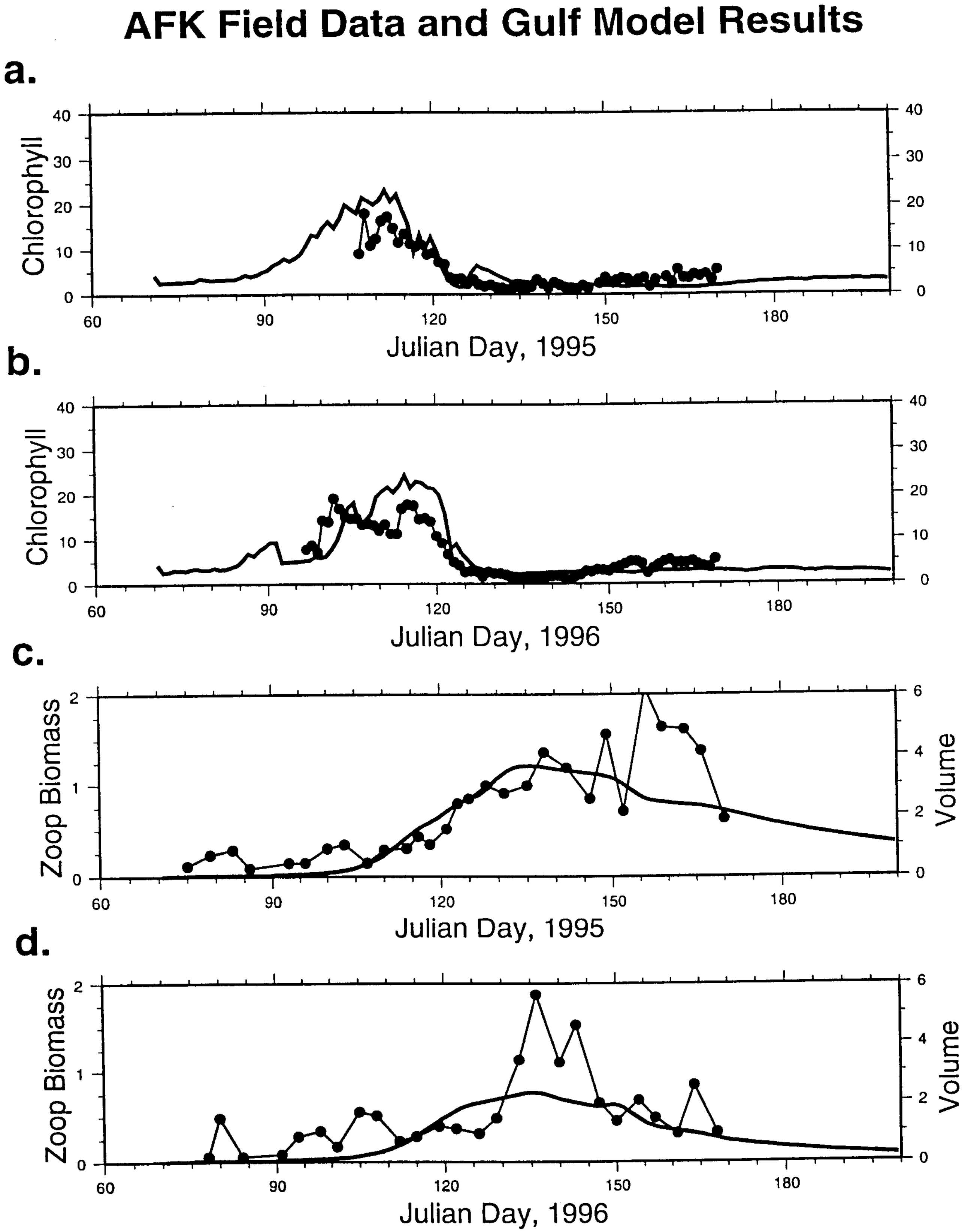


Figure 9. AFK field data and results from Gulf of Alaska simulations. In all cases the thick solid line shows the model result and the thin line with symbols shows the field data: a) chlorophyll (mg Chl m^{-3}) at 10 m for 1995, b) chlorophyll (mg Chl m^{-3}) at 10 m for 1996, c) model zooplankton biomass (g wet weight m^{-2}) and settled volume () in 1995, and d) model zooplankton biomass (g wet weight m^{-2}) and settled volume () in 1996.

Chapter 11.

Juvenile Herring Growth and Habitats (96320T)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Juvenile Herring Growth and Habitats

Restoration Project 95320T
Annual Report

Kevin D.E. Stokesbury
Evelyn D. Brown
Robert J. Foy
Brenda L. Norcross

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska
99775-7220

April 1997

Juvenile Herring Growth and Habitats

Restoration Project 95320T
Annual Report

STUDY HISTORY: Restoration Project 95320T was initiated as the core project of the Herring Recruitment Dynamics Project, a multi-investigator ecosystems study and part of the Sound Ecosystem Assessment (SEA; PWSFERPG 1993) program in Prince William Sound (PWS). SEA was initiated because the lack of knowledge of the ecological processes affecting pink salmon and herring confounded the identification of damage caused by the *Exxon Valdez* oil spill. The PWS herring population crashed in 1993 possibly due to a viral infection (VHSV). This viral infection occurs more frequently in fish exposed to oil. Local residents, frustrated by the loss of valuable fisheries and the inability to accurately identify the causes, strongly voiced support for research. They formed a group, appealed to the EVOS Trustee Council, and as a result of their effort SEA was created in 1994. Research on juvenile herring began in April 1995.

ABSTRACT:

The purpose of this project is to determine spatial distributions and habitats of age 0 to 2 year old Pacific herring (*Clupea pallasi*). It is linked to the Herring Recruitment subgroup of SEA and provides data for the three objectives (1. Overwintering Survival model, 2. Summer Habitat Model, 3. Monitoring Strategy). In 1996 we completed 2 acoustic and 4 aerial broadscale surveys; 4 diel summer surveys, sampling Eaglek, Whale, Ziakof, and Simpson Bays; and 4 winter surveys sampling Whale, Ziakof and Simpson Bays. Aerial survey techniques appear to provide an accurate means of estimating juvenile herring densities and distributions. Preliminary results suggest that adult and juvenile herring distributions differ. Adult herring were found in large schools in Zaikof Bay in March and in the Latouche Passage area in July. Juvenile herring recruited into the bays throughout the Sound (fork length 15 to 74 mm). Each bay supported juvenile herring from August throughout the fall. These bays appear to be nursery areas for juvenile herring until they near maturity (age $1^1/_2$ to 2). Further, it appears that juvenile herring grow faster in some bays than in others. The relative importance of prey appears to vary spatially and seasonally.

KEY WORDS: *Clupea pallasi*, Pacific herring, juvenile, habitat, Prince William Sound, distribution

CITATION: Stokesbury, K.D.E., E.D. Brown, R.J. Foy, and B.L. Norcross. 1997. Juvenile Herring Growth and Habitats, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 95320T), University of Alaska Fairbanks SFOS IMS, Fairbanks, Alaska.

INTRODUCTION

The purpose of this project is to determine spatial distributions and habitats of age 0 to 2 year old Pacific herring (*Clupea pallasi*). It is linked to the Herring Recruitment Dynamic subgroup of SEA and provides data for the three objectives (1. overwintering survival model, 2. summer habitat model, 3. monitoring strategy) which will determine the physical and biological mechanisms influencing the recovery of Pacific herring. Pacific herring is listed as "not recovered" in the "Resources and Services Injured by the Spill" *Exxon Valdez* Oil Spill Restoration Plan.

The Herring Recruitment Model is being developed as the integration of submodels, each of which focuses on a stage in the early life history of Pacific herring (*Clupea pallasi*). We hypothesize that, like other clupeids, year-class strength of Pacific herring in Prince William Sound (PWS) is determined during its early life history. All field work, laboratory experiments, and data analysis for all involved components of SEA relate to one or more of these submodels. Two major SEA hypotheses are the focus of these submodels and will be linked within the overall Herring Recruitment Model (Figure 1). The key focus of the effort is the Herring Overwinter Hypothesis which states that survival of herring through their first winter is critical to year-class strength and is dependent upon their condition when they enter winter. We will test this hypothesis by examining distribution and condition of herring in the fall, throughout the winter and again in the spring. We expect to see changes in condition indices related to the physical and biological variables of different geographic locations. A bioenergetic model, combining SEA field and laboratory observations together with energetic information from Atlantic herring studies, is being constructed to predict the likelihood of overwinter survival for recruiting herring. In support of the herring Overwinter Hypothesis we will examine how the Lake/River hypothesis applies to transport and distribution of herring at the larval stage. We will employ larval drift simulations, using the Circulation and Transport Models for PWS being formulated by Mooers and Wang as part of the Ocean Dynamics Model, to determine the expected drift of larval herring within PWS and determine how that affects the distribution of summer juvenile nursery areas. We expect to examine various drift patterns in response to simulated lake (i.e. retention), river (i.e. rapid movement through the sound), and combinations of varying amounts of "lake" and "river" in accordance with the recent evolution of the lake/river hypothesis. The larval drift synthesis is a tool which will link the Summer Habitat Model, which examines location and characteristics of summer nurseries utilized by juvenile herring, with the Overwintering Survival Model. The Summer Habitat Model will determine the survival and growth rates of juvenile herring and the quality of nursery areas by examining changes in herring distribution, density, length, weight, energy (kJg-1), interspecific biological variables (prey abundance, predation) and physical variables (oceanographic conditions, bathymetry). These data will define the initial conditions of herring entering into the Overwintering Survival Model.

This project is a component of the SEA project, Dr. T. Cooney, chief scientist. Within SEA, coordination exists between projects linking physical and biological data. Multiple authors on proposed publications reflects that integration. In addition, this project coordinates with the APEX and NVP ecosystem projects via field logistics (vessels, equipment and samples), shared data (catch, aerial survey data, and acoustics results), and joint publications. We anticipate that coordination with these groups will increase during FY98 for the purpose of planning the monitoring of key species (i.e. herring) in the ecosystem that directly or indirectly impact oil-spill injured species (fish, birds, mammals) and resources (commercial and subsistence fisheries).

OBJECTIVES

The research objectives of this project are:

1. Develop an Overwinter Survival Model for juvenile herring.
2. Develop a Summer Habitat Model for juvenile herring.
3. Develop a Monitoring Strategy for juvenile herring.

For the Overwinter Survival Model:

Describe overwinter distribution, size, condition, energy needs, and relative abundance of juvenile herring, physical and biologic characteristics of herring nursery areas and overwintering bioenergetics.

Tasks:

1. Collect data on the whole body energy content of age 0 and 1 herring in the late fall and winter. This information will be collected for the 1995, 1996, and 1997 year classes.
2. Determine changes in bioenergetics over the winter season using time sequence (monthly) sampling of juvenile herring from two or more index sites in 1996-97 and 1997-98.
3. Examine stomach contents of over-wintering recruits and make energetic estimates for consumption during the winter of 1996-97 and 1997-98.
4. In the laboratory determine the energy need of fasting herring.
5. Using field and laboratory measurements of over-winter energy needs, and literature values for Atlantic herring develop a model to predict winter survivorship.

6. Describe spring, pre-bloom biological and habitat conditions as an endpoint of Overwintering Survival Model and beginning of second year Summer Habitat Model.

7. Compile historic biolgocial and physical data for the purpose of model verification

For Summer Habitat Model:

Describe summer and fall distribution, size, condition and relative abundance of juvenile herring (biological data), and physical and biological characteristics of herring nursery areas (habitat data) to evaluate quality of summer growth of herring and as initial conditions for the Overwintering Survival Model.

Tasks:

1. Use Circulation and Transport Models (Ocean Dynamics Model) to simulate drift of larval herring and distribution to summer nursery areas.

2. Determine distribution of juvenile herring during the spring, summer and fall using broad scale surveys which include simultaneous overflights, acoustics and net collections.

3. Determine physical (salinity, temperature, depth, currents, light levels, bathymetry) and biological (zooplankton, competitors) parameters which determine good vs. bad nursery areas measured by condition of herring (length, weight, age, growth rates, stomach contents, energetic condition and stable isotopes).

4. Develop maps of key habitats (nursery areas) for juvenile herring within PWS.

5. Describe the retention characteristics of herring nursery areas using information from the larval drift simulations, physical oceanographic measurements and biological data (spatial distributions, isotopes, growth rates) indicating immigration or emigration.

6. Develop maps of possible retention areas with different historical spawning sites and transport conditions.

7. Compare historic distributions reported by local and traditional knowledge with distributions described by this study

For Monitoring Strategy:

Tasks:

1. Identify key index sites and develop monitoring techniques by relating aerial, acoustic and net sampling data during summer surveys to condition of juvenile herring.

METHODS

To address the above hypotheses, we have formulated our approach into two component models, each with several subcomponents. These models and subcomponents are described in chronological order of herring life history (Figure 1).

The first subcomponent is embryo survival. This component is not a SEA program, but rather projects funded by EVOS outside of SEA. For the starting point of our Summer Habitat Model, we intend to combine the results of 1) the ADF&G spawn deposition survey, 2) the Haldorson, Quinn and Rooper egg loss model which predicts losses due to physical factors and predation, 3) estimates of baseline egg mortality (Brown et al. in prep), and 4) estimates of baseline levels of viable hatch (Hose et al. in press; Kocan et al. in press). From this we will know the location of spawning of herring, an estimate of the amount of spawn, and the expected percentage of viable larvae produced (Figure 2).

The output of that subcomponent is the input into the Larval Drift Model (Figure 1). We will initially examine the direction of transport without incorporating the population size component. We will run the Ocean Circulation and Transport Model with input at the locations of herring spawning and test observed distribution of particles. Distribution predicted by this subcomponent will be verified by the distribution of age-0 herring during the summer. We will compare the Larval Drift Model results to the transport and retention of larval Atlantic herring (*Clupea harengus*) in North Atlantic (Graham and Davis 1971; Graham and Townsend 1985; Sinclair and Iles 1985; Sinclair 1988). We will also use 1989 as a test case. By inputting location of spawning and physical conditions which we know occurred in 1989, we can test the model against the offshore distribution of larvae observed in May, June and July 1989 (Norcross and Frandsen 1996) and the nearshore distribution observed in May 1989 (McGurk 1990; McGurk and Brown 1996). We will also use spawning location information from 1995, 1996 and 1997 and correlated with the distribution of larvae to the distribution of herring observed from the aerial and acoustic surveys. This simulation will be an iterative process.

The output of the larval drift simulation is the input for the Summer Habitat Model (Figure 1). From October 1995 to August 1997 acoustic and aerial surveys were conducted and these data will be processed, analyzed, interpreted and combined in 1998 to determine herring nurseries. The broadscale distribution of age-0 herring was observed during October 1995, March and July 1996. These surveys covered most of PWS and adjacent waters to Resurrection Bay. The Sound is very large and resources were limited so the survey focused on regions where fishermen had observed juveniles and where earlier ADF&G surveys indicated high densities of herring (<1 km from shore; Figure 3). Sampling from the air provided approximately weekly estimates of horizontal distribution of herring across the Sound.

The broad scale survey was conducted for 12 hours each day. Five vessels were used during the 10 day survey: an acoustic vessel (refer to the Acoustic chapter for details on equipment and processing), a trawler (1.52 x 2.13 Nor'Eastern Astoria trawl doors, head rope 21.34 m, foot rope 28.96 m, estimated 3 x 20. 0 m mouth, 10.16 cm mesh wings, 8.89 cm middle and a 32 mm cod end liner; 1000 µm Tucker trawl), a seiner (250 x 34 m and 20 m, 25 mm stretch mesh), a processing boat which also supported the inshore frye skiff, and an oceanographic vessel (CTD, ADCP Doppler). The acoustic vessel cruised at 8-9 knots along a zig-zag pattern <1 km from shore with observations continuously recorded from the ship's sonar. When a school of fish was encountered the acoustic vessel slowed to 5-6 knots and surveyed the school with the acoustic sonar equipment (as well as the observer's comments of the ships sonar). The seine, trawler or frye skiff (50 x 8 m, 3 mm stretch mesh) then sampled the fish school. Oceanographic data, zooplankton and icthyoplankton data were also collected at the mouth, middle and head of 13 Bays. The net collections were used to verify acoustic targets and life-history data. We speciated each catch and randomly sampled 1000 herring for length frequencies. From each area we collected 450 herring for Age-Weight-Length analysis, 15 herring for stomach content analysis, 100 herring for energetics. When a different species dominated the catch we randomly sampled 1000 and measured their fork length. We removed the stomachs of predator species and determined the presents or absents of herring, fish, or invertebrates. We also collected numerous samples for other researchers (Table 1).

We are now processing the acoustic data from these cruises. Jay Kirsch's group at the PWSSC collects the data in the field with us and performs the preliminary crunch, removing all the nonbiological signals, such as the bottom. This data is converted into kg/m^{-3} units per 40 x 1 cell, with the lat.'s and long.'s and transported to our laboratory at UAF. We examine the echograms and catch data and determine the species proportion and size modes. We convert the kg/m^{-3} to numbers of individual fish per species, per size mode for each cell. We remove all signals smaller than 1 juvenile herring per 100 m^3. This agrees with the echogram signal and follows a similar sorting pattern to (MacLennan and Simmonds 1991) and (Gunderson 1993). This gives us measurements for the larger schools when we used the biosonic acoustics, we then use this data to calibrate our ship board observations for the less dense areas. This will give us a series of measurements that we can use in parametric (acoustic) and non-paramentric (ship board observations) tests.

These broadscale surveys provided a preliminary estimate of oceanographic patterns and distribution of herring. However, the broadscale survey is a continuous transect along the coastline of Prince William Sound. There are 3 major limitations of this design:

1. It is not a random sample and estimates represent only the densities of fish within the transect strip and cannot be extrapolated to the surrounding area (Krebs 1989; Gunderson 1993). One approach is to randomize the cells and we are examining this

possibility, plus the problems of autocorrelation and extremely skewed distributions. Systematic acoustic surveys may be superior to a random survey designs, stratified random surveys are by far the best design as they address both biological sampling problems and ensure strong statistical power because they conform to the assumptions of most models (Sokal and Rohlf 1981; Krebs 1989; Simmonds and Fryer 1996).

2. It is a temporal point measurement, areas were only surveyed during a single point in time. Clupeid distributions are strongly effected on a short temporal scale by the tidal cycle and the diel (day/night) cycle (Scott and Scott 1988; Stokesbury and Dadswell 1989; Stokesbury and Dadswell 1991).

3. Oceanographic data collect during the broadscale are point measures, i.e. the salinity, temperature, current, when a particular school was sampled. If there is any delay between vessels these results will be confounded by changes in the tidal cycle and light intensity. It is impossible to determine the underlying patterns of distribution or responses to environmental factors with single point measurements (Green 1979).

We have addressed these limitations by employing a factorial design, based on Green's (1979) principles of sampling to derive the survival rate of juvenile herring from density changes using a life table (Begon and Mortimer 1982). Densities must be estimated precisely and accurately on both spatial and temporal scales. This design will provide all the parameters required for the ALEWIFE Fish Model (Cooney 1995 ; Chapter 7; Fig. 19). In this factoral design each spatial replicate (bay) has 3 temporal replicate samples within 24 hours, allowing us to estimate the variability in densities caused by tidal and diel cycles and allow accurate measurements of the oceanographic conditions of each bay (Gunderson 1993) (Figure 4). This design allows an overall estimate of changes in survival rates of Prince William Sound juvenile herring and comparisons between and within bays on different spatial and temporal scales, i.e. 24 hours, monthly, annually. The four bays are, Eaglek, Whale, Ziakof and Simpson. These bays were selected because:

1. herring overwinter in bays

2. spatially segregated; North South, East and West.

3. located at a distinct position along the prevailing PWS current relating directly to the lake/river hypothesis (Cooney 1995: Chapter 7 Fig. 11-17; and Chapter 9).

4. strong evidence that herring spawn/recruitment in each of these bays

Each bay was surveyed three times in a 24 hour period using sidescan sonar (Figure 4). Net collections of herring were coupled with acoustics estimates of horizontal and vertical distribution and abundance and aerial estimates of horizontal distribution. These net collections are used to ground-truth both acoustic and aerial estimates for species size and composition. Subsamples of herring were retained and later evaluated for size, age, stomach contents, condition (energetics and standard fisheries age-weight-length (AWL)), and stable isotopes (trophic analysis). Simultaneous with net collections for fish were vertical plankton tows to estimate availability of food for planktivorous herring. Oceanographic parameters collected include salinity and temperature at depth (CTD), estimates of current structure (ADCP), light levels and bathymetry at location. The main effort in 1998 will be to process, analyze and interpret these data. Evaluation of these parameters will be used as estimates of the health of the population at each location.

RESULTS AND DISCUSSION

Larval Drift Model

The Ocean Circulation and Transport Model is being developed and the first results are being published in the manuscript:

Mooers, C.N.K. and J. Wang. 1997. On the development of a three-dimensional circulation model for Prince William Sound, Alaska. Continental Shelf Research. submitted Dec. 1996.

This model will be the bases for the Larval Drift Model which is presently being developed.

Summer Habitat Model

In this component we are determining the biological and physical variables influencing the spatial and temporal distribution of Pacific herring (*Clupea pallasi*) in Prince William Sound. This is a combined effort with support for acoustics and oceanography from PWSSC and technical support from Cordova Fish and Game.

The first manuscripts from this work are:

Brown and Norcross 1997. Assessment of forage fish distribution and relative abundance using aerial surveys. Fisheries Research. draft. Appendix I

Foy, R. J., B. L. Norcross, A. Blanchard. 1997. Spatial and Temporal Differences in the Diet of Herring (Clupea pallasi) in Prince William Sound, Alaska. Appendix II

Summer Growth and Survival

We are testing 2 main hypotheses:

1. Bays in Prince William Sound are nursery areas for juvenile herring.

2. Biological and physical variables in these Bays determine the survival and growth of juvenile Pacific herring and dictate cohort strength.

Pacific herring (*Clupea pallasi*) usually begin to spawn in their third year when they have reached a size of about 185 mm and a weight of 95 g. Females can produce as many as 40,000 eggs each year until they reach an age of about 15 years (Robinson 1988). Pacific herring deposit their eggs in mid-April in the nearshore low intertidal or subtidal zone, primarily on marine vegetation (Brown et al. 1996). The knowledge of herring distribution in PWS is largely dictated by the distribution of the fishing effort. Little is know about the location of the juveniles. Therefore our first task was to search the Sound for juvenile herring and determine where they metamorphose, spend their summers and overwinter.

We surveyed and collected 67 trawl and 59 seine collections from 7 to 31 March 1996. The 1995 year class are about 11 months old and have grown to a size between 60 and 120 mm (Figure 5). These fish just survived their first winter. The second mode are juvenile herring which have just survived their second winter. The third mode are mature adults that will spawn in April (Figure 5). It therefore appears that juvenile herring overwinter in these nearshore areas within the Bays (Figure 6). The majority of adults were congregated in a very large school within Ziakof Bay (24,200 - 29,100 metric tons of herring; J. Kirsch pers. comm. based on our March 96 survey) although a few smaller schools were sampled within the Sound.

In early May, after approximately three weeks at 8° C water temperature, the herring eggs hatch into larval herring. They are about 8 mm long and have a yolk sac which is absorbed within 6 days. They metamorphosis from the larval to juvenile form when they reach a size of 25 mm to 30 mm, which can take from 4 to 10 weeks. During this time larval are transported away from the spawning areas, although studies in British Columbia have found significant densities remaining nearshore (Robinson 1988). Post-larval fish were collected with a box trawl designed to sample larval and juvenile fish, and with small shore seines on loan from APEX. The first size mode represents 3 month old herring, these herring just metamorphosed from larval to juveniles (Figure 7). We collected these juveniles in the nearshore bays of PWS (Figure 8). Each of the 4 bays we are focusing on had very high densities of post-larval herring. We are presently analyzing sample to determine if larval herring were present within these Bays in May and June or if they were transported in from other areas via currents. After spawning the adult herring resume feeding in the near shore area and then migrate out to their offshore feeding grounds. The juveniles appear to remain in these bays. We successfully collected them there in October 1996.

There is a great deal of debate over the relationship between herring and pollock populations in PWS. In March of the 59 seine collections only 3 were 100% pollock (2 Eaglek, 1 Aialek Bay) and these species rarely mixed (4 sets: 3 in Eaglek, 1 in Sawmill). The trawl data indicates that the passages were the primary location where both herring and pollock were collected but generally there was little spatial overlap between these species (12 areas >80% herring, 8 areas > 80% pollock; 4 with 50/50).

The density data is the driving force of the life table from which juvenile survival will be estimated. Site fidelity is a key assumption if survival is going to be estimated for each Bay (for Prince William Sound this estimate will be derived with 3 degrees of freedom). To examine site fidelity we will examine growth and spatial distribution of juvenile herring in each bay. Movement is a problem as we will not know if density shifts in a bay are caused by mortality or emigration. However, we will assume that these fish do not leave Prince William Sound and therefore these four bays are representative of PWS herring population densities. The preliminary data suggests that there may be site fidelity of the 0-1 herring and possibly until sexual maturity in these bays.

By following the temporal shifts in density and age structure we intend to estimate life tables for 3 cohorts of juvenile herring, 1995, 1996 and 1997. This work will complement ADF&G's present research as they use life tables to determine adult stocks, thus our information is readily available and interpretable for their managers.

Overwintering Survival Model

The Overwintering Survival Model evaluates distribution and condition of age 0 and 1 herring as they enter pass through and complete the winter. The objective of this sampling is to determine change in condition of herring over the course of winter in concert with the hypothesis that herring which enter winter in poor condition due to "bad" nursery habitats will not survive winter, while those from "good" habitats will successfully survive winter. Dr. A.J. Paul is leading this effort, he and his co-authors have submitted the following manuscripts:

Paul, A.J., J.M. Paul, and E.D. Brown. 1997. Fall and spring somatic energy content for Alaskan Pacific herring (*Clupea pallasi*) relative to age, size and sex. Journal of Experimental Biology and Ecology. submitted.

Paul, A.J., J.M. Paul, and E.D. Brown. 1997. Ovarian energy content of Pacific herring from Prince William Sound, Alaska. Alaska Fishery Research Bulletin. submitted

Kline, T.C.Jr., and A.J. Paul. Isotopic signature and somatic energy content of young of the year Pacific herring at two sites in Prince William Sound Alaska: implications for tropic studies. Canadian Journal of Fisheries and Aquatic Sciences. submitted.

Refer to Dr. Paul's and Dr. Kline's sections in this Annual report for more details on these manuscripts.

The difficulty of sampling during the winter months in Prince William Sound hampered our time-sequence collections of juvenile herring from the four bays. We were able to collect herring and oceanographic data during November, December and February from Simpson Bay as well as several collections in Zaikof and Whale during these months. In 1998, the

1996-97 data will be analyzed, an additional Oct.-March sample will be collected, and this model will be linked to the Ocean Dynamics Model to determine the effect of the timing of the phytoplankton bloom on successful herring recruitment.

LITERATURE CITED

Begon, M. and M. Mortimer. 1982. Population Ecology. Blackwell Scientific Publications, Oxford.

Brown, E.D., and E. Debevec. In prep. Effect of the *Exxon Valdez* oil spill on survival of Pacific herring (*Clupea pallasi*) eggs: Comparison of *in situ* observations with laboratory incubations. Under revision after submission to Can. J. Fish. Aquat. Sci.

Cooney, R. T. 1995. Sound ecosystem assessment (SEA) - A science plan for the resoration of injured species in Prince William Sound, Alaska. Exxon Valdez Oil Spill Restoration Project Annual Report (95320), Alaska Department of Fish and Game Anchorage, Alaska.

Graham, J.J. and C.E. Davis. 1971. Estimates of mortality and year class strength of larval herring in western Maine, 1964-67. ICES Rapp. R.-V. 160: 147-152.

Graham, J.J. and D.W. Townsend. 1985. Mortality, growth, and transport of larval Atlantic herring *Clupea harengus* in Maine Coastal waters. Trans. Am. Fish. Soc. 114: 490-498.

Green, R. H. 1979. Sampling design and statistical methods for environmental biologists. John Wiley & Sons, New York.

Gunderson, R. D. 1993. Surveys of Fisheries Resources. John Wilet & Sons, Inc., New York.

Hose, J.E., M.D. McGurk, G.D. Marty, D.E. Hinton, E.D. Brown, and T.T. Baker. 1996. Sublethal effects of the *Exxon Valdez* oil spill on herring embryos and larvae: morphologic, cytogenetic and histopathologic assessments, 1989-1991. Can. J. Fish. Aquat. Sci. 53: 2355-2365

Kocan, R.M., J.E. Hose, E.D. Brown, T.T. Baker. 1996. Herring embryo (*Clupea pallasi*) sensitivity to Prudhoe Bay petroleum hydrocarbons: laboratory evaluation and *in situ* exposure at oiled and unoiled sites in Prince William Sound. Can. J. Fish. Aquat. Sci. 53: 2366-2375

Krebs, C. J. 1989. Ecological Methodology. Harper & Row, Publishers, Inc., New York.

MacLennan, D. N. and E. J. Simmonds. 1991. Fisheries Acoustics. Chapman & Hall, London.

McGurk, M.D. 1990. Early life history of Pacific herring: Prince William Sound herring larvae survey. Final report to NOAA-NOS, Contract 50ABNC-7-00141, Anchorage, AK.

McGurk, M. D. and E. D. Brown. 1996. Egg-larval mortality of Pacific herring in Prince William Sound, Alaska, after the *Exxon Valdez* oil spill. Can. J. Fish. Aquat. Sci. **53**: 2343-2354

Norcross, B.L. and M. Frandsen. 1996. Distribution and abundance of larval fishes in Prince William Sound, Alaska during 1989 after the *Exxon Valdez* oil spill. *In* S.D. Rice, R.B. Spies, D.A. Wolfe and B.A. Wright (eds.). *Exxon Valdez* Oil Spill Symposium Proceedings. *Am. Fish. Soc. Symp.*

Robinson, S. M. C. 1988. Early life history characteristics of Pacific herring, *Clupea harengus pallasi* Valenciennes 1847, in the Strait of Georgia, Brithish Columbia: hydrodynamics, dsipersal, and analysis of growth rates. Department of Zoology.

Scott, W. B. and M. G. Scott. 1988. Atlantic fishes of Canada. Can Bull. Fish. Aquat. Sci. 219: 731 p.

Simmonds, E. J. and R. J. Fryer. 1996. Which are better, random or systematic acoustic surveys? A simulation using North Sea herring as an example. ICES J. mar. Sci. 39-50

Sinclair, M. 1988. Marine Populations. Washing Sea Grant Program, Seattle, WA.

Sinclair, M. and T.D. Iles. 1985. Atlantic herring (*Clupea harengus*) distributions in the Gulf of Maine-Scotian Shelf area in relation to oceanographic features. Can. J. Fish. Aquat. Sci. 41:1055-1065.

Sokal, R. R. and F. J. Rohlf. 1981. Biometry - the principles and practice of statistics in biological research. Freeman, San Francisco, 859p.

Stokesbury, K. D. E. and M. J. Dadswell. 1989. Seaward migration of juveniles of three herring species, *Alosa*, from an estuary in the AnnapolisRiver, Nova Scotia. Can. Field-Nat. 103: 388-393.

Stokesbury, K. D. E. and M. J. Dadswell. 1991. Mortality of juvenile clupeids during passage through a tidal, low-head hydroelectric turbine at Annapolis Royal, Nova Scotia. N. Am. J. Fish. Manag. 11: 149-154.

Table 1. List of researchers we collected samples for during the May-August SEA Herring cruises.

1. Ken Bouwens, UAF; arrowtooth flounder, all sizes.
2. Kathy Frost, ADF&G Fairbanks, AK.; Marine Mammal Ecosystem. Needed various size fish of any species.
3. Jeff Short, Auke Bay, Juneau AK.; Needed herring and pollock.
4. Molly Sturdavent, Auke Bay, Juneau AK.; Needed capelin, sandlance, eulachon and pollock.
5. Tom Kline, PWSSC, Cordova AK.; Isotopes
6. John Piatt, NBS, Anchorage AK.; Needed juvenile herring and pollock
7. A.J. Paul, Seward Marine Center, Energetics, herring and pollock.
8. James Raymond, Univ. of Nevada; Needed blood and liver samples from herring in the Gravina or Montague area.
9. Steve Moffitt, ADF&G Cordova. Herring AWL.
10. Richard Kocan, UW; Disease; 60 juvenile herring from 5 sites, would like heart, liver and spleen removed, put in tubes, and kept cool.
11. Gary Marty, UC-Davis; Disease; Looking at herring from the Montague Is. area

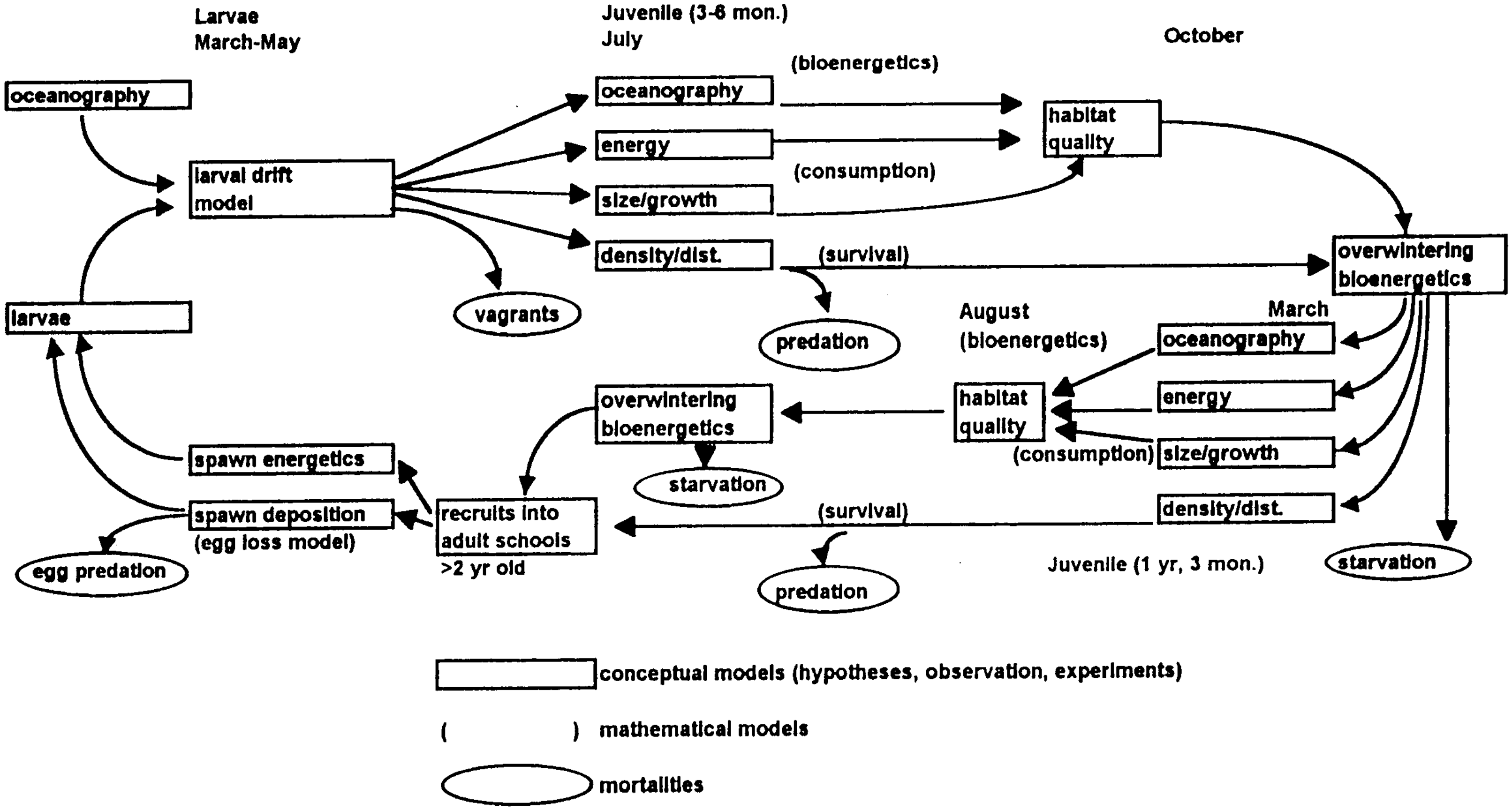
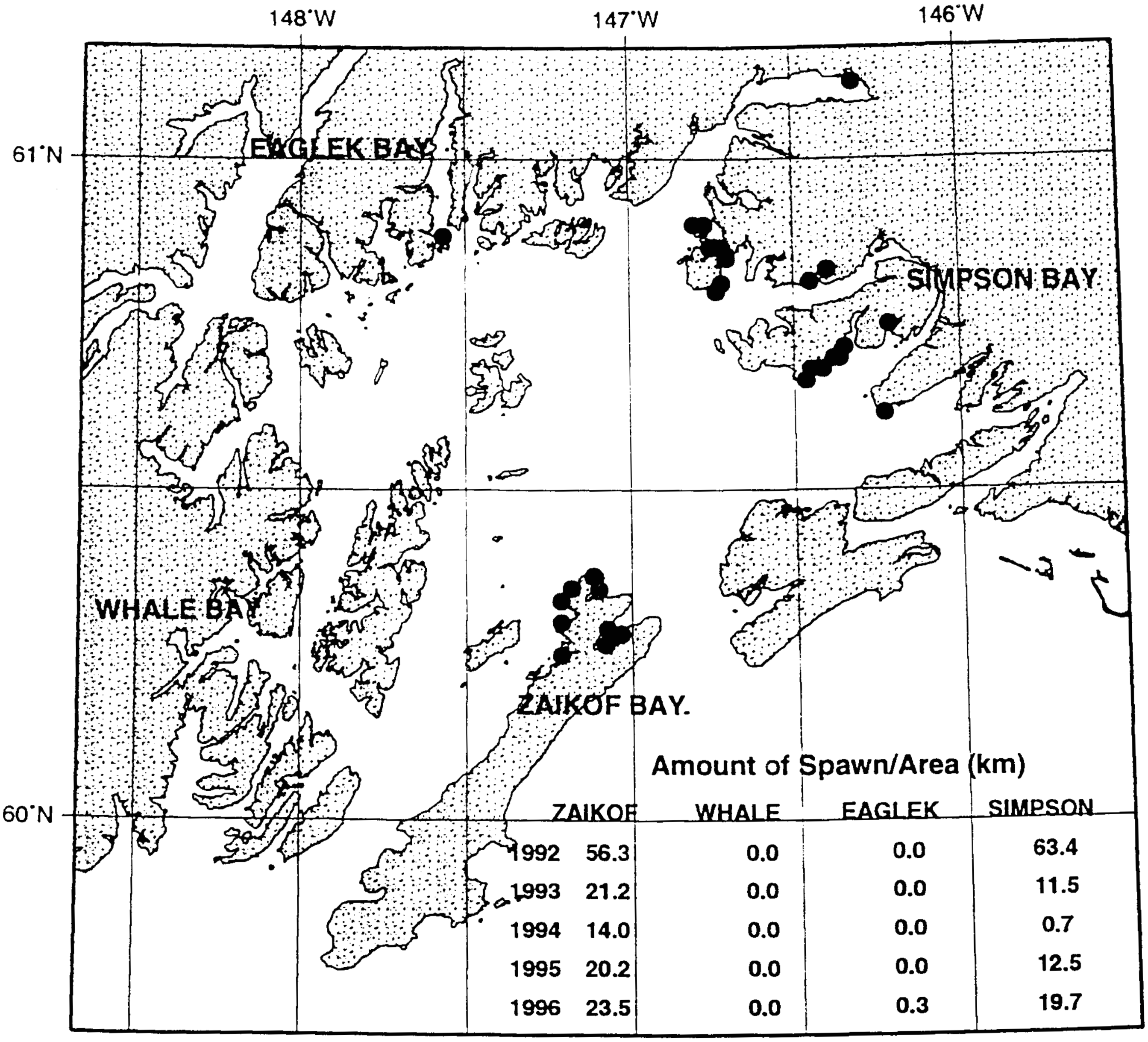


Figure 1. Herring Recruitment Model



Amount of Spawn/Area (km)

	ZAIKOF	WHALE	EAGLEK	SIMPSON
1992	56.3	0.0	0.0	63.4
1993	21.2	0.0	0.0	11.5
1994	14.0	0.0	0.0	0.7
1995	20.2	0.0	0.0	12.5
1996	23.5	0.0	0.3	19.7

Figure 2. Pacific herring spawning locations from 1990-1996. These data are summarized from reports produced by Alaska Fish & Game, Cordova. The dots represent the areas where spawning was observed and the distance of coast line is indicated in the table.

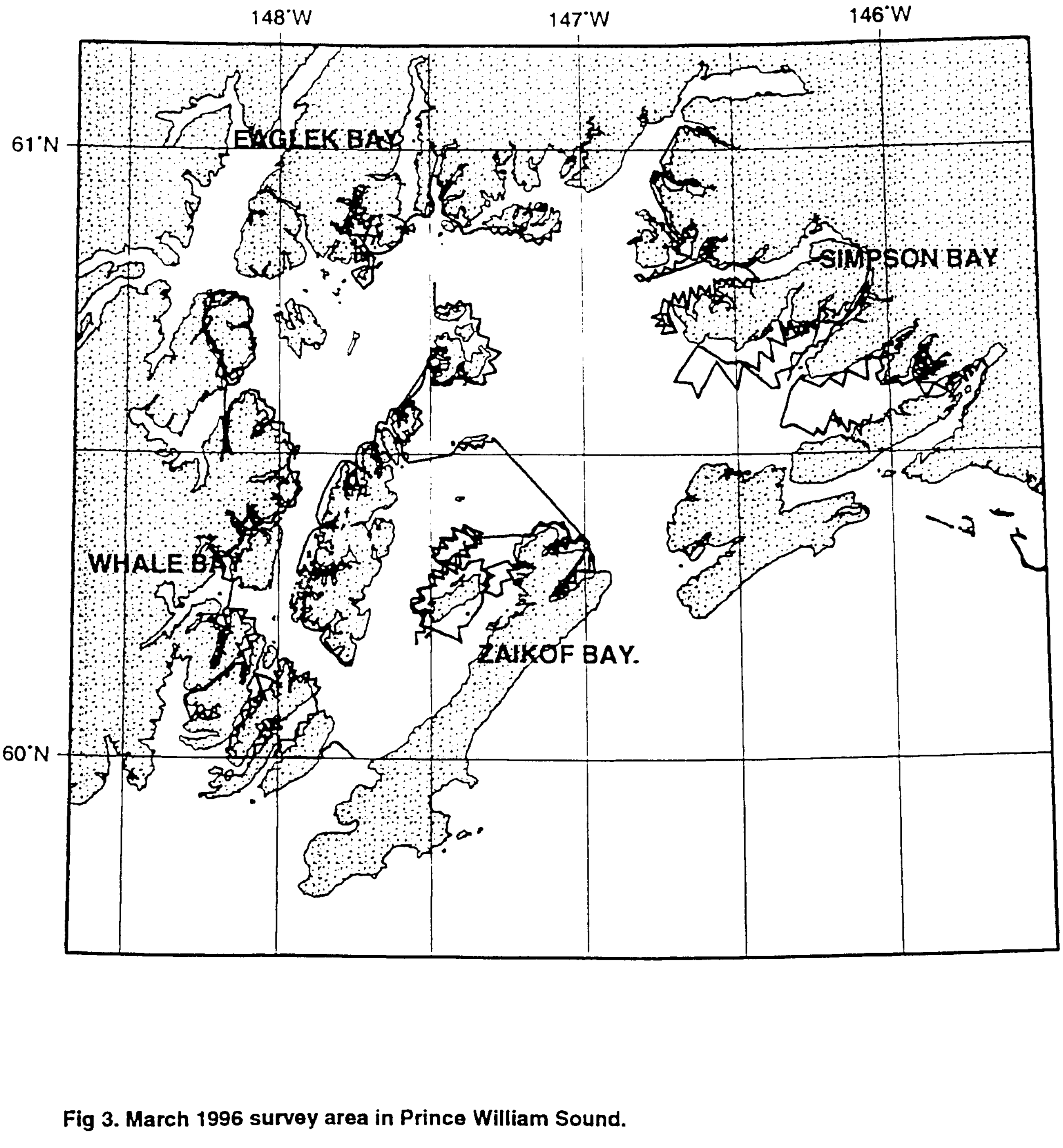
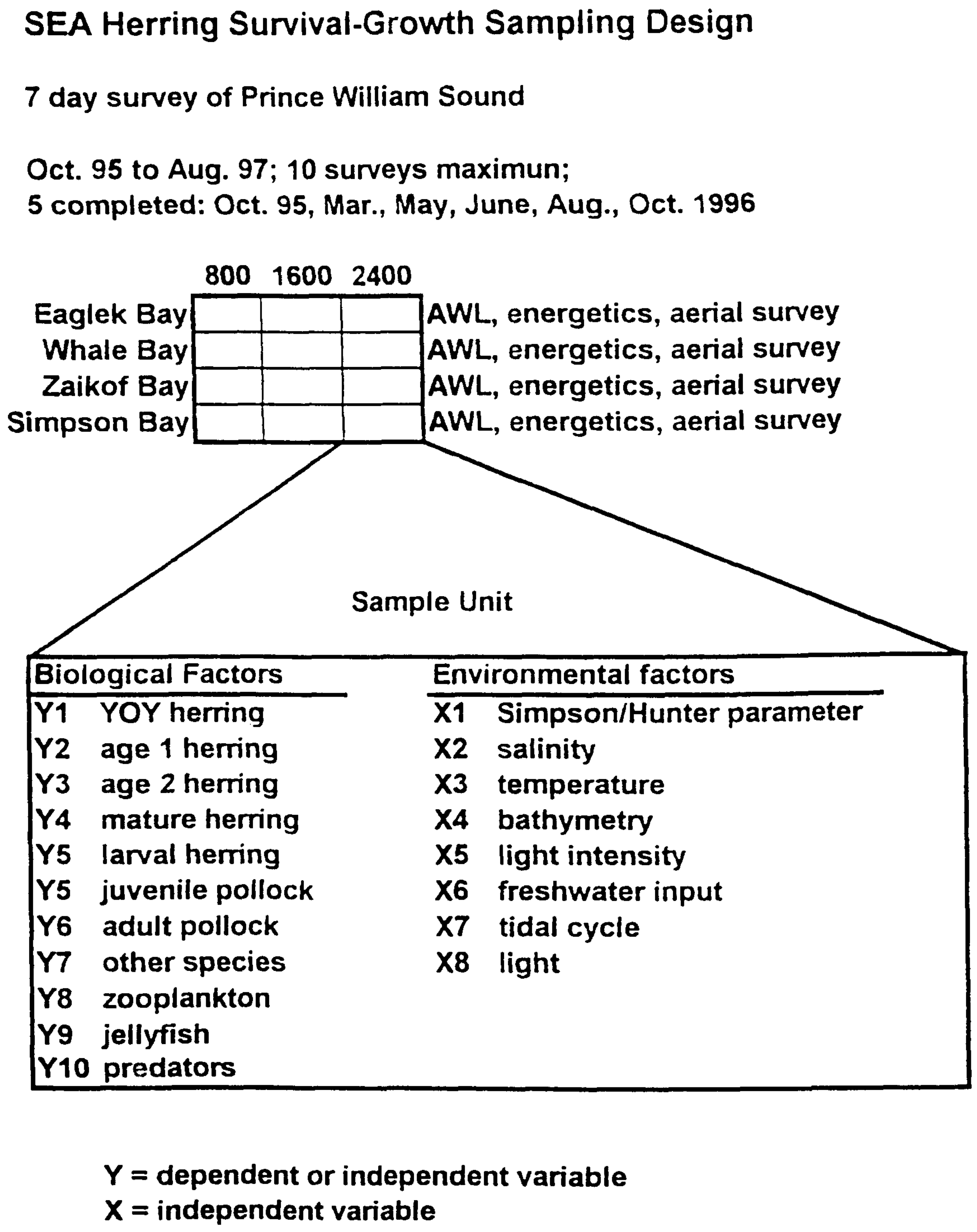


Fig 3. March 1996 survey area in Prince William Sound.



SEA Herring Survival-Growth Sampling Design

7 day survey of Prince William Sound

Oct. 95 to Aug. 97; 10 surveys maximun;
5 completed: Oct. 95, Mar., May, June, Aug., Oct. 1996

	800	1600	2400	
Eaglek Bay				AWL, energetics, aerial survey
Whale Bay				AWL, energetics, aerial survey
Zaikof Bay				AWL, energetics, aerial survey
Simpson Bay				AWL, energetics, aerial survey

Sample Unit

Biological Factors		Environmental factors	
Y1	YOY herring	X1	Simpson/Hunter parameter
Y2	age 1 herring	X2	salinity
Y3	age 2 herring	X3	temperature
Y4	mature herring	X4	bathymetry
Y5	larval herring	X5	light intensity
Y5	juvenile pollock	X6	freshwater input
Y6	adult pollock	X7	tidal cycle
Y7	other species	X8	light
Y8	zooplankton		
Y9	jellyfish		
Y10	predators		

Y = dependent or independent variable
X = independent variable

Figure 4. 4-bay diel sampling design.

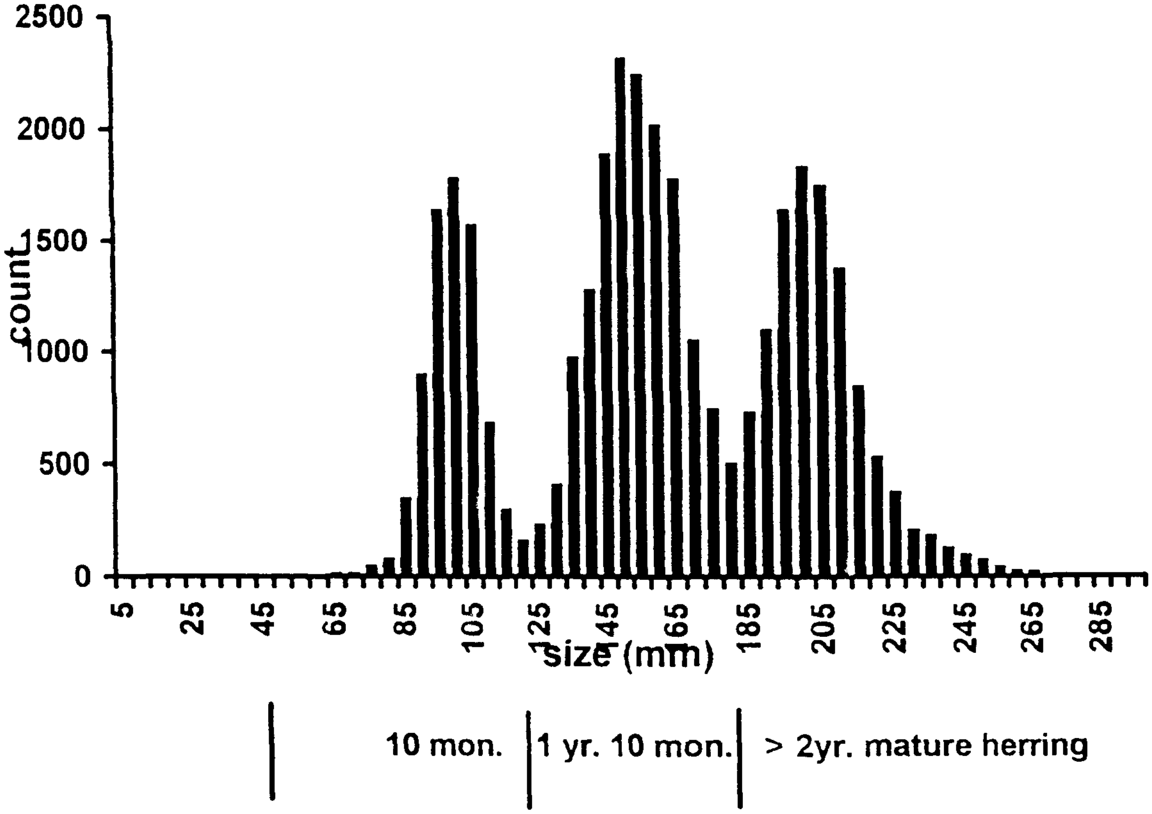


Figure 5. Size ranges of herring collected during March 1996 cruise.

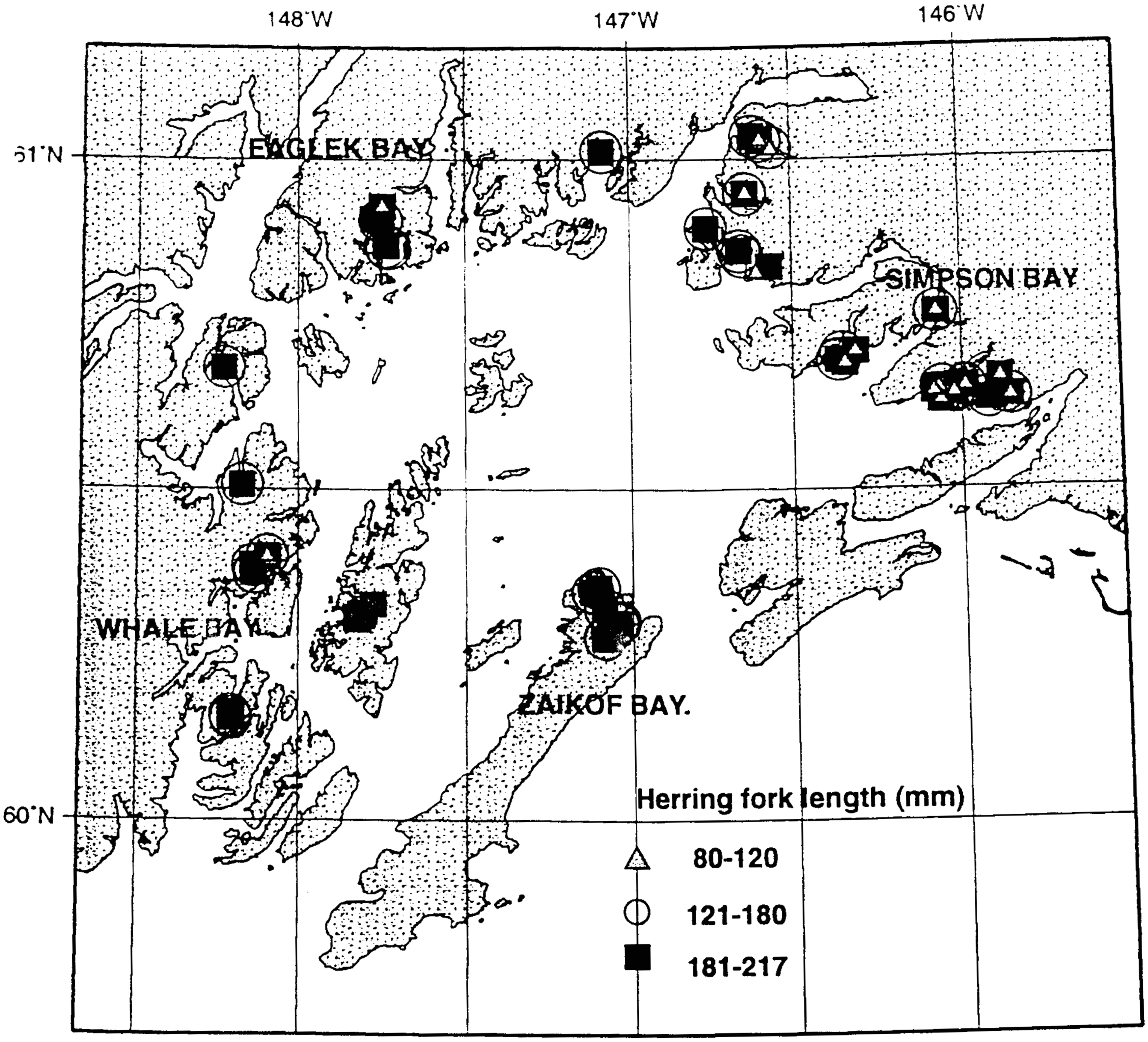


Figure 6. Spatial distribution of Pacific herring in Prince William Sound March 1996; present/absent data, i.e. if a size mode represented 10% of the catch it is marked.

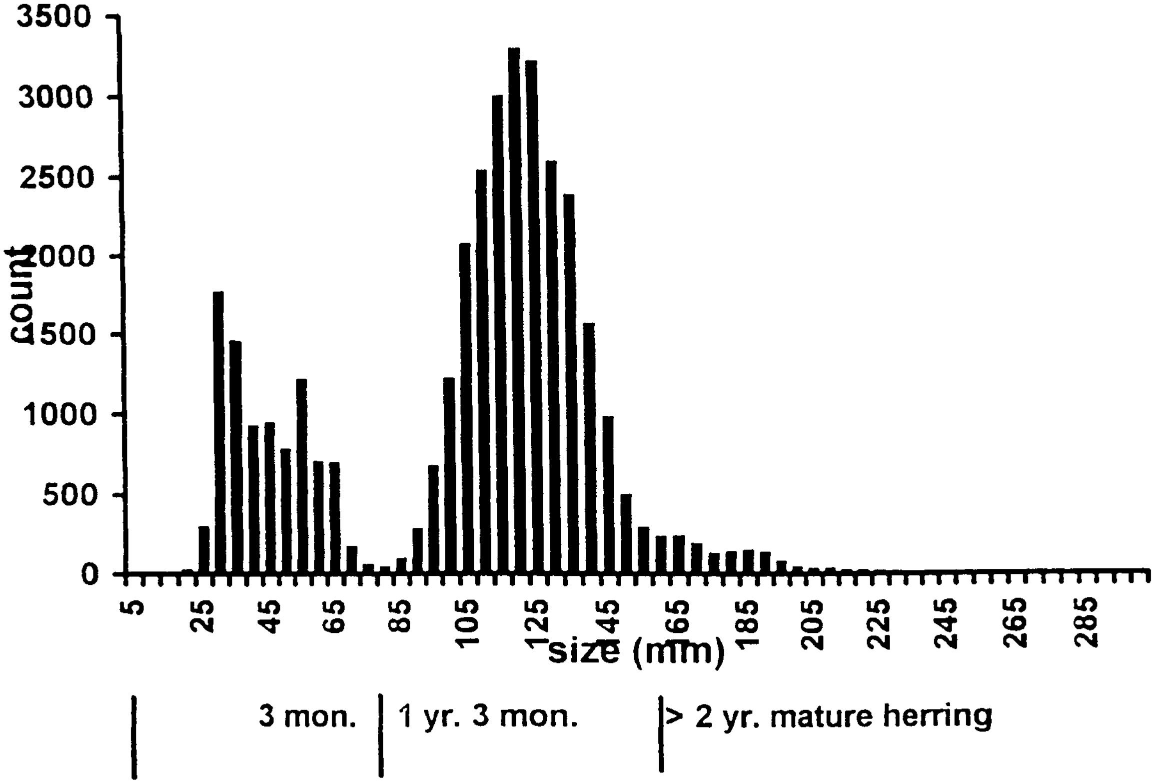


Figure 7. Size ranges of herring collected during July-August 1996 cruise.

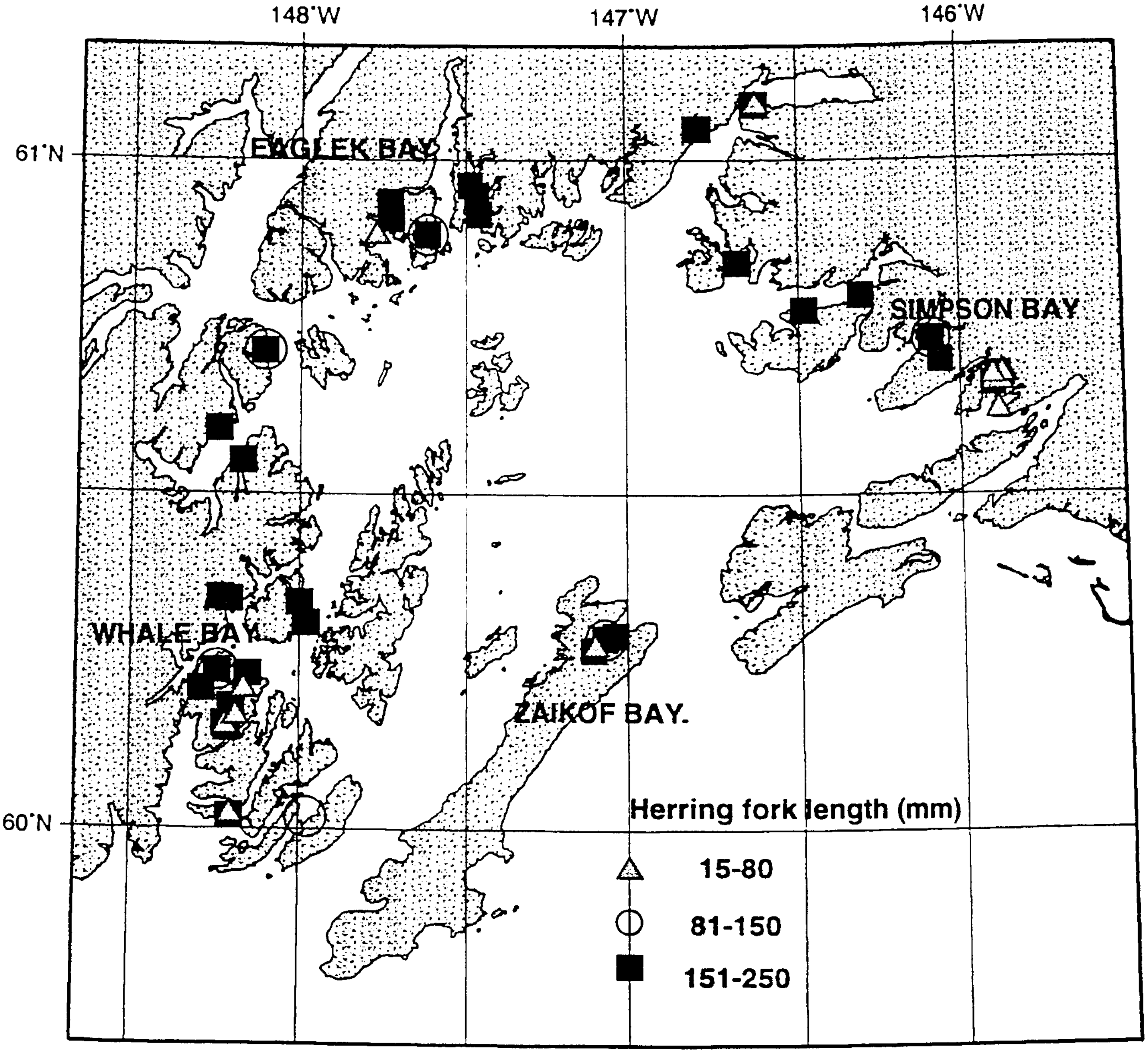


Figure 8. Spatial distribution of juvenile herring in Prince William Sound July-August 1996; present/absent data, i.e. if a size mode represented 10% of catch it is marked.

Apendix I

Evelyn D. Brown and Brenda L. Norcross. 1997. Assessment of Forage Fish Distribution and Abundance Using Aerial Surveys: Survey Design and Methodology. Draft for Fisheries Research

Assessment of Forage Fish Distribution and Abundance Using Aerial Surveys: Survey Design and Methodology

Fisheries Research

Evelyn D. Brown and Brenda L. Norcross
University of Alaska Fairbanks, School of Fisheries and Ocean Science, Institute of Marine Science
P.O. Box 757220, Fairbanks, Alaska 99775-7220, U.S.A.

Draft
April 2, 1997

Key Words: Aerial survey, line transect, herring distribution

Abstract

Broadscale aerial surveys were conducted in Prince William Sound and Outer Kenai, Alaska in 1995 and 1996 to provide information about distribution and relative abundance of juvenile Pacific herring and other forage fish including Pacific sandlance. Flight paths and sightings along shoreline transects were recorded using a laptop computer with automatic logging from a GPS. Survey condition bias was reduced by establishing weather and tidal stage criteria for flights. Each species of fish has a characteristic shape, color and sometimes behavior. Photographic documentation of the different schools is used for measuring differentiation ability and correcting observations. Sightings are compared to diver and net catch observations to provide validation of aerial identification. A PVC tube with a mylar grid held at a specific angle was used to measure the surface area of schools. The frequency distribution of schools sizes was used to establish a preferred altitude and a visual swath within which detection was uniform. The measurements were corrected for altitude and used to calculate fish density. A narrow-strip line transect best describes the survey design. Abundance estimates are a function of visual swath, surveyor bias, spatial distribution pattern (probability of detection) and school density along the transect line. Accuracy is established using results of double counts. Precision is established by calculating detection probabilities based spatial patchiness and by comparing density estimates to independent counts from acoustics or other remote sensing devices. An example of aerial survey data, including temporal and spatial trends in fish abundance and bird foraging activity, is described.

Introduction

Little was known about the distribution and relative abundance of juvenile Pacific herring, *Clupea pallasi*, and other forage fish in Prince William Sound (PWS), Alaska prior to the *Exxon Valdez* oil spill in 1989. Herring, sardines, anchovy, capelin, and sandlance are known to school in tight aggregations with distinctive shapes and are often found in oceanic surface waters (Mais 1974; Squire 1978; Fresh 1979; Blaxter and Hunter 1982; Hara 1985a; Misund 1993; Carscadden et al. 1994). Many pelagic fish are arranged in shoal or school groups (Cram and Hampton 1976; Smith 1978; Fiedler 1978). Distribution of herring and capelin is thought to be contiguous with known areas of seasonal aggregations unique to a particular population (Templeman 1948; Campbell and Winter 1973; Sinclair 1988; Stocker 1993).

In Prince William Sound (PWS), locations of herring (mainly adults) in the summer are known from historic fishing sites (Rounsefell and Dahlgren 1931) and archaeological records of native middens (DeLaguna 1938). Locations of spring adult spawning aggregations have been recorded since 1973 by the Alaska Department of Fish and Game (ADFG) (Brady 1987; Biggs et al., 1992). Anecdotal information from biologists and fishermen indicates that groups of small herring schools are visible from the air "all over the sound" during the summer (unpublished data, E. Brown and J. Seitz, University of Alaska, Fairbanks; Dan Sharp, personal communication, ADFG, Cordova). These historic records indicate that: 1) the summer distribution of adult herring is much broader than in the spring, 2) summer catches often included juvenile herring (age 2 or less) while spring catches at spawning sites did not, 3) juvenile herring are broadly distributed in PWS, and 3) there are large fluctuations in relative abundance of herring over a several year period reflecting variability in year class strength. If the scale of distribution and numbers of juvenile herring schools varies (probably in relation to year class strength), increased knowledge would alert us as to the availability of herring as forage food and to the health of the fishery in the future.

Information about distribution is needed in order to design effective surveys to assess populations. If the exact location of fish aggregations are not known and the distribution is highly contiguous, the number or size of sampling units or transects needed to assess distribution can be large (Fiedler 1978; Lo and Hunter, in prep). Ship surveys used to resolve distribution questions can be costly because they are slow, sonar beams (used to assess schools acoustically) are narrow and cover a small swath of water, and have limited access to many nearshore areas where fish may aggregate. Conversely, surveys from aircraft are relatively cost-effective because they are fast, the sampling swath in measured in hundreds of meters instead of meters, and they are not limited by shallow water. In addition, aerial surveys can cover a region over a shorter period of time enabling researchers to compare distributions from two separate regions in a single temporal period.

Fishermen have used aircraft to locate schooling fishes for many years (Lo et al. 1992; Hunter and Churnside 1995). The Alaskan herring fisheries have long depended on aircraft for stock assessment and to guide fishing vessels (Brady 1987; Funk et al. 1995). Canadian researchers in British Columbia have observed juvenile herring schools from the air during the summer and have initiated a summer juvenile herring survey to provide indices of future recruitment (Jake Schweigert, Department of Fisheries and Oceans, Nainaimo, British Columbia, Canada, personal communication).

Aerial surveys typically lack precision and are not sufficiently accurate to provide a stand alone estimate of stock biomass (Krebs 1989; Gunderson 1993; Hunter and Churnside, 1995). Variability due to sighting conditions, changes in vertical distribution of fish schools, and surveyor bias largely go unmeasured (Hunter and Churnside, 1995). In recent years, access to military technology has lead to an increased use of sophisticated light sensing and radar equipment for aerial fish school assessment that can eliminate some of the variability and bias and improve accuracy of aerial surveys (Hunter and Churnside 1995). However, this equipment is still relatively expensive to use.

This study measured and recorded sighting conditions, surveyor bias and variability due to changes in vertical distribution by: 1) correlating aerial survey with acoustic survey results (which provide an independent measure of fish density; Cram and Hampton 1976) and 2) using spectrographic imagers, which record without bias (Borstad et al. 1992; Funk et al. 1995), simultaneously with aerial techniques. The purpose of this paper is to demonstrate that aerial surveys can be designed and conducted to effectively and efficiently assess the distribution and relative abundance of near-surface schooling fishes. A secondary objective is to integrate the results of this survey with sea bird and marine mammal sightings since lack of forage fish has been cited as possible cause for recently observed population declines in Alaska (Merrick et al. 1987; Pitcher 1990; Loughlin et al. 1992; Hatch and Piatt 1994; Piatt and Naslund 1995)

School Shapes, Recognition, and Measurement

Different fish species have characteristic shapes and sometimes color. Herring have been described as round (Misund 1993; Figure 1) and often brown in color (Brad Hiel, Alaskan Fish Spotters Assoc., Homer, Alaska, personal communication). Capelin are often described as gray with dynamic crescent or U-shaped shaped schools (Carscadden et al. 1994). Anchovy schools are crescent or irregularly shaped (Squire 1978; Hara 1985a) and become more elongated at night (Hara 1985b). Schools of juvenile sandlance occur nearshore in dense, but not opaque, irregularly shaped schools (Martin Robards, U.S. Fish and Wildlife, N.B.S., Anchorage Alaska, personal communication; Figure 2). Jellyfish, especially moon jellies (*Aequorea sp.*), are easy to identify from the air because they are white, they form large irregularly shaped aggregations, and they remain stationary when the airplane lands for visual inspection (Figure 3). In this study, school shapes were described as round (Figure 1; generally herring), oblong (Figure 2), crescent or U-shaped (generally capelin; Carscadden et al. 1994), irregular, or streaks (Figure 3; generally jellyfish).

Fish schools were counted and surface area was estimating using a sighting tube. The sighting tube was constructed of PVC pipe with a grid drawn on mylar on the end (Figure 4). The focal length of the tube was 216 mm and can be calibrated for ground distance covered by reference line (X) for any survey altitude, when length of the grid reference line (L), focal length of the tube (F), and survey altitude (A) are known, by using the equation:

$X = A\ ({}^{L}/{}_{F})$ (Lebida and Whitmore 1985; Brady 1987). (1)

At an altitude of 305 m (1000 ft) the following categorical school sizes were related to a specific length or tick-mark on the mylar grid and correspond to the listed school diameter using equation 1:

dab	0.05-0.15 ticks or 0.7-2.1 mm on the tube represents a 1-3.0 m school diameter on the ground
small	0.20-0.30 ticks or 2.8-4.1 mm represents a 4.0 - 5.8 m school diameter
medium	0.40-0.70 ticks or 5.5-9.7 mm represents a 7.8 - 13.7 m school diameter
large	0.75 ticks or 10.4 mm and larger represents a school 14.7 m school diameter or larger (Figure 4).

The use of the grid was particularly important for large schools. For elliptical shaped schools, maximum length and maximum width provided a rough estimate of surface area; for irregularly shaped schools (U-shaped, long wavy bands, etc.) length and width of separate sections were measured and combined to give a total estimate. In 1995, the surface area of schools was estimated by categorizing school size and checking occasionally with the tube for eyesight calibration. In 1996, the surface area of every school was directly measured with the tube. Video or still cameras were taken as often as possible to provide validation of school recognition when matched with catches and for measurement of recognition error (explained below).

Field Data Collection

Broad scale aerial surveys covered PWS and Outer Kenai from Hinchinbrook Entrance to Nuka Point (Figure 5). A survey of the entire area required 6 days and consisted of 3-6 hrs each day flying a Cessna 185 float plane at approximately 110 knots. An area approximately 1/5 the size of PWS (about 3,400 km^2) was denoted at the beginning of each survey day and the pilot followed the shoreline within this area to the best of his ability. Areas inaccessible due to topography or weather were not sampled. The transect or shoreline was followed in a single line but double backs were allowed when school or recorded feature density was high to ensure total counts within a given swath area. Since the flight path was recorded, the increase in sampling frequency of areas with high feature densities was measured to ensure that proper statistical weighting was given.

Preferred Altitude

The preferred altitude range was established at 275 - 365 m (900-1200 ft) based on school size. Juvenile herring schools (modal frequency 3-50 m^2; Figure 6) were much smaller than spawning aggregations (modal frequency 100 - 300 m^2 measured in Bristol Bay; Funk et al. 1995). Therefore the preferred altitude for herring (Lebida and Whitmore, 1985) or capelin (Carscadden et al. 1994) spawner surveys (457 m or 1500 ft) was too high to distinguish 1 m^2 schools. An altitude of 305 m (1000 ft) provided a swath width of 762 m (Figure 7) but allowed distinction of an object as small as the smallest school observed as well as a single gull or sea otter. At times lower altitudes were flown due to a low cloud ceiling, but each altitude change was noted on the computer during the survey.

Visual Swath

The visual swath, dependent on altitude, was established in 1995. By flying repeatedly over a familiar landscape (an airport runway with numbers and letters) at each possible altitude, the transect or swath width was established perpendicular to the airplane. The swath width included the area within which we could accurately observe features that were a similar size to schools or gulls we encountered during the survey (Figure 7) and that could be measured with the sighting tube held at a fixed angle of 30 degrees (Lebida and Whitmore, 1985). Ground reference points of known or easily measurable surface areas, such as a helipad, were used to train the eye to the scale on the sighting tube grid for any specific altitude flown prior to each survey series.

Preferred Season

Plots of monthly herring school counts and total school surface area recorded per survey day for PWS in 1995-96 are plotted in Figures 8 and 9. Although in both years, there was a sharp increase in the numbers of schools observed per survey from May until June, there was a decrease in total surface area of schools observed per survey in 1996. In 1996, observation of a number of large spawning schools in May was followed by a shift in school size with increased numbers of smaller schools showing up in June. Since surface area is exponentially related to school radius (πr^2) a few large schools will result in significantly more surface area than many small schools. By July, numbers of schools and school surface areas increased in 1995, but decreased in 1996. The downward trend in

August occurred in both years, but counts that month were only slightly less than in July. From these preliminary results, we determined that the preferred months to census juvenile herring was June and July in order to avoid including adult spawners in the data and to fly at a time when numbers of surface schools are at a maximum.

Preferred Tide Stage and Time of Day

We tried to account for or eliminate the effects of time of day or tide stage on the survey results by flying repeat surveys during the day or flying during the same tide stage whenever possible. Carscadden et al. (1994) preferred sunny days with the sun angle between 20° and 45° in order to reduce glare and lands shadows for aerial photography of capelin schools but did not mention tide as affecting survey results. Borstad (personal communication, G.A. Borstad Assoc., Sidney, British Columbia) preferred sunny days with the sun directly overhead for aerial imaging of schools. Although we did not target surveys for a particular time of day, we did target surveys for the slack low or flood tide stage (Lebida and Whitmore, 1985), noting in the log program whenever this was not possible. In order to explore the effects of tide or time of day, all sightings of herring schools within the months of June and July were categorized into three daylight and three tidal components: early (0600 to 1000), midday (1030-1430), early evening (1600-2000), flood tide, ebb tide and low tide (no surveys were done at slack high water). Survey results were standardized by sightings per survey (all surveys approximately equal in length). Although there were more schools and surface area of schools counted during midday and ebb tide periods, the means were not significantly different ($p>0.05$) from mean sightings taken other periods. Because of the high variability of the data, this analysis of means should be repeated using duplicate surveys of single bays or regions flown within a 48 hr period. Based on preliminary results, we concluded that our criteria for tide preference was appropriate for future surveys.

Data Collection

Both flight path (transect) and features along path were recorded during the survey. A hand held GPS connected to a lap top computer with a flight log program recorded latitude, longitude, and time of day in a 2 second interval. At the beginning of each flight, information detailing pilot, weather, water visibility, wind, wind direction, tide stage, wave height and other notes concerning the survey were recorded in the log program. Information or "sightings" such as numbers of fish schools, species of fish, surface area of schools, numbers of birds or mammals, behavior of birds, or oceanographic features (tidal fronts) were recorded on the computer log program. Net captures, acoustic surveys, diver surveys, validation via landing on top of schools, or observations recorded on film were also recorded on the log program. However, school validation was often a post-processing procedure since net catch, acoustic, or other data had to be matched after editing and since not all validation efforts were observed from the air. For each observation, the computer logging was interrupted, the sighting noted and the approximate location linked to the last latitude and longitude recorded. Single or double letter codes were developed for fish, bird and mammal species (such as h for herring, sd for sandlance, kw for kittiwakes, hs for harbor seals etc). Bird behavior was recorded as foraging or plunging (pl), resting on water (rw), resting on shore (rs), aggregated tightly on water over school (tw), traveling (tr) or flying in a "broad area search" (bs).

In order to minimize the effect of survey condition bias on accuracy of the results, we selected criteria for determining whether a survey should be flown or not. We did not fly if the winds were over 25 knots (creating a sea state of over 1 beaufort scale or 1 m wave heights), if the average ceiling (cloud cover) was below 300m, or on rainy days.

Survey Design and Data Analysis

Adaptive sampling methods using a modified line transect were adopted for this survey. The main data output is a measure of relative (rather than absolute) density of fish schools and other detectable events such as foraging gulls (Iron 1992). Using anecdotal information from fishermen and aerial surveyors, it was determined that most of our observations were likely to be nearshore. Although we sampled offshore to test this hypothesis, we choose to modify the standard line transect (Thompson 1992; Krebs 1989) by following a shore line as a transect path. We sampled offshore areas when crossing bays and bodies of water to reach other shorelines. We eliminated the problem of decreasing detectability with distance perpendicular to the transect center (Krebs 1989; Gunderson 1993) because we established an altitude dependent visual swath with uniform detectability (described in previous section). Therefore, we assumed that detectability was a function of survey conditions (water visibility, precipitation, surface water disturbances or wind-driven waves), glare, spatial distribution of schools and school aggregates, and surveyor bias. This method is equivalent to the "narrow-strip" method suggested by Thompson (1992). Only features observed within the visual swath were recorded. It is therefore likely that density or abundance estimates derived from this survey are a function of: 1) effective area surveyed (altitude), 2) detectability, and 3) density of the detection's along the transect line (Thompson 1992). Surveyor bias is related to density because counting error increases with counting rate (especially in situations where there are a lot of schools; Gunderson 1993). In this situation, most surveyors tend to undercount (Krebs 1989). It is for this reason that a measure of survey bias is critical.

Estimating Density

Using narrow-strip transect methodology we can ignore the probability of sightings with distance estimates. The narrow-strip is the visual swath. Density is estimated using the following equation (Thompson 1992):

$$\hat{D} = \frac{y_0}{2w_0L} \tag{2}$$

where y_0 is the number of fish or total surface area of fish schools spotted along the transect length L, w_0 is the maximum distance from the center line to which delectability is uniform ($2w_0$ is equivalent to swath width), and $\hat{D}$ is the estimate of fish schools or school surface area along that transect section. Within a study region with an area A, the total number of fish schools or school surface area ($\hat{\tau}$) is estimated as:

$$\hat{\tau} = A\hat{D} = \frac{Ay_0}{2w_0L} \tag{3}$$

Because transects were not selected randomly, we do not attempt to expand the density estimates to areas not surveyed. Since all schools recorded were inside the visual swath, no observations are left out of the analysis. This removes the disadvantage of using narrow-strip methodology since generally observations are left out of the analysis (Thompson 1992). It would be difficult to use other methods of expansion of the data since estimates of distance off transect line were not estimated in this survey.

Estimating Accuracy and Precision

In order to use the survey as an index of abundance, the accuracy and precision of the survey results had to be established. In order to establish precision which is most affected by surveyor bias, synoptic independent or double counts were completed (Seber 1982; Rivest et al. 1995). By comparing recults from two individual surveyors to one another, a level of error or bias can be estimated and used to account for vaiability is survey results. Rivest et al. (1995) found that aerial surveyor visibility bias measured using double counts was relatively small (10-13% of total). Simultaneous double counts eliminates the confounding bias from variable survey conditions, generally encountered when estimating individual surveyor bias, since both surveyors experience the same survey conditions during each count. In order to measure individual ability to recognize schools, several surveyors are shown up to 100 randomly sorted photographs of pre-identified fish schools and scored on their accuracy in identification . This identification error along with surveyor bias is incorporated in the estimates of fish school density. Higgins (1990) found that bias from aerial surveyors is best represented by a linear correction model with a multiplicative error term. With only four repeat surveys conducted with independent counts, the results of the double counts and estimates of surveyor bias are not included in this report.

Estimation of accuracy of this technique is critical in order to apply it as an abundance estimator. Since herring are generally clustered in discrete aggregations or school groups (Templeman 1948; Cram and Hampton 1976; Blaxter and Hunter 1982; Sinclair 1988; Stocker 1993), detection of the schools is a function of the diameter of both school aggregations and individual schools (Hunter and Churnside 1995). Since the probability of school detection (*p*) affects the confidence in the abundance estimate (Thompson 1992; Lo and Hunter, in prep.), the number of swaths or transects flown should be a function of *p*. The following two equations can be used to estimate *p* within length of coast or ocean L:

$$p = 1 - \prod_{i}^{M} [1 - \frac{x_i + y}{L}] \qquad (4)$$

and

$$x_i = \underset{j}{\mathrm{Y}} x_{ij} \qquad (5)$$

where y is the swath width, x_i is the diameter of fish school group i and x_{ij} is the diameter of fish school j within aggregation i. Lo and Hunter (in prep.) ran simulations on how swath width affected the probability of detection of anchovy schools and found that the chance encounter with an aggregation of schools given the size of the habitat had much more effect on *p* than the swath width. For herring in PWS, because of the reduced area of distribution as compared with pelagic anchovy, *p* is probably more affected by swath width.

Accuracy of the density estimates collected by air can only be truly estimated by comparing aerial survey results to results of an independent survey of relative biomass, which is assumed to be a true value. Optimally, the aerial and acoustic surveys are synoptic. Acoustic measurements were made in several areas overlapping aerial transects. Both data sets are plotted graphically; overlapping catches, acoustic sightings identified by target strength are compared to sightings of herring schools and other fish. In 1996, overflights were conducted synoptically with both broadscale and repeat acoustic surveys (within particular bays) and with diver surveys. An example of the overlay of this data is presented in the results.

Regional and Seasonal Distribution Comparisons

All processed and corrected flight data was plotted graphically. Visual reviews of the plots reveal the type of distribution (contiguous) and approximate size of school aggregates. For statistical analysis, the size of a particular sampling unit (approximate size of aggregates) are estimated to use as replicates within a particular region of interest. Besides visual analysis, the surface area in a sample unit is determined by gridding each region into successively smaller units and examining the means and variance of each grid size. The comparison of the means to the variance indicates the type of distribution, whether random, contiguous or regular. The distribution type is confirmed by calculating a poison (random) and negative binomial (contiguous) and comparing the calculated distributions to the actual distributions observed to determine the best fit. The actual size of the spatial aggregation (ecological unit) is estimated by calculating indices of dispersions (e.g. Mortisita's Index or Standardized Index; Krebs 1989). An alternative method is to conduct a power analysis to determine the unit size that gives us the lowest variance in the ANOVA. However, this latter method may not provide enough information. The optimal range of sample units (school aggregation size) for analysis is described in km^2 . The range in size of the ecological unit may vary with fish density and habitat type. This possibility can be examined via this type of analysis.

For statistical comparisons, the density of fish is estimated for each ecological unit within a given season or year and compared for significant differences. The densities of units are compared to similarly gridded observations of other fish species whether gathered by aerial means or acoustics as well as hydrographic data (water temperature and salinities).

An Example of Aerial Survey Results

Herring and Pacific sandlance (*Ammodytes hexapterus*) schools seen from the air in 1996 from two regions in PWS (Figure 5) were plotted with bird observations along with identification of schools by divers and net catches. Herring and sandlance school surface areas by location were plotted for southwestern (July 17-18; Figures 10) and central PWS (July 20-21; Figure 11). The total lineal distance flown for each day was 227.64 km on 7/17, 215.05 km on 7/18, 97.21 km on 7/20 and 175.75 km on 7/21. Diver-identified fish schools (Steve Jewett, personal communication, University of Alaska, Fairbanks) and net captures (Lew Haldorson, personal communication, University of Alaska, Juneau) were plotted to show validation of aerial identified species. When the surface areas of schools along the transect were plotted (Figures 12 and 13), the patchy aggregations of school groups was obvious pointing to a contiguous distribution. These plots serve as an example of how the data can be analyzed visually prior to statistical treatments. Bouts of predation by gulls (Figure 10-11), diving birds, and marine mammals were easily discernible from the air.

Densities of school surface areas were also calculated from the survey data for these four days. Although herring schools were much more numerous in the SW area than sandlance (Figure 12), sandlance schools were larger and dominated over herring in terms of density in both areas. In the SW area, the density of herring was 1.12×10^{-5} m^2 school surface area · m^{-2} transect area versus 1.36×10^{-5} for sandlance (Figure 14). In the central area, sandlance schools were more numerous (Figure 13) and the density (5.67×10^{-5}) was much higher than in the SW area (Figure 14). Herring were less numerous and densities were lower (4.13×10^{-6}) in the central area compared to the SW.

Two of the most commonly sighted fish species from the air during the months of this survey were herring and sandlance. Herring schools were characteristically round and opaque with a dark brown coloring and generally found at an average of 24 m (St Dev. 32 m) from shore (Figure 1). Sandlance schools were oblong or irregularly shaped, gray in color and translucent to the bottom (Figure 2; bottom features such as rocks or changes in substrate were easily seen through the school) and found much closer to the beach on an average at 4 m (St. Dev. 1.2 m) from shore. In 1996, herring schools averaged 47.2 m^2 (St. Dev. 63.31) while sandlance schools averaged 190.8 m^2 (St. Dev. 382.7). Because of the variability in school size, size alone was not always sufficient to differentiate the two within the data set. However, because over 95% of the herring schools were characterized as round and 90% of the sandlance schools were characterized as oblong or irregular, the two can be differentiated by shape. The actual measurements of individual ability to recognize schools will provide a more quantitative estimate of the differentiation.

Proportions of schools associated with foraging birds were summarized in 1995. In May the proportion of schools with birds was 50% increasing to 71.1% in June (Figure 15). Foraging fell off in July to 57.6% with the declining trend continuing in August to 42.3%. There is no doubt that the majority of these birds were actively foraging on the schools since of the 276 behaviors recorded, 104 were plunging and 121 were milling (behaviors associated with actively feeding birds; Irons 1992). The trend of increasing proportion of schools with birds was opposite the trend in abundance of schools and school surface area (Figures 8 and 9). This may represent predator swamping (large numbers of schools available compared to numbers of birds), a restriction in bird foraging area due to nesting activity (personal communication, Dave Irons, US Fish and Wildlife Service, Anchorage, Alaska), or prey switching whereby alternate prey is available to the birds. The results of this survey provides sea bird researchers a "bird's eye" view of the seasonal forage available to the birds as shown their association with schools and behavior.

Discussion and Recommendations

The shortcomings of aerial survey as a monitoring tool are obvious. There is surveyor bias (overcounting or undercounting), survey conditions can greatly affect survey results (which we reduced by flying in fair weather), silt from river runoff can impact the ability to see into the water column, and only a small percentage of schools sighted from the air can be validated via catches or divers. The strengths of this survey method are that a large area can be covered in a short period of time and the costs are far less than a survey conducted from vessels alone.

This survey provides information about overlap in distribution between the two species readily visible from the air (herring and sandlance) as well as seasonal and spatial changes in bird and mammal foraging on fish schools. This information may give sea bird and mammal researchers insight as to changes in diet, condition and reproductive success of their respective study animals. It can specifically provide insight as to when prey switching occurs for birds. An example would be that observed reductions in gulls associated with fish schools spotted from the air may coincide with out migration of salmon fry from streams and increased predation by birds on those fry. This phenomena was observed from the air in 1996 between May and June in eastern PWS. Logerwell and Hargreaves (1996) found a negative relation to forage fish and sea bird density, but they cite the cause as fish avoidance of the nets. The same problem can occur with boat avoidance during acoustic vessel surveys. In addition, forage fish are often in areas where vessels, acoustics and nets cannot reach. All of these problems are avoided when using an airplane.

When coupled with net catch and habitat data, the seasonal and interannual trends in observations of surface schools can be better interpreted. The increase in surface schools nearshore in June and July may be due to increases in food availability or predator avoidance. This habitat data is available for the years this survey was conducted. The difference in seasonal distribution of surface schools between the two years shown in Figures 8 and 9 could be due to differences in year class strength. Pacific herring in PWS metamorphose from the larval stage in July (Norcross et al. 1996) and are likely observed from the air as new schools starting during that month. In June, only age-1 juvenile herring are likely to be visible from the air. Depending on which year class was stronger, the peak of numbers and surface areas of schools may vary between the two months. Catch data available for the years of this survey will provide the answer.

Although we are just beginning to plot and analyze the data, it was important to document the work we have done and compare it to other survey techniques. Aerial survey methodology has improved dramatically in the past 10 yrs. The use of GPS, high resolution and night vision cameras, and remote sensing devices (Nakashima and Borstad 1993) such as LIDAR (light detecting and ranging derived by analogy from radar; Oliver et al. 1994) and CASI (compact airborne spectographic imager; Borstand et al. 1992) have allowed researchers more precision in mapping flight paths and visual swaths as well as unbiased survey results (Hunter and Churnside, 1995). Although the remote sensing tools are efficient, they are expensive and take highly trained staff to operate. The methods outlined for this survey are much cheaper due to lower technology, but have the associated problems of surveyor bias. The results and utility of this survey could be greatly improved with the correlation to synoptic acoustic data and by conducting a companion CASI survey for at least a portion of the survey area. With the correlation to independent survey methods, we can determine the amount of precision expected from our survey results and decide if this tool alone is sufficient to answer the research questions posed. It may be that the most cost-effective yet sufficiently accurate monitoring tool available may be a combination of a broadscale survey using the techniques described in this report paired with a smaller scale acoustic and CASI survey.

Acknowledgments

This project was funded by the Exxon Valdez Oil Spill Trustee Council through the Sound Ecosystem Assessment project. However, the findings presented by the authors are their own and do not necessarily represent the Trustee Council position. Personnel from Alaska Department of Fish and Game (ADFG), in particular James Brady, John Wilcock and Dan Sharp were instrumental in providing me with ideas, training, and a sighting tube. I wish to thank researchers Kevin Stokesbury, Steve Jewett and Lew Haldorson from the University of Alaska and Tom Dean, Coastal Assoc. for coordination with their acoustic, catcher and diver vessels. I would like to thank all of those who flew with me and shot film from the back seat or conducted independent counts. Finally, I would like to thank Cordova Air Service (Kim and Dave Erbey) for their excellent aircraft and flexibility in scheduling and in particular Pat Kearny my survey pilot.

Literature Cited

Biggs, E.D., B.E. Haley, and J.M. Gilman. 1992. Historic database for Pacific herring in Prince William Sound, Alaska, 1973-1991. Alaska Dept. Fish and Game Regional Information Report No. 2C91-11, Anchorage, Alaska. 335 pp.

Blaxter, J.H.S., and J.R. Hunter. 1982. The biology of clupeoid fishes. Adv. Mar. Biol. 20: 1-223.

Borstad. G.A., D.A. Hill, R.C. Kerr, and B.S. Nakashima. 1992. Direct digital remote sensing of herring schools. Int. J. Remote Sending 13(12): 2191-2198.

Brady, J. A. 1987. Distribution, timing, relative biomass indices for Pacific herring as determined by aerial surveys in Prince William Sound 1978-1987. Prince William Sound Data Report No. 87-14. Alaska Department of Fish and Game, Div. of Commercial Fisheries, Juneau, AK. 11 pp.

Carscadden, J., B. Nakashima, and D.S. Miller. 1994. An evaluation of trends in abundance of capelin (Mallotus villosus) from acoustics, aerial surveys and catch rates in NAFO Division 3L, 1982-89. J. Northw. Atl. Fish. Sci. 17: 45-57.

Campbell, J.S., and G.H. Winter. 1973. Some biological characteristics of capelin, *Mallotus villosus*, in the Newfoundland area. ICNAF Redb. 1973 (III): 137-144 (also ICNAF Res. Doc. 73/90, Ser. No. 3048).

Cram, D.L., and I. Hampton. 1976. A proposed aerial/acoustic strategy for pelagic fish stock assessment. J. Const. Int. Explor. Mer. 37(1): 91-97.

DeLaguna, F. 1938. Chugach pre-history.

Fiedler, P.C. 1978. The precision of simulated transect surveys of northern anchovy, *Engraulis mordax*, school groups. Fish. Bull., U.S. 76(3): 679-685.

Fresh, J.L. 1979. Distribution and abundance of fishes occurring in the nearshore surface waters of Northern Puget Sound, Washington M.S. Thesis, Univ. of Washington, Seattle, 120 p.

Funk, F.C., G.A. Borstad, S.A. Akenhead. 1995. Imaging spectrometer detects and measures the surface area of Pacific herring schools in the Bering Sea. Third Thematic Conference on Remote Sensing for Marine and Coastal Environments, Seattle WA, September, 1995. pp II-833-844.

Gunderson, D.R. 1993. Surveys of Fisheries Resouces. John Wiley and Sons, Inc., New York, New York, pp. 183-205.

Hatch, S.A. and J.F. Piatt. 1994. Status and trends of seabirds in Alaska. U.S. Department of the Interior, National Biological Survey, Report on Status and Trends of the Nation's Wildlife, Washington D.C., in press.

Hara, I. 1985a. Shape and size of Japanese sardine school in the waters off the southeastern Hokkaido on the basis of acoustic and aerial surveys. Bull. Jap. Soc. Sci. Fish. 51(1): 41-46.

Hara, I. 1985b. Moving direction of Japanese sardine school on the basis of aerial surveys. Bull. Jap. Soc. Sci. Fish. 51(12): 1939-1945.

Higgens, P.S. 1990. Counting errors in aerial surveys of spawning salmon: some effects on long-term management performance and economic benefit from Wood River sockeye salmon (*Oncorhynchus nerka*). Masters Thesis, Simon Fraser University, British Columbia, Canada. 98 pp.

Hunter, J.R. and J.M. Churnside. 1995. Airborne fishery assessment technology: a NOAA workshop report. NOAA AWFSC Admin. Rep. La Jolla, California, LJ-95-02. 71 pp.

Irons, D.B. 1992. Aspects of foraging behavior and reproductive biology of the Black-legged Kittiwake. PhD. Dissertation, University of California, Irvine. 143 pp.

Krebs, C.J. 1989. Ecological Methodology. Harper Collins Publishers, New York, New York. pp. 93-104

Lebida, R.C. and D.C. Whitmore. 1985. Bering Sea herring aerial survey manual. Bristol Bay Data Report No. 85-2. Alaska Department of Fish and Game, Div. Commercial Fisheries, Anchorage AK.

Lo, N.C.H., and J.R. Hunter. In prep. Some statistical considerations of using light detecting and ranging (LIDAR) technololgy to assess biomass of epipelagic fish. Southwest Fisheries Science Center, La Jolla, CA.

Lo, N.C.H., L.D. Jacobson, and J.L. Squire. 1992. Indices of relative abundance from fish spotter data based on delta-lognormal models. Can. J. Fish. Aquat. Sci. 49 (12): 2515-2526.

Logerwell, E.A., and N.B. Hargreaves. 1996. The distribution of sea birds relative to their fish prey off Vancouver Island: opposing results at large and small spatial scales. Fish. Oceanogr. 5 (3/4): 163-175.

Loughlin, T.R., Perlov, A.S., Vladimirov, V.A. 1992. Range-wide survey and estimation of total numbers of Steller sea lions in 1989. Mar. Mamm. Sci. 8: 220-239.

Mais, K.F. 1974. Pelagic fish surveys in the California Current. Calif. Dept. Fish Game, Fish. Bull. 162:1-79.

Merrick, R.L., T.R. Loughlin, and D.G. Calkins. 1987. Decline in abundance of the northern sea lion, *Eumetopias jubatus*, in Alaskam 1956-86. Fishery Bulletin 85: 351-365.

Misund, O.A. 1993. Abundance estimation of fish schools based on a relationship between shcool area and school biomass. Aquat. Living Resour. 6:235-241.

Nakashima, B.S. and G.A. Borstad. 1993. Detecting and measuring pelagic fish schools using remote sensing techniques. ICES Report C.M. 1993/B:7 Session T, Fish Capture Committee. 18 pp.

Oliver, C.W., W.A. Armstrong, and J.A. Young. 1994. Development of an airborne LIDAR system to detect tunas in the eastern tropical Pacific purse-seine fishery. NOAA-TM-NMFS-SWFSC-204. Southwest Fisheries Science Center, La Jolla, CA. 67 pp.

Piatt, J.F. and N.L. Naslund. 1995. Abundance, distribution and populatin status of Marbled Murrelets in Alaksa *in* C.J. Ralph, G.L. Hunt, M. Raphael, and J.F. Piatt, editors, Conservation Assessment for the Marbled Murrelet. U.S. Forest Service Technical Report, in press.

Pitcher, K.W. 1990. Major decline in numbers of harbor seals, *Phoca vitulina richardsi*, on Tugidak Island, Gulf of Alaska. Mar. Mamm. Sci. 6: 121-134.

Rivest, L-P., F. Potvin, H. Crépeau, and G. Daigle. 1995. Statistical methods for aerial surveys using the double-count technique to correct visibility bias. Biometrics 51: 461-470.

Rounsefell, G.A and E.H. Dahlgren. 1931. Fluctuations in the supply of herring (Clupea Pallasii) in Prince William Sound, Alaska. Bull(9), 264-291.

Seber, G.A.F. 1982. The estimation of animal abundance and related parameters, 2nd Ed. Griffin, London.

Sinclair, M. 1988. Marine Populations. An Essay on Population Regulation and Speciation. Washington Sea Grant, Seattle WA. 252 pp.

Smith, P.E. 1978. Precision of sonar mapping for pelagic fish assessment in the California Current. J. Const. Int. Explor. Mer. 38(1): 33-40.

Squire, J.L., Jr. 1978. Northern anchovy school shapes as related to problems in school size estimation. Fish. Bull., U.S. 76(2): 443-448.

Stocker, M. 1993. Recent management of the British Columbia herring fishery, p. 267-293. In L.S. Parsons and W.H. Lear [eds.] Perspectives on Canadian marine fisheries management. Can.Bull.Fish.Aquat.Sci. 226.

Templeman, W. 1948. The life history of the capelin (*Mallotus villosus*) in Newfoundland waters. Res. Bull. Newfoundland Govt. Lab. No. 17, p. 1-151.

Thompson, S.K. 1992. Sampling. John Wiley and Sons, New York, New York. pp. 176-204.

Figures

Figure 1. A juvenile Pacific herring school seen from the air in Prince William Sound (Bill Ostrand, photo)

Figure 2. A juvenile Pacific sandlance school seen from the air in Prince William Sound (Evelyn Brown, photo)

Figure 3. An aggregation of moon jellyfish seen from the air in Prince William Sound (Evelyn Brown, photo)

Figure 4. Diagram of the sighting tube and the mylar grid with tick marks for measurements of schools.

Figure 5. Map on the survey area on the south-central coast of Alaska with delineation of the southwestern and central survey areas within Prince William Sound.

Figure 6. Frequency distribution of herring and sandlance schools sizes in Prince William Sound.

Figure 7. The visual swath in meters established flying over known, land-marked distances on the ground at different altitudes.

Figure 8. Seasonal variation in numbers of herring schools observed per survey from the air in 1995 and 1996 in Prince William Sound.

Figure 9. Seasonal variation in total surface area of schools observed per survey from the air in 1995 and 1996 in Prince William Sound.

Figure 10. Aerial observations of herring, sandlance, unknown forage fish, jellyfish, and foraging birds plotted with diver observations and net catches conducted within the same 24 hr period in southwestern Prince William Sound on July 17 and 18, 1996. The circles (fish), diamonds (jellyfish), and squares (birds) are sized by total surface areas of schools, aggregations, or total numbers of birds observed at each location.

Figure 11. Aerial observations of herring, sandlance, unknown forage fish, jellyfish, and foraging birds plotted with diver observations and net catches conducted within the same 24 hr period in central Prince William Sound on July 20 and 21, 1996. The circles (fish), diamonds (jellyfish), and squares (birds) are sized by total surface areas of schools, aggregations, or total numbers of birds observed at each location.

Figure 12. Surface area (m^2) of herring and sandlance schools sighted along the survey transect in southwestern Prince William Sound on July 17 and 18, 1996.

Figure 13. Surface area (m^2) of herring and sandlance schools sighted along the survey transect in central Prince William Sound on July 20 and 21, 1996.

Figure 14. Density of herring and sandlance schools (m^2 surface area of schools / m^2 surface area of transect) in southwestern and central Prince William Sound sighted on July 17, 18, 20 and 21, 1996.

Figure 15. Percentages of fish schools sighted from the air with birds associated with them in Prince William Sound in 1995 from May until August.

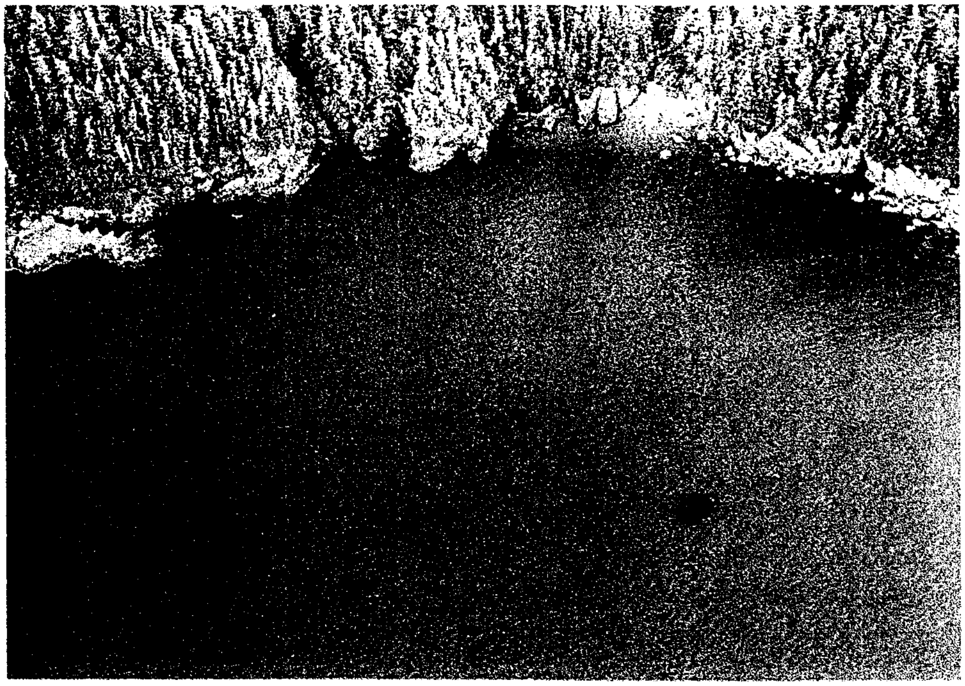


Figure 1. A juvenile herring school seen from the air in Prince William Sound (Bill Ostrand, photo)

Figure 2. A juvenile Pacific sandlance school seen from the air in Prince William Sound (Evelyn Brown, photo)

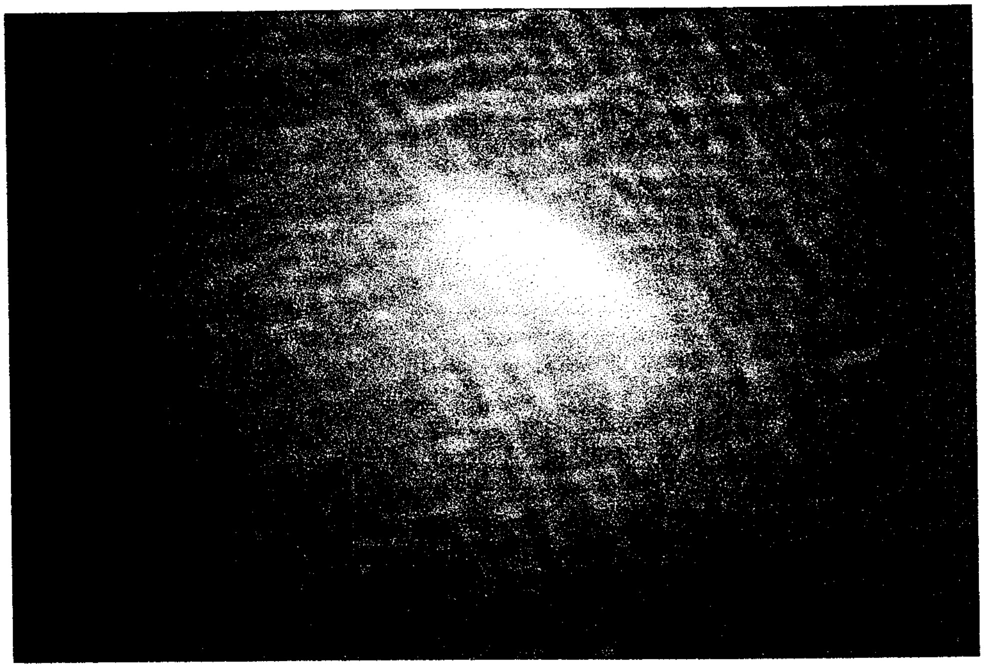


Figure 3. An aggregation of moon jellyfish seen from the air in Prince William Sound (Evelyn Brown, photo)

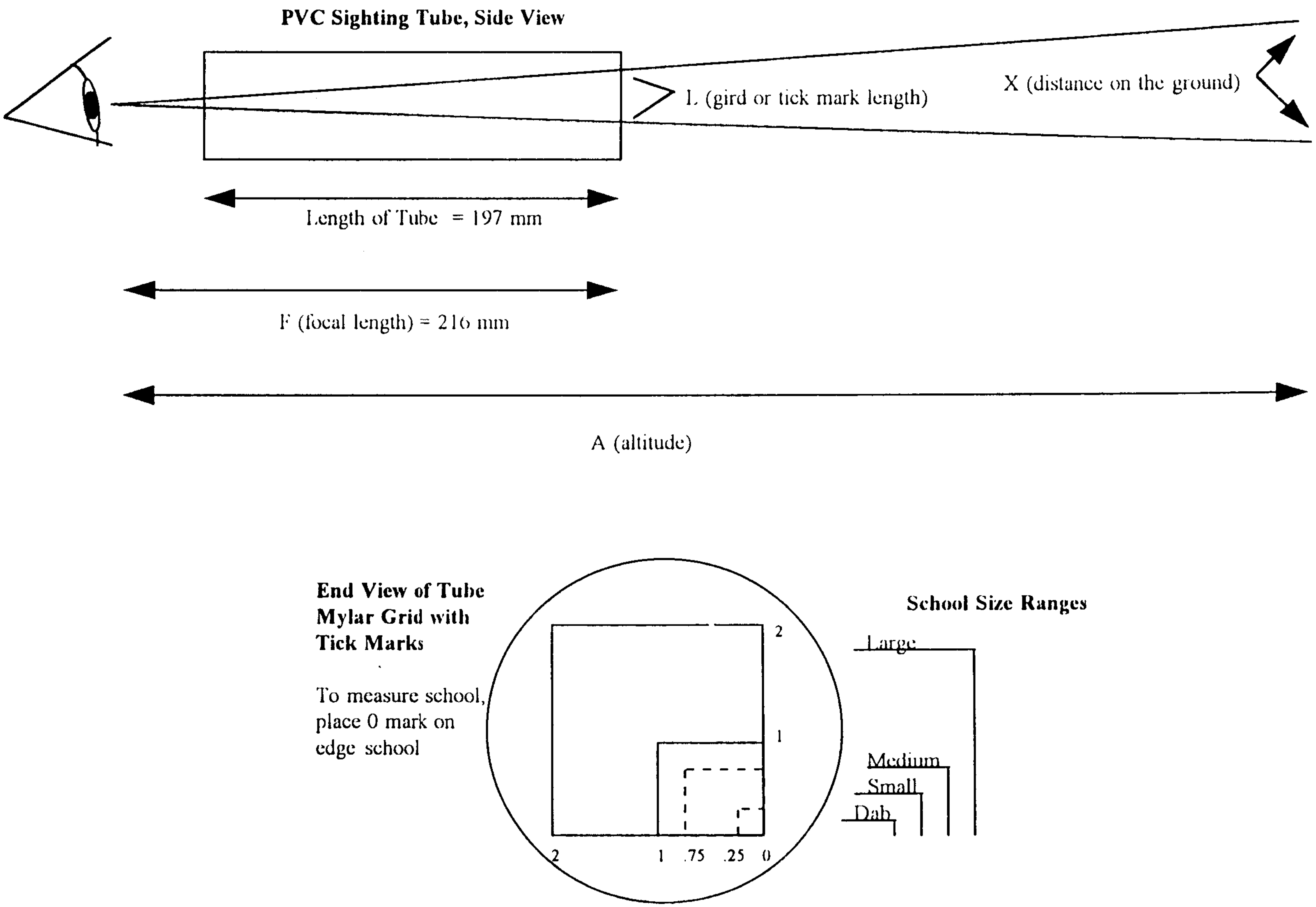


Figure 4. Brown and Norcross, 1997

Figure 5. Brown and Norcross, 1997

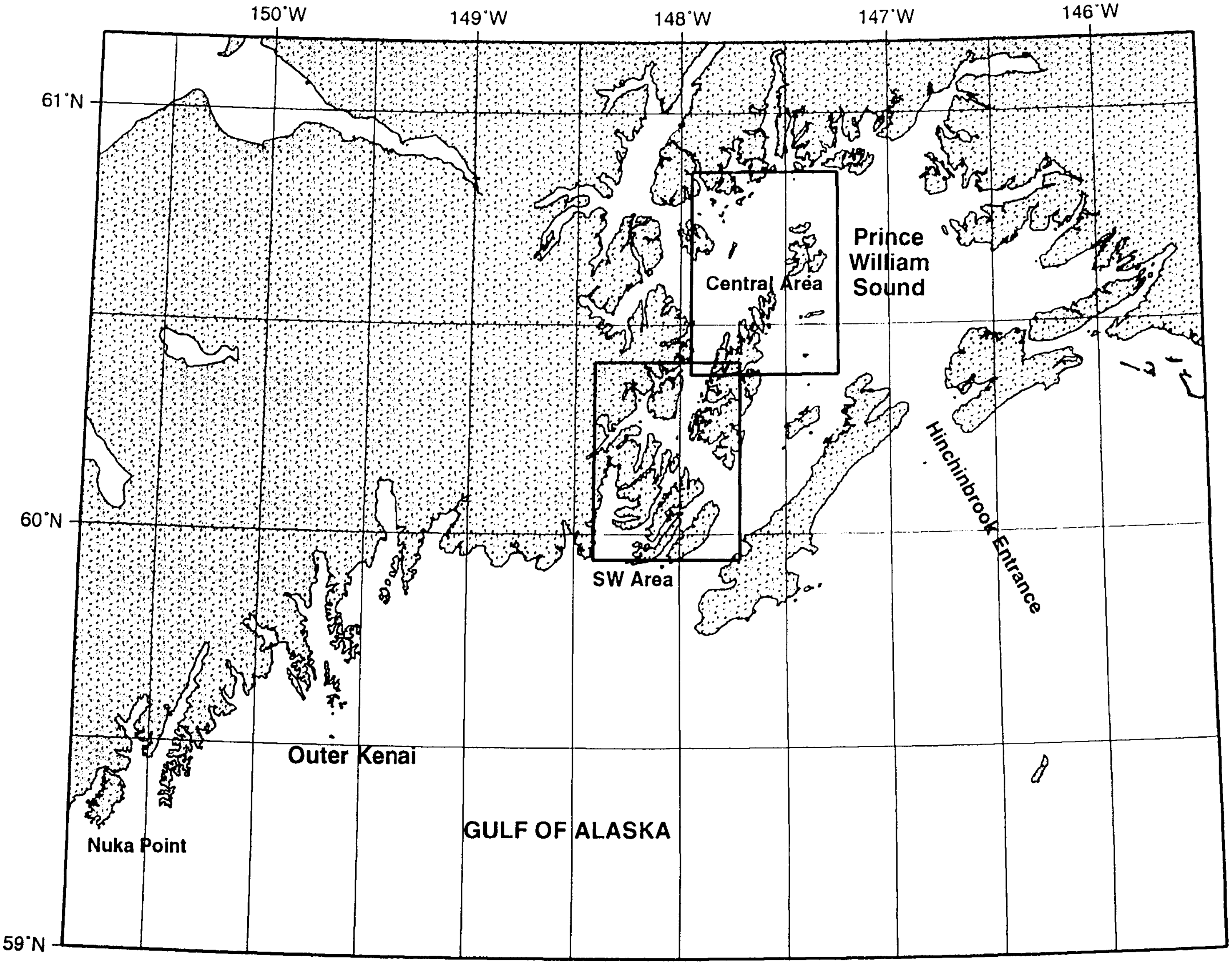


Figure 6. Brown and Norcross, 1997

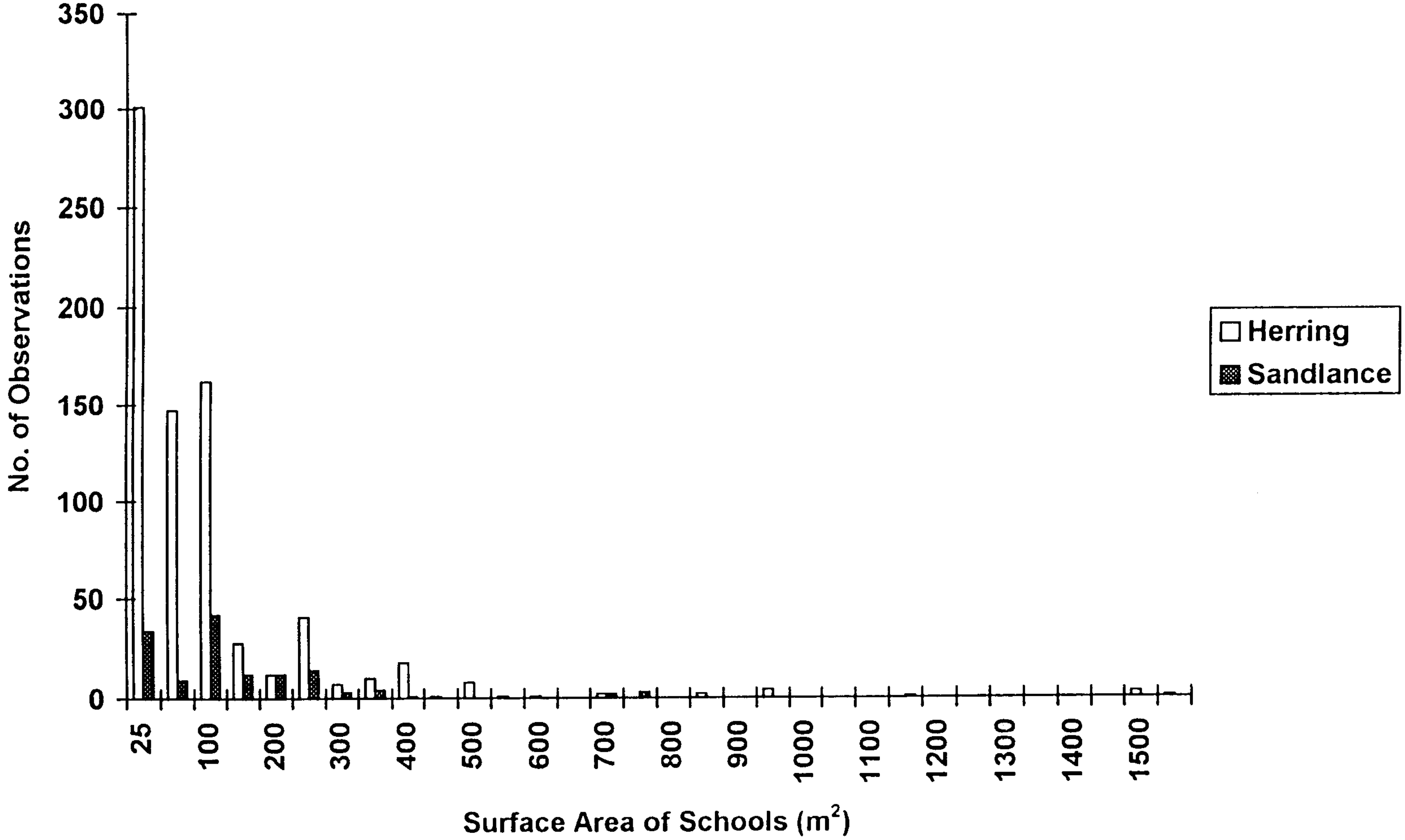


Figure 7. Brown and Norcross, 1997

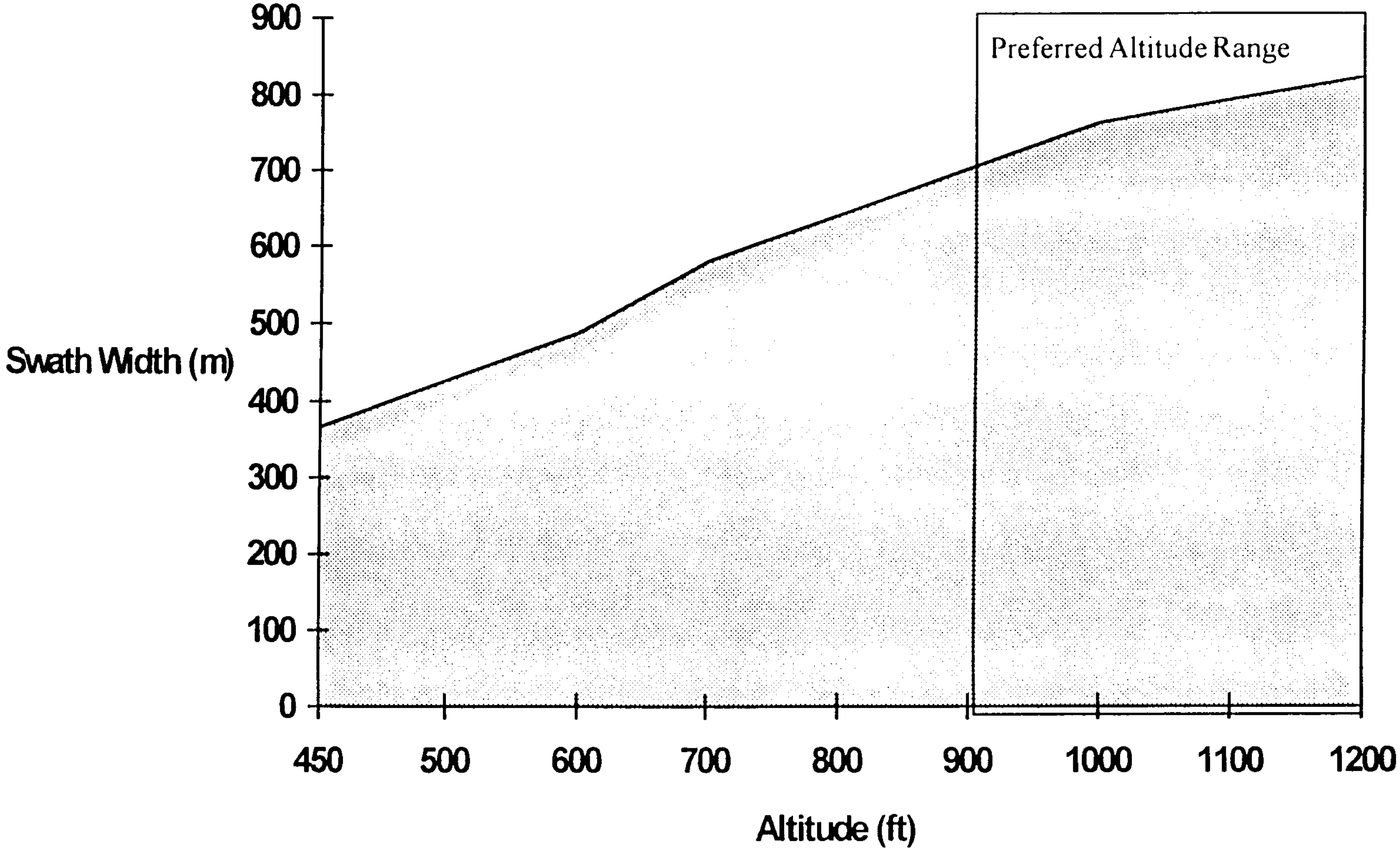


Figure 8. Brown and Norcross, 1997

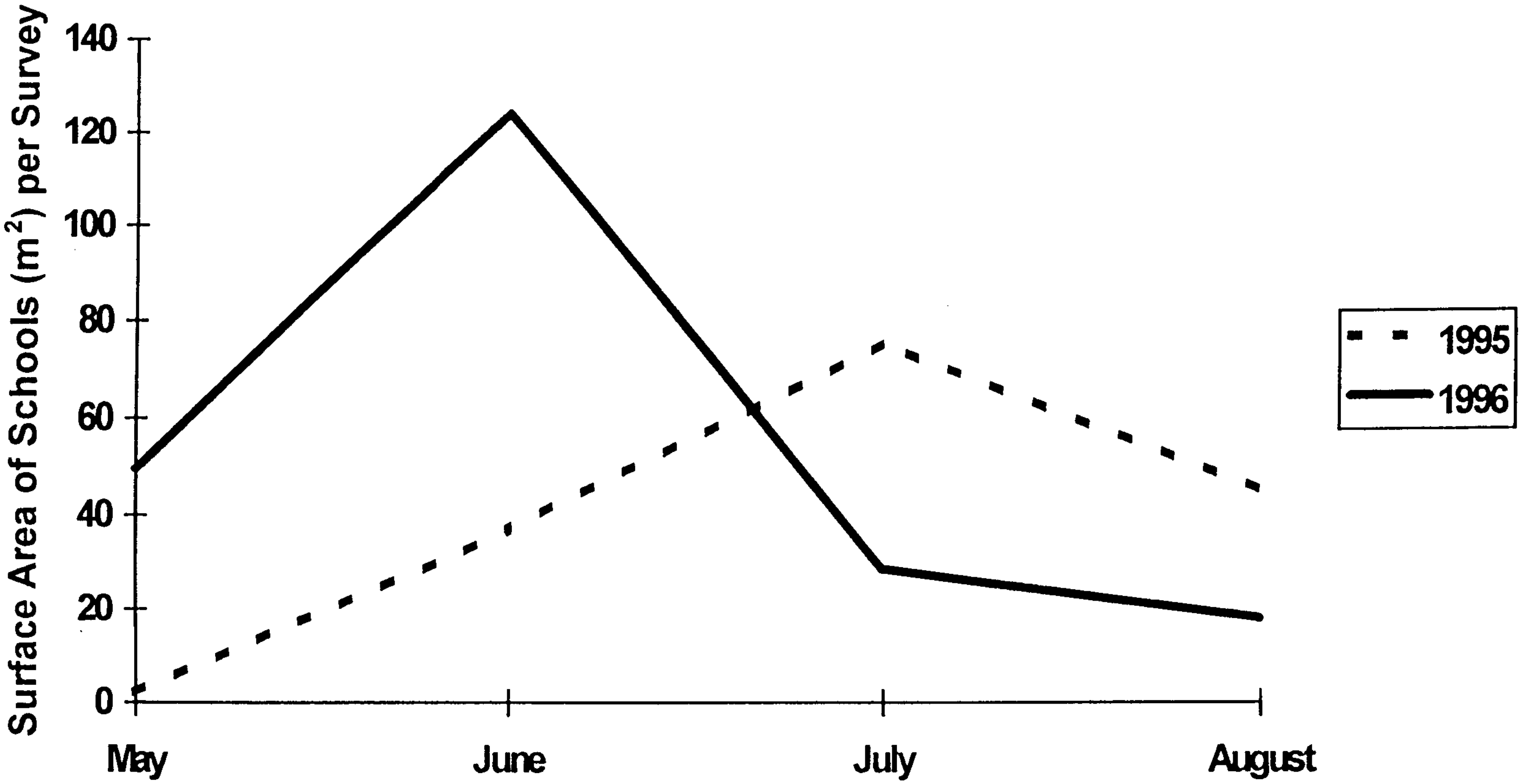


Figure 9. Brown and Norcross, 1997

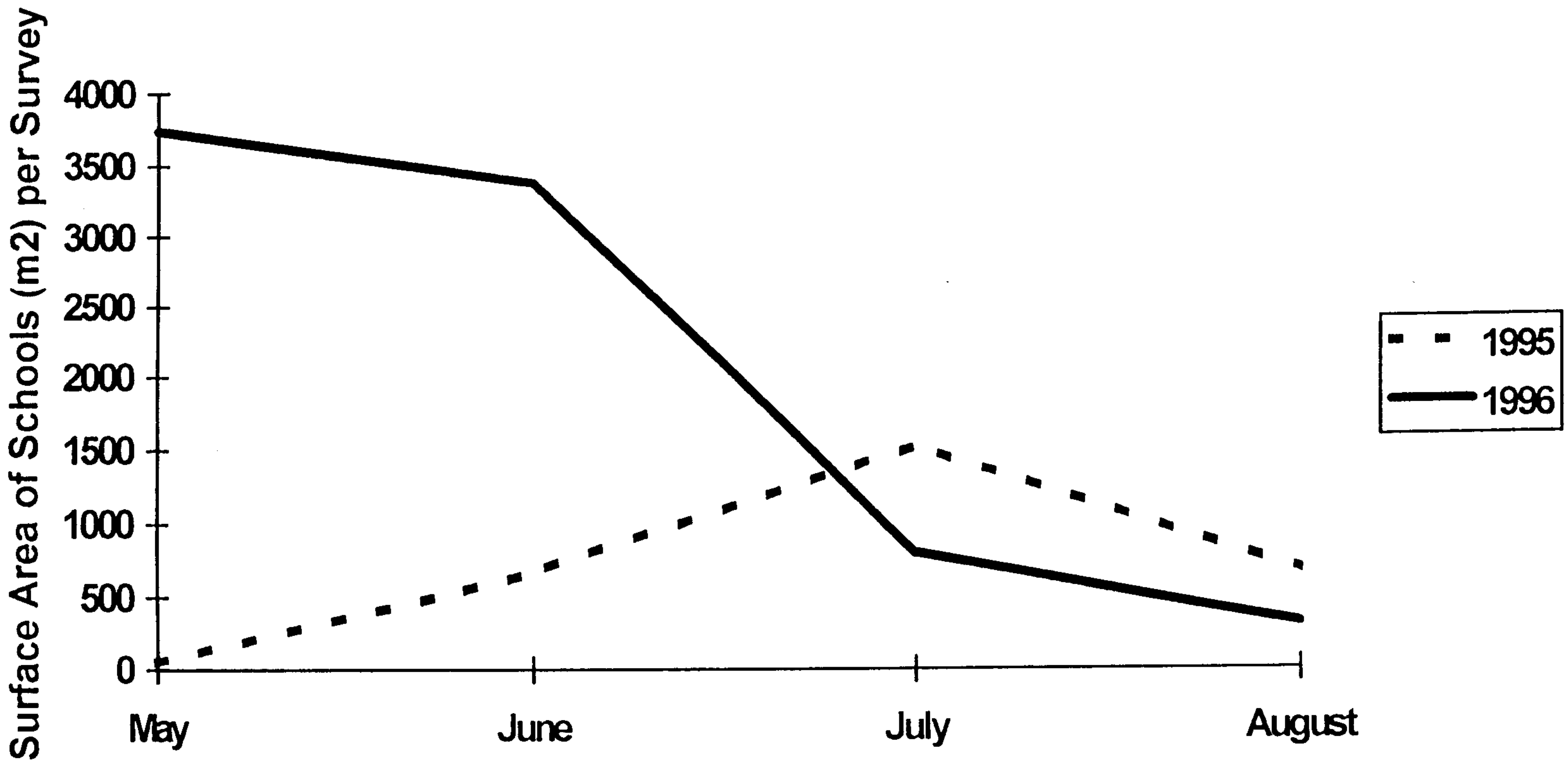
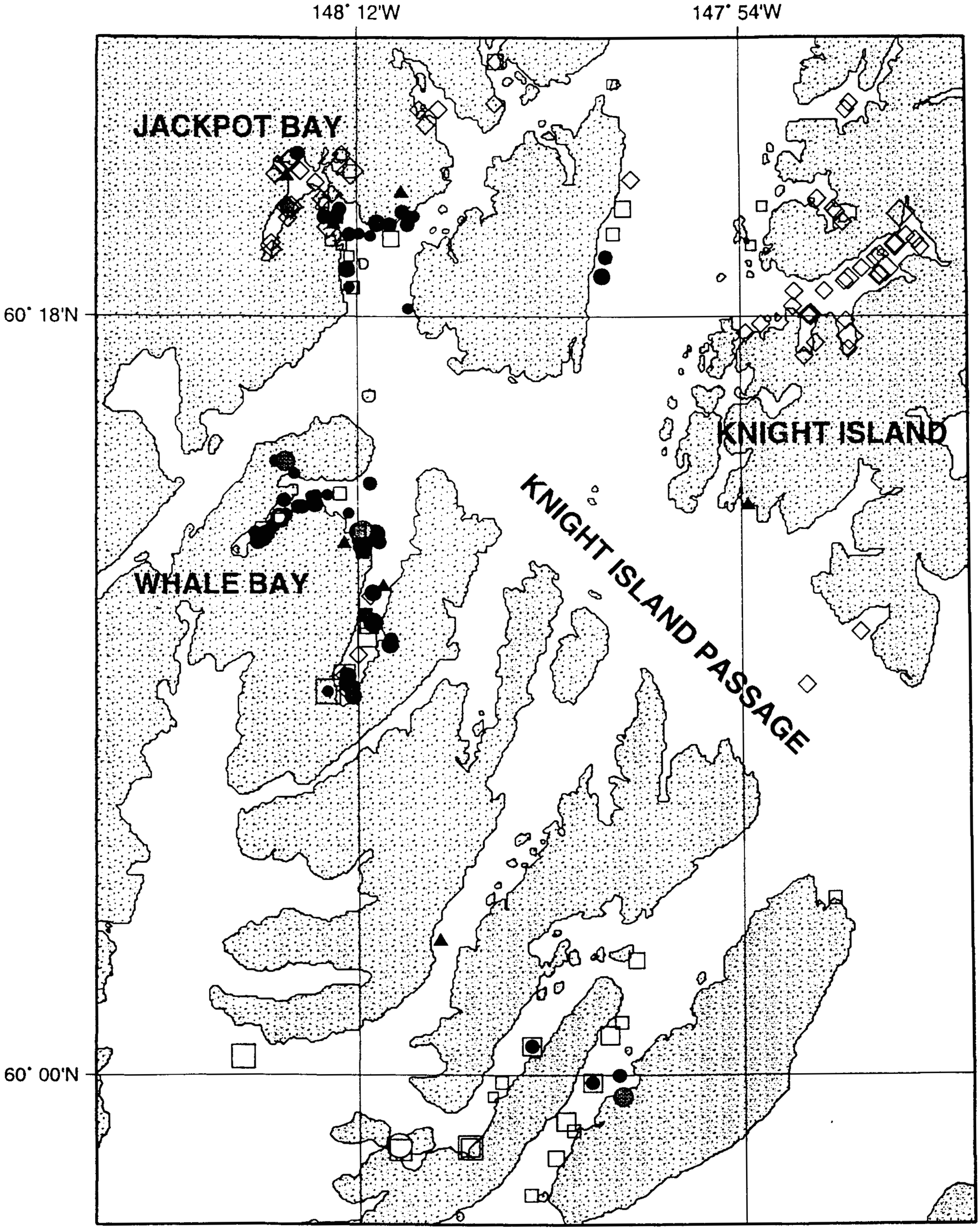


Figure 10. Brown and Norcross 1997



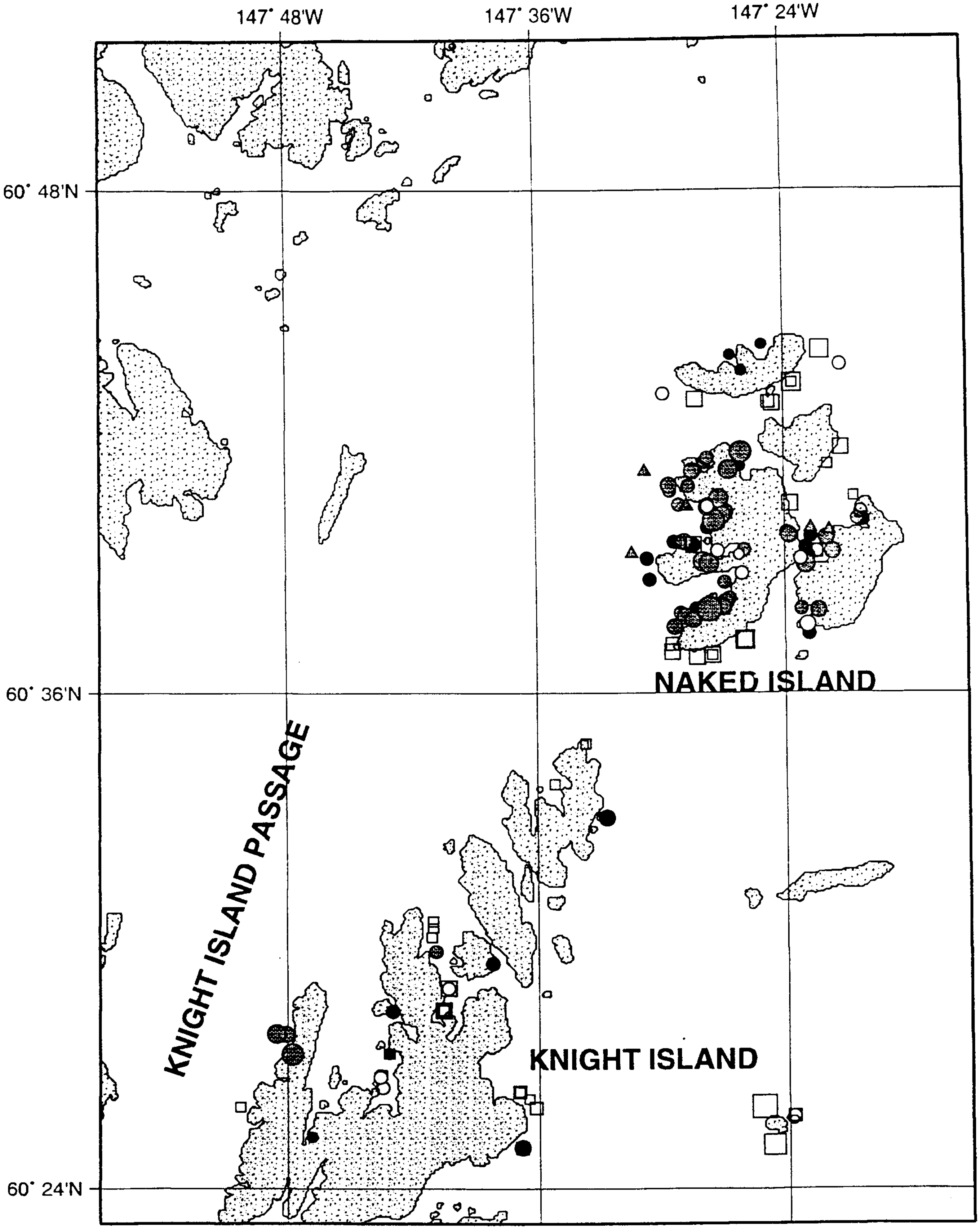
Key: **Aerial Observations** **Net Catches & Diver Observations**

● Herring ○ Unknown Fish ▲ Herring

● Sandlance □ Birds

◇ Jelly Fish

Figure 11. Brown and Norcross, 1997



Key: Aerial Observations — Net Catches & Diver Observations

- ● Herring
- ○ Unknown Fish
- ▲ Sandlance
- ● Sandlance
- □ Birds
- ◇ Jelly Fish

Figure 12. Brown and Norcross, 1997

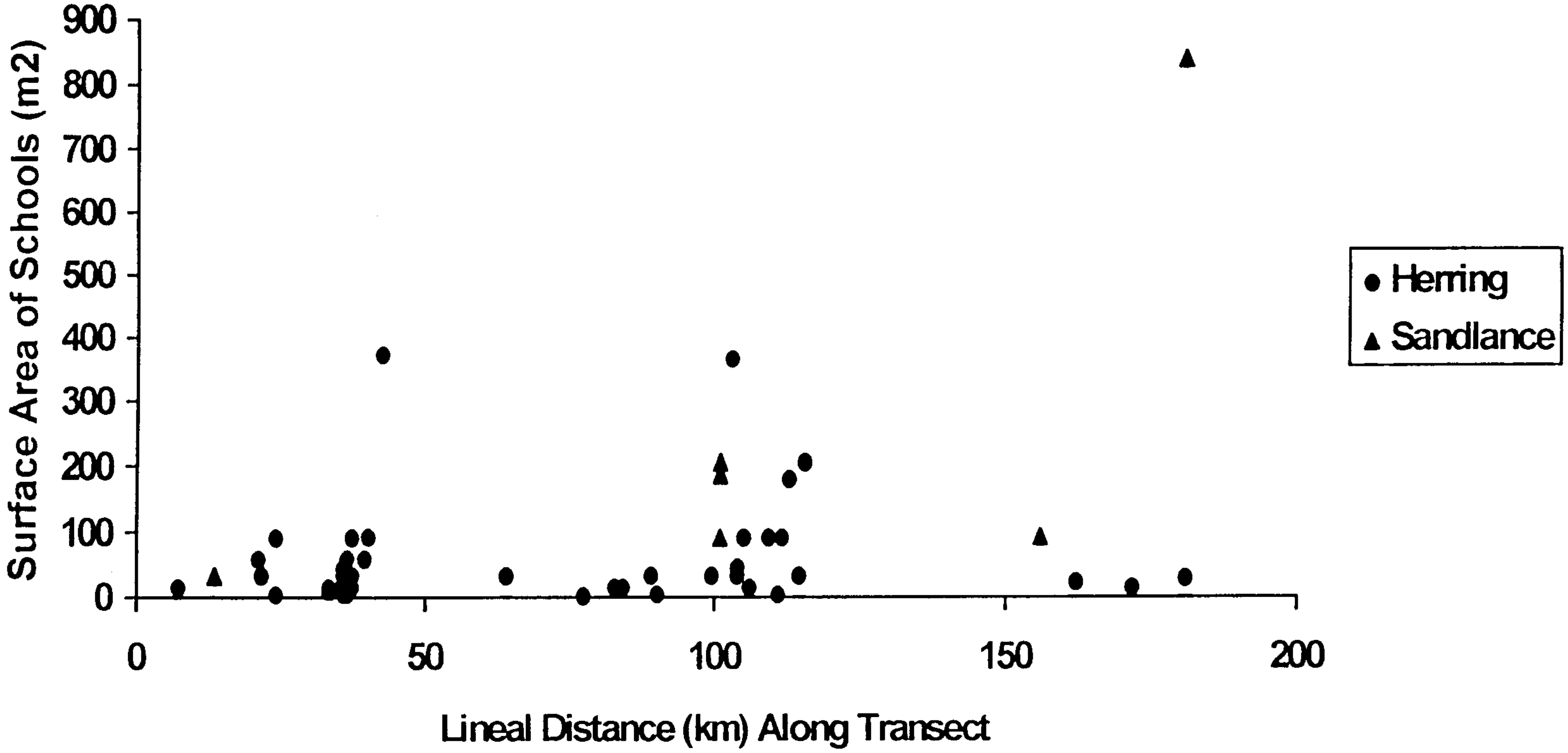


Figure 13. Brown and Norcross, 1997

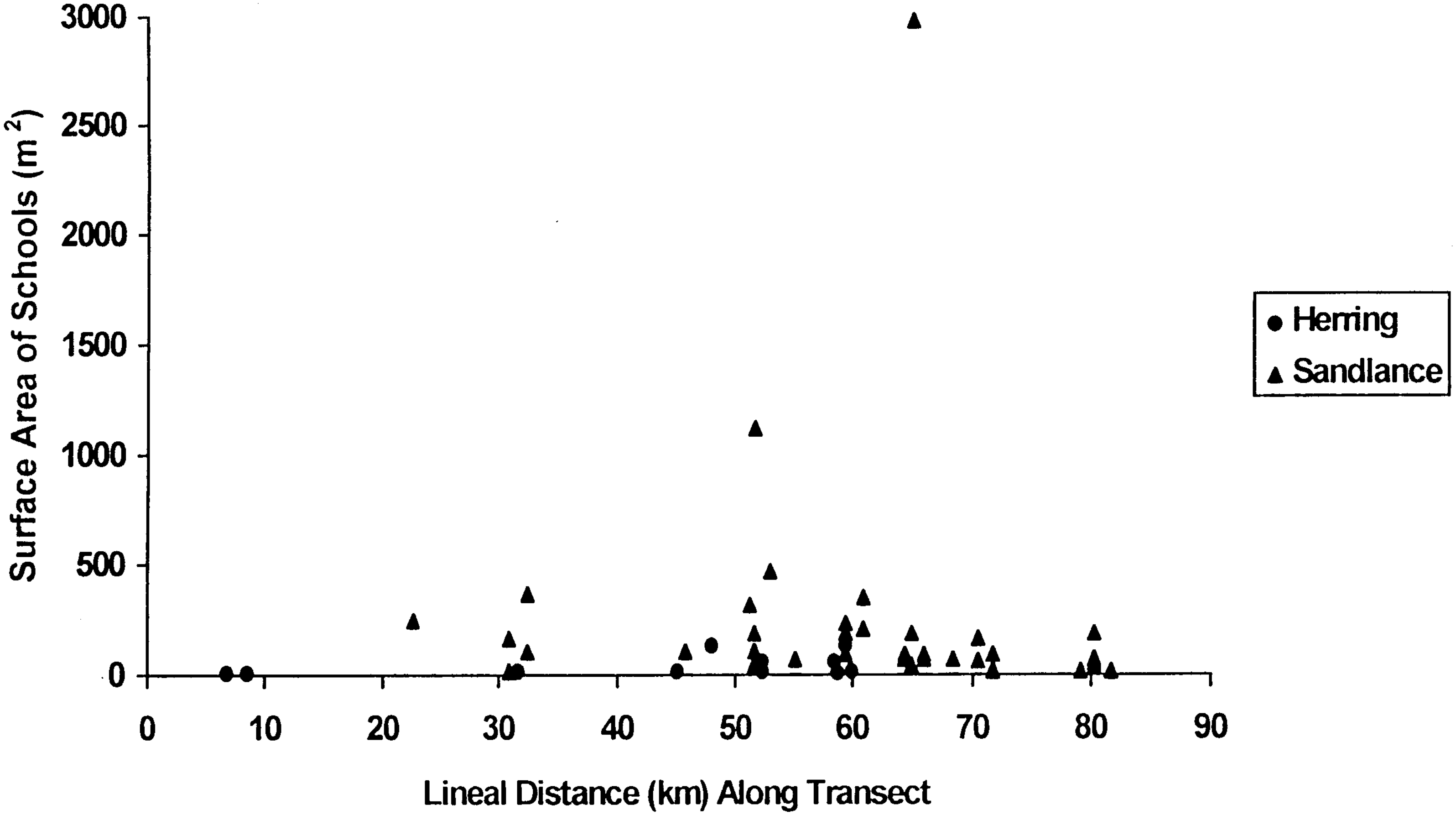


Figure 14. Brown and Norcross, 1997

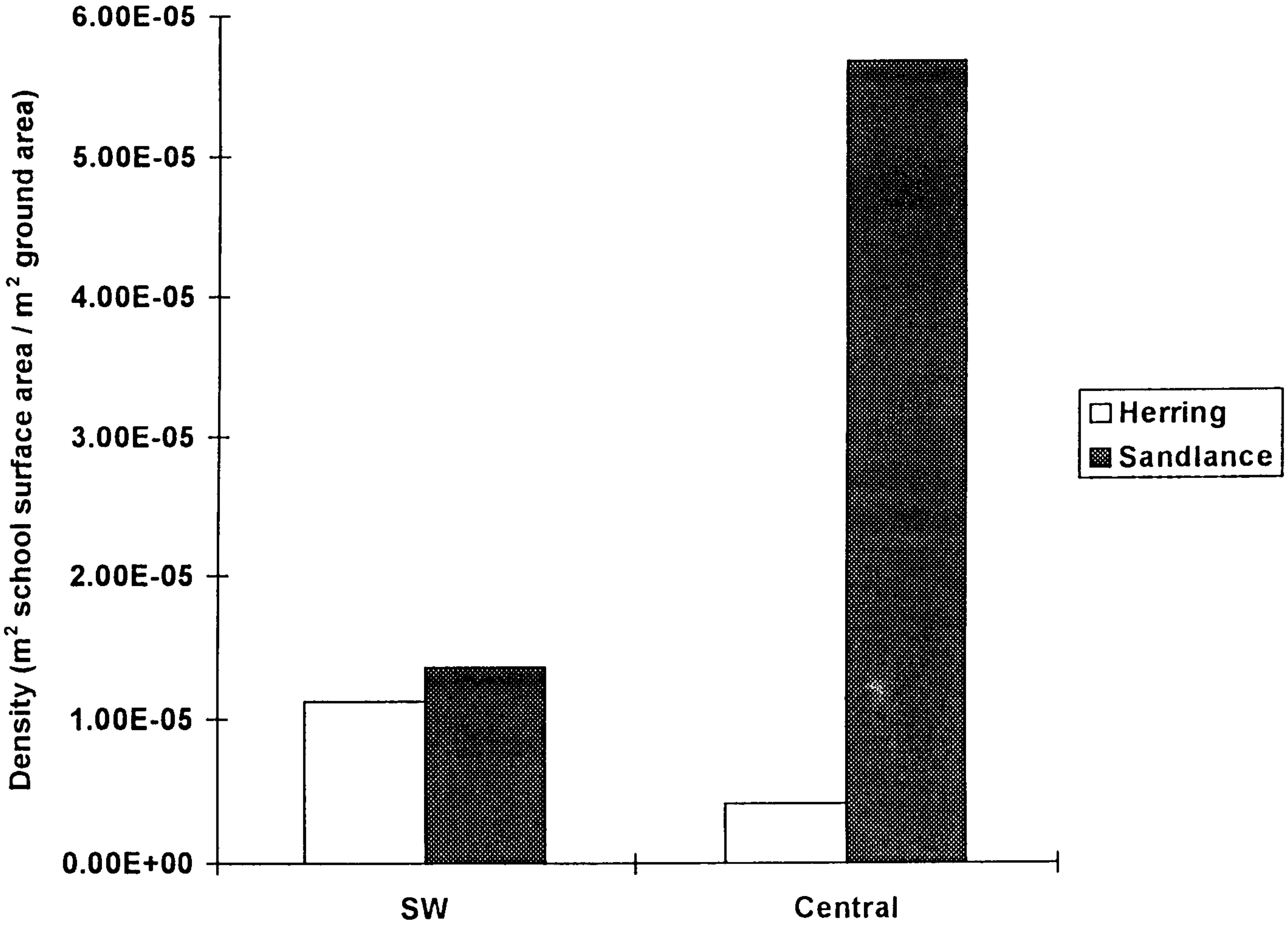
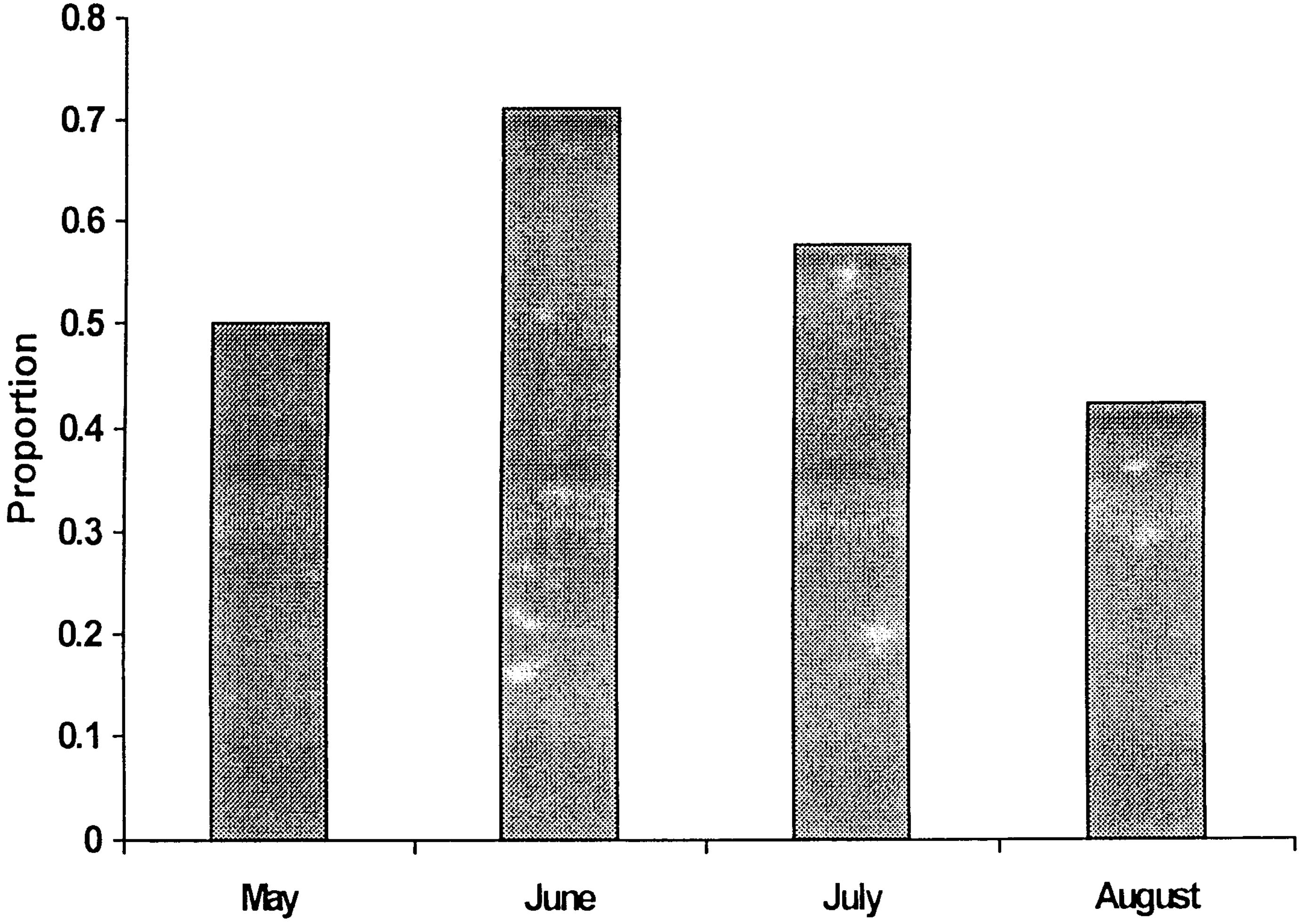


Figure 15. Brown and Norcross, 1997



Apendix II

Foy, R. J., B. L. Norcross, A. Blanchard. 1997. Spatial and Temporal Differences in the Diet of Herring (Clupea pallasi) in Prince William Sound, Alaska

DRAFT

Spatial and Temporal Differences in the Diet of Herring (Clupea pallasi) in Prince William Sound, Alaska

Robert J. Foy
Brenda L. Norcross
Arny Blanchard

Introduction

Pacific herring, Clupea pallasi Valenciennes, are distributed along the Asiatic and North American continental shelves in the North Pacific Ocean. In Prince William Sound, Alaska, herring have historically been an important fish commercially as well as biologically. Reduced abundances resulting in the closure of the commercial fishery have led to questions about the recruitment processes in Prince William Sound. When studying recruitment it is important to understand underlying mechanisms that create variation at particular stages in the development of the fish (Houde 1987; Miller et al. 1991). Although no one factor completely dominates the variation found in year-class strength, it is important to determine the life history stages and mechanisms within those stages that that dominate the variance in mortality and therefore control recruitment. Starvation and slow growth rates can lead to high mortality and decreased recruitment. An important aspect of herring recruitment variation, therefore, is that associated with the feeding behavior and success of larvae and juveniles prior to recruitment.

Bollens et al. (1992) found a lack of overlap in ichthyoplankton and their prey suggesting an increased dependence on the juvenile stage for variability in recruitment based on food consumption. This suggests the need to look beyond the larval stage of some fish species to account for temporal and spatial patterns in feeding related to the variability in recruitment. We believe the juvenile stage of herring development incurs a significant amount of variation in mortality and therefore recruitment to older stages, and we hypothesize that much of the variation in herring mortality in Prince William Sound can be explained through the understanding the feeding ecology of juveniles. A study of herring juvenile feeding ecology necessitates an understanding on both temporal and spatial scales within Prince William Sound. Little is known of the feeding ecology of juvenile herring in Prince William Sound, especially with respect to spatial and temporal characteristics. Identification of seasonal prey species in herring diet is an important first step to understanding the trophic interactions of herring and its prey. The objective of this study is to describe the relative importance of prey categories in the diet of juvenile herring from four bays within Prince William Sound during the spring, summer, and fall.

Materials and methods

Herring were collected from 24 sites in Prince William Sound (Figure 1), Alaska during April, May, June, October, and November of 1995 and March of 1996. Each site was an area, usually a bay, where at least one catch of fish was made. Juvenile herring schools were targeted and caught using a purse seine vessel with a 250 m x 34 m or 250 m x 20 m, 150 mm stretch mesh anchovy net and also from a trawl vessel with a 40 m x 28 m, 150 mm mesh mid-water wing trawl net. From each catch, 15 fish less than 150 mm were randomly sampled. Fork length was measured before each fish was preserved in a 10 percent buffered formaldehyde solution. After at least 24 hours of preservation, samples were transferred to 50 percent isopropanol for transport and further analysis.

In the laboratory, each fish was blotted dry, weighed, and measured before the stomach was removed. The stomach was removed and weighed to the nearest 0.001 g. After stomach contents were removed, the stomach was reweighed to determine gut content weight. Prey in the stomach were identified to the lowest possible taxonomic level.

After diet identification, prey were pooled into nine taxonomic categories from each site to facilitate further analysis (Table 1). An index of relative importance (IRI) (Pinkas 1971) was calculated for each prey category in each bay.

The IRI was calculated as:

$$IRI = (N + W) * F$$

where N = number of prey, W = percent weight of prey, and F = percent frequency of fish consuming the prey. An IRI was calculated for each prey taxon category consumed by herring at each of the sites.

Four sites (Simpson Bay, Eaglek Bay, Whale Bay, and Zaikof Bay) were analyzed individually throughout the year in order to compare spatial and temporal differences in prey IRI's.

An analysis of variance was used to compare the mean lengths of herring among the four bays as well as among months in each bay. Although March samples were from 1996, we chose to compare them in chronological order by month in order to analyze the complete feeding period from spring to fall.

Results

A total of 1200 herring were randomly sampled from all sites in Prince William Sound across the six sampling periods (Figure 1). Prey were placed into categories based on their taxonomic class or order (Table 1). Prey that constituted less than one percent of the stomach contents were placed in the 'other' category. In March 1996, 665 fish were sampled from 18 sites in Prince William Sound (n ranged from 10 to 121 herring per site). Total IRI's for prey categories across the sound in March ranged from 0 to 38 percent;

large calanoid copepods were the most important prey (Figure 2). In April and May of 1995, 150 fish were sampled from 4 sites (n ranged from 22 to 68 herring per site). Total IRI's for prey categories ranged from 0 to 81 percent in April and 0 to 55 percent in May (Figure 2). Large calanoid copepods were the most important prey in both months. In June of 1995, 75 fish were sampled from 2 sites (n was 21 and 54 herring per site). Total IRI's for prey categories ranged from 0 to 74 percent. Medium calanoid copepods were the most important prey categories. In October of 1995, 166 fish were sampled from 6 sites (n ranged from 19 to 72 herring per site). Total IRI's for prey categories ranged from 0 to 68 percent. Larvacea were the most important prey categories. In November of 1995, 144 fish were sampled from 3 sites (n ranged from 15 to 69 herring per site). Total IRI's for prey categories ranged from 0 to 50 percent. Larvacea were the most important prey categories followed by medium calanoids (IRI = 36 percent).

Of the sites previously described, 4 bays which were repeatedly sampled, were used for spatial analysis. Eaglek Bay in Northwest Prince William Sound was only sampled once in March, 1996. Stomach contents from 121 herring were analyzed from Eaglek Bay. Euphausids were the most important diet group (IRI = 82 percent), followed by small calanoids, malacostraca, large and medium calanoids (Figure 3).

Simpson Bay in Northeast Prince William Sound was sampled in two months. In March of 1996 and October 1995, stomach contents of 27 and 72 herring, respectively, were analyzed from Simpson Bay. IRI's revealed that in March cerripedia (barnacle larvae) were the dominant prey category while in October, Larvacea was dominant (Figure 3). Small and medium calanoids were found in smaller quantities in October.

Whale Bay in Southwest Prince William Sound was sampled in two months. In March of 1996 and October 1995, stomach contents from 44 and 30 herring, respectively, were analyzed from Whale Bay. Small calanoids were the most important prey species in March with much smaller amounts of barnacles, medium, and large calanoid copepods (Figure 3). In October, Larvacea comprised most of the important categories followed by small calanoid copepods and minor amounts of euphausids, large, and medium calanoid copepods.

Zaikof Bay in Southeast Prince William Sound was the only site at which all four timer periods were sampled. In March of 1996, gut contents from 53 herring were analyzed from Zaikof Bay. Large calanoid copepods were the dominant prey category followed by medium calanoid copepods (Figure 3). In May of 1995, gut contents from 22 herring were analyzed. Large calanoid copepods were again dominant followed by medium and small calanoid copepods. In June of 1995, gut contents from 54 herring were analyzed. Small calanoid copepods were the most important prey followed by lesser amounts of barnacles, cladocera, and medium calanoid copepods. In October 1995, gut contents of 30 herring were analyzed. Larvacea were the most important prey category followed by malacostroca and small calanoid copepods.

The mean lengths of the herring from the four bays in March and October used for gut content analysis were found to be significantly different ($P < 0.001$ for both months) (Table 2). The analysis of herring lengths within each of the four bays found that lengths of herring were significantly different in each month from each bay ($P < 0.001$ in each case).

This study showed both spatial and temporal shifts in the importance of herring prey categories. A first look at the importance of prey categories over all sites sampled reveals that large calanoid copepods dominate the juvenile herring diet in March, April, and May of 1995 and 1996 (Figure 2). In June, however, the large species of copepods became significantly less important whereas medium calanoid copepods dominated the prey chosen by juvenile herring. And finally in the fall, species of larvacea dominated the diet content of herring.

After encountering temporal variability around Prince William Sound, it was necessary to focus on four bays to detect any variation in prey importance on a finer level. Temporal variability was evident within each bay with prey switching between spring, summer, and fall months (Figure 3). Substantial spatial variability was also found between the bays. Barnacle nauplii were significantly more important in Simpson Bay in March 1996 than the other bays. Though they were present in Whale Bay and Zaikof Bay to a lesser extent, they were not found in Eaglek Bay. As found in the analysis of the overall Sound, large calanoid copepods were the most important prey categories in the spring months in Zaikof Bay. Euphausids were the most important prey categories in Eaglek Bay in March 1996. The most consistent feeding pattern was found in the fall with larvacea as the most important prey categories in each of the 3 bays sampled. It is interesting to note, however, that the second most important category in each bay was different. Small calanoid copepods in Whale Bay were relatively important with an IRI of 39 percent in October. In Zaikof Bay, malacostraca species were relatively important with an IRI of 24 percent in October.

Discussion

The shifting of prey importance in the diet of herring is both a function of the shifting of prey species dominance as well as probable changes in the selectivity by the fish. It is not sufficient to measure total prey biomass within preferred prey sizes of larval redfish (Sebastes spp) (Anderson 1994). Availability of prey categories was found to be instrumental in determining the observed feeding conditions. When Atlantic herring in the Baltic Sea prey on a mixed diet of zooplankton, mysids, and amphipods, faster growth rates due to higher energy densities result than when the diet consisted only of zooplankton (Arrhenius and Hansson 1993). Faster feeding rates would also would also increase growth rates resulting in better condition (Ware 1975; Shepherd and Cushing 1980; Houde 1987; Andersen 1994). As herring grow larger and gape size increases, larger prey with perhaps greater energetic value should become available. Spatial distribution of herring in Prince William Sound is related to isotopic and energetic values (Kline and Paul in review). They hypothesize that there is a shift in carbon source as a result of fish size. Therefore, a larger fish has a different prey selection available to it. Spatial differences in prey composition as well as changes in prey selectivity due to fish growth could help to explain why herring have different isotopic and energetic values. Such comparisons emphasize the need to incorporate an understanding of the zooplankton biomass present in order to develop selectivity indices and compare to gape size estimates in future studies.

It is important to note that the IRI's used in this study are an averaged index of prey importance. Choosing the scale of the index to be at the level of each bay limits a discussion of prey importance to that within each bay. It may prove useful in future studies to further divide the herring into discrete length categories to assess the importance of prey with respect to the fish size. Table 2 points out that the length frequencies encountered in each bay were significantly different and could possibly drive the spatial and temporal differences in prey importance discovered.

References

Anderson, J. T. 1994. Feeding ecology and condition of larval and pelagic juvenile redfish Sebastes spp. Marine Ecology Progress Series. 104:211-226.

Arrhenius, F., and S. Hansson. 1993. Food consumption of larval, young and adult herring and sprat in the Baltic Sea. Marine Ecology Progress Series 96:125-137.

Bollens, S. M., B. W. Frost, H. R. Schwaninger, C. S. Davis, K. J. Way. and M. C. Landsteiner. 1992. Seasonal plankton cycles in a temperate fjord and comments on the match-mismatch hypothesis. Journal of Plankton Research 14(9):1279-1305.

Houde, E. D. 1987. Fish early life dynamics and recruitment variability. American Fisheries Society Symposium 2:17-29.

Kline, T. C., and A. J. Paul. in review. Fall isotopic and somatic energy signatures of young of the year Pacific Herring at two sites in Prince William Sound, Alaska: implications for trophic studies.

Miller, J. M., J. S. Burke, and G. R. Fitzhugh. 1991. Early life history patterns of Atlantic North American flatfish: likely (and unlikely) factors controlling recruitment. Netherlands Journal of Sea Research 27(3/4):261-275.

Pinkas, L., M. S. Oliphant, and I. L. K. Iverson. 1971. Food habits of albacore, bluefin tuna, and bonito in California waters. California Department of Fish and Game Fisheries Bulletin 152:1-105.

Shepherd, J. G. and D. H. Cushing. 1980. A mechanism for density-dependent survival of larval fish as the basis of a stock recruitment relationship. ICES J. Cons. 39:160-167.

Ware, D. M. 1975. Relationship between egg size, growth and natural mortality of larval fish. Journal of Fisheries Research Board of Canada 32:2503-2512.

Table 1. Taxon list showing diet groupings (bold) for index of relative importance analysis. Foy and Norcross 1997

- Copepoda
  - **Calanoida (large)**
    - *Calanus marshallae*
    - *Candacia columbiae*
    - *Eucalanus bungii*
    - *Euchaeta elongata*
    - *Metridia ochotensis*
    - *Neocalanus cristatus*
    - *Bradyidius saanichi*
  - **Calanoida (medium**
    - *Acartia tumida*
    - *Calanus pacificus*
    - *Centropages abdominalis*
    - *Epilabidocera longipedata*
    - *Lucicutia flavicornis*
    - *Metridia ochotensis*
    - *Metridia pacifica*
    - *Pseudocalanus* spp

  - **Calanoida (small)**
    - *Acartia clausi*
    - *Acartia longiremus*
    - *Eurytemora pacifica*

- **Cirripedia** (cyprid and nauplius)

- Branchiopoda
  - **Cladocera**
    - *Evadne* spp
    - *Podon* spp

- **Larvacea**
  - *Oikopleura* spp

- **Malacostraca**
  - Cumacea
  - Decapoda (zoea)
    - *Crangon* spp
  - Isopoda
  - Amphipoda
    - Gammaridea
    - Hyperiidea
  - **Euphausiacea**
    - *Euphausia* spp

- **Other**
  - Arachnida
  - Insecta
  - Ostracoda
  - Copepoda
    - Cyclopoida
    - Harpacticoida
    - Poecilostomatoida

  - Gastropoda
  - Bivalvia

  - Polychaeta (larva and juvenile)
    - *Sagitta* spp

  - Bryozoa (larva)
  - Chaetognatha
  - Cnidaria
  - Nemertea

Table 2. Mean (standard error) lengths and sample size of herring sampled in four bays and four months in Prince William Sound. Foy and Norcross 1997

		March		May		June		October
Site	n	mean (se)	n	mean (se)	n	mean (se)	n	mean (se)
Simpson Bay	29	122.9 (3.2)					91	80.9 (1.7)
Eaglek Bay	146	140.7 (2.3)						
Whale Bay	60	115.6 (3.3)					30	94.9 (1.5)
Zaikof Bay	100	172.5 (3.0)	22	106.6 (0.9)	60	107.3 (0.9)	31	75.4 (1.9)

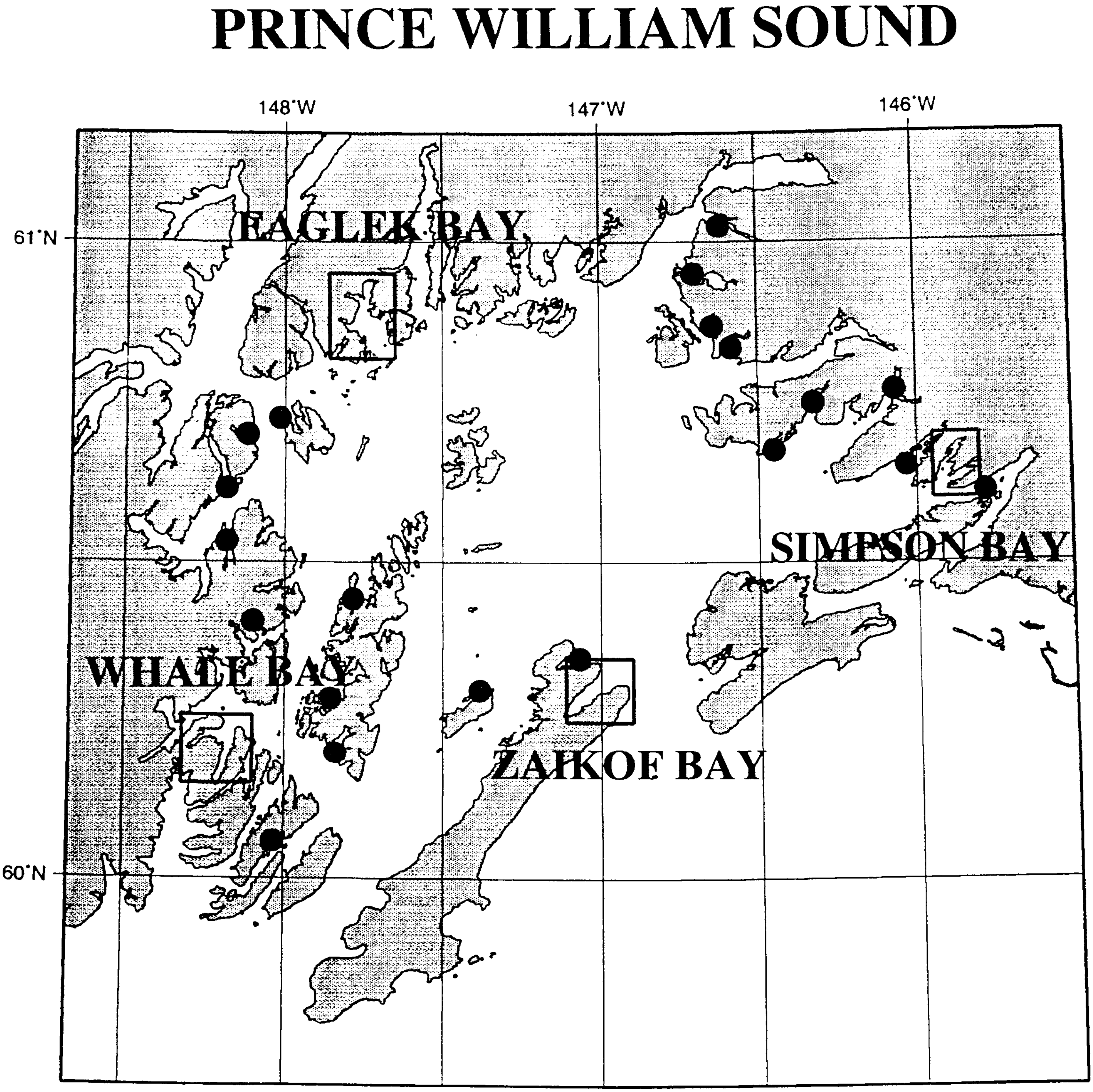


Figure 1. Sampling sites in Prince William Sound. Boxed bays represent primary research sites.

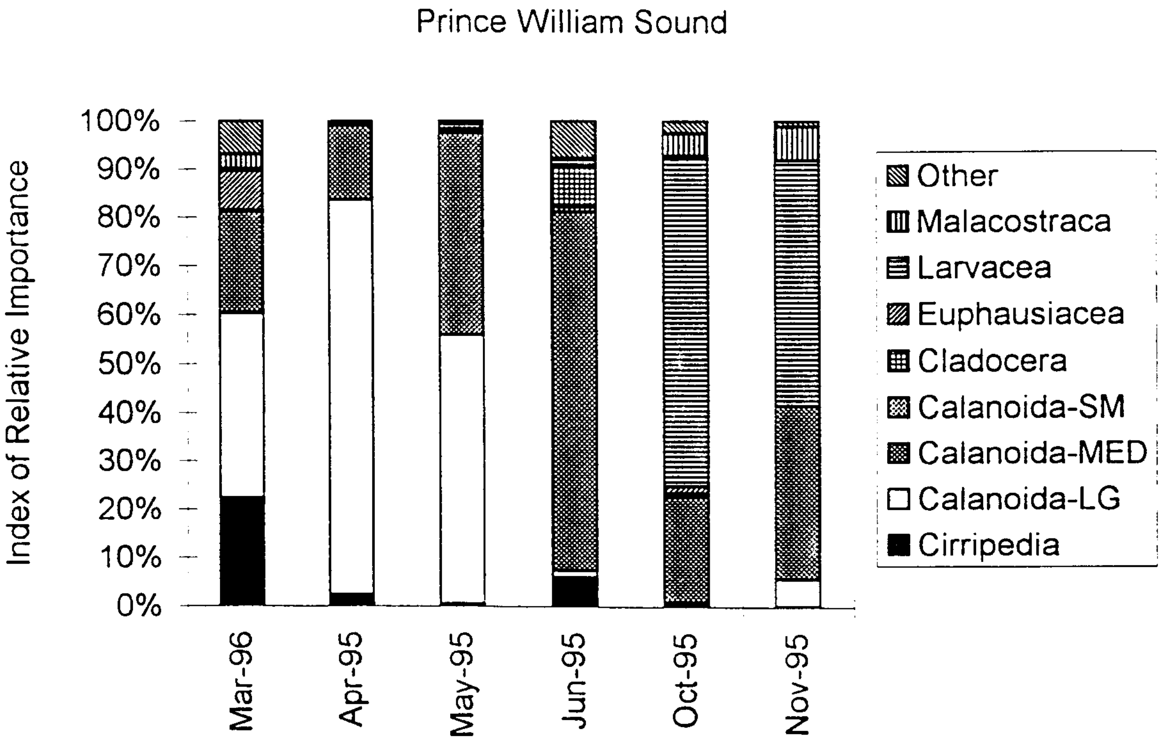


Figure 2. Average Indices of Relative Importance of herring diet from all sites sampled in Prince William Sound. Foy and Norcross 1997

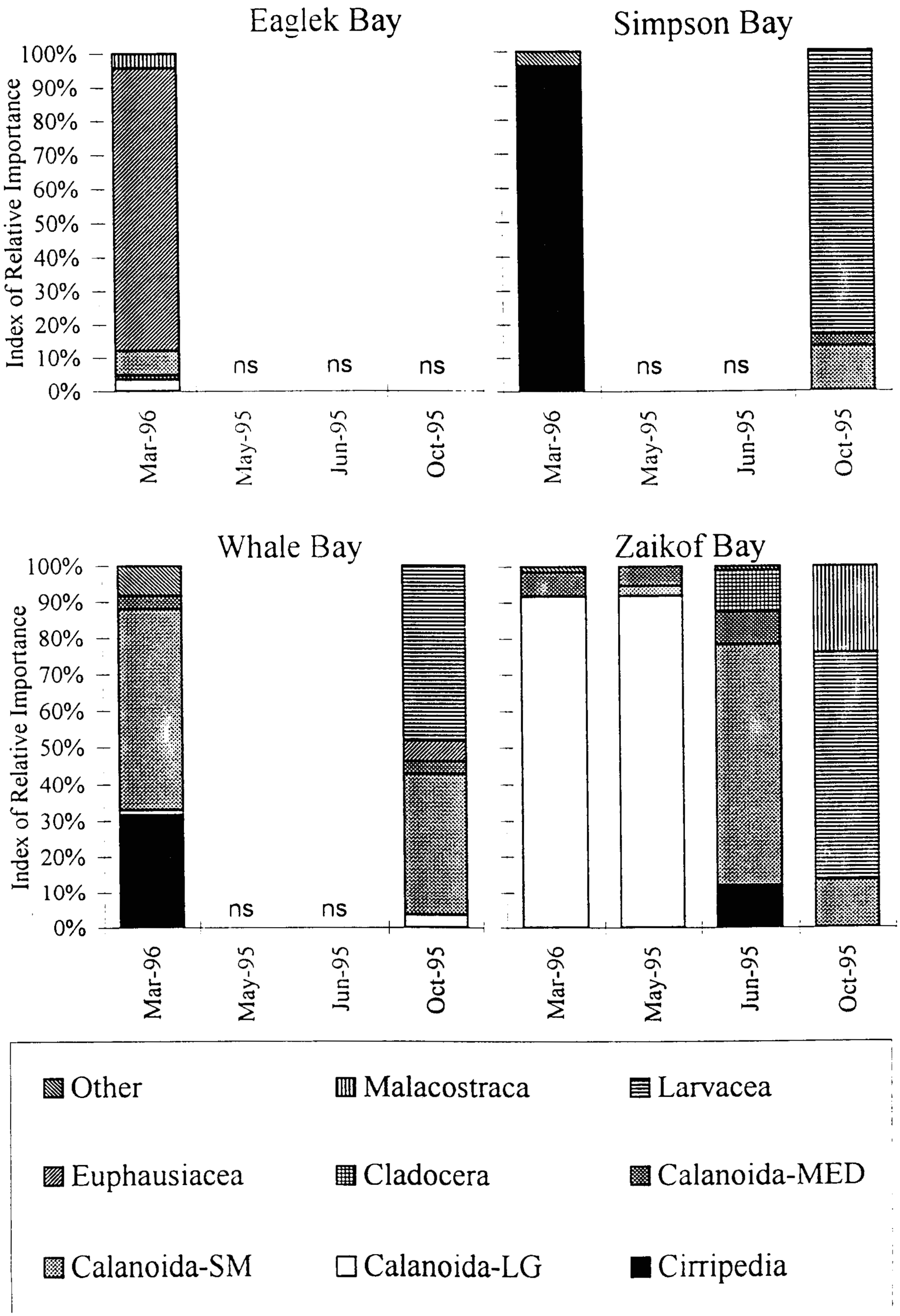


Figure 3. Indices of Relative Importance of herring prey in four bays in Prince William Sound. ns = no sample. Foy and Norcross 1997

Chapter 12.

Fish Energetics (96320U)

Exxon Valdez Oil Spill
Restoration Project Annual Report

SEA Fish Energetics

Restoration Project SEA 320U
Annual Report

This annual report has been prepared for peer review as part of the Exxon Valdez Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Dr. A. J. Paul
University of Alaska, Seward Marine Center
POB 730, Seward, AK 99664

April 1997

SEA Fish Energetics

Restoration Project SEA 320U
Annual Report

Study History: SEA is a hypothesis driven ecosystem study designed to obtain an understanding of the mechanisms that influence levels of production for herring in Prince William Sound by investigating their early life stages. SEA research focuses on the timing and magnitude of energy and carbon flowing through the food web. Tracking this flow provides insight into links between primary and secondary production and species interactions. Food and predation are key forces that operate within the context of environmental parameters like temperature and transport. This component of SEA provides information on whole body energy content of key fish species so that interactions within and between species can be quantified, and insight into the feeding conditions on geographical and temporal scales can be described. The data from it supports inquiries into the River-Lake hypothesis, the Over-Winter hypothesis, and the key question "is it food impeding recovery of herring". Energetic data flows to the SEA models which will be used to predict production potential. This project was initiated in April of 1995, thus this report constitutes the second year of a three year field sampling program.

Abstract: The Exxon Valdez oil spill may have altered the trophic structure of the plankton feeding fish community by injuring intertidal spawning species: pink salmon and herring. This project has started to describe the interannual variations in the somatic energy cycle of juvenile *Clupea pallasi*. Collections were made in the spring and fall of 1995-96, and summer, fall, winter and spring 1996-97. This information was not previously available and is needed to determine if food resources are limiting growth of recruits and to determine if the over-winter period is important in regulating recruitment of age 0 herring. The analysis of somatic energy content (SEC) showed that there was large geographical differences in the nutritional status of recruiting herring based on whole body energy content. This is also true for fish at individual capture sites. Other SEA components are examining the physical oceanographic and prey distribution patterns related to these differences. The energy profile of over-wintering herring showed recruits from the 1994 year class over-wintered with a surplus of stored energy, but in 1995 many of that years recruits were food limited and exhibited nutritional stress during the winter of 1995-96.

During the fall of 1995 and spring of 1996, the SEC of Pacific herring relative to age, size and sex was examined. Whole body energy (kJ.g^{-1} wet wt) exhibited a wide range of values relative to fish length. In the fall young of the year recruits had an average of 5.7 kJ.g^{-1} wet wt for whole body samples vs 8.0 for age 1 and 9.4-10.2 kJ.g^{-1} for fish of ages 2 to 7. Many of the young of the year (YOY) fish in the fall collection had not maximized energy stores for over-wintering. The following spring the 1995 year class which had just survived their first winter averaged 4.4 kJ.g^{-1} wet wt for somatic samples, and age 1 fish had similar values, while herring ages 2 to 7 had SEC >5 kJ.g^{-1}. The difference in somatic energy content between adult male and female herring captured in fall and again in the spring just prior to spawning, was about 4 kJ.g^{-1} wet wt, or about a 40% change. Thus, all age classes of herring rely heavily on stored energy to survive the winter. The difference in mean values for somatic energetic content for YOY herring was only about 1.4 kJ.g^{-1} suggesting only those with higher than average energy stores survived the winter. The fall measures of SEC showed the YOY, and 1 year old Pacific herring, stored markedly less energy to over-winter

than older herring. Thus, energetically the recruiting year class. and those entering their second winter, are the most at risk for nutritionally related over-winter mortality.

Ovarian energy content (OEC) of ripe whole ovaries and $kJ.g^{-1}$ of ovary, were examined for Pacific herring. Specimens were collected in 1995 and 1996. The OEC of whole ovaries was related linearly to whole body weight, but OEC $kJ.g^{-1}$ wet weight was not. Just prior to spawning OEC was typically between 5 and 7 $kJ.g^{-1}$ wet weight. There were no significant differences in OEC $kJ.g^{-1}$ wet weight between groups of females from different capture sites in the 1995 collections, but in 1996 there were small but significant differences in OEC values related to capture site. When the OEC values from all fish collected in 1995 were pooled and compared to all those collected in 1996, there was no significant difference in $kJ.g^{-1}$ wet weight between years. The number of ova present just prior to spawning exhibited no clear relationship to OEC $kJ.g^{-1}$ wet weight. About 97% of OEC was expended during spawning. The OEC measurements were used to make estimates of the energy from herring spawn added to Prince William Sound beaches from 1988 to 1995. Since 1989, when there was a massive oil spill, the amount of energy added to the Prince William Sound ecosystem by herring eggs has decreased from 68×10^9 kJ to 10×10^9 kJ in 1995, which in addition to being a concern for recruitment, could also be important to species relying on herring spawn as an energy source. If egg predator populations remain stable or increase while the amount of herring spawn decreased the impact of predation may be limiting recruitment.

This project measures fall and spring somatic energy content of juvenile pollock (*Theragra chalcogramma*) to compare their nutritional status to that of competitors like juvenile herring and pink salmon fry. This energetic profile will aid in the understanding of how pollock compete with these two injured fish species. Pollock are a major prey of many seabird species injured by the oil spill and our energetic measures will be useful in estimating bird energy intake. Information on the pollack energetics will not be processed until late 1997.

The information gathered by this energetics project is being related to SEA zooplankton surveys, prey selection studies and trophic isotopic studies through the SEA modeling effort. The data also supports the APEX predator-feeding analysis.

Key Words: *Clupea pallasi,* herring, energetics, ovary, somatic energy, *Theragra chalcogramma,* pollock.

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Figure 2. Whole body energy content kJ.g^{-1} wet weight relative to age for Pacific herring captured in Prince William Sound, Alaska, during the fall of 1995 (upper) and spring of 1996 (lower). The data is plotted as mean and standard deviations.

Project Data:

Table 1 provides a list of samples collected for energetic analysis. Samples are frozen fishes that are dried and combusted. The process destroys the sample. Small amounts of tissue from selected fishes are passed on to SEA project 320I (Kline). The data collected is energy content of whole body tissues. Energetic data is stored as SIGMAPLOT, EXCEL, and ASCII files. The data becomes available as the material is published in journals. The custodian is Dr. A. J. Paul, University of Alaska, Seward Marine Center, POB 730, Seward, AK 99664 (Phone 907 224-5261; Fax 224-3392; email ffajp@aurora.alaska.edu).

Executive Summary:

During its second year this project examined somatic energy content of age 0 and 1 herring (spring and late fall), age 0 pollock (spring and late fall), herring ovaries just prior to spawning, and adult herring bodies during fall and spring. These parameters are key measures for SEA models which predict levels of fish production and species interactions. The key results for the species under study include:

Herring ovaries: Examination of the amount of energy in herring ovaries was used to estimate the deposition of herring egg energy on beaches in PWS between 1988 and 1995. Since 1989, when there was a massive oil spill, the amount of energy added to the Prince William Sound ecosystem by herring eggs has decreased from 68 x 10^9 kJ to 10 x 10^9 kJ in 1995. This precipitous decline in the amount of herring egg energy deposited on the beaches is a reflection of very poor recruitment since the 1989 oil spill.

Herring somatic energy: 1) There is considerable geographical variation in the fall energy content of recruits captured in different areas. 2) From the spring sampling it appears that recruits from the 1994 year class were well nourished and passed the over-winter period in good condition allowing for hope that a reasonable survival of individuals will follow. 3) Most of the 1995 year class were undernourished when entering the winter and were in poor condition the following spring. 4) Herring recruits store energy for poor feeding conditions in winter and as their length increases so does energy content at a much higher level than seen in pink salmon fry or pollock 5). The results of the surveys demonstrate that YOY herring metamorphose in July and so they start this phase of development long after the spring bloom is ended. They then have just a few months to prepare for the poor feeding conditions of winter and are at a disadvantage relative to older year classes of herring that have the whole spring and summer period to feed. Because of this YOY herring are susceptible to being under-nourished for over-wintering. Based on our current, and incomplete, knowledge of the energy needs for age 0 herring during the over-winter period it appears that many individuals are under nourished. These measures of energy storage and use will provide insight into the potential of individuals to survive winter. It will also help understand the effect of "River and Lake" conditions, and be used to estimate consumption of herring by predators. SEA measures secondary standing stock by a variety of methods. Herring are users of zooplankton and their SEC at the end of the feeding season reflects secondary productivity. The somatic energy values provide a separate measure by which the SEA prey standing stock estimates can be evaluated.

Age 0 pollock: Pollock exhibit the same growth mode as pink salmon fry (see 1996 annual report), preferentially increasing in length. Pollock recruits appear to increase in length during the winter at some sites and maintain their nutritional status or improve it unlike herring who lose somatic energy during the winter. The energetic profile for age 0 pollock will aid in the understanding of how pollock compete with the two injured: species pink salmon fry and herring recruits.

Introduction:

During the second field season this project focused on somatic energy content of two species of pelagic fish in the EVOS region. It started to explore over-winter survival of juvenile herring and herring reproductive energetics. A portion of the effort examined somatic energy in age 0 pollock during the fall and spring, which are trophic analogs with herring, so the nutritional status of these forage species can be compared. In recent history, herring and pollock have been among the most abundant pelagic forage fishes in south central Alaska. After the Exxon Valdez oil spill the herring population of Prince William Sound has been exhibiting reduced abundance, increased prevalence of disease, and spawning anomalies that may be related to pollution. This research effort will help identify the role of food in delimiting survival of recruiting herring.

Typically high latitude fishes store energy during spring and summer feeding and throughout the winter reallocate energy to maintenance and reproduction (Smith *et al.*, 1990). Thus, seasonal tissue samples must be taken to account for the temporal variation in energy content. Age 0 and 1 year old herring store energy during the summer feeding season and either fast or feed at low rates during the winter. If they have insufficient energy stores to maintain normal schooling activities until the spring zooplankton bloom, then high mortalities might occur. Low energy storage might be due to low zooplankton standing stocks or to competition for food resources.

Objectives: The objectives of this project were:

1. Describe the interannual somatic energy content of herring especially ages 0 and 1 relative to geographical location.
2. Examine fall and spring energy stores of juvenile herring from several sites in Prince William Sound and describe the role nutritional status plays in over-winter survival.
3. Describe the spawning energetics of herring. Measure ovarian energy relative to weight, age and spawning site in female herring.
4. Measure fall and spring energy content of adult herring.
5. Measure fall and spring somatic energy content of juvenile pollock and make comparisons of their nutritional status to geographical location and that of juvenile herring.
6. Relate the analysis of all the above objectives to SEA zooplankton surveys, prey selection studies and trophic isotopic studies through the SEA modeling effort and multi-author journal papers.

Methods:

The methods applied to the energy cycles were similar to those used by the investigator in previous bioenergetic studies (Harris *et al.*, 1986; Paul *et al.*, 1993, Smith *et al.*, 1988; Smith *et al.*, 1990). All fish lengths in 320 U were standard length (SL) measured to the nearest mm. All whole fish or ovary weights were taken to the nearest 0.1 g. All calorimetric samples were weighed to the 0.0001 g level.

Herring Ovarian Energetics

Colleagues in the Alaska Department of Fish and Game, who were monitoring gonad ripeness for a possible roe fishery, collected adult herring just prior to and after spawning.

Collections for this project were made from several sites when the product quality was at its peak, indicating spawning was imminent. Ripe females were collected 14 April to 14 May 1995 and 15-16 April 1996 and frozen immediately. In 1995 adult female herring were collected from 3 sites, Eaglek Bay in northern Prince William Sound (*n*=35), Fish Bay in Port Fidalgo (*n*=29) and Rocky Bay on Montague Island (*n*=46) just prior to spawning. Just after the spawning was completed 26 spent females were collected from Zaikof Bay on Montague Island. In the spring of 1996 ripe females were collected at Boulder Bay (*n* = 40) on Bligh Island, Rocky Bay (*n* = 50) on Montague Island, Rocky Point (*n* = 50) in northeastern Prince William Sound, Stockdale Harbor (*n* = 50) on Montague Island, and Sunny Bay in Port Fidalgo (*n* = 47). No spent females were collected in 1996.

In the laboratory the fish were partially thawed for measurement, but not enough so that the carcass lost fluids. The females were measured for whole body wet weight to 0.1 g. Both ovaries were removed from the female and weighed to the nearest 0.1 g. Then a subsample, weighing about 0.1 g of 1 ovary was removed, weighed, and all the eggs in it were counted. These subsamples typically contained about 100 eggs. The number of ova in the ovaries was estimated from the number of ova per gram in the subsample and the ovary weight. Because the fish were ready to spawn the clumps of eggs could be separated by physical manipulation and then counted under a microscope. The gonosomatic index was determined by dividing ovary weight by wet body weight. The relationship of gonosomatic index to OEC was examined to illustrate the variability associated with the degree of ripeness that results because not all fish spawn at the same time.

Ovarian subsamples of 10 to 15 g were removed from each ripe female for measurement of OEC. The wet weight of the subsample was taken to the nearest 0.1 g. After freeze drying for 24 h, ovarian tissues were placed in a convection oven at 60°C until they reached a constant weight. Individual sample wet and dry weight values were used to calculate the moisture content. Dried tissues were ground in a mill and measurements of OEC $kJ.g^{-1}$ were made by bomb calorimetry. OEC was converted to $kJ.g^{-1}$ wet weight using the percent moisture in the ovary subsample. The energy content of whole ovaries was obtained by multiplying $OEC.g^{-1}$ by ovary weight.

Energetic estimates of whole ovaries just after spawning were obtained from females collected at Zaikof Bay 2 April 1995. The whole ovary was weighed and treated as above for energy measurement. Whole dried ovaries were combusted for each calorimetric analysis.

Scales were removed from every fish just above or below the lateral line, 3 rows behind the operculum for aging. They were cleaned manually and mounted on glass slides. Mounted scales were placed in a microfiche reader, and winter annuli counted in the conventional manner. The age is equivalent to the number of winter annuli counted because all herring in Prince William Sound hatch in the spring.

Somatic Energy of Herring

Juvenile herring were captured with 50m diameter x 4m deep purse seines with 3 mm stretch mesh. At each collection site at least three sets were made to capture specimens. Adult herring were collected with commercial herring purse seines (182m diameter, 22m deep, 3cm mesh). After capture all fish were immediately frozen in seawater aboard ship and kept frozen until processing. During the fall of 1995 YOY and age 1 herring were collected from Green Island 25 October (n = 100); Jack Bay on 3 November (n = 100); Knowles Head 1 November (n = 98). Larger fish were taken at Green Island 25 October (n = 174); Jack Bay 3 November (n = 91); and Knowles Head 1 November (n = 100). During 1996 YOY and age 1 herring were collected at Port Fidalgo 11 March (n = 80); Boulder Bay 11 March (n = 94) and in Rocky Bay on 17 March (n = 58). During the following spring ripe herring were collected between 15-17 April 1996 at Boulder Bay (n = 90); Port Fidalgo 15 April (n = 97); Rocky Bay 16 April (n = 100); and Stockdale Harbor 17 April (n = 100).

In the laboratory the fish were partially thawed, just enough to handle, but not enough so fluids were lost. Scales were removed from every fish just above or below the lateral line, 3 rows behind the operculum for aging as above. All fish were measured for standard length (SL) to the nearest mm, then weighed to the nearest 0.1 g. The SEC of the whole individual was determined in terms of $kJ.g^{-1}$ wet weight. Herring under 150 mm SL were freeze dried whole. Larger fish while still partially frozen were ground, then the ground body made into a paste in a mortar. A 30 g subsample was then freeze dried. After freeze drying, test tissues were placed in a convection oven at 60°C until they reached a constant weight. Individual tissue wet and dry weight values were used to calculate the moisture content of every fish. Dried tissues were ground in a mill and measurements of caloric content made by bomb calorimetry. All calorimetric samples were weighed to the 0.0001 g level with a single sample burned per fish.

Somatic Energy of Age 0 Pollock

Pollock under 115 mm SL were collected at several sites and frozen in seawater for analysis. Fish were analyzed for standard length, wet weight, condition factor [CF = g wet wt x 100/(cm standard length)^3], and whole body energy content using standard calorimetric methods noted above.

Results:

Herring Ovarian Energetics

Whole ovary energy in kilo-Joules (kJ) was correlated with body wet weight ($r^2 \geq 0.76$). Whole ripe ovaries typically contained 50 to 300 kJ wet weight. The linear relationships between the energy content for whole ovaries and fish weight in 1995 and 1996 had slightly different regression equations, but the differences were small. Energy content of the whole ovary (Y) was related to ovary weight (X) by the equations: $Y(\text{kJ}) = 5.4X + 4.8$; $r^2 = 0.99$, $P < 0.0001$ in 1995; in 1996 this relationship was Y (kJ) = $5.4X + 3.7$; $r^2 = 0.98$, $P < 0.0001$. Energy content of the whole ovary was not strongly related to the gonosomatic index. Whole ovary energy of spent females averaged 0.9 kJ (range 0.1-6.0) showing that most of the energy contained in the ovaries was expended with spawning. The spent ovaries consisted primarily of structural tissues with very few eggs inside. In 1995 a 150 g female expended about 97% of the energy stored in the ovary with spawning. We calculated population OEC based on mean numbers of females from the 1988-1995 Prince William Sound roe fishery population and age-specific biomass surveys. That population OEC estimate indicates a marked decline in the amount of energy supplied to Prince William Sound by the herring spawning since 1992 (Figure 1). The results of the OEC study will be published in Paul et al. (1997).

Somatic Energy of Herring

In the fall there was a tendency for somatic energy content (SEC) to increase with age, the most profound differences being between the YOY and age 1 fish, and the other age groups (Figure 2 upper panel). The average SEC values for all YOY fish (n = 214) and age 1 herring (n = 78) were 5.7 (± 0.6) and 8.0 (±1.2) $kJ.g^{-1}$ wet wt respectively. The SEC values for YOY herring were significantly lower than those of age 1 fish. Likewise, the age 1 fish had significantly lower (MW test; $P<0.0001$) SEC values than the 2 year old fish. The age 2 and older fish had similar SEC values with mean values ranging from 9.4 to 10.2 kJ.g^{-1} wet wt. There was considerable range in SEC values between individuals at any SL, or weight indicating many individuals did not eat enough to maximize their energy reserves.

The following spring the individual plots of SEC demonstrated that after over-wintering, all size classes of herring had markedly less stored energy than those captured in the fall (Figure 2 lower panel). Like the fall samples, there was also lots of variability in individual SEC values in the spring specimens relative to measures of fish size. The average SEC values for all YOY (n = 64) and age 1 (n = 178) fish in their respective age classes were nearly identical at 4.4 (± 0.6) and 4.4 (±0.6) kJ.g^{-1} wet wt respectively. The SEC values for YOY herring were not significantly lower than those of age 1 fish (MW test). The age 1 fish had significantly lower (MW test) SEC values than the 2 year old fish. The age 2 and older fish had SEC with mean values ranging from 5.2 to 6.3 kJ.g^{-1} wet wt with lots of variability. These results are being prepared for publication.

Somatic Energy of Age 0 Pollock

Pollock samples from the SEA study area have all been processed, but the data will not be analyzed in time for this report. The data will provide insight into how recruiting herring and age 0 pollock compete for food resources and their relative success and link to APEX studies of pollock-bird interactions, APEX and SEA fish stomach analysis-isotope studies, and assessments of secondary productivity.

Disscussion:

Our population ovarian energy content estimate indicates a marked decline in the amount of energy supplied to Prince William Sound by the herring spawning since 1992 (Figure 1). This decline in population OEC is primarily due to decreased female biomass. In 1991 there was a good recruitment of age 3 fish that resulted from the pre-oil spill 1988 spawning, but there were very few females recruiting from the 1992 to 1995 year classes. The effect of such large interannual variations in the kilo-Joule input to the ecosystem from herring eggs is unknown, but may be significant. If egg predator populations remain stable or increase while the amount of herring spawn decreased the impact of predation may be limiting recruitment. Our size-OEC relationships can be used to make more sophisticated estimates of ovary energy input into Prince William Sound in future models using more detailed individual fish information available in the extensive Alaska Department of Fish and Game herring fisheries data base. These in turn can be used in egg predator consumption estimates and herring recruitment models based on energetics.

The examination of somatic energy content of age 0 herring, and their competitors age 1 herring and age 0 pollock shows promise for understanding the level of competition between these pelagic analogs. Coupled with SEA models and APEX and SEA stomach analysis these prey competition interactions could be quantified in EVOS synthesis models now under consideration for funding. The somatic energy measures should identify individuals that have not stored enough energy to survive the winter period. The bioenergetic over-winter model (Mason) hopes to be able to identify poor year classes 3 years in advance of their entry into the fishery. It will not be able to identify strong year classes ahead of time but will alert managers to year classes which have potential to recruit to the fishery. The SEC signatures also are a reflection of zooplankton standing stock.

This project is focused on collecting information on the geographical and interannual variability in nutritional status of herring recruits. Thus, until the field collections are completed, and analyzed in 1998 it is difficult to interpret the significance of the project's findings. The existing data does suggest that over-winter analysis of whole body energy content of YOY herring is a measurement that has potential to identify poor year classes years in advance of their entering the fishery.

CONCLUSIONS

Somatic and specific tissue energy measurements are a valuable tool for identifying the transfer of energy through the food web to pelagic fish. They measure subtle differences that are not observable from length wet weight measures. Quantifying energy transfers is critical to building SEA and other EVOS models and the energetics component of SEA provides critical input values. for these models. Energetics measures are being used to simulate and test SEA hypothesis Lake-River and Over-Wintering and the production and competition models. Additionally the energetic data set allows for trophic comparisons of pelagic analogs like pollock and herring, and transfer of energy to other animals like APEX birds. Satifactory progress is being made towards achiving all objectives. No metholodical problems have occured. The project should be successfully competed on time for all objectives relating to the tasks of this individual SEA project.

ACKNOWLEDGEMENTS

Several SEA staff aided in field collections, laboratory analysis and data handling. Youth Area Watch also aided in some fish collections and laboratory work. The Seward Marine Center Laboratory provide all the facilities.

LITERATURE CITED

Harris, R., T. Nishiyama, and A. J. Paul. 1986. Carbon, nitrogen and caloric content of eggs, larvae, and juveniles of the walleye pollock, *Theragra chalcogramma*. J. Fish. Biol. 29: 87-89.

Paul, A. J., J. M. Paul, and R. L. Smith. 1993. The seasonal changes in somatic energy content of Gulf of Alaska yellowfin sole *Pleuronectes asper* Pallas 1814. J. Fish Biol. 43: 131-138.

Paul, A. J., J. M. Paul, and E. D. Brown. 1997. Ovarian energy content of Pacific herring from Prince William Sound, Alaska. Alaska Fishery Research Bulletin. In Press.

Smith, R. L., A. J. Paul, and J. M. Paul. 1988. Aspects of energetics of adult walleye pollock, *Theragra chalcogramma* (Pallas), from Alaska. J. Fish. Biol. 33: 445-454.

Smith, R. L., J. M. Paul, and A. J. Paul. 1990. Seasonal changes in energy and the energy cost of spawning in Gulf of Alaska Pacific cod. J. Fish. Biol. 36: 307-316.

Table 1. List of samples collected for energetics.

Juvenile herring

LOCATION		DATE	BOAT #	SET #	FISH #	FILE
BOULDER BAY		3/11/96	11	1018	1-43	J34
AREA 623		3/11/96	12	1014	44-94	J34
CULROSS PASSAGE	AREA 605	3/28/96	12	1066	1-46	J44
DRIER BAY		3/19/96	12	1042	1-14	J40
AREA 622			11	1045	15-27	J40
			12	1041	28-74	J40
			11	1044	75-89	J40
			12	1040	90-150	J40
EAGLEK BAY		5/10/95		9530013	1-100	J11
AREA 584		11/5/95		9512053	1-96	J20
				951205?	97-100	J20
		3/13/96	12	1026	1-51	J36
			12	1024	52-88	J36
			12	1022	89-150	J36
		5/10/96	4	1044	10819-10843	NH1
			4	1045	10844-10868	NH1
			4	1047	10869-10893	NH1
		6/10/96	12	1168	10894-10993	NH5
			12	1169	10994-11043	NH5
			12	1170	11044-11093	NH5
		8/1/96	2	1265	12522-12621	NH11
			2	1270	12622-12640	NH11
			4	1071	12641-12740	NH11
		10/8/96	12	1321	740-789	J53
			12	1322	790-837	J53
			12	1323	840-886	J53
			12	1324	887-934	J53
HODGKIN PT.,		5/17/95		9520117	1	J3&6

ESTHER ISLAND		5/18/95		9520119	2	J3&6
AREA 502				9520124	3-7	J3&6
				9530059	8-9	J3&6
(files J3 & J6 were				9530063	10	J3&6
combined for this				9530066	11-13	J3&6
sample)				9530067	14	J3&6
				9550627	15-17	J3&6
		5/14/95		9520090	1-14	J3&6
				9530036	15-17	J3&6
				9530037	18-19	J3&6
GREEN ISLAND	AREA 630	10/25/95		9512032	1-100	J24
HOGG BAY		5/7/95		9530010	1-100	J8
AREA 582		11/8/95		9512061	1-25	J29
				9512062	26-41	J29
				9512063	42	J29
JACK BAY		11/3/95		9512050	1-89	J21
AREA 604				9511052	90-100	J21
		3/12/96	12	1017	1-50	J35
			11	1021	51-76	J35
			12	1015	77-125	J35
			12	1016	126-131	J35
			11	1015	132-150	J35
JACK POT BAY	AREA 610	7/8/96	2	1245	13468-13617	NH16
KNOWLES HEAD	AREA ?	11/1/95		9512040	1-98	J26
MacLEOD HARBOR	AREA 580	3/28/96	12	1050	1-95	J43
PT. HELEN, KNIGHT IS.	AREA 522?	8/8/95		95107-1T	1-100	J9

NAKED ISLAND		3/18/96	12	1037	1-49	J39
AREA 520			12	1038	50-80	J39
			11	1041	81-94	J39
ORCA INLET		10/26/94	TPNH	9422	1-93	J2
AREA 517		4/30/95		9520001	1	J10
				9520003	2-10	J10
				9520005	11-13	J10
				9590002	14-22,101	J10
				9590004	23-31	J10
				9530001	32-51	J10
				9590003	52-100	J10
PADDY BAY		3/23/96	11	1049	1-120	J41
AREA 610			12	1052	121-136	J41
			11	1063	137-150	J41
PORT FIDALGO	AREA 585	3/11/96	12	1013	1-80	J33
PORT GRAVINA		10/29/94	TPRH	9415	1A1-4A10 (100 fish)	J1
AREA 518 &528		5/27/95		9520127	1-100	J7
				9520129	101	J7
	AREA 621	7/3/96	2	1213	13368-13467	NH15
ROCKY BAY	AREA 583	3/17/96	12	1035	1-58	J38
SAWMILL BAY	AREA 616	11/7/95		9512059	1-100	J23
SHEEP BAY		3/8/96	11	1007	1-75	J32
AREA 611			12	1008	76-100	J32
			12	1006	101-125	J32
			12	1007	126-150	J32
SIMPSON BAY		10/16/95		9512002	1-50	J27
AREA 601				9512003	51-100	J27

	3/7/96	12	1002	4-104	J31
		12	1003	105-153	J31
	5/15/96	4	1049	10470-10568	NH4
		4	1050	10570-10668	NH4
		12	1103	10669-10693	NH4
		12	1105	10769-10818	NH4
		4	1052	10694-10743	NH4
		12	1106	10744-10768	NH4
	6/15/96	4	1056	11594-11643	NH8
		12	1199	11644-11693	NH8
		12	1201	11694-11743	NH8
		12	1202	11819-11868	NH8
		12	1204	11869-11918	NH8
		12	1205	11919-11968	NH8
	8/5/96	2	1289	13168-13267	NH14
		2	1292	13268-13367	NH14
	10/3/96	12	1299	300-348	J50
		12	1300	349-399	J50
		12	1302	400-447	J50
		12	1307	592-641	J50
	11/6/96	12	1343	1220-1319	J62
	12/5/96	?	1346	1320-1412	J70
		?	1347	1413-1512	J70
SNUG CORNER COVE AREA 603	11/3/95		9512046	1-100	J28
TIPPING PT., PERRY IS.	5/5/95		9520034	1-6	J4
AREA 506			9520035	7-10	J4
			9540029	11-61	J4
	5/6/95		9590027	62-65	J4
			9590029	66-70	J4
			9590032	71-112	J4
WHALE BAY	10/19/95		9512012	1-48	J25
AREA 602			9513004	51-98	J25

	3/24/96	12	1045	1-51	J42
		11	1053	52-101	J42
		12	1043	102-150	J42
	5/12/96	12	1091	10001-10075	NH2
		11	1088	10151-10250	NH2
		12	1093	10076-10150	NH2
	6/11/96	4	1053	11094-11143	NH6
	6/12/96	4	1054	11144-11218	NH6
		4	1055	11744-11818	NH6
		12	1181	11219-11267	NH6
	7/9/96	2	1247	12169-12268	NH10
		4	1063	12269-12421	NH10
		2	1248	12422-12521	NH10
	8/2/96	4	1072	12741-12840	NH12
		4	1075	12841-12940	NH12
	10/7/96	12	1317	642-689	J52
		12	1318	690-734	J52
	11/5/96	12	1338	935-1034	J60
ZAIKOF BAY	5/2/95		9540014	1-2	J5
AREA 521			9520015	3-9	J5
			9540011	10-57	J5
	3/16/96	11	1036	1-25	J37
		12	1030	26-85	J37
		12	1032	86-106	J37
	5/13/96	11	1089	10251-10379	NH3
	5/14/96	12	1099	10380-10427	NH3
		12	1100	10430-10469	NH3
	6/13/96	11	1157	11269-11343	NH7
		12	1193	11344-11443	NH7
	6/14/96	12	1196	11444-11518	NH7
		12	1198	11519-11593	NH7
	7/11/96	2	1260	11969-12168	NH9
	8/4/96	2	1280	12941-13016	NH13
		2	1278	13018-13067	NH13

		2	1288	13068-13167	NH13
	10/5/96	12	1308	448-493	J51
	10/9/96	11	1215	542-591	J51
	10/10/96	12	1334	494-540	J51
	11/5/96	12	1340	1035-1169	J61
	11/6/96	12	1342	1170-1219	J61
	12/5/96	12	1348	1513-1547	J71
	12/6/96	12	1350	1548-1599	J71
RESURRECTION BAY	3/95	fasting experiment 1		1-33	SMORT
AREA 524	12/1/95	fasting experiment 2		1-22	STV1
	12/28/95	fasting experiment 2		1-22	STV2
	1/25/96	fasting experiment 2		1-22	STV3
	3/20/96	fasting experiment 2		1-30	MORT2
	4/1/96	fasting experiment 2		1-18	LIVE95KJ
	3/19/96	SEA spring sample		1-50	J30

POLLOCK INVENTORY

DRIER BAY	3/19/96	12	1040	1471-1479	P27
AREA 622		12	1039	1480-1512	P27
EAGLEK BAY	11/5/95		9512053	1-50	POL1
AREA 584			9512054	51-99	POL1
	3/14/96	12	1025	1371-1421	P26
		11	1031	1422-1470	P26
	5/10/96	11	1080	10001-10075	NP1
	6/10/96	11	1140	10366-10415	NP5
		11	1141	10417-10515	NP5

		8/1/96	2	1265	13568-13652	NP9
		10/8/96	12	1324	2252-2401	P43
HOGG BAY		11/7/95		9511070	1-8	POL2
AREA 582				9512063	9-41	POL2
				9512062	42-68	POL2
				9512061	69-100	POL2
KNOWLES HEAD		11/1/95		9512040	1-2	POL3
AREA ?				9512041	3-8	POL3
				9511041	9-19	POL3
				9512042	20-69	POL3
				9511042	70-100	POL3
ORCA NARROWS		3/7/96	11	1001	1001-1031	P20
AREA 517			11	1002	1032-1070	P20
ORCA BAY			11	1004	1171-1270	P22
PADDY BAY	AREA 610	3/23/96	11	1052	1513-1612	P28
PORT GRAVINA		3/10/96	11	1011	1271-1320	P24
AREAS 518 & 528			11	1012	1322-1370	P24
SAWMILL BAY		11/7/95		9511063	1-2	POL4
AREA 616				9511065	3-14	POL4
				9512058	15-38	POL4
				9512059	39-100	POL4
		3/27/96	12	1049	1613-1663	P30
SIMPSON BAY		10/16/95		9512001	1	POL5
AREA 601				9512002	2-9	POL5
				9512005	10-16	POL5
				9512006	17-29	POL5
				9511005	30-49	POL5
				9512003	54-100	POL5
		3/7/96	11	1003	1071-1120	P21

		11	1067	1121-1170	P21
	5/15/96	11	1092	10276-10365	NP4
	6/15/96	11	1170	10776-10876	NP8
		11	1174	10877-10977	NP8
	10/3/96	12	1299	1700-1774	P40
		11	1179	1775-1843	P40
WHALE BAY	10/18/95		9512010	1-37	POL6
AREA 602			9512009	-62	POL6
	5/12/96	11	1088	10076-10225	NP2
	6/11-12/96	12	1179	10516-10539	NP6
		12	1181	10549-10593	NP6
		12	1182	10603-10678	NP6
	8/3/96	2	1276	13368-13467	NP10
	10/8/96	11	1195	2140-2176	P42
		12	1318	2177-2251	P42
ZAIKOF BAY	10/20/95		9512015	1-80	POL7
AREA 521			9512016	81-100	POL7
	5/13/96	11	1090	10226-10275	NP3
pollock	6/13-14/96	11	1157	10679-10753	NP7
		12	1196	10754-10774	NP7
	8/4/96	2	1280	13468-13567	NP11
	10/5,9-10/96	11	1215	1850-1916	P41
		11	1191	1917-2064	P41
		11	1222	2065-2137	P41

ADULT HERRING WHOLE BODY ENERGY

PORT FIDALGO (Sunny Bay area)	4/15/96	50 males, 47 females	AH12
ROCKY BAY	4/16/96	50 males, 50 females	AH13

BOULDER BAY	4/15/96	50 males, 40 females	AH11
STOCKDALE HARBOR	4/17/96	50 males, 50 females	AH10
HERRING WHOLE OVARY INVENTORY			
STOCKDALE HARBOR	4/17/96	50 ovaries	OVA10
BOULDER BAY	4/15/96	40 ovaries	OVA11
PORT FIDALGO	4/15/96	47 ovaries	OVA12
ROCKY BAY	4/16/96	50 ovaries	OVA 13
ROCKY POINT	4/16/96	50 ovaries	OVA14

Chapter 13.

Synthesis and Integration (96320Z)

Exxon Valdez Oil Spill
Restoration Project Annual Report

Sound Ecosystem Assessment (SEA): Synthesis and Integration

Restoration Project 96320-Z
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

Robert T. Cooney

Institute of Marine Science
University of Alaska Fairbanks
Fairbanks, Alaska 99775-7220

April 1997

Sound Ecosystem Assessment (SEA): Synthesis and Integration

Restoration Project 96320-Z
Annual Report

Study History: Project 96320-Z was established in 1996 to assist the SEA lead scientist prepared and distribute single, integrated SEA DPDs and Annual Reports. Funding was also provided to assist with the important aspects of synthesis and integration within the multi-project SEA program. These activities are facilitated by conference calls, subgroup meetings and workshops of all investigators and selected staff and students.

Abstract: Support for synthesis and integration activities within the SEA program was used to receive, collate, reproduce and submit the single, integrated SEA FY97 DPD and FY95 Annual Report. Funding was also used to sponsor (travel) model subgroup meetings, and a workshop of all SEA principal investigators, selected staff and students in September.

Key Words: Synthesis, integration, SEA

Project Data: Much of the synthesis and integration activity in SEA was conducted using information and data services provided by 96320-J. This includes a SEA web-page and associated cyber tools.

Citation: Cooney, R. T. 1997. Sound Ecosystem Assessment (SEA): Synthesis and Integration, Exxon Valdez Restoration Project Annual Report (Restoration project 96320-Z), Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, Alaska.

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Executive Summary

Funding allotted to 96320-Z was used to submit a single integrated FY97 DPD and FY95 Annual Report. This project also sponsored travel for the herring model subgroup to meet in Anchorage in May, and to bring the entire SEA organization together for a three-day workshop at the Seward Marine Station in late September. At that time the workshop reviewed the status of all projects, received updates from each of the modeling subgroups, and explored ideas for improving the efficiency of reporting SEA results to peers and the EVOS Trustee Council. It was decided that future reporting would be handed primarily by manuscripts for the reviewed literature. Also, initial ideas were explored regarding the structure of the close-out activities, including assignments to selected investigators to search for appropriate journals to which a major SEA synthesis could be submitted. Dr. James Brady was invited to attend the meeting and agreed to serve as the Alaska Department of Fish and Game contact for developing management applications arising from the SEA program.

Objectives

The following objectives were stated in the approved FY96 DPD:

1. Convene two (or more) internal meetings of SEA principal investigators to discuss and debate program scientific results, and to apply these findings to hypothesis testing.

2. Use SEA information to address timely reporting and program planning required of program 320 each year to include collecting, copying , collating and distributing single integrated reports and proposals.

Methods

The SEA lead scientist (Dr. Cooney), working with the SEA executive committee (Dave Eslinger, Vince Patrick, Mark Willette) and other SEA principal investigators, sets the agenda for full meetings of SEA. Subgroups and others requesting travel support approach the lead scientist with justification for such travel. Decisions are based on scientific need. Funds are expended until they are exhausted. The lead scientist receives digital and hard copies of reports and proposals. These are collated, copied and distributed to the Trustee Council, and internally to all SEA scientists.

Results

The SEA FY97 single, integrated DPD was submitted by 15 April, 1996. The single, integrated FY95 Annual Report was submitted by 1 May, 1996. The SEA herring workgroup met in May in Anchorage for a subgroup modelling workshop. All of SEA attended a program status and planning workshop in Seward in September, 1996.

Discussion

Funding year FY96 was the first year that funds were made available to address the tasks associated with the timely submission of SEA reports and proposals in a single, integrated format. This provide the lead scientist with local support to compete these tasks. I judge this was funding well spent. The ability to convene subgroups and meetings of all SEA principal investigators, staff and students is crucial to the success of the program. The isolation of the Seward meeting provided three days of uninterrupted discussion that led to several good ideas about making the reporting and proposing more efficient, and described better ways to pursue the collective science endeavors. Travel for subgroup meeting was well spent.

Conclusions

The SEA program must respond in a timely manner to reviews, proposals, and reporting schedules assigned by the Trustee Council. Because of the size and complexity of the study, support is needed for a variety of synthesis and integration activities associated with these tasks, and with the cooperative science. This project allows the lead scientist the necessary flexibility to address the overall management of SEA in a way that would be impossible without such support.

Acknowledgments

All SEA principal investigators, their staffs and students are acknowledged for assistance with proposal and report writing, and for participating aggressively in the process of science, including the debate and application of results to management tools. I am particularly indebted to Rosemary Ruff (UAF) and Nancy Bird and Penny Oswalt (PWSSC) for assistance with proposals, budgets and reports. Jennifer Allen provided network services that assisted in all of the synthesis and integration activities. Lastly, I acknowledge the unselfish assistance of Bill Hauser (ADF&G) with budgeting and other program tasks.