Exxon Valdez Oil Spill
Restoration Project Annual Report

Toward Long-Term Oceanographic Monitoring of the Gulf of Alaska Ecosystem

Restoration Project 99340
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.

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Study History: EVOS funding for this project was initiated in October 1998 and continues through FY00 with this annual report being the second produced. This work builds upon, indeed continues, measurements of temperature and salinity determined as a function of depth (CTD sampling) at a hydrographic station near Seward (GAK1) that were begun 30 years ago. Prior to the initiation of this study sampling at GAK1 was nominally monthly and conducted opportunistically from research vessels transiting to and from Seward. Between 1990 and 1995 NOAA funding maintained the monthly sampling on a more systematic basis. Funding from EVOS has systematized the sampling even further by supporting an instrumented mooring at GAK1, which consists of six temperature and salinity sensors deployed at discrete depths throughout the water column. In addition, EVOS funding has maintained the monthly CTD sampling. This project complements additional ecosystem sampling being conducted on the Gulf of Alaska shelf under the auspices of the Northeast Pacific Global Ocean Ecosystem Dynamics (NEP-GLOBEC) Program. The PI is also a participant in this GLOBEC study, which is supported jointly by NOAA and NSF.

Abstract: This project built upon a 30-year time series of temperature and salinity obtained from hydrographic station GAK 1 on the Gulf of Alaska (GOA) shelf near Seward. Results from the past year showed a transition from the anomalously fresh and warm conditions of spring 1998 to the anomalously salty but near normal temperature conditions of spring 1999. The shelf salinity differences were accompanied by other substantial differences between these two years. Dissolved NO_3 concentrations were 30 – 50% lower in 1998 and mixed layer formation occurred earlier than in 1999. The alongshore mass and freshwater transports were 1.5 and 2 times greater in 1998 than in 1999. We also found large seasonal, interannual, and interdecadal variability in coastal salinity and freshwater forcing of the GOA. Time series of coastal discharge estimates, measured discharge, the 1st EOF of precipitable water over the Northeast Pacific Ocean, and coastal salinity data all suggest a decrease in freshwater discharge into the northern GOA from late 1950s through mid-1970s. Monthly sea level anomalies at Seward are significantly correlated with monthly anomalies of vertically integrated (0-200m) salinity and the 0/200db dynamic height. Sealevel might be a proxy for shelf salinity variations here and perhaps elsewhere in the GOA.

Key Words: Alaska Coastal Current, Gulf of Alaska shelf, ocean ecosystem monitoring, temperature-salinity variability.

Project Data: Two types of data are available: 1) monthly temperature and salinity profiles collected by CTD (accessible from website: www.ims.uaf.edu:8000/gak/gak1.dat and 2) hourly measurements of temperature and salinity at 28, 58, 198, and 245 m depth for March through December 1998 are accessible from the PI (weingart@ims.uaf.edu).

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EXECUTIVE SUMMARY

This annual report summarizes the activities and analyses of the second year of this anticipated four-year project. The project goals were only partially achieved due to a software problem in the instruments involved in the GAK1 mooring. The problem involved adjusting the instrument clocks while the instruments are operating under the delayed start protocol. Unfortunately this problem was not apparent to us or to the manufacturer prior to mooring deployment. Consequently the instruments never turned on under the delayed start protocol and so no data were collected by the instruments on the GAK 1 mooring between December 1998 and December 1999. We did not discover this problem until we recovered the instruments in December 1999. We also re-deployed the GAK1 mooring at that time after insuring that the software problem was resolved. Analyses over the past year have focussed on interpreting some of the historical data available from GAK 1 with a particular emphasis on understanding seasonal and interannual variability in freshwater on this shelf. I am also a PI in the Gulf of Alaska GLOBEC Long Term Observations Program (LTOP) and regard the GLOBEC and EVOS programs as being complementary. Therefore, my analyses have used data from each program to understand better physical oceanographic variability on this shelf. The results discussed below were presented at the January 2000 EVOS workshop and also at the Ocean Sciences meeting held in San Antonio, Texas in January 2000. The major findings of the past year were that:

1. The Alaska Coastal Current mass and freshwater transports in spring 1998 (during the 1997-98 El Niño) were 1.5 and 2.0 times as large as those of spring 1999. The difference in freshwater transport between spring 1998 and 1999 is equivalent to 8000 $m^3\ s^{-1}$, which is the same magnitude as the mean annual discharge from the Columbia River. The shelf was considerably fresher in spring 1998 and this freshening was accompanied by NO_3 concentrations that were 30 – 50% lower than those of 1999. There were also differences in phasing of the springtime mixed layer. In 1998 the mixed layer was well developed by May, whereas the mixed layer was poorly developed over the shelf in May 1999.
2. The alongshore baroclinic transport in the upper 75m of the water column and within 30 km of the coast carries at least 50% of the total coastal discharge (as estimated by Royer, 1982) into the Gulf of Alaska. This component of the freshwater transport is equivalent to twice the annual discharge of the Yukon River. Variations in freshwater forcing and the baroclinic transport of freshwater are large on seasonal, interannual, and interdecadal time scales. On average freshwater transport increases fivefold between spring and fall. This freshwater transport estimate is based only on that portion of the transport calculable from the ocean's density field and probably underestimates the total freshwater transport by the Alaska Coastal Current. I suggest that the Alaska Coastal Current might provide up to 25% of the annual freshwater supply to the southeast Bering Sea shelf. This finding suggests the potential importance of the Gulf of Alaska shelf to the Bering Sea ecosystem.
3. Time series of coastal discharge estimates, measured discharge, the leading empirical orthogonal function of precipitable water over the Northeast Pacific Ocean, and coastal salinity data all suggest a decrease in freshwater discharge into the northern Gulf of Alaska from the late 1950s through the mid-1970s. Discharge increased from the mid-70s through the early-80s with this increase coincident with the regime shift of the 1970s and with the Pacific Decadal Oscillation. These findings add to other suggestions of a freshening across the North Pacific Ocean basin since the 1970s.

4. Monthly sea level anomalies at Seward Alaska are significantly correlated with monthly anomalies of vertically integrated (0-200m) salinity and the 0/200db dynamic height. Hence sea level could serve as a proxy for shelf salinity variations here and perhaps elsewhere in the Gulf of Alaska.
5. The Gulf of Alaska watershed and coastal ocean is severely undersampled with respect to precipitation, river discharge, and salinity. Long-term time series of these are lacking and even the maintenance of existing discharge and weather stations is uncertain. There is a need to develop proxy variables that can be used to reliably estimate runoff and coastal salinity.

This project is closely connected to the ongoing GLOBEC program of which this PI is also involved. As the GLOBEC data set matures we will be better able to understand the mechanisms responsible for change at GAK 1 and the relation between the inner shelf (GAK 1) and outer shelf.

Introduction:

The Gulf of Alaska experiences large seasonal and interannual variations in meteorological and oceanographic forcing (Royer, 1996; 1993) which affects biological production (Mantua et al., 1997). Quantifying this variability and its causes are necessary for understanding the structure of, and changes in, the northern Gulf of Alaska marine ecosystem. Natural physical variability could influence the recovery of many of the marine species and marine services affected by the *Exxon Valdez* oil spill. The information provided by this project should help EVOS investigators working in the Gulf of Alaska analyze progress in recovery and restoration progress within the context of the long-term variability of the physical environment. This monitoring project represents a step toward this capability by building upon the historical record of temperature and salinity measurements made on the Gulf of Alaska shelf at hydrographic station GAK 1 near Seward, Alaska (**Figure 1**).

This annual report describes the first year's accomplishments and ongoing efforts of what is anticipated to be a four-year program. Several of the analyses are still underway and so the results and conclusions are only tentative. However, they are meant to offer a glimpse into the program and the direction in which we anticipate the research proceeding.

Objectives:

As stated in the original proposal our general objectives are to:

I. quantify the thermohaline variability on time scales from the tidal to the interdecadal,
II. interpret existing data so that a better understanding of climate forcing and its effects on marine ecosystems can be construed,
III. guide the development of a cost-effective long-term monitoring program, and
IV. provide information useful for designing process studies necessary to develop ecosystem models for this shelf.

I contend that long-term data sets are required to address these issues. Toward that end the fundamental goal of this program is to continue the now 30-year time series of temperature and salinity at hydrographic station GAK1. This is being done through a combination of monthly CTD measurements and through yearlong deployments of a mooring containing temperature and conductivity (T/C) recorders. We have also formulated several project-specific objectives to guide progress toward these generic objectives. Specifically we will:

1. Determine the within-month variance of temperature and salinity at a given depth. This information has been lacking for GAK 1 so it is difficult to determine the significance of a single monthly measurement (as determined from the CTD data) relative to the variability observed within a given month. These basic statistics can be used to estimate the statistical significance of temperature or salinity anomalies observed in the past.
2. Determine the rate of change of water mass properties (temperature and salinity) and the phasing of these changes at different depths. Some of these features might be temporally aliased with monthly sampling. They need to be resolved to understand the dominant oceanic

time scales and the relationship between low-frequency variations (monthly and longer) and shorter period fluctuations (synoptic scale events).

3. Determine the seasonal and vertical distribution of variance in temperature, salinity and dynamic height. That is, determine if distinct vertical "modes" of variability exist and how these modes vary in time.

4. Assuming that the temperature/conductivity recorders provide a useful estimate of dynamic height, then determine the joint effects on Seward sea level of dynamic height and winds. Over what time-scales are these variables coherent with one another and with Seward sea level?

Methods:

We collected monthly conductivity-temperature-depth (CTD) data nearly monthly from either the Institute of Marine Science's 25' *Little Dipper* or the *R/V Alpha Helix*. The sensors on the CTDs used were calibrated annually by the manufacturer (e.g., Seabird of Bellevue, Washington). In addition, field checks were made on the conductivity sensor from bottle salinities collected during the cast. The bottle samples are analyzed on the salinometer at the Seward Marine Center. Salinities have an accuracy of ~0.01 or better and temperatures are accurate to 0.005°C or less.

The monthly sampling was supposed to be complemented with hourly measurements from six temperature/conductivity recorders (Seabird MicroCats; SBE model 37-SM) incorporated in a taut wire, subsurface mooring at GAK1. The mooring was deployed in December 1998 and recovered in December 1999. After recovering the mooring, we discovered that none of the six instruments had started at their pre-programmed start time in December 1997. Prior to deployment, the Institute of Marine Science's mooring engineer checked all instruments. This check also tested the delayed start procedure. The instruments performed correctly during the test and were then pre-programmed for an in-water start time. Prior to deployment the mooring engineer checked the instrument clocks and noted a slight drift in each one. He therefore adjusted the clock to the latest GPS time and then deployed the instruments. Unbeknownst to us (or to Seabird at the time) the clocks cannot be adjusted without repeating the delayed start procedure. None of the instruments ever turned on to begin sampling and, consequently a year's worth of data was not collected at the mooring. (We discovered the problem during the December 1999 recovery and re-deployment cruise and talked extensively to Seabird during this cruise to ascertain the problem. We were therefore able to avoid a similar mistake on the instruments deployed.) We had made some progress on the first three of the project specific objectives with results from the first mooring as reported in the first year's annual report (Weingartner, 1999). However, those results were regarded as tentative. Unfortunately, the problems we encountered this year do not allow us to refine those tentative conclusions.

Most of our analytical effort during this past year concentrated on trying to quantify seasonal, interannual, and interdecadal variability in freshwater on the Gulf of Alaska shelf. Freshwater forcing affects ocean salinity. In the Gulf of Alaska salinity controls the horizontal and vertical density gradients and therefore circulation and mixing. Consequently, changes in freshwater content and distribution could significantly influence the Gulf of Alaska shelf ecosystem. Quantifying regional variations in salinity (or freshwater forcing) is difficult because the measurement network is sparse and there are few continuous long-term measurements of ocean salinity, precipitation, and/or coastal discharge from around the gulf. We used a variety of different data sets to accomplish this task. An important goal of this exercise is to see if there is consistency among the various data sets used. If the various data sets corroborate one another then we have greater confidence that any signals present are indeed real. This exercise also suggests directions for future research. The data sets examined include:

1. 30 (gappy) years of nominally monthly CTD data from hydrographic station GAK 1 and sea level from Seward, Alaska and ~40 cruises (since 1980) along the Cape Fairfield Line in the northern Gulf of Alaska (**Figure 1**). This line encompasses the bulk of the Alaska Coastal Current (Johnson et al., 1988; Stabeno et al., 1995).
2. Time series of monthly discharge anomalies for the Gulf of Alaska from 1931 through 1998 (computed following Royer, 1982) and kindly provided to us by T. Royer.
3. Time series of the Pacific Decadal Oscillation (PDO) for the same period as Royer's discharge data (obtained from website: tao.atmos.washington.edu/datasets).
4. 40 to 50 years of monthly USGS discharge records from streams entering the north central and eastern gulf (**Figure 2**). We use normalized monthly anomalies of the discharge since the drainage basins vary from 20 and 70000 km^2. The website containing these data is: h2o-nwisw.er.usgs.gov/nwis-w/AK/
5. ~40 years of monthly atmospheric precipitable water obtained from the NCEP/NCAR reanalyzed meteorological fields interpolated onto a 2.5° grid between 65°-35°N and 160°-120°W (**Figure 3**). The website containing these data is: www.cdc.noaa.gov./cdc/data.nmc.reanalysis.html#surface;
6. 70 years of coastal surface salinity data from British Columbia archived by Canada's Dept. Fisheries and Oceans (**Figure 2**). The website containing these data is: www.ios.bc.ca/ios/osap/data/lighthouse/bcsp.html.

The data sets in items 4 and 5 were examined using empirical orthogonal function (EOF) analysis (e.g., Kutzbach, 1967). This technique decomposes data distributed through time and at discrete stations into discrete modes. The modes result from an eigenanalysis of the correlation matrix computed from all the data. The analysis decomposes the total variance into modes that are orthogonal to one another. For each mode the analysis produces an eigenvector, a temporal amplitude function, and an eigenvalue. The eigenvalues represent the fraction of the total system variance explained by a single mode. The eigenvector describes how the amplitude of a given mode varies in space and the time amplitude function describes how the particular mode varies in time.

Results and Discussion:

The following three subsections tie directly to general objectives I and II listed in the Objectives section.

Comparison of winter-spring 1998 (El Niño) and winter spring 1999 (La Niña)

The monthly temperature and salinity data collected at GAK 1 (and over the Gulf of Alaska shelf as part of the GLOBEC LTOP) showed that late winter 1999 temperatures were near normal but that salinities in the upper 100 m of the water column were about 0.25 psu above normal. However, in May 1999 water temperatures in the upper 50 m were about 0.5°C below normal and salinities were ~0.5 psu above normal. We believe the May 1999 conditions on the inner shelf were due to a cooler than normal spring that delayed the onset of snowmelt. Temperature and salinity conditions were near normal by June and have remained that way through December. While these salinity anomalies appear to be small they might be ecologically significant. We show this by comparing the cross-shelf distribution of salinity and nitrate in April 1998 and 1999 (**Figure 4**). Salinities within 100 km of the coast in April 1998 were much lower than in April 1999. However, in April 1999 shelf nitrate concentrations were 30 – 50% greater than in April 1998. Comparison of the May sections from these two years shows that the inner shelf was more strongly stratified in 1998 than in 1999. This is consistent with the delay in melting due to a cool spring in 1999, for the depth of the shelf mixed layer in spring is dependent upon the addition of freshwater, which stratifies the water column. Since stratification is essential to the onset of the spring bloom (e.g., Mann and Lazier, 1991) these findings imply that the timing and magnitude of the spring bloom for these two years might have been very different. Such differences could be an interannual manifestation of the optimal stability "window" hypothesis advanced to explain interdecadal fluctuations in North Pacific salmon stocks (Gargett 1997, Gargett et al., 1998).

We suggest several causes for these differences. Rainfall and air temperatures for the period from late fall 1997 through spring 1998 were above normal. Discharge was above normal in the gulf and even as far south as the Columbia River based on inspection of USGS discharge records. Hence there was more freshwater discharge into the Gulf of Alaska then compared to the comparable period in 1999. Cyclonic (coastal downwelling favorable) wind stress was generally stronger and more extensive over the Northeast Pacific in the 97-98 period than during the comparable period in 98-99 as shown in the space and time-averaged upwelling indices of (**Figure 5**). Flow over the shelf and slope of the Gulf of Alaska is relatively swift and originates at least as far south as the British Columbian shelf (Thompson et al., 1989). Consequently, environmental perturbations introduced into the ocean far to the south can be advected into and around the gulf on the order of a few months. The strong, extensive and persistent winds of 97-98 would have intensified the flow around the gulf possibly bringing shelf and slope water northward from as far south as Oregon. Indeed, Strub and James's (*submitted*) analysis of satellite altimeter data suggest that this was indeed the case.

Seasonal cycle in freshwater content and transport in the Alaska Coastal Current

Table 1 compares the salinity, alongshore baroclinic transport, and the freshwater transport averaged over March, April, and May 1998 with that for 1999. The comparison is based on data collected during GLOBEC cruises along the Cape Fairfield transect, which is approximately 20 km east of GAK 1 (**Figure 1**). (GAK 1 lies on the inshore edge of this current and reflects conditions within it.) The calculations are performed using data from the upper 100m of the water column and within 30 km of the coast. This choice is motivated by the fact that ~75% of the alongshore baroclinic transport on the Gulf of Alaska shelf occurs within 30 km of the coast (Danielson et al., 1999) and that the Cape Fairfield Line encompasses the bulk of the Alaska Coastal Current. The estimates of the freshwater fraction on the shelf depend upon a suitable choice for the reference salinity, which was chosen to be 34.42. This value is the mean salinity of the Gulf of Alaska for stations having bottom depths greater than 1000m. For 1998 salinities were about 0.4 psu lower, but the baroclinic (freshwater) transport was about 1.5 (2) times greater in 1998 compared to 1999. The freshwater transport differences were ~8000 $m^3 s^{-1}$ which is approximately equivalent to the mean annual discharge of the Columbia River!

We also investigated the seasonal cycle in baroclinic transport, freshwater content, and freshwater transport within the Alaska Coastal Current. Before discussing these results we show (**Figure 6**) the mean annual cycle of: 1) coastal discharge into the Gulf of Alaska (following the methodology of Royer, 1982), the upwelling index (available from www.pfeg.noaa.gov), and 2) mean monthly salinities at standard depths at GAK 1. The seasonal variability in wind stress (represented in **Figure 6** as the upwelling index) and freshwater discharge is large. The mean monthly "upwelling index" at locations on the GOA shelf is negative in most months, indicating the prevalence of coastal convergence or downwelling. Cyclonic winds are strongest from November through March and feeble or even weakly anticyclonic in summer when the Aleutian Low is displaced by the North Pacific High (Royer, 1975; Wilson and Overland, 1986). The seasonal runoff cycle is maximum in early fall, decreases rapidly through winter when precipitation is stored as snow, and attains a secondary maximum in spring due to snowmelt (Royer, 1982). Runoff dilutes the upper ocean in summer and fall, while high salinity water from the continental slope floods the shelf bottom. The deep onshore transport is in response to the summer relaxation of cyclonic winds. The annual salinity range is a minimum at 75 and 100m and we use the former as the reference depth for computing alongshore baroclinic and freshwater transports and freshwater content. (The fact that salinity changes very little throughout the year at 75 m is important in computing the freshwater content because changes in content are then due to addition or deletion of freshwater rather than the vertical displacement of isohalines.) Transports are referenced to 75 db between 4 and 30 km offshore with westward transport negative. Freshwater content is expressed as a height upon integrating vertically (*dz*) and across shore (*dy*) and relative to the reference salinity (S_r=34.42). The results are shown in **Figure 7** and while highly variable suggest that:

1. Baroclinic transport increases *twofold* and freshwater transport increases *fivefold* between spring and fall with both in-phase with the discharge cycle (**Figure 6**).
2. The baroclinic component of the mean annual freshwater transport in the 0-75m layer is ~400 km^3-yr^{-1} (or twice the mean annual Yukon River discharge).
3. Freshwater content remains constant from July though November although discharge (**Figure 6**) doubles rapidly during this time. This means that ocean dispersal processes are removing freshwater from the upper 75m of the inner shelf.

These transport estimates are underestimates insofar as they do not include the (unknown) barotropic component of flow over the inner shelf and depend to some extent on the choice of reference level in computing the baroclinic transport. The barotropic transport component is likely westward (Stabeno et al., 19) and choosing a deeper reference level, (100 db instead of 75 db) would result in slightly larger baroclinic transports. Therefore the transport results are probably conservative estimates. We conclude this section by noting that the Alaska Coastal Current ultimately enters the southeast Bering Sea shelf. Order of magnitude estimates suggest that the Alaska Coastal Current supplies ~25% of the freshwater influx into the Bering Sea. This transport has implications for the shelf nutrient budgets as well because NO_3 and salinity are apparently correlated (Ruehs et al., 1999). Consequently, variations in salinity and/or nutrients on the Gulf of Alaska shelf could impact the Bering Sea ecosystem as well.

Interannual variability freshwater forcing in the Gulf of Alaska

We examine several different data sets in exploring longer-term salinity and freshwater variations in the Gulf of Alaska. We begin first with a comparison of monthly discharge anomalies (computed following Royer, 1982) and the Pacific Decadal Oscillation (PDO) for the period 1931 through 1998 (website: tao.atmos.washington.edu/datasets). Time series of both (smoothed with a 25-month running mean to emphasize low-frequency variability) are shown in **Figure 8**. Note that for both series the interdecadal differences are similar in magnitude to shorter period variations. Moreover, the series generally correspond to one another. In particular, there was low discharge and negative PDO from ~1950 - 1980 and high discharge and positive PDO from 1935 - 1950. The mid-1970 transition from negative to positive discharge and PDO coincides with the "regime shift" (Mantua et al., 1997). The coherence (**Figure 9**) between the *unsmoothed* series is significant at the 95% level at periods of 6 months where discharge leads PDO by about 2 months and in the 2 – 3 year period range. For the latter PDO leads discharge by ~6 months and it explains ~60% of the discharge variance. Coherence increases over the low frequency portion of the spectrum (>10 years) however the discharge record is not long enough to resolve (statistically) the relationship at these low frequencies.

We next examined the temporal variability in streamflow from south central and southeast Alaska. The streams chosen had at least 30 years (10 rivers) to 50 years (8 rivers) of continuous records. Of the hundreds of streams and rivers flowing into the gulf the number continuously gauged is extremely small. (It appears that ever fewer gauges are being maintained so that even this relatively long, but nevertheless meager, data set is likely to dwindle in scope and duration.) **Figure 10** shows the time amplitude function for the 1st EOF mode of streamflow discharge for the set of 8 and 10 rivers respectively. For both cases the first mode captures a large fraction of the total variance (~43%) and is significant based on North et al.'s (1982) test. In particular we note that the decline in discharge from 1959 to the mid-1970s and the subsequent rise thereafter. This transition in the 1st EOF for streamflow also coincides with the timing of the regime shift shown in **Figure 8.**

Precipitable water is the vertically integrated moisture content in the atmosphere and represents the potential amount of water available for precipitation. The first EOF is significant following North et al. (1982) and explains ~30% of the total variance for this variable over the Northeast Pacific Ocean. **Figure 11** shows the time amplitude function for the 1st mode, which is smoothed with a 13-month running mean to highlight low-frequency variance. This mode captures the decrease in atmospheric water from ~1960 to the mid-1970s and then the subsequently rapid increase through the early 1980s. Again this pattern is consistent with those of **Figures 8 and 10**. The 1st mode eigenvector (**Figure 12**) shows that the maximum amplitude is in the northeast Gulf of Alaska. Amplitudes diminish very rapidly south of about 52°N over the central and eastern portions of the domain and in particular the amplitude decreases by nearly 40% between 54°N and 50°N along the west coast of North America.

Coastal surface salinities collected at four stations along the British Columbian (**Figure 2**) coast provide further corroboration of the precipitable water results. **Figure 13** shows monthly coastal salinity anomalies (smoothed with a 13-month running mean) beginning in the early 1930s. Salinities increased from the late 1960s to the mid-1970s and decreased thereafter at station Langara (54°N); the farthest north station available. However, this decadal scale salinity increase and decrease is not evident at the lighthouses further south. These sites are also where the amplitude of the 1st EOF mode for precipitable water is substantially reduced in comparison to the Langara site (**Figure 13**). Thus the British Columbian coastal salinity data are consistent with the precipitable water results in this regard.

Note also that the lighthouse data suggest a freshening trend (since at least the 1930s) along the British Columbian coast [Freeland et al., 1997]. That trend is not reflected in Royer's discharge time series (**Figure 8**) however. The causes and geographical extent of this trend are unknown, but because these waters feed the Alaska Coastal Current this freshening might indeed exist in the northern gulf.

The following subsections relate directly to general objectives III and IV listed in the Objectives section.

Long term monitoring implications

Royer (1979) first suggested a possible relationship between dynamic height, freshwater, and sea level and this idea was discussed first in last year's annual report (Weingartner, 1999) and incorporated into an objective for the 1999 work plan. We therefore assembled Seward sea level data over the period of the GAK 1 occupations. We then computed monthly anomalies of corrected sea level, GAK 1 surface dynamic height referenced to 200 db, and GAK 1 vertically integrated (0 – 200 m) salinity. **Figure 14** shows scatter plots of sea level vs. dynamic height and salinity and indicates the correlations. The results show that sea level anomalies are significantly correlated with dynamic height and vertically integrated salinity anomalies at GAK1. Dynamic height and vertically integrated salinity anomalies (not shown) are also significantly correlated ($r = .93$; $P << .01$) underscoring the dominant role of salinity in controlling dynamic height variability on the Gulf of Alaska shelf. Although dynamic height explains only ~20% of the sea level variance, the predictive skill is similar in magnitude to that between monthly sea level and large scale atmospheric pressure patterns (Chelton and Davis, 1982). Further, the low skill might be due to sampling differences: sea level records were sampled hourly and averaged into monthly means, whereas the dynamic heights are from single hydrographic casts during a month. The GAK 1 mooring should lead to improvements in this relationship because it will sample hourly temperature and salinity at discrete depths. Hence the estimates of monthly means and anomalies should improve.

Under GLOBEC support we are examining the historical and GLOBEC-supported data from the Cape Fairfield to see if there is a significant positive correlation between monthly anomalies in 0/100 db ACC baroclinic transport and inner shelf (eventually GAK 1) dynamic heights. The relationship appears to vary seasonally (although the number of degrees of freedom is small in some seasons): it is largest in fall and early spring ($r > 0.8$), negligible in summer, and negative in winter. We do not understand these seasonal changes in these correlations (assuming that they are real and not random deviations) but suspect they are tied to the ACC response to seasonal changes in winds and discharge. If in fact a reliable relationship can be constructed between GAK 1 dynamic height and Alaska Coastal Current transport, then it might be possible to predict mass and freshwater transports (on at least monthly or longer time scales) from a single hydrographic station or mooring on the inner shelf. If so the results would be useful for ecosystem monitoring, model evaluation (and perhaps data assimilation) and in retrospective studies.

Conclusions

The results from the past year's effort lead to the following conclusions.

1. Variations in freshwater forcing and the baroclinic transport of freshwater are large on seasonal, interannual, and interdecadal time scales. On average freshwater transport increases fivefold between spring and fall. Alaska Coastal Current freshwater transport in spring 1998 (during the 1997-98 El Niño) was twice that of spring 1999.
2. The alongshore baroclinic transport in the upper 75m of the water column and within 30 km of the coast carries at least 50% of the total coastal discharge (as estimated by Royer, 1982). into the Gulf of Alaska.
3. Time series of coastal discharge estimates based on Royer's (1982) method, measured discharge, the leading EOF of precipitable water over the Northeast Pacific Ocean, and coastal salinity data all suggest a decrease in freshwater discharge into the northern Gulf of Alaska from the late 1950s through the mid-1970s. Discharge increased from the mid-70s through the early-80s; coincident with the regime shift of the 1970s and with the PDO (Mantua, 1997; Overland et al., 1999). These findings add to other suggestions of a freshening across the North Pacific Ocean basin since the 1970s (Wong et al., 1999).
4. Monthly sea level anomalies at Seward Alaska are significantly correlated with monthly anomalies of vertically integrated (0-200m) salinity and the 0/200db dynamic height. Hence sea level could serve as a proxy for shelf salinity variations here and perhaps elsewhere in the Gulf of Alaska. The Gulf of Alaska watershed and coastal ocean is severely undersampled with respect to precipitation, river discharge, and salinity. Long-term time series of these are lacking and even the maintenance of existing discharge and weather stations is uncertain. There is a need to develop proxy variables that can be used to reliably estimate runoff and coastal salinity.

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Table 1. Comparison between 1998 and 1999 of March, April, and May Alaska Coastal Current salinity, baroclinic transport, and fresh water transport along the Cape Fairfield Line.

MARCH, APRIL, MAY	Mean Salinity (psu)	0/75db Baroclinic Transport ($x10^5$ m^3 s^{-1})	Fresh Water Transport ($x10^4$ m^3 s^{-1})
1998	31.81	2.9	2.0
1999	32.18	2.0	1.2

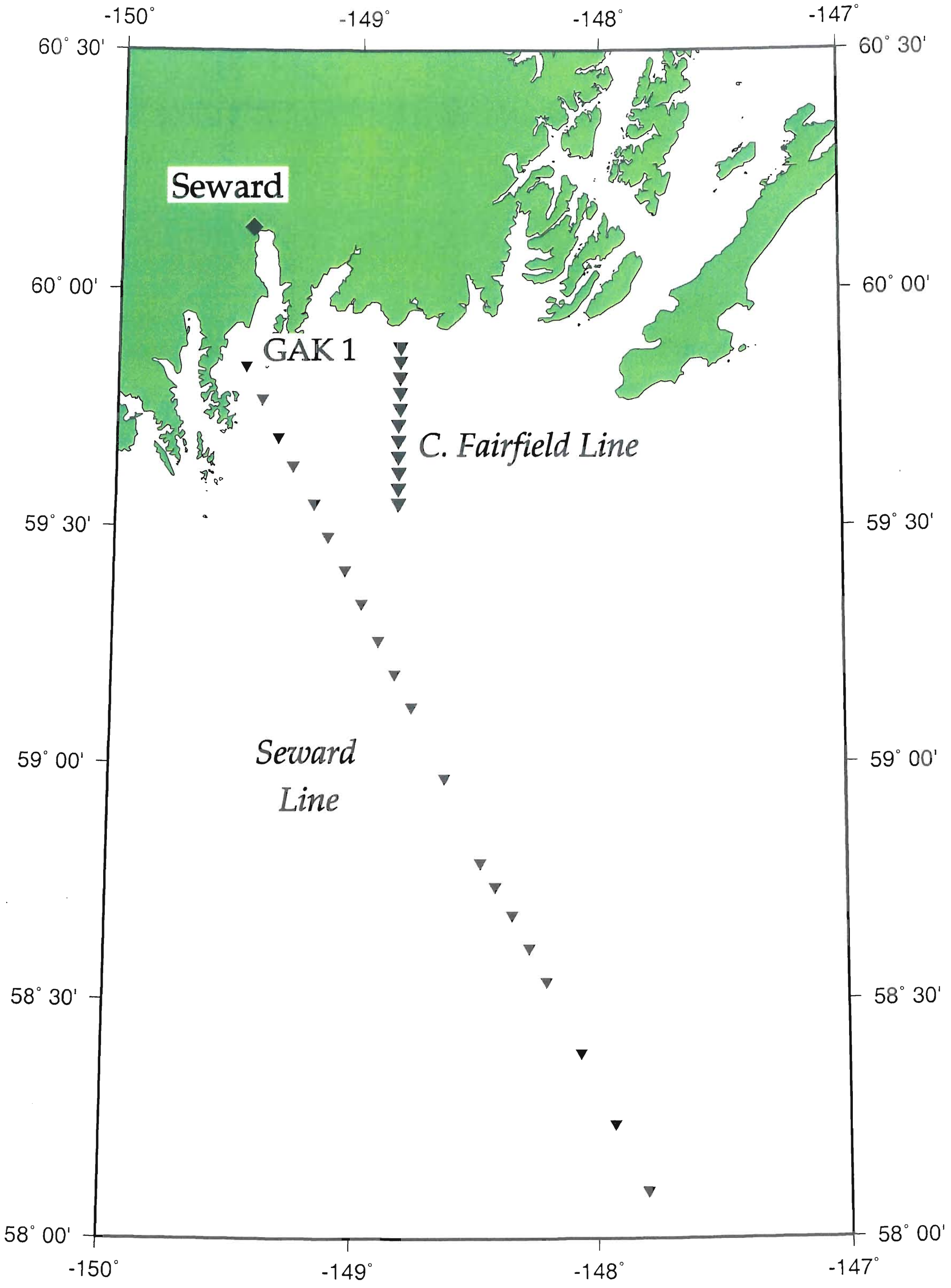


Figure 1. Location map of the northern Gulf of Alaska showing the position of hydrographic station GAK 1, the Seward Line and the Cape Fairfield Line.

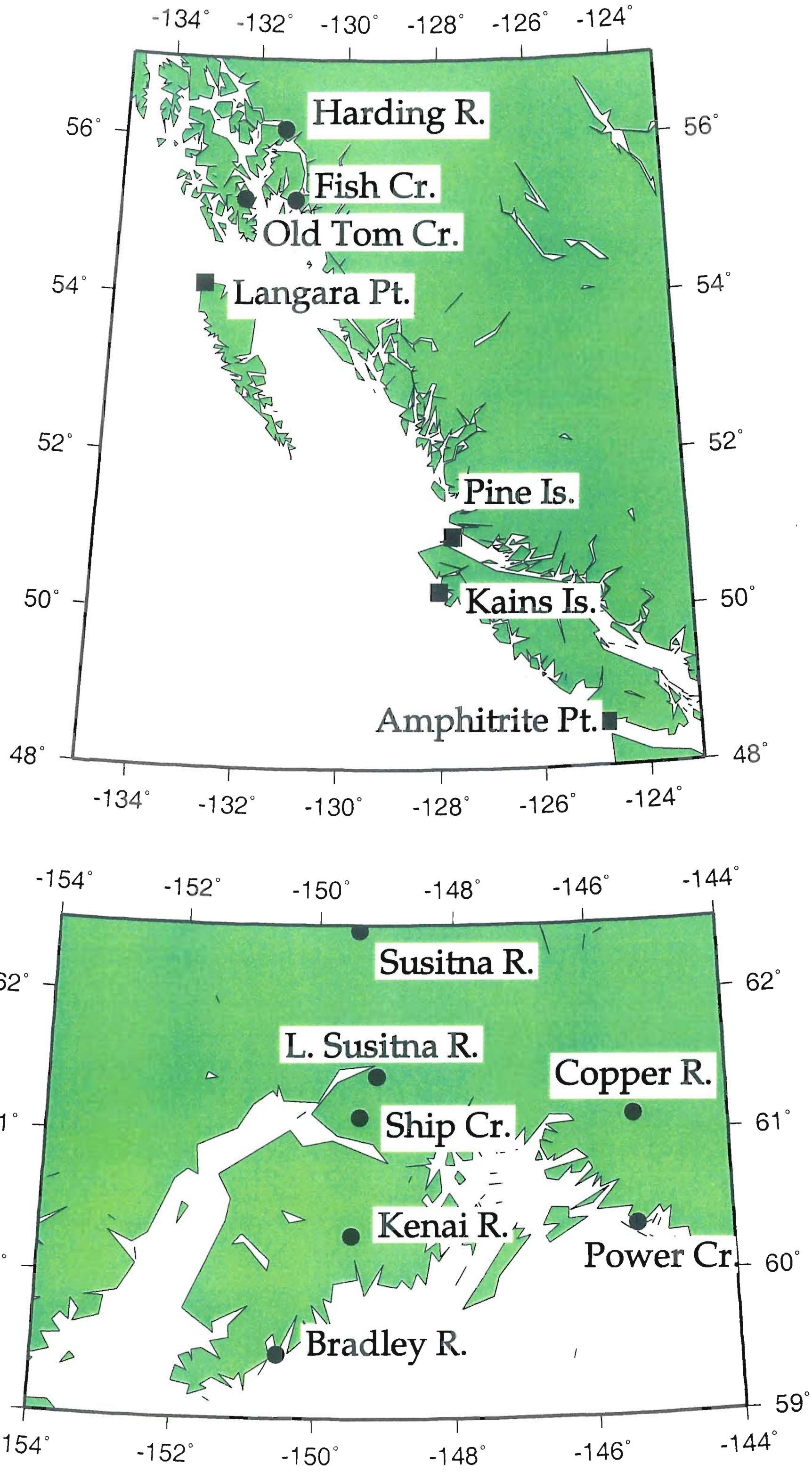


Figure 2. Location map of USGS stream gauges (solid circles) and British Columbia lighthouses for which monthly coastal surface salinity data were taken

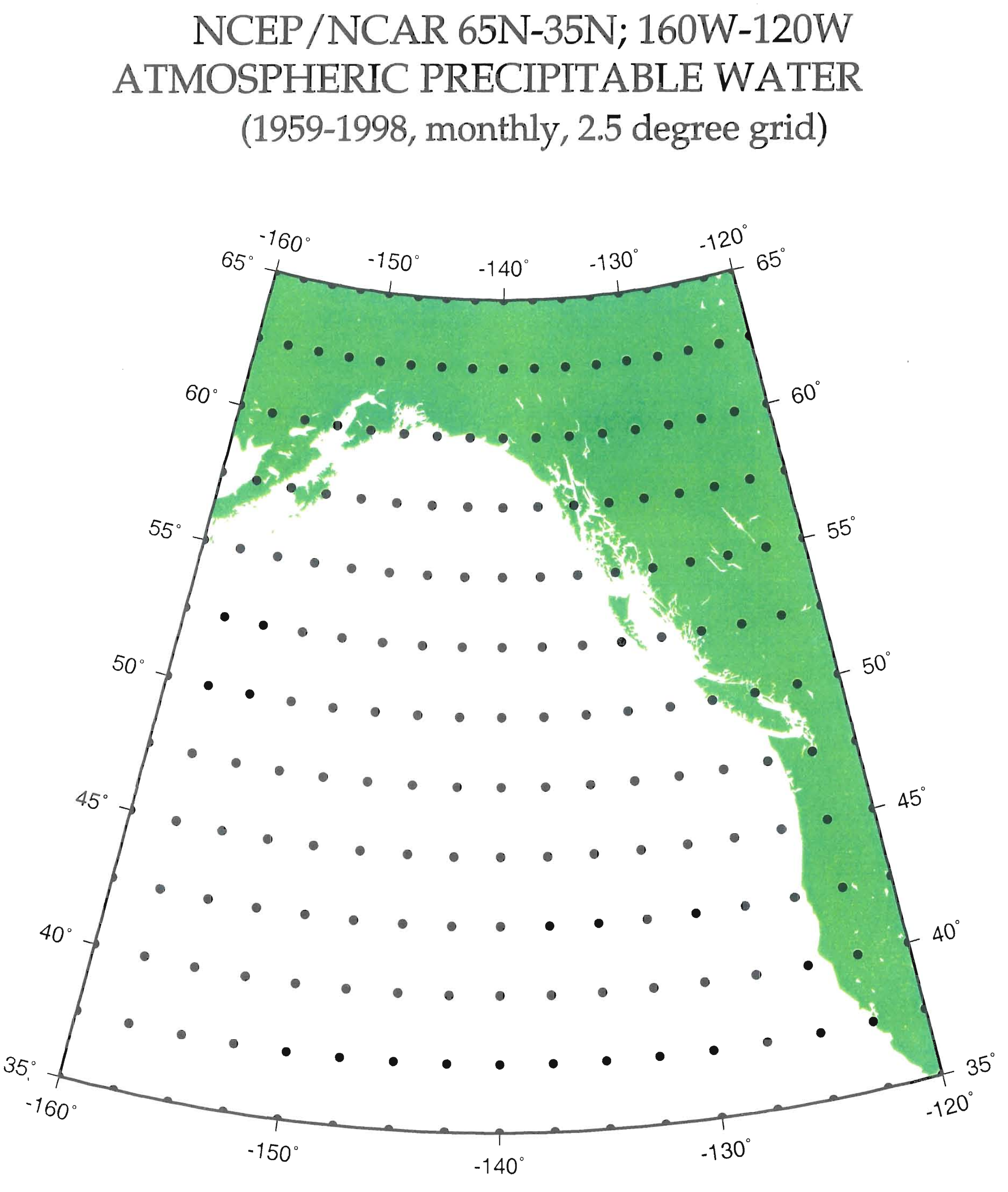


Figure 3. Location map of the NCEP 2.5 degree grid over the Northeast Pacific Ocean for which monthly precipitable water estimates are available for from 1959 – 1998.

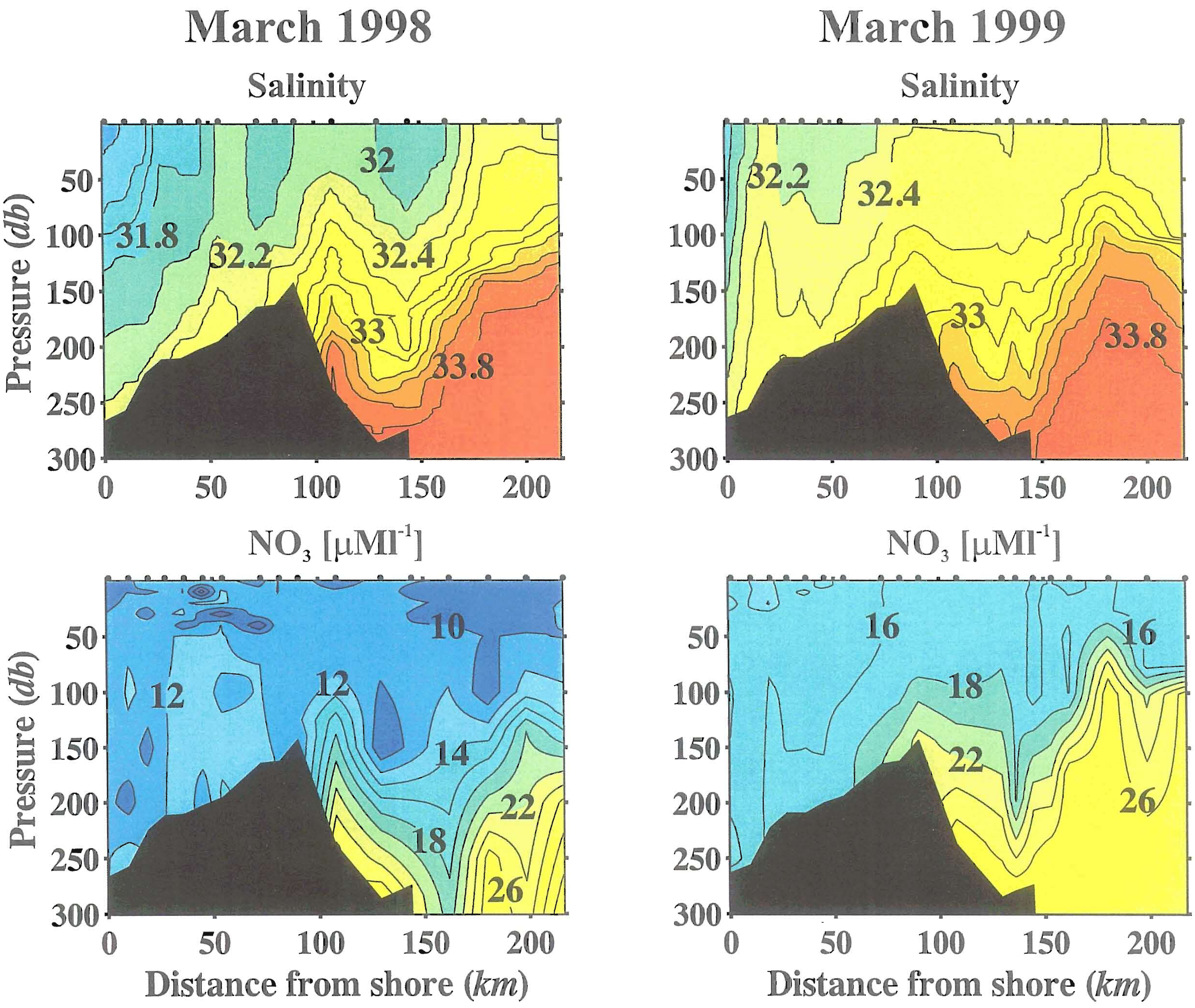


Figure 4. Cross-shelf distributions (0-300 *m*) of salinity and NO_3 for April 1998 and April 1999. The data were collected along the Seward Line with GAK1 on the left (0 *km*) and the continental slope on the right.

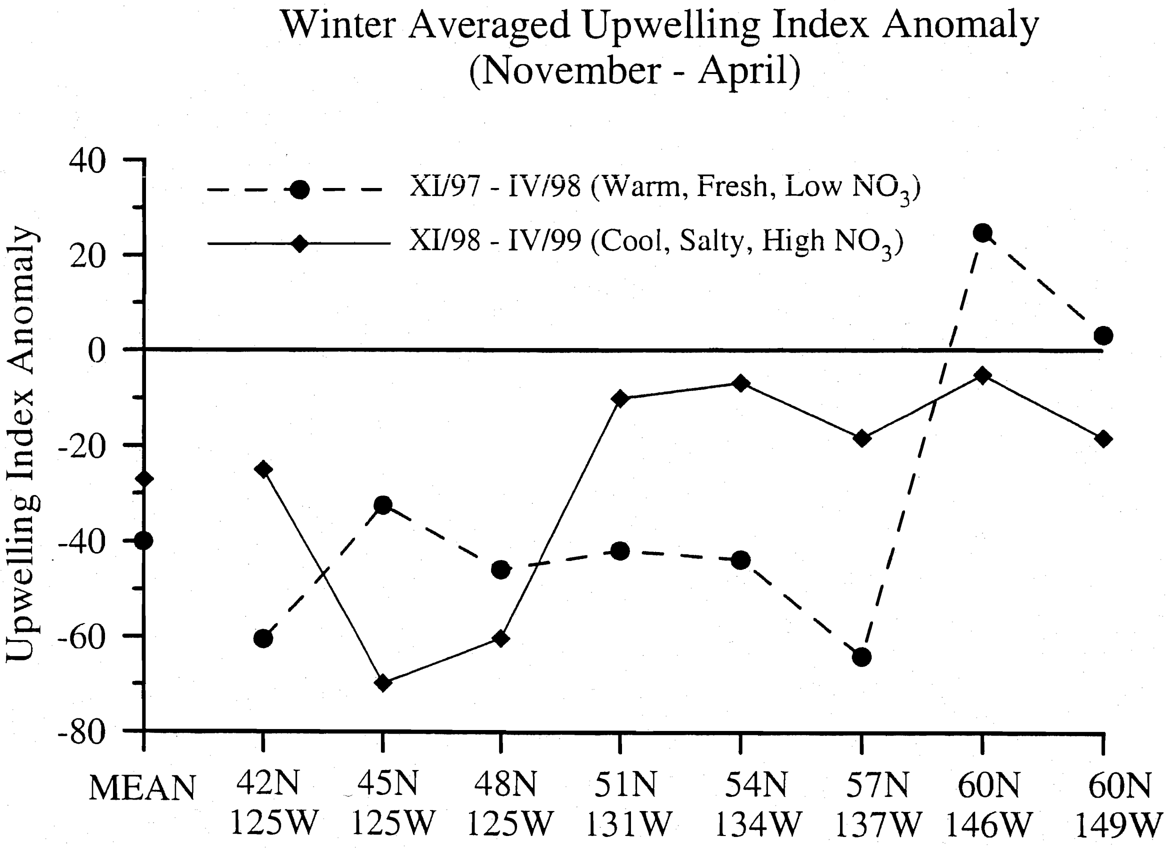


Figure 5. Comparison of the time- and space-averaged monthly anomalies in upwelling along the Northeast Pacific coast. The anomalies were averaged from November through April for the indicated year at the locations indicated on the x-axis. Negative values indicate anomalously strong downwelling (or cyclonic wind stress).

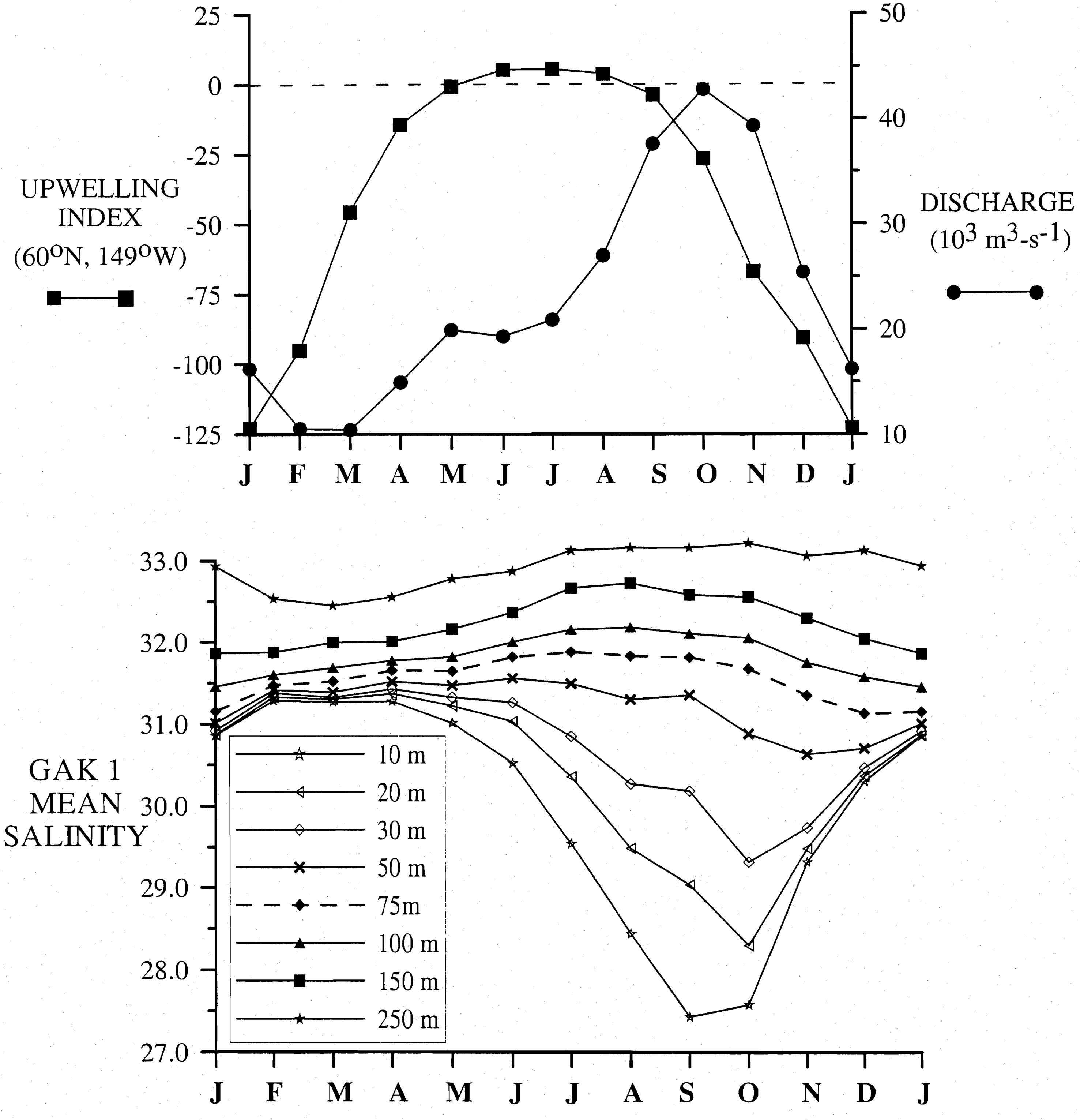


Figure 6. The mean annual cycle of coastal discharge into the Gulf of Alaska and the upwelling index (upper panel) and mean monthly salinities at standard depths at GAK 1 (lower panel).

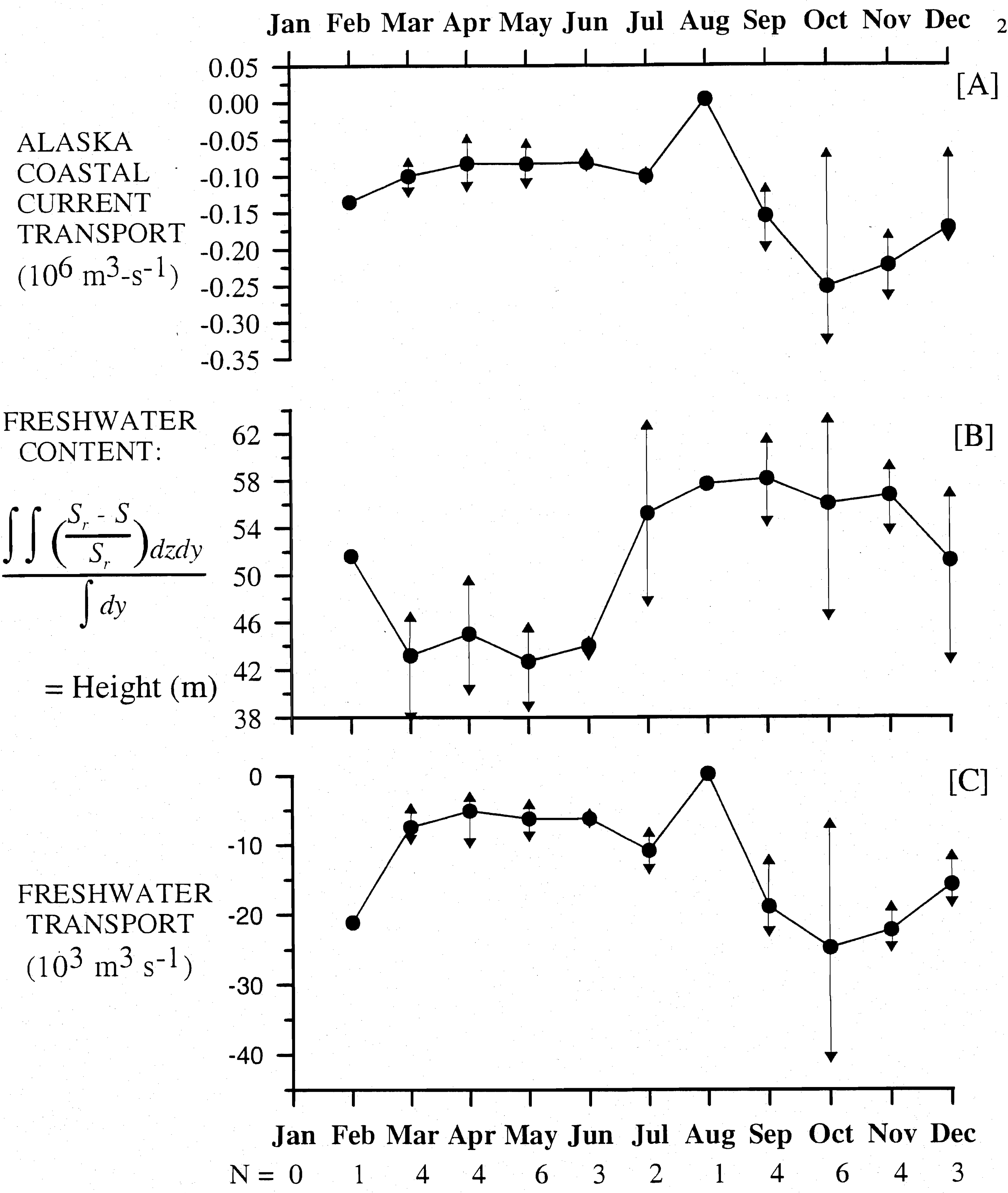


Figure 7. Mean monthly: a) 0 – 75 db baroclinic transport, b) freshwater content, and c) freshwater transport computed from data collected along the Cape Fairfield Line and within 30 km of the coast.

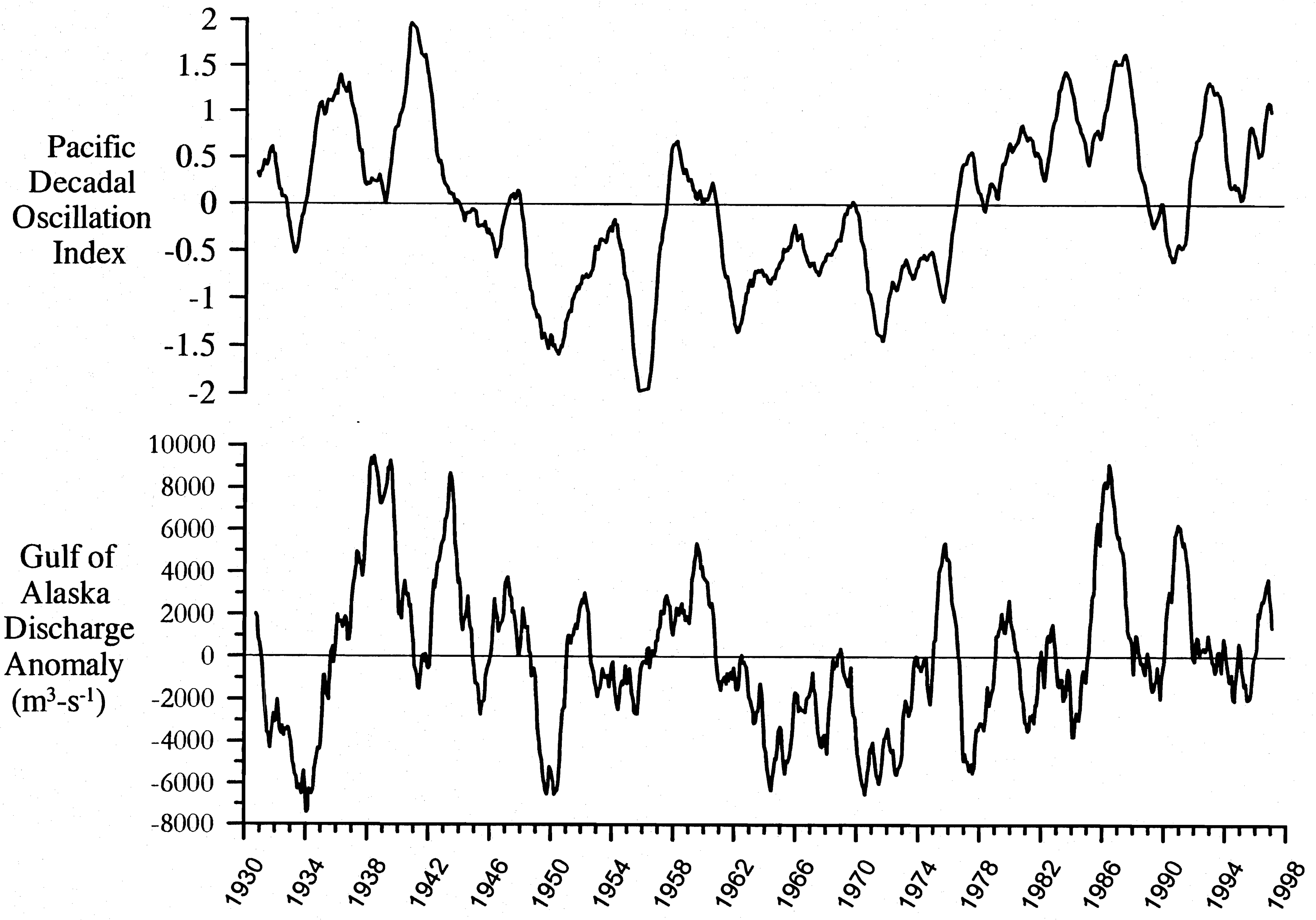


Figure 8. Time series of the monthly Pacific Decadal Oscillation (PDO) and coastal discharge into the Gulf of Alaska based on Royer' (1982) method. The series are smoothed with a 25-month running mean to emphasize low-frequency variations.

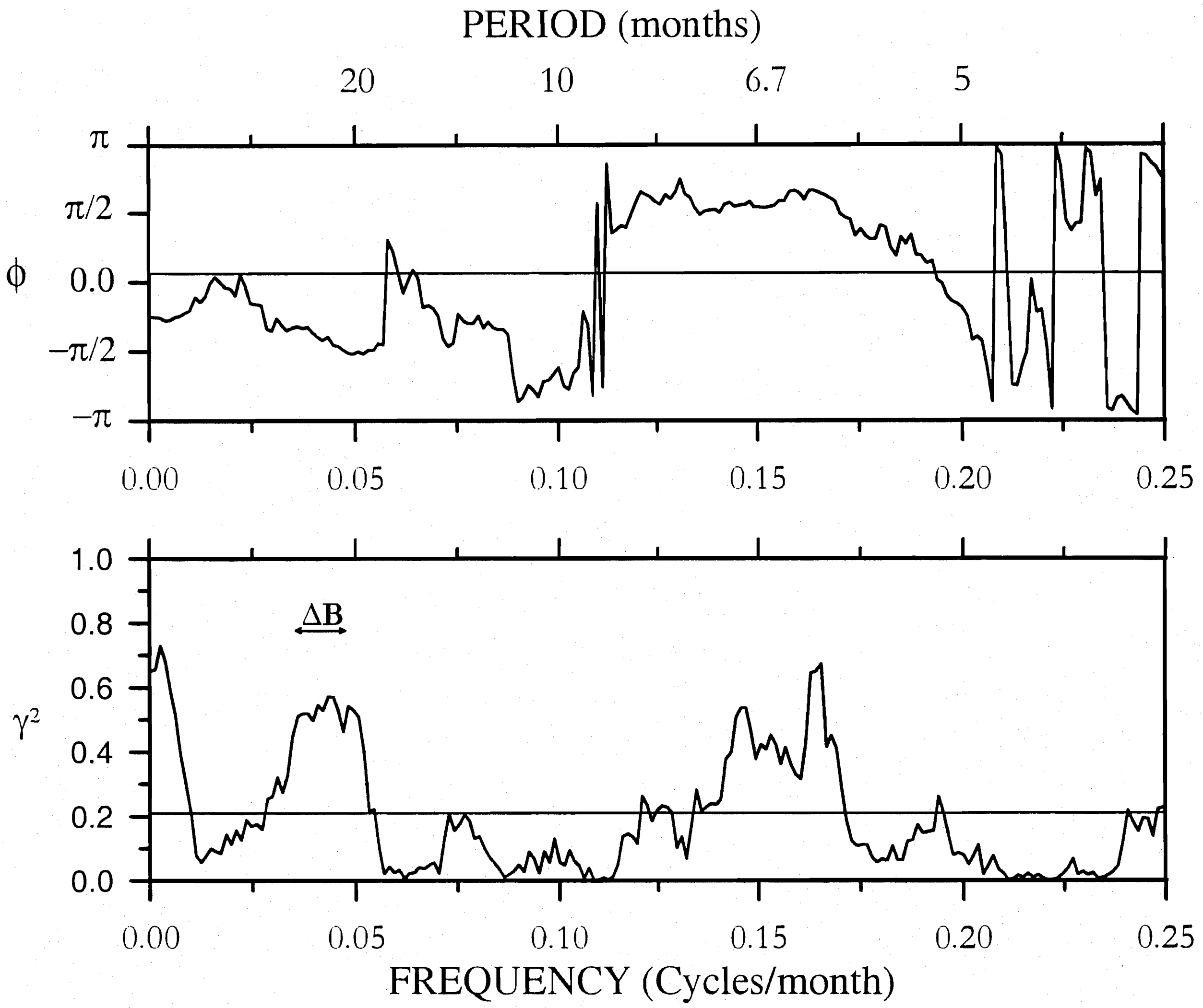
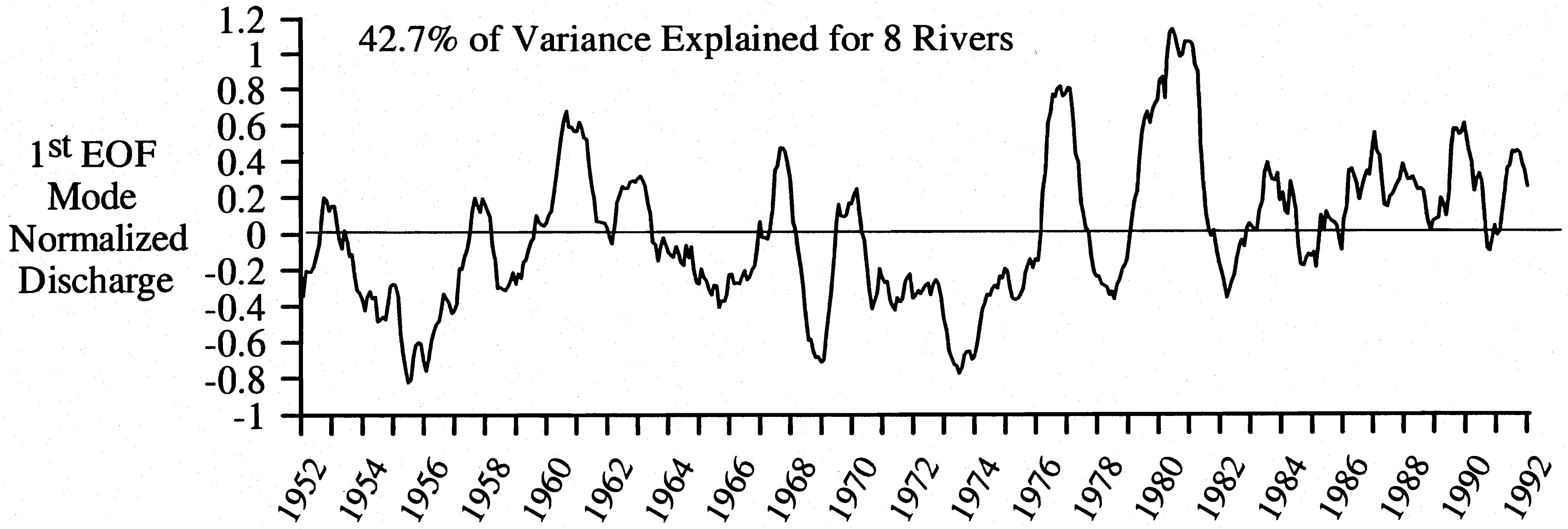


Figure 9. Coherence squared (γ^2) and phase (ϕ) between the *unsmoothed* series of Figure 8. Each spectral estimate has 22 degrees of freedom and was smoothed over the indicated bandwidth (ΔB). The horizontal line indicates the 90% significance level for γ^2.



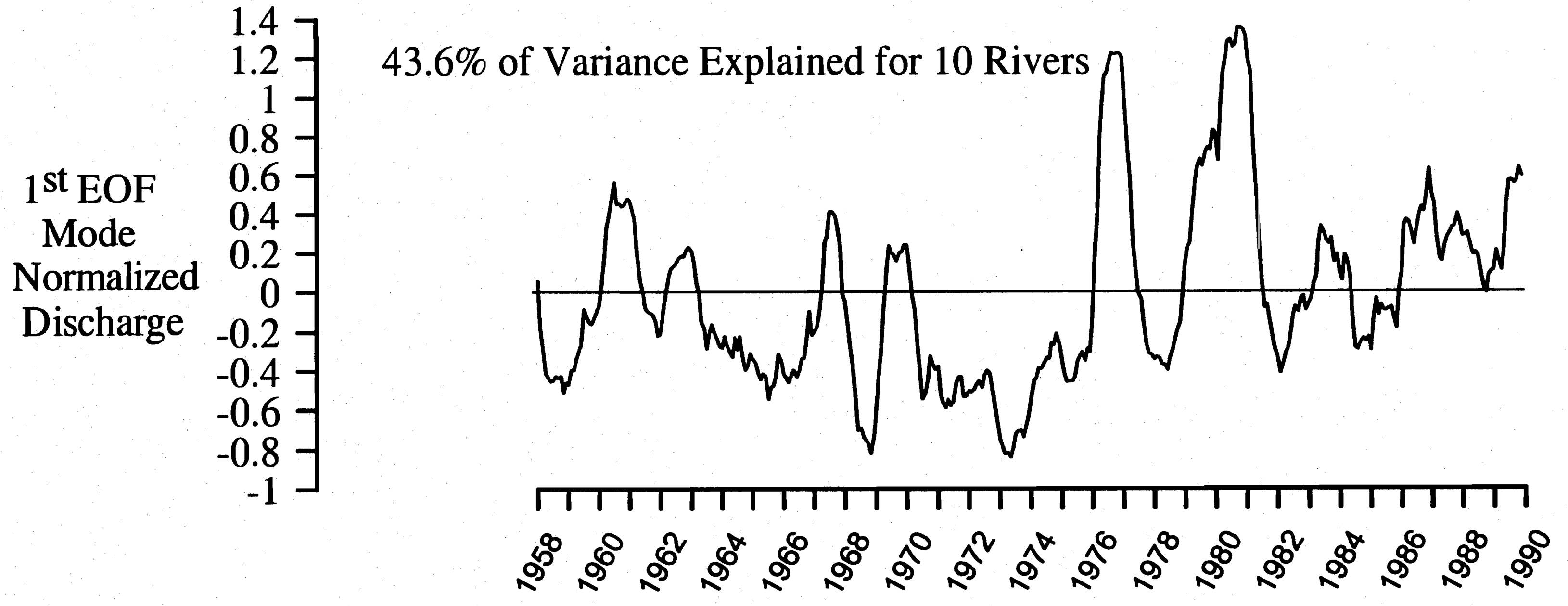


Figure 10. The time amplitude function for the 1st EOF mode of streamflow discharge for the set of 8 and 10 rivers.

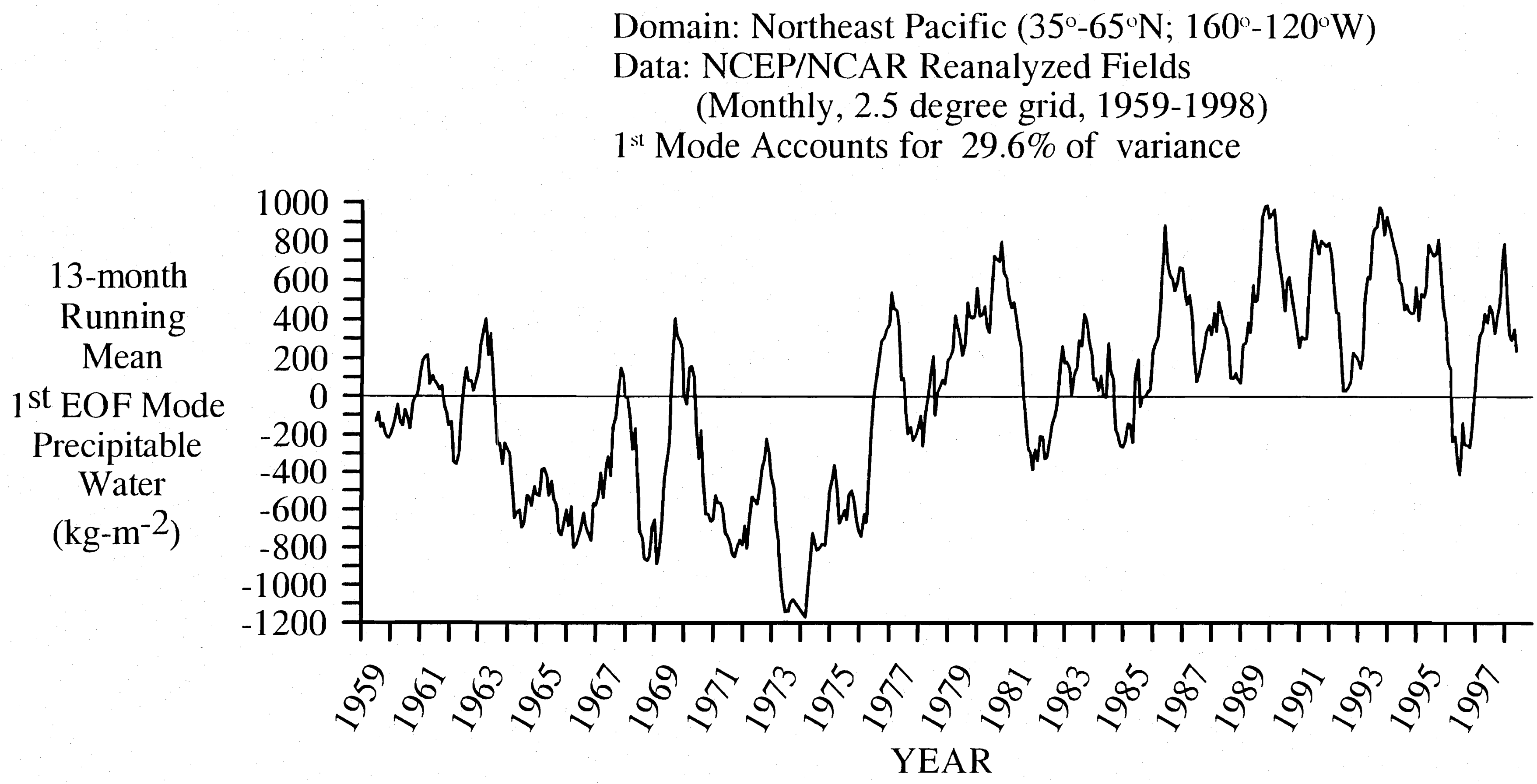


Figure 11. The time amplitude function for the 1st EOF mode of precipitable water.

SPATIAL PATTERN
FIRST EOF
PRECIPITABLE WATER

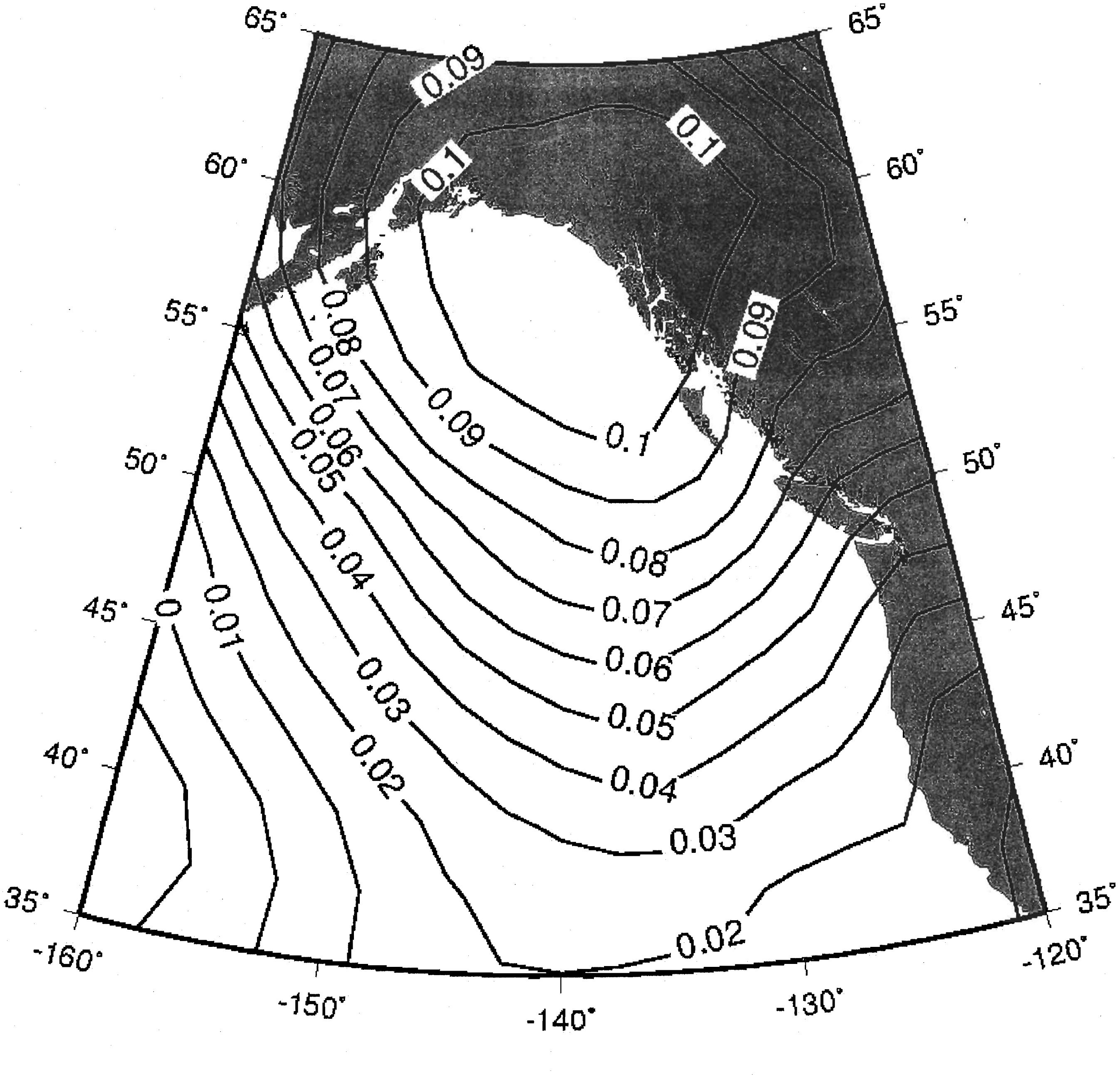


Figure 12. The eigenvector for the 1st EOF mode of precipitable water.

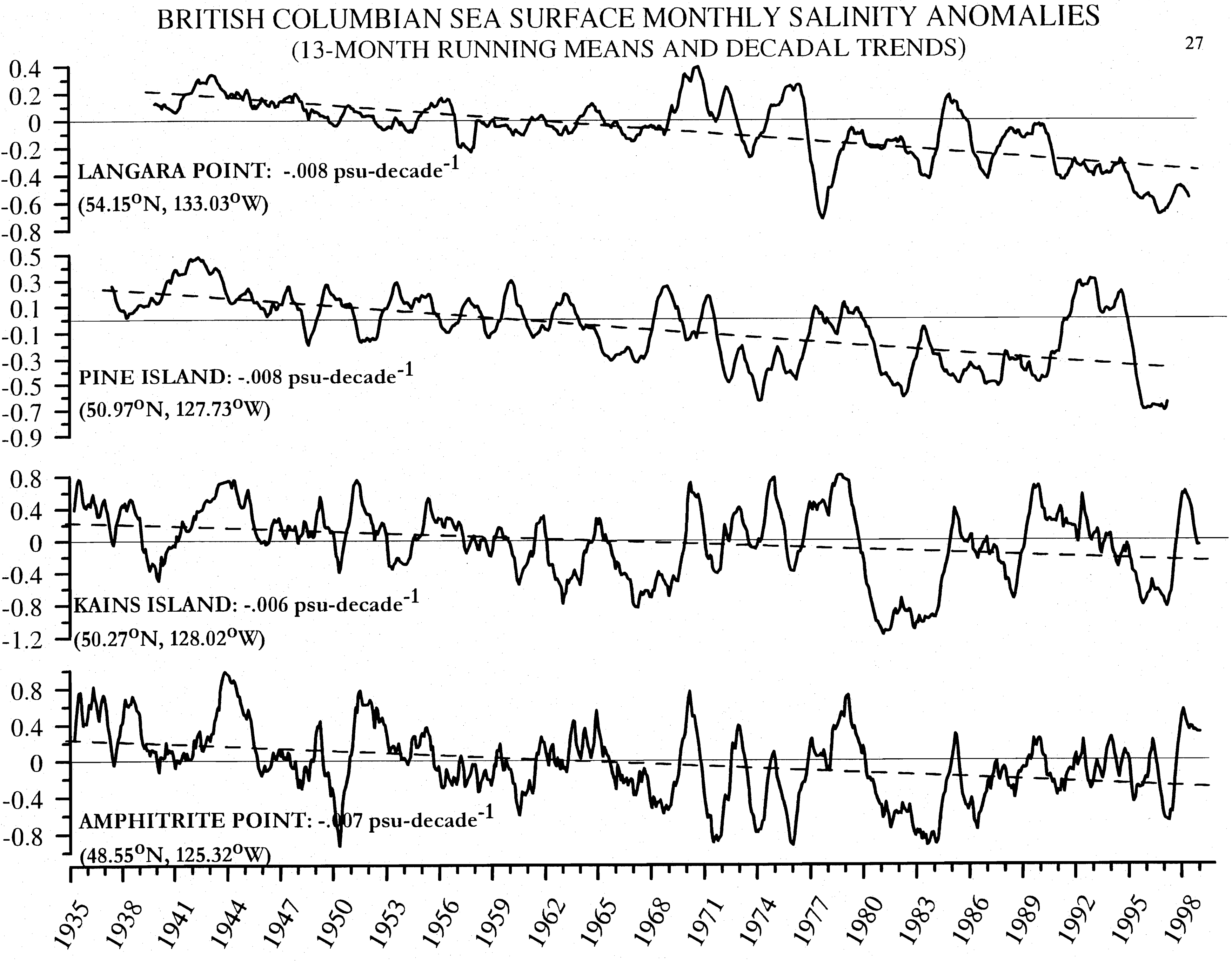
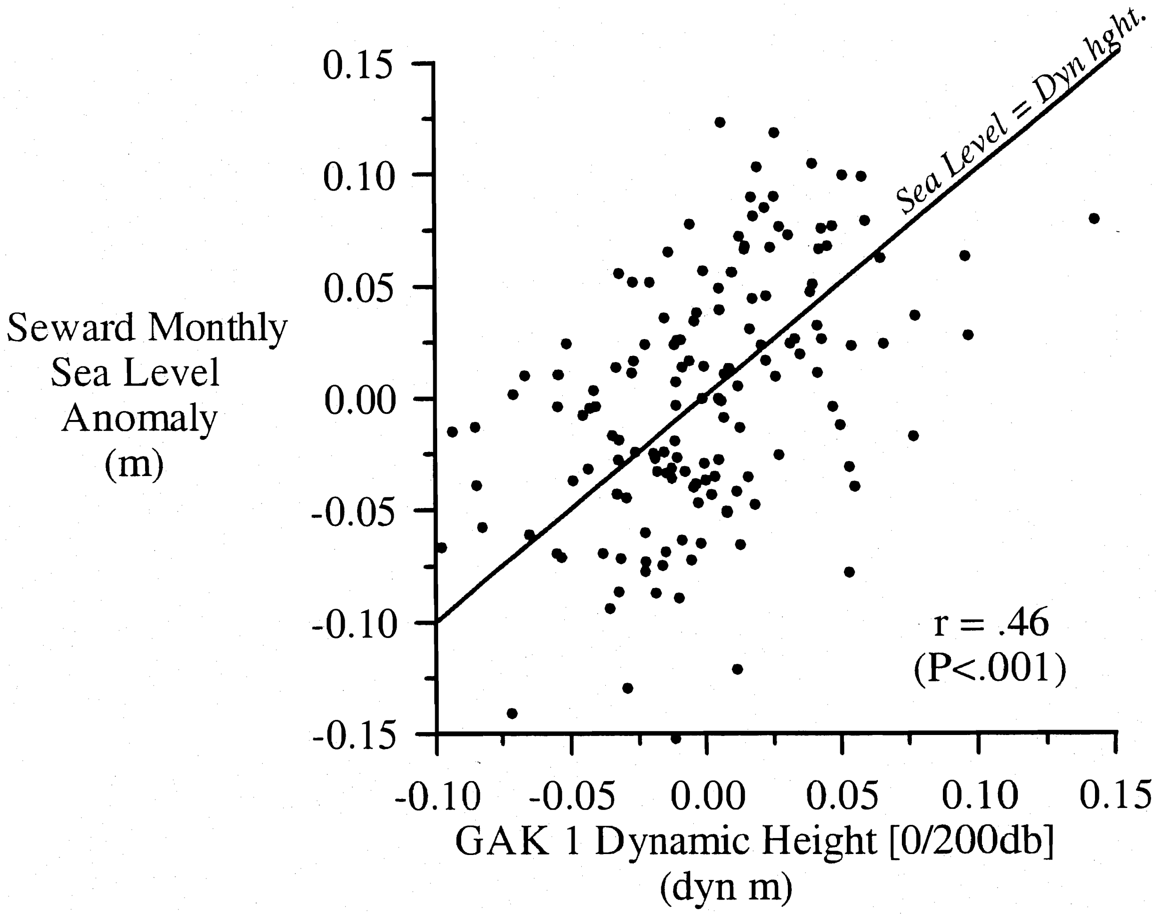


Figure 13. Monthly anomalies of coastal surface salinities along British Columbia.



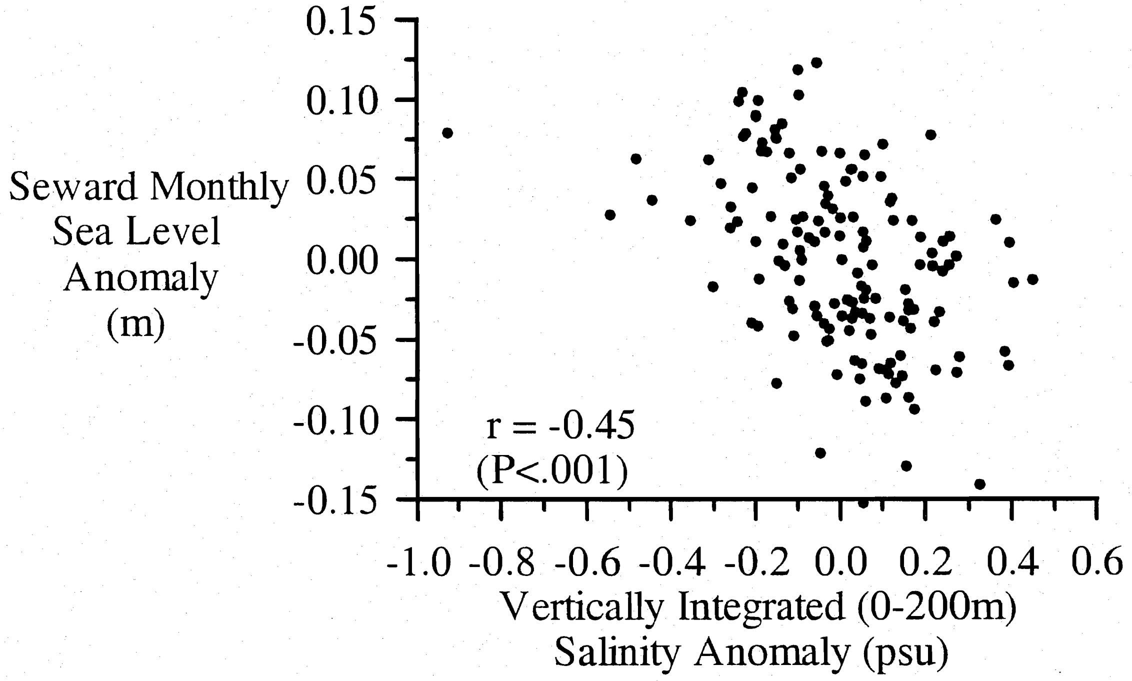


Figure 14. Scatter (correlation) plots of monthly anomalies of Seward sea level versus 0/200 db dynamic height and 0 – 200 m salinity.