Exxon Valdez Oil Spill
Restoration Project Final Report

Acquisition of Continuous Plankton Recorder Data

Restoration Project 070624
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Study History

The first project supported by the EVOS Trustee Council (02624-BAA), built on a large scale plankton sampling program that was initially funded by the North Pacific Marine Research Initiative in 2000 and 2001. Recognising the relevance to the planned GEM program, the EVOS TC awarded one year of funding for two transects in 2002, one north-south and one east-west. The North Pacific Research Board then provided funding for the east-west transect from 2003 (and has done so ever since). Funding for the north-south transect was continued through the EVOS TC GEM program for a total of four more years via projects 030624 and 040624. After the GEM program ended, the value of the plankton data to herring restoration efforts was acknowledged with an additional year of funding as Restoration project 070624. Annual reports have been submitted in August of each year and this report represents the final report for all four projects.

The following publications resulted from these projects:

Lindley, J.A., and Batten, S.D. (In press) Distribution and seasonal cycles of decapod crustacean larvae in Continuous Plankton Records from the North Pacific Ocean. Submitted to Journal of the Marine Biological Association, UK.
Mackas, D.L., Batten, S.D., and Trudel, M., (2007) Effects on zooplankton of a warming ocean: recent evidence from the Northeast Pacific. Progress in Oceanography, 75, 223-252
Batten, S.D. and Freeland, H.J. (2007). Plankton populations at the bifurcation of the North Pacific Current. Fisheries Oceanography, 16, 536-546.
Kirby, R.R., Lindley, J.A., and Batten, S.D. (2007). Spatial heterogeneity and genetic variation in the copepod *Neocalanus cristatus* along two transects in the North Pacific sampled by the Continuous Plankton Recorder. Journal of Plankton Research, 29, 97-106
Batten, S.D and Crawford, W.R. (2005). The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. Deep Sea Research II, 52, 991-1009.
Lindley, J.A., Batten, S.D., Coyle, K.O and Pinchuk, A.I. (2004). Regular occurrence of *Thysanoessa inspinata* (Crustacea: Euphausiacea) in the Gulf of Alaska. Journal of the Marine Biological Association of the UK, 84, 1033-1037.
Batten, S.D. and Welch, D.W. (2004). Changes in oceanic zooplankton populations in the North-east Pacific associated with the possible climatic regime shift of 1998/1999. Deep Sea Research II, 51, 863-873.
Batten, S.D., Welch, D.W., and Jonas, T. (2003). Latitudinal differences in the duration of development of *Neocalanus plumchrus* copepodites. Fisheries Oceanography, 12 (3), 201-208.

Abstract

The Continuous Plankton Recorder has been deployed on a seasonal basis in the north Pacific since 2000, accumulating a database of abundance measurements for over 290 planktonic taxa in over 3,500 processed samples. There is an additional archive of over 10,000 samples available for further analyses. *Exxon Valdez* Oil Spill Trustee Council financial support has contributed to about half of this tally, through four projects funded since 2002. Time series of zooplankton variables for sub-regions of the survey area are presented together with abstracts of eight papers published using data from these projects. The time series covers a period when the dominant climate signal in the north Pacific, the Pacific Decadal Oscillation (PDO), switched with unusual frequency between warm/positive states (pre-1999 and 2003-2006) and cool/negative states (1999-2002 and 2007). The CPR data suggest that cool negative years show higher biomass on the shelf and lower biomass in the open ocean, while the reverse is true in warm (PDO positive) years with lower shelf biomass (except 2005) and higher oceanic biomass. In addition, there was a delay in plankton increase on the Alaskan shelf in the colder spring of 2007, compared to the warmer springs of the preceding years. In warm years, smaller species of copepods which lack lipid reserves are also more common. Availability of the zooplankton prey to higher trophic levels (including those that society values highly) is therefore dependent on the timing of increase and peak abundance, ease of capture and nutritional value. Previously published studies using these data highlight the wide-ranging applicability of CPR data and include collaborative studies on; phenology in the key copepod species *Neocalanus plumchrus*, descriptions of distributions of decapod larvae and euphausiid species, the effects of hydrographic features such as mesoscale eddies and the North Pacific Current on plankton populations and a molecular-based investigation of macro-scale population structure in *N. cristatus*. The future funding situation is uncertain but the value of the data and studies so far accumulated is considerable and sets a strong foundation for further studies on plankton dynamics and interactions with higher trophic levels in the northern Gulf of Alaska.

Key words

Biological Oceanography, Continuous Plankton Recorder, Cook Inlet, Gulf of Alaska, Monitoring, Phytoplankton, Plankton, Prince William Sound, Zooplankton.

Project data

Data exist as abundances per sample for 291 zooplankton and phytoplankton taxonomic entities together with sample location, time and date of collection (with position reported as the mid-point of each 18 km sample). Data from 3,648 processed samples from 1997 (pilot transect) and 2000-2007 are available from Sonia Batten, email soba@sahfos.ac.uk . Some data can be viewed and plotted at http://pices.int/projects/tcprsotnp/default.aspx.
Temperature data from temperature loggers mounted on the CPR are also available. Files can be downloaded at http://pices.int/projects/tcprsotnp/default.aspx

Citation
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Executive Summary

The Continuous Plankton Recorder has been deployed on a seasonal basis in the north Pacific since 2000, accumulating a database of abundance measurements for over 290 planktonic taxa in about 3,500 processed samples. There is an additional archive of over 10,000 samples available for further analyses. *Exxon Valdez* Oil Spill Trustee Council financial support has contributed to about half of this tally, through four projects funded since 2002.

These data have been used in a variety of collaborative studies; to describe the responses of the plankton to short term climate variability including changes in phenology in a key copepod species, to describe distributions of decapod larvae and euphausiid species, to examine the effects of hydrographic features such as mesoscale eddies and the North Pacific Current and in molecular-based investigation of macro-scale population structure. Perhaps the most important contribution of the EVOS TC support is a baseline of plankton variables that describe seasonal and interannual variability in quantity and species composition, including responses to the alternating modes of the dominant climate signal in the North Pacific, the Pacific Decadal Oscillation. Because all upper trophic levels depend on plankton as a food source, either directly or through trophic linkages, this variability is important to understand. Predicting and modelling the abundance and health of resources considered valuable to society depends on an understanding of variability in their prey. CPR data from the Alaskan shelf, for example, show a five-fold change in plankton biomass in May between 2003 and 2007 coupled with a change in taxonomic composition, a time when many predators are timing their reproduction or migration to take advantage of an expected peak in prey. This change in plankton biomass was mostly because of a delay in plankton increase in the colder spring of 2007, compared to the warmer springs of the preceding years. In warm years, smaller species of copepods which lack lipid reserves are more common. Availability of the prey to higher trophic levels is therefore dependent on the timing of increase and peak abundance, ease of capture and nutritional value.

Funding of the CPR survey beyond 2008 is uncertain, however, at a time when ocean conditions have returned to cooler conditions, perhaps leading to more productive and positive circumstances for valued resources, continued measurement and understanding of the foundation of the marine food chain remains important.

Introduction

There is growing recognition that zooplankton respond rapidly to climate change and also provide a critical link between changes in the atmosphere and important upper trophic level populations that ultimately rely on plankton as a food source (e.g., Mantua et al., 1997; Hare et al 1999; Logerwell et al 2003). In the Pacific, the realization that long–term biological patterns occur in the plankton was really only recognized during the last decade (Roemmich & McGowan, 1995), a discovery made possible through the long-term CalCOFI biological data set for the region off California. This recognition has since been refined, improving our understanding of the geographic extent of the changes in the atmosphere and plankton populations and how phasing of such events propagates through to affect higher trophic levels in the ocean, with the link to decadal-scale salmon abundance now broadly recognized (Beamish

1993; Beamish et al 2000; Brodeur et al., 1996; Mantua et al. 1997; Hare et al., 1999; Welch et al 2000). The occurrence of climate-driven regimes in marine fish populations in the North Pacific has also been formalised (e.g. Hare & Mantua, 2000). During this period, it was also appreciated that coupled physical/biological shifts were strongly correlated to climatic indices such as the Pacific Decadal Oscillation (PDO) on multidecadal scales and El Niño/La Niña events at short time scales (Chavez et al., 2002a,b; Hopcroft et al. 2002).

The *Exxon Valdez* Oil Spill Trustee Council support has contributed to a larger effort to use Continuous Plankton Recorders (CPR) to collect plankton samples from the North Pacific and define how changes in the plankton are occurring in the North Pacific. The Pacific CPR program was initiated following a recommendation from the North Pacific Marine Science Organisation (PICES, 1998) that the CPR be used to address the lack of open ocean plankton data. CPRs have been deployed for over 60 years in the north Atlantic from Ships-of-Opportunity, providing a wealth of time series data (Reid et al., 2003). Prior to the start of the Pacific CPR program, the North Pacific had only a few regional zooplankton time series, and the CPR offered the most cost-effective way to sample larger areas on a seasonal basis.

The first proposal was funded by the North Pacific Marine Research program to collect plankton samples along two transects in 2000 and 2001. The EVOS TC was then developing its Gulf Ecosystem Monitoring (GEM) program and followed with a third year of support for the north-south transect from Alaska to California (which was later shifted to terminate in Washington state; Fig 1), which continued through 2006 while the GEM program was running. Local technicians at the Prince William Sound Community College and at the Fisheries and Oceans Canada laboratory in Sidney, British Columbia were trained early in 2003 to unload, service and carry out initial sample processing of the CPR samples. This enabled sample analysis to proceed much more quickly so that preliminary data were available within two months of sample collection. A collaboration was developed with researchers on project 03614 to install a thermosalinograph on the vessel and link the physical environment to plankton dynamics determined from the CPR. Simple temperature recorders were also placed on the CPR through 2000 to 2003. At the end of 2003 the transect changed location from between Prince William Sound (PWS) and California (AC) to between Cook Inlet and Tacoma (AT). This was originally intended to be an additional transect but when the vessel running the PWS route became unavailable and the funding requested for two north-south transects was reduced to one we focussed solely on the Cook Inlet transect, which has proved to be very successful. In 2007 an additional year of support was given under the EVOS TC Herring Restoration project, since the CPR was able to sample and monitor levels of herring prey over the shelf to the west of PWS, where adult herring are believed to forage.

Since 2003 the North Pacific Research Board (NPRB) has supported the longer but less frequent ~6,500km transect running east-west across the north Pacific. GEM funding initially supported a trial observer on this transect to census bird and mammal populations, which has been funded by the NPRB (since 2002). Although financial support has remained shared between the NPRB and the EVOS TC since 2003, data analysis for the Pacific CPR survey has often merged data from both transects. The CPR is a large-scale sampler and provides information on plankton dynamics at the meso to macro scale. Integrating the data from both transects enables the identification of changes or variability that occur over the entire Gulf of Alaska region (or even wider), or that are specific to sub-regions

Objectives

The activities outlined in this report are considered to be ocean monitoring and as such do not directly test specific scientific hypotheses; ocean ecosystems have proven to be strongly variable at interannual and longer time scales, and baseline measurements of the nature and amplitude of this variability need to be tracked in the north Pacific in order to both inform societal choices about resource management and to provide the data scientists need to refine their understanding of the structure and function of the north Pacific ocean. The two major objectives running through all projects were (1) to maintain an approximately monthly sampling program through spring and summer of each year on a transect from Alaska to the west coast of the continental USA, and (2) to process the samples and increment the data available for analysis in the database. However, other objectives were also proposed in some projects to address specific data analysis requirements as they arose. The original objectives for each project are listed below (in some cases these are abbreviated from original proposals):

Project 02624

1. To develop and apply the ship of opportunity approach to oil tankers and other large merchant vessels in order to obtain data on lower trophic levels for the Gulf of Alaska and adjacent waters.
2. To deploy the CPR from ships of opportunity on selected transects and to process the samples obtained for plankton species abundances.
3. To further enhance the use of ships of opportunity by supplementing the biological data with physical sensors.

Project 030624

1. To add to the existing database of seasonal plankton data acquired by the CPR across the North Pacific on the existing transects. Also to process the remaining 1997 shelf samples.
2. To integrate physical data and fluorescence/chlorophyll data collected on the same vessel (via project 02614) with the plankton observations made from Prince William Sound to California.
3. To compare marine bird and mammal observations made on the Vancouver to Japan transect (funded by the NPRB) with the plankton and temperature data collected from the CPR and a temperature logger.
4. To process a subset of samples rapidly (within 1-2 months of collection), assess plankton communities in relation to data from previous years and publish results on a web-site in a timely fashion.

Project 040624

1. Ongoing sample collection and processing as before. Full, quality-controlled data from each transect to be made available within 9 months after collection. In addition, a subset of samples was to be processed within 2 months of collection and results (e.g., comparison with other data) published on the website within 3 months of collection.
2. Setting up of a new transect from Anchorage to Seattle/Tacoma.

3. Euphausiid distribution/abundance and comparison with juvenile salmon to be conducted in FY04.
4. Taxonomic classification of decapod larvae to be undertaken and completed by the end of FY04.

Project 070624

1. Continue acquisition of plankton data on a transect from Cook Inlet to Tacoma to determine zooplankton abundance and variability. Sampling carried out 6 times, approximately monthly between March and September 2007, to cover the period of zooplankton productivity in the spring and summer period. The purpose is to collect this data in order to understand how key food resources for Prince William Sound herring vary.

Methods

1. Plankton sample collection

A full description of the CPR instrument and sampling is given in Batten et al. (2003a) and Richardson et al (2006) describe data analysis methods. The CPR was deployed from the stern of a ship (the tanker *Polar* (formerly *ARCO) Alaska* until 2003, AC, and the *Horizon Kodiak* from 2004 onwards, AT) and towed in the surface layer at a depth of about 6 m on its regular route from Alaska to the west coast of North America (Fig 1). Sampling was intended to be carried out roughly monthly from spring through summer but varied somewhat depending upon the turnaround time of the vessel and commercial activities.

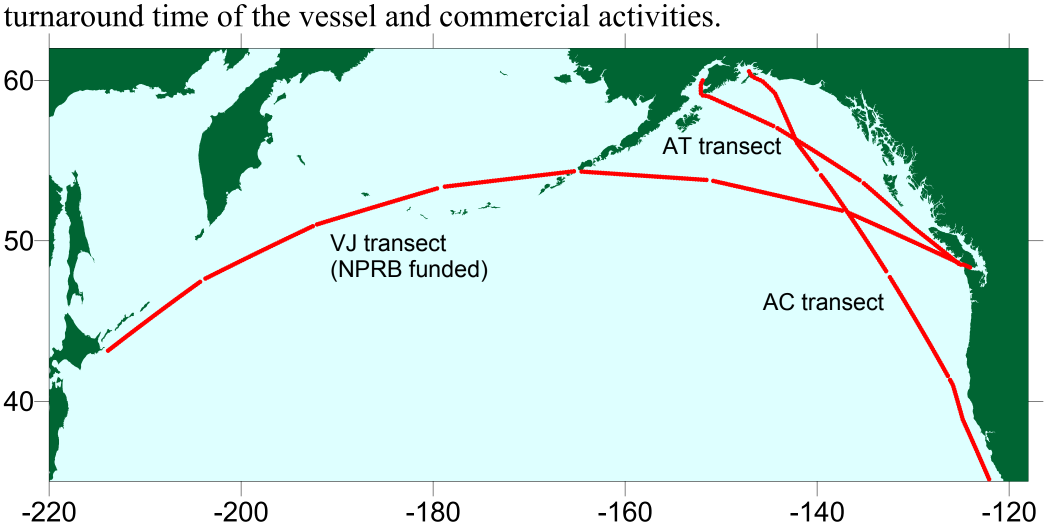

Fig 1. Normal routes of ships towing CPRs, AT and AC transects funded by EVOS TC

The CPR was supplied to the ship with sufficient internal cassettes preloaded with filtering mesh and formaldehyde preservative to cover the sampling transect. Each cassette was deployed for a maximum of ~800km (450 nautical miles), after which the crew recovered the CPR, changed the cassette and redeployed it (normally within 30 minutes of recovery, unless activities of the ship prevented this). The ship's officers kept a log of deployment and recovery positions and any course changes.

Water and plankton enter the front of the CPR through a small square aperture (1.27 cm), pass along a tunnel, and then through the silk filtering mesh (with a mesh size of 270 µm) which retains the plankton and allows the water to exit at the back of the machine. The movement of the CPR through the water turns an external propeller which, via a drive shaft and gear-box, moves the filtering mesh across the tunnel at a rate of approximately 10 cm per 18 km of tow. As the filtering mesh leaves the tunnel it is covered by a second band of mesh so that the plankton are sandwiched between these two layers. This mesh and plankton sandwich is then wound into a storage chamber containing buffered 40% formaldehyde preservative (which dilutes in the seawater to a concentration of about 4%, sufficient to fix and preserve the plankton). As the ship approaches port the CPR is recovered for the final time and stored onboard until the ship docks. At this time the mechanisms are offloaded and shipped to PWS Community College technicians. There the samples are unloaded and sent to the laboratory in British Columbia for processing while the gear is serviced, reloaded with filtering mesh and returned to the ship for the next tow. The towed mesh is processed according to standard CPR protocols; first cut into separate samples (each representing 18 km of tow and about 3 m^3 of seawater) which are randomly apportioned amongst the analysts for plankton analysis. Every fourth sample is distributed for analysis, except for the Alaskan shelf where consecutive samples are processed with the remainder being archived. The ship's log is used to determine the mid-point latitude and longitude of each sample, along with the date and time of each sample.

2. Taxonomic analysis

The first step was the assessment of phytoplankton colour (the greenness of the sample) which was determined by comparison with standard colour charts. This is a semi-quantitative representation of the total phytoplankton biomass and includes the organisms that are too fragile to survive the sampling process intact but which leave a stain on the mesh (Batten et al., 2003b). Hard-shelled phytoplankton are then semi-quantitatively counted under a purpose-built microscope by viewing 20 fields of view (diameter 295 µm) across each sample under high magnification (x 450) and recording the presence of all the taxa in each field (presence in 20 fields is assumed to reflect a more abundant organism than presence in 2 fields for example). Small zooplankton are then identified and counted into categories of abundance from a sub-sample by tracking across the filtering mesh with the microscope objective (a 2 mm diameter field of view = 2% of the sample width) whilst all zooplankton larger than about 2 mm are removed from the mesh and counted without sub-sampling. Identification in all cases is carried out to the most detailed practicable taxonomic level and is a compromise between speed of analysis and scientific interest. For example, since copepods make up the majority of the zooplankton, most copepods are identified to species level whilst rarer groups, or those not preserved well by the sampling mechanism (such as chaetognaths), are identified to a lower level. A list of taxa and their abundance category on each sample is thus generated and from this summary indices (such as zooplankton biomass, diatom abundance) can also be calculated.

Full, quality controlled data are normally available 9-12 months after collection. In order to get a more rapid 'first look' at each transect a portion of the samples were processed within 2 months of the ship's return. Every 16^{th} off-shelf sample and every 4^{th} shelf sample was processed rapidly. This represents 25% of the total samples that are eventually processed. Quality control was carried out following a routine procedure developed for the Atlantic CPR survey: After all samples on a transect have been processed, adjacent samples are compared and counts that differ significantly from both adjacent samples are sent back for re-counting of the taxa concerned.

Once the count has been checked and required corrections are made, the final data are entered into the database.

3. Collection of temperature data

A small self-powered, self-logging temperature recorder (Vemco Minilogger^{TM}) was attached to the tail section of the CPR in 2000 to 2003. This unit recorded temperature every 10 minutes and the ship's log was then used to estimate a position for each temperature record.

4. Data analysis

Abundance data are often used directly from the database, for example in single species studies. However, summary indices that describe more of the community can be very useful. Mesozooplankton biomass is one such index and is estimated from the abundance data by multiplying the abundance of each taxon by its taxon-specific dry weight, and summing these values for each sample. The dry weight values were derived from empirical measurements of an individual organism's length and dry weight (Planque and Batten, 2000). If measurements were not available for a particular taxon, dry weights were calculated from the published length of the organism and the empirical length to weight ratio for the closest taxonomically available organism.

Results

The Pacific CPR database currently contains 3,596 processed samples collected between 2000 and 2007 and an additional 52 samples from the pilot transect in 1997. Approximately 3 times as many samples are archived but have not been processed. Of these samples slightly more than half were from the north-south transects (1,241 from the AC transect and 894 from the AT transect).

This first section will focus on the time series of observations in the northern Gulf of Alaska. The subsequent section will give the titles and abstracts of the publications resulting from these projects which deal with very specific (and wide-ranging) research areas.

1. Time series

Regions of the Northeast Pacific through which the transects passed were defined to simplify data analysis and presentation of results (Fig 2). Shelf areas were distinguished from comparative open ocean areas to give six regions that have been used in the time series analyses; the shelf south of PWS (sampling within the Sound itself was too infrequent for meaningful analysis), Cook Inlet and the shelf to the SE of Cook Inlet, the oceanic northern Gulf of Alaska, the shelf surrounding the Aleutian Islands and the oceanic western Gulf of Alaska. These latter two regions were sampled by the east-west transect and although the data do not show such a good seasonal resolution they are useful comparisons to the north-south transects. Data for each of

these regions can be found and plotted via the project's web site at
http://pices.int/projects/tcprsotnp/default.aspx

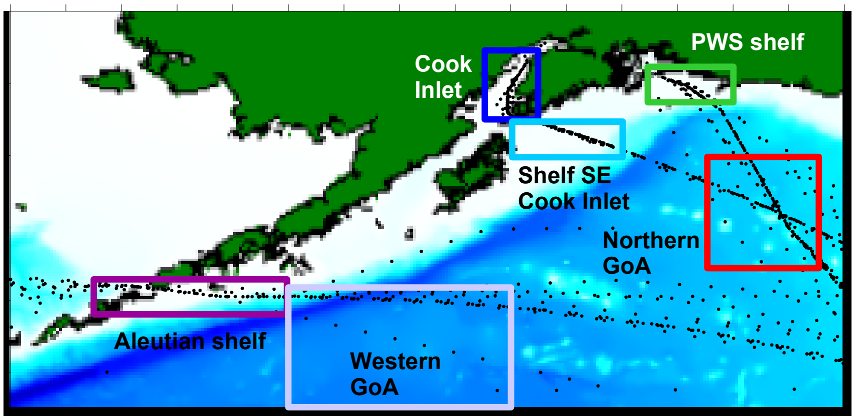

Figure 2. Transect regions described in the text. The 'Aleutian shelf' and 'Western Gulf of Alaska' regions are sampled by the NPRB-funded transects.

1.1. Mesozooplankton biomass

Mean mesozooplankton biomass is a useful summary of the standing stock (abundance) of zooplankton present. Some months in each year were un-sampled (the spread of 5 or 6 transects over the 7 months between March and September, as well as occasional mechanical failure inevitably left some months unsampled), interpolation was necessary to fill the gaps in the data. The value for the missing month was calculated as the monthly mean multiplied by the ratio of that year's annual mean to the overall annual mean. For example, if May 2002 was not sampled then the interpolation value was: mean of all sampled Mays x (mean of months sampled in 2002/mean of all years). Interpolating in this way allows a high or low biomass year to influence the missing month's value, but retains the seasonal cycle. Figure 3 shows the abundance time series for three of the regions showing the strong annual cycle with a peak in late spring/summer in the shelf regions (note that June was poorly sampled in the PWS shelf region and the interpolation suggests that June is low when in fact most years may show a smooth spring peak). The shelf to the south east of Cook Inlet is 'downstream' from the shelf region south of PWS. Although there will be local processes occurring in each region the scale of the CPR sampling means that small scale patchiness is generally smoothed out and larger scale forcing dominates the patterns seen.

By summing the monthly means we can create an index of annual biomass to better examine interannual variability in zooplankton biomass (Figure 4). During the time period that we have sampled and are describing in this report (2000 to 2007) the dominant climate signal, the Pacific Decadal Oscillation (PDO) switched from negative (1999 to 2002) to positive (2003 to 2006) and returned to negative again late in 2006.

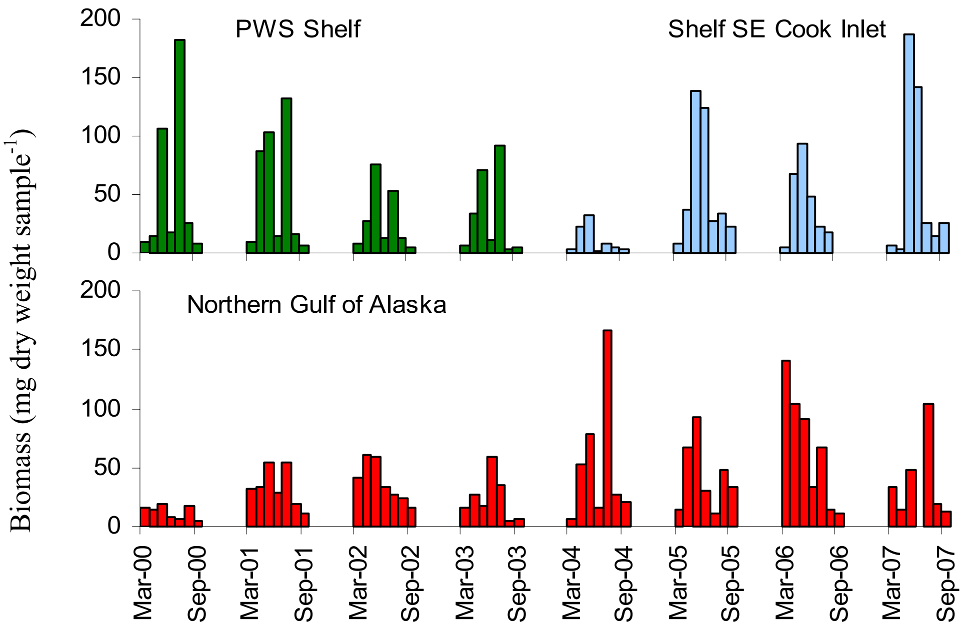

Figure 3. Mean monthly biomass for 3 regions of the transects. Unsampled months have been interpolated from monthly & annual means.

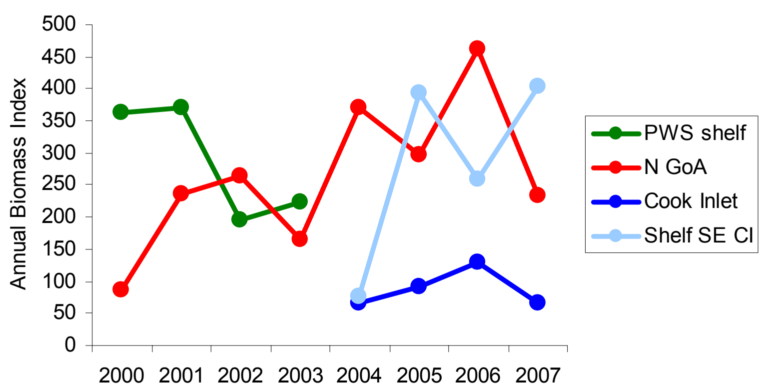

Figure 4. An annual biomass index for each region

In broad terms, a negative PDO leads to cooler conditions around the rim of the Gulf of Alaska while a positive PDO generally produces warmer conditions. Zooplankton respond to these climate effects not only by changes in their absolute abundance (e.g. McGowan et al. 1998) but by changes in community composition and diversity (e.g. Peterson & Schwing, 2003; Mackas et al. 2004; Hooff & Peterson, 2006). Although the current time series are short, the CPR data suggest that cool, negative years show higher biomass on the shelf and lower biomass in the open ocean, while the reverse is true in warm (PDO positive) years with lower shelf biomass (except 2005) and higher oceanic biomass.

The interannual variability within a region is perhaps best seen when different years are overlaid, as in Figure 5 for the shelf SE of Cook Inlet (sampled from 2004 to 2007). As well as demonstrating changes in the abundance of zooplankton (2004 being very low, about one fifth the magnitude of 2006/07) there are changes in seasonality too; April 2007 had the lowest levels of biomass of all four years, which then increased to the highest May/June biomass values measured. Spring 2007 was noticeably cold; observations from the GAK-1 oceanographic sampling south of Seward show that the first part of 2007 was anomalously cold with more saline surface water and fresher deeper waters; "*May 2007 observations show we have had an anomalous spring and summer… the temperatures and salinities lie outside of the long-term* *month of May standard deviations and from March-June of 2007, the deep waters are colder than any year since the early 1970s."* http://www.ims.uaf.edu/gak1/. This was reflected in a delay in the spring biomass peak in 2007 which was already increasing in April of previous, warmer years. Such changes in seasonality could affect predators, which time their migrations or reproduction to take advantage of an expected peak in their food supply. A similar result was found during zooplankton sampling of the Seward Line in May. During warm years, later stages of *Neocalanus* copepods are more abundant in May, suggesting they will complete the growth phase of their life cycle and descend to depth earlier. Once at depth, they are no longer available to their predators, including commercial fish species. In 2007 there was a significant reduction in the development rate (Hopcroft et al., 2008).

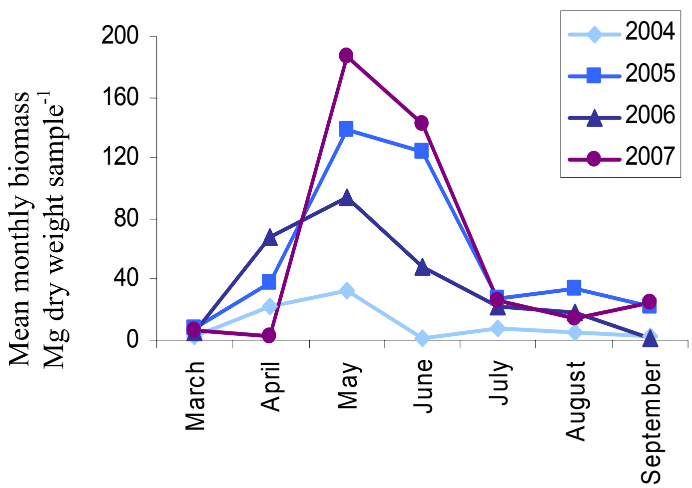

Figure 5. Mean monthly biomass for the shelf region SE of Cook Inlet showing the interannual variability in seasonality

1.2. Species composition

As well as food quantity, the nutritional quality of prey is likely also important to the success of higher trophic levels. Little is known about the biochemical composition of zooplankton species and the needs of their predators, however, changes which influence the species composition of the zooplankton may also impact the higher trophic levels, even if there is no change in the absolute amount of biomass. It is thought that prey availability may be more important to predator growth than absolute prey abundance (see references in Mackas et al., 2007). Both timing of prey biomass peaks (previous section) and prey type will affect prey availability. Larger subarctic copepods tend to be more lipid rich than their smaller, more southerly distributed counterparts and may be easier to catch. Figure 6 shows some of the more common zooplankton taxa and their contribution to the mean monthly zooplankton abundance for 3 of the regions.

Pteropods, a group of pelagic molluscs, show up sporadically in large numbers such as on the Alaskan shelf in 2000 and 2005 and in the oceanic northern Gulf of Alaska in 2000 and 2001. They are a food source for pink and chum salmon but little is known about the factors that control their distribution and abundance. The large *Neocalanus* copepods are not as numerous as smaller species such *Pseudocalanus* or *Acartia* and are most common in the spring (if Figure 6 was redrawn in terms of biomass then their contribution would be more pronounced).

Euphausiids (though not necessarily captured efficiently by the CPR) were abundant in spring 2001 on the Alaskan shelf and sporadically through the northern GoA time series.

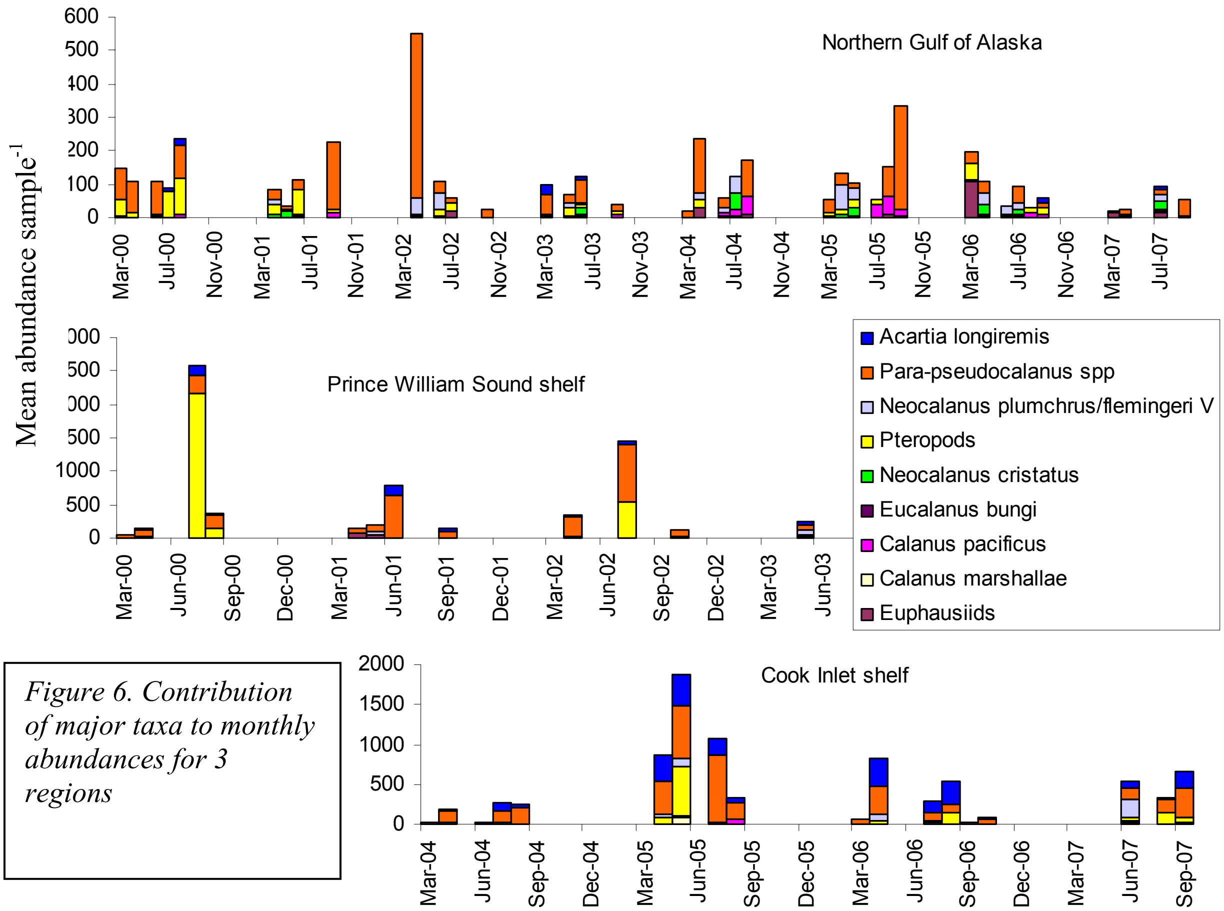

Figure 6. Contribution of major taxa to monthly abundances for 3 regions

Responses to the varying periods of warm and cool conditions occurring in different years are also evident in the less common taxa. Two warm water copepods are shown in Fig 7, for each of the six regions, and it is clear that abundances are higher in all regions in the warm years of 2003-06, with numbers declining again through 2007. *Calanus pacificus* was abundant enough in the northern GoA in 2004 and 2005, and on the shelf south of Cook Inlet in 2005 that the signal can also be seen in Fig 6.

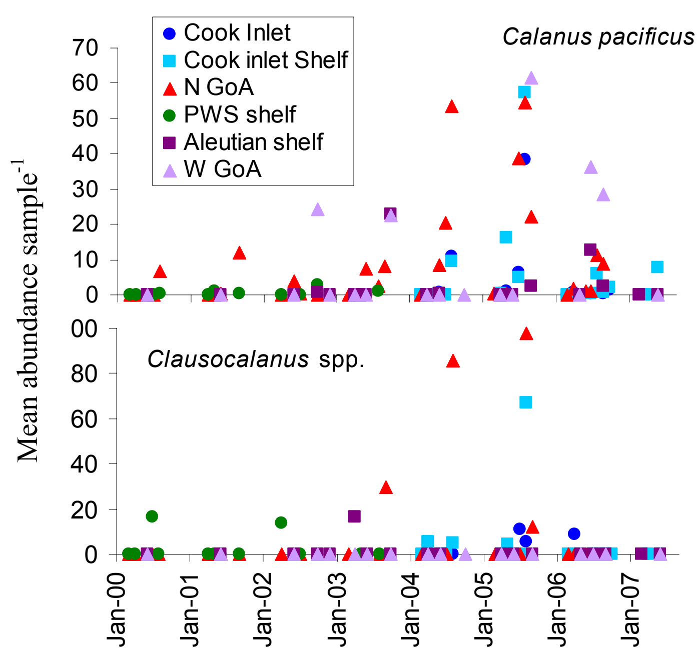

Figure 7. Mean monthly abundance of two warm water copepods in each of the 6 regions

Climate effects along the Seward Line are generally more subtle (Coyle

& Pinchuk 2003), and often operate differentially over the inner shelf vs over deeper waters. In warmer years a mix of generally smaller, shorter-lived species inhabits the north east Pacific that may be of less nutritional value to fish stocks than their typically larger and more lipid-rich sub-arctic species.

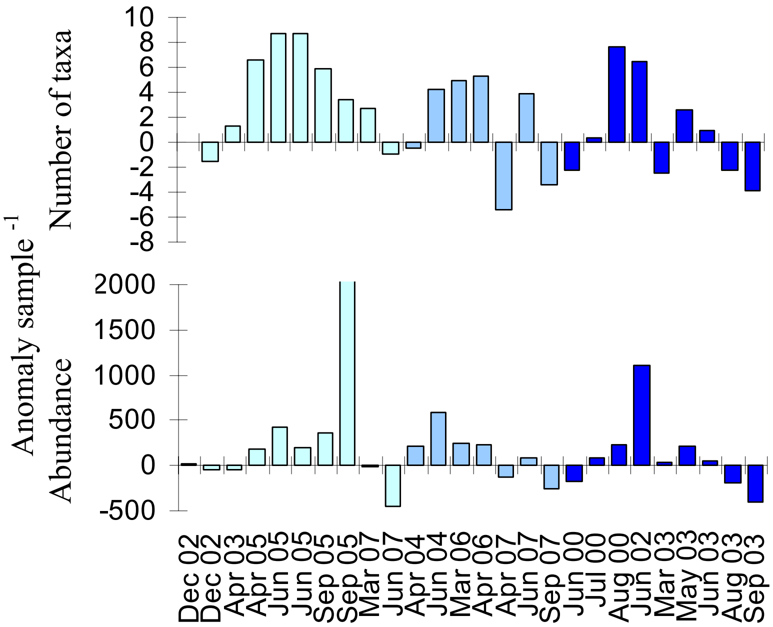

Fig 8. Anomalies of number of mesozooplankton taxa (upper) and total mesozooplankton abundance (lower) found in samples from within eddies when compared to samples collected when eddies were not present. Light blue = W GoA, Mid blue = central N GoA, dark blue = NE GoA.

1.3. Eddies

Mesoscale anticyclonic eddies forming along the eastern continental margin of the Gulf of Alaska in winter transport large quantities of coastal water to the open ocean (e.g. Miller et al., 2005; Ladd et al. 2007). Okkonen et al. (2003) observed Sitka Eddies carrying deep-ocean and shelf waters across the continental margin near Kodiak Island at all depths from surface to bottom of continental shelf and upper slope. Therefore, when eddies are present on the continental margin, they boost cross shelf exchange by several orders of magnitude. Eddies are readily visible via sea surface height anomalies as recorded by altimetry satellites and available at (http://argo.colorado.edu/~realtime/welcome/). The CPR transects in the northeast Pacific opportunistically passed close to, and sometimes through, some of these eddies. The fate of the biological organisms entrained within the eddies, and the influence of the eddies on the oceanic fauna, have recently begun to be addressed. Mackas and Galbraith (2002) describe the results of zooplankton surveys across an eddy off the west coast of British Columbia and show elevated levels of entrained near-shore and slope species that persist within the eddy for over a year. Elevated levels of offshore species were also found to occur through retention processes (Mackas et al., 2005). Previous work with CPR data from 2000 and 2001 found shelf species of diatoms and calanoid copepods recorded in CPR samples within or in close proximity to eddies. Several oceanic taxa also showed higher concentrations within eddies. Significantly reduced occurrences of shelf taxa in oceanic samples were seen in 2001, coinciding with a weaker eddy than observed in 2000 (Batten & Crawford, 2005).

With eight years of CPR transects now available we are currently working on a further analysis of the effect of eddies on zooplankton variables. Ship tracks were overlaid on the altimetry images and samples within eddies identified. A total of 26 eddies in the north-east Pacific were sampled, although the number of samples processed from each eddy was often small. The number of mesozooplankton taxa and total mesozooplankton biomass within the eddy was compared to a monthly mean for that region when eddies were not present and the anomalies calculated (Figure 8). Further work needs to be done to examine the effects of factors such as the age of the eddy, distance from the shelf, season and the strength of the anomaly but it is clear that eddies generally increase both the number of taxa (or diversity) and the absolute amount of zooplankton present within that region of the ocean. They are therefore likely to act as 'hot-spots' of prey availability for higher trophic levels.

2. Abstracts of publications resulting from these projects.

2.1. Distribution and seasonal cycles of decapod crustacean larvae in CPR samples.

Lindley, J.A., and Batten, S.D. (In press) Distribution and seasonal cycles of decapod crustacean larvae in Continuous Plankton Records from the North Pacific Ocean. Submitted to Journal of the Marine Biological Association, UK.

Decapoda taken in CPR samples from the Pacific in 1997 and 2000-2003 have been identified and measured. Some previously undescribed larval stages were referred to species and characteristics of these are described. Distributions and seasonal occurrence of decapod taxa in the samples are described and discussed with particular emphasis on the dendrobranchiate shrimp *Sergestes similis* and the brachyurans *Cancer* spp. and *Chionoecetes* spp. There is a prolonged larval season at low levels of abundance off the Californian coast but in the more northern waters there is shorter productive period but numbers of larvae per sample are high, particularly in June. Larvae of *Chionoecetes* and other Oregoninae were found only from May to July.

2.2. Effects on zooplankton of a warming ocean.

Mackas, D.L., Batten, S.D., and Trudel, M., (2007) Effects on zooplankton of a warming ocean: recent evidence from the Northeast Pacific. Progress in Oceanography, 75, 223-252

The consequences for pelagic communities of warming trends in mid and high latitude ocean regions could be substantial, but their magnitude and trajectory are not yet known. Environmental changes predicted by climate models (and beginning to be confirmed by observations) include warming and freshening of the upper ocean and reduction in the extent and duration of ice cover. One way to evaluate response scenarios is by comparing how ''similar'' zooplankton communities have differed among years and/or locations with differing temperature. The subarctic Pacific is a strong candidate for such comparisons, because the same mix of zooplankton species dominates over a wide range of temperature climatologies, and observations have spanned substantial temperature variability at interannual-to-decadal time scales. In this paper, we review and extend copepod abundance and phenology time series from net tow and Continuous Plankton Recorder surveys in the subarctic Northeast Pacific. The two strongest responses we have observed are latitudinal shifts in centers of abundance of many species (poleward under warm conditions), and changes in the life cycle timing of *Neocalanus plumchrus* in both oceanic and coastal regions (earlier by several weeks in warm years and at warmer locations). These zooplankton data, plus indices of higher trophic level responses such as reproduction, growth and survival of pelagic fish and seabirds, are all moderately-to-strongly intercorrelated (r = 0.25–0.8) with indices of local and basin-scale temperature anomalies. A principal components analysis of the normalized anomaly time series from 1979 to 2004 shows that a single ‘‘warm-and-low-productivity’’ vs. ‘‘cool-and-high-productivity’’ component axis accounts for over half of the variance/covariance. Prior to 1990, the scores for this component were negative (‘‘cool’’ and ‘‘productive’’) or near zero except positive in the El Nino years 1983 and 1987. The scores were strongly and increasingly positive (‘‘warm’’ and ‘‘low productivity’’) from 1992 to 1998; negative from 1999 to 2002; and again increasingly positive from 2003-present. We suggest that, in strongly seasonal environments, anomalously high temperature may provide misleading environmental cues that contribute to timing mismatch between life history events and the more-nearly-fixed seasonality of insolation, stratification, and food supply.

2.3. Plankton populations at the bifurcation of the North Pacific current.

Batten, S.D. and Freeland, H.J. (2007). Plankton populations at the bifurcation of the North Pacific Current. Fisheries Oceanography, 16, 536-546

As the eastward flowing North Pacific Current approaches the North American continent it bifurcates into the southward flowing California Current and the northward flowing Alaska Current. This bifurcation occurs in the south-eastern Gulf of Alaska and can vary in position. Dynamic height data from Project Argo floats have recently enabled the creation of surface circulation maps which show the likely position of the bifurcation; during 2002 it was relatively far north at ~53º N then, during early 2003, it moved southwards to a more normal position at ~45°N. Two ship-of-opportunity transects collecting plankton samples with a Continuous Plankton Recorder across the Gulf of Alaska were sampled seasonally during 2002 and 2003. Their position was dependent on the commercial ship’s operations; however most transects sampled across the bifurcation. We show that the oceanic plankton differed in community composition according to the current system they occurred in during spring and fall of 2002 and 2003, although winter populations were more mixed. Displacement of the plankton communities could have impacts on the plankton’s reproduction and development if they use cues such as day length, and also on foraging of higher trophic level organisms that use particular regions of the ocean if the nutritional value of the communities is different. Although we identify some indicator taxa for the Alaska and California currents, functional differences in the plankton communities either side of the bifurcation need to be better established to determine the impacts of bifurcation movement on the ecosystems of the north-east Pacific.

2.4. Spatial heterogeneity and genetic variation in the copepod *Neocalanus cristatus*.

Kirby, R.R., Lindley, J.A., and Batten, S.D. (2007). Spatial heterogeneity and genetic variation in the copepod *Neocalanus cristatus* along two transects in the North Pacific sampled by the Continuous Plankton Recorder. Journal of Plankton Research, 29, 97-106

We present a macrogeographic study of spatial heterogeneity in an important subarctic Pacific copepod and describe the first genetic analysis of population structure using Continuous Plankton Recorder (CPR) samples. Samples of *Neocalanus cristatus* were collected at a constant depth of ~7 m from two CPR tow-routes, (i) an east–west ~6500-km transect from Vancouver Island, Canada to Hokkaido Island, Japan, and (ii) a north–south transect of ~2250 km from Anchorage, Alaska to Tacoma, Washington. Analysis of these samples revealed three features of the biology of *N. cristatus*. First, *N. cristatus* undergoes small-scale diel vertical migration that is larger among stages CV–adult (3–6 times more abundant at 7 m at night), than stages CI–CIV (only 2–4 times higher at night). Secondly, while there were no regions where *N. cristatus* did not appear, each transect sampled a few large-scale macrogeographic patches. Thirdly, an analysis of molecular variation, using a partial sequence of the *N. cristatus* cytochrome oxidase I gene, revealed that 7.3% ($P < 0.0001$) of the total genetic variation among *N. cristatus* sampled from macrogeographic patches by the CPR could be explained by spatial heterogeneity. We suggest that spatial heterogeneity at macrogeographic scales may be important in plankton evolution.

2.5. The influence of coastal origin eddies on oceanic plankton populations.

Batten, S.D and Crawford, W.R. (2005). The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. Deep Sea Research II, 52, 991-1009.

Mesoscale anticyclonic eddies that form along the eastern continental margin of the Gulf of Alaska in winter transport large quantities of coastal water to the open ocean. The Continuous Plankton Recorder (CPR) sampled repeated transects that passed close to, or through these eddies in 2000 and 2001. Shelf species of diatoms and calanoid copepods were recorded in CPR samples within, or in close proximity to eddies and they persisted through the sampling period. Several oceanic taxa also showed higher concentrations within the eddies. Significantly reduced occurrences of shelf taxa in oceanic samples were seen in 2001, coinciding with a weaker eddy than observed in 2000. Images of ocean temperature and chlorophyll-a, prepared from satellite observations, reveal changes in offshore transport mechanisms by eddies between winter and spring, and between southern and northern eddies in this region. These effects may also explain some of the seasonal and geographical variability in the CPR samples. Between April and June of 2000 the Haida Eddy straddled the low chlorophyll-a waters of the gulf and the high chlorophyll-a waters of the continental margin, and entrained each water type into the neighbouring region. The resulting swirling patterns were clearly observed in SeaWiFS imagery. Sitka eddies failed to penetrate into low chlorophyll-a waters during these months and were less effective in stirring high and low chlorophyll-a concentrations. Surface currents in surrounding waters, simulated by the ocean surface current simulations (OSCURS) model, were used to provide some insights into the likely fate of planktonic organisms once they leave the eddies. We show that these eddies may play a significant role in distributing plankton species.

2.6. Regular occurrence of *Thysanoessa inspinata* in the Gulf of Alaska.

Lindley, J.A., Batten, S.D., Coyle, K.O and Pinchuk, A.I. (2004). Regular occurrence of *Thysanoessa inspinata* (Crustacea: Euphausiacea) in the Gulf of Alaska. Journal of the Marine Biological Association of the UK, 84, 1033-1037.

Over a period of five years (1997-2002) the euphausiid *Thysanoessa inspinata* has been recorded in plankton samples from the eastern Gulf of Alaska, as far north as 59°N. Until recently the northern limit of distribution of the species was assumed to be little further north than 50°N but the species is present in oceanic samples off the Alaskan continental shelf throughout the year and occurs regularly in the waters of the eastern Gulf.

2.7. Changes in oceanic zooplankton populations in the North-east Pacific

Batten, S.D. and Welch, D.W. (2004). Changes in oceanic zooplankton populations in the North-east Pacific associated with the possible climatic regime shift of 1998/1999. Deep Sea Research II, 51, 863-873.

There is increasing evidence that the winter of 1998-1999 saw a shift in the ecosystem structure of the North-east Pacific. The Continuous Plankton Recorder sampled plankton along a transect from Alaska to California in 1997, the warm period preceding the regime shift, as well as the subsequent cool period of 2000 and 2001. Analyses of mesozooplankton biomass and species composition show significant changes in the plankton communities of the open Gulf of Alaska and the Alaskan shelf, consistent with the changing environmental conditions. Boreal calanoid copepod species showed lower abundances in the warm period while subtropical species showed higher abundances and a more northerly distribution. During the colder period, boreal species had higher abundances and subtropical species were less abundant on the northern part of the transect. Differences were greatest between the years of 1997 and 2001 with 2000 appearing as a 'transition' year. The communities in the open Gulf of Alaska appear to be as responsive to climate change as shelf ecosystems, whose responses have been reported elsewhere. The composition changes have implications for higher trophic levels that forage in the open ocean, and for the forcing of the downwelling ecosystem of the Alaskan continental shelf ecosystem by events offshore.

2.8. Latitudinal differences in the duration of development of *Neocalanus plumchrus* copepodites

Batten, S.D., Welch, D.W., and Jonas, T. (2003). Latitudinal differences in the duration of development of *Neocalanus plumchrus* copepodites. Fisheries Oceanography, 12 (3), 201-208.

Quasi-synoptic sampling along a transect from Alaska to California carried out in spring and summer 2000 using Continuous Plankton Recorders reveals that the abundant calanoid copepod *Neocalanus plumchrus* (Marukawa) reaches the surface at approximately the same time across the region. However, monthly sampling also reveals that the timing of peak biomass (when 50% of the population consists of copepodites at stage CV) occurs about 5 weeks earlier at the southernmost part of its range than at the northernmost part, with intermediate areas having intermediate timings. Surface water temperature differed by about 4˚C between the warmer south and the cooler north, and we suggest that such a difference would reduce development duration by about 3 weeks. If food supply in the north is more conducive to lipid accumulation, as seems possible from phytoplankton biomass data, then the use of the differences in timing of peak *N. plumchrus* biomass in each area as a measure of the differences in development time may not be accurate. We find that the estimate of the time of peak biomass varying by about 5 weeks between north and south may be an exaggeration of the actual difference in the development duration. Temperature is probably the most important factor governing the shorter development duration of *N. plumchrus* in southern latitudes.

Conclusions

The data and studies summarised in this report have shown how CPR data have been used in a variety of collaborative studies;

- To describe the responses of the plankton to short term climate variability including changes in phenology in a key copepod species, *Neocalanus plumchrus*. Peak biomass of this species can occur several weeks earlier in warm years influencing the overall cycle and pattern of mesozooplankton biomass.
- To describe distributions of decapod larvae and euphausiid species including new information on range extent and larval descriptions.
- To examine the effects of hydrographic features such as mesoscale eddies and the North Pacific Current. Eddies can act as 'hot-spots', with increased numbers of taxa and individuals in parts of the Gulf of Alaska, particularly the west.
- In molecular-based investigation of macro-scale population structure. Mitochondrial DNA was extracted from *Neocalanus cristatus* in CPR samples. As well as concluding that spatial heterogeneity was more important than interannual variability this study shows the value of the archive of samples to future genetic studies.

Perhaps the most important contribution of the EVOS TC support is a baseline of plankton variables that describe seasonal and interannual variability in quantity and species composition, including responses to the alternating modes of the dominant climate signal in the North Pacific, the Pacific Decadal Oscillation. Because all upper trophic levels depend on plankton as a food source, either directly or through trophic linkages, this variability is important to measure and understand. Predicting and modelling the abundance and health of resources considered valuable to society depends on an understanding of variability in their prey. CPR data from the Alaskan shelf, for example, show a five-fold change in plankton biomass in May between 2004 and 2007 (Fig 5) coupled with a change in taxonomic composition (Figs 6 and 7), at a time when many predators are timing their spring reproduction or migration to take advantage of an expected peak in prey. This change in plankton biomass was mostly because of a delay in plankton increase in the colder spring of 2007, compared to the warmer springs of the preceding years. In warm years, smaller species of copepod, which lack lipid reserves, are more common. Availability of the prey to higher trophic levels is therefore dependent on the timing of increase and peak abundance, ease of capture and nutritional value.

Funding of the CPR survey beyond 2008 is uncertain, however, at a time when ocean conditions have returned to cooler conditions, perhaps leading to more productive and positive circumstances for valued resources, continued measurement and understanding of the foundation of the marine food chain remains important.

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