



# The Northeast Pacific GLOBEC Program: Coastal Gulf of Alaska

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## Introduction

The Gulf of Alaska (GOA) continental shelf encompasses approximately 370,000 km<sup>2</sup>, or about 13% of the U.S. continental shelf, and supports a rich and diverse marine ecosystem including some of the largest commercial fisheries in the U.S. Exclusive Economic Zone. Of particular economic importance is the salmon fishery, which was worth on the order of \$170 million (landed value) in 2000 accrued from a catch of over 100 million fish. However, there is con-

siderable variability on both interannual and longer time scales in harvest and recruitment success to this and other GOA fisheries. Of recent interest are compelling indications that abundances of salmon, other fish species, and zooplankton vary on decadal scales in association with North Pacific basin-scale climate changes (Beamish, 1995; Mantua et al., 1997; Roemmich and McGowan, 1995; Brodeur et al., 1996; Francis et al., 1998; Anderson and Piatt, 1999; Hollowed et al., 2001).

Salmon recruitment success appears to be predominantly established during the first year of life after the juvenile salmon leave nearshore nursery areas and move onto the shelf (Francis and Hare, 1994; Pearcy, 1992). For pink salmon (*Oncorhynchus gorbuscha*), migration onto the shelf begins in July, peaks in August and diminishes through fall (Boldt, 2001), although juveniles may remain on the shelf through December (Welch et al., 1998). Individual growth and mortality are high during this phase of the life history (Parker, 1968; Pearcy 1992; Boldt, 2001; Beamish and Mahnken, 2001) and depend on the complex interplay of a number of factors such as the composition, abundance, density, and condition of planktonic prey, predator types and abundances, disease, turbulence, and water temperature. Climate perturbations could influence any of these variables both directly and indirectly. Direct effects, such as control of predator abundance or juvenile salmon growth rates by water temperature are relatively easy to study. Indirect effects, such as "bottom up" processes, are more difficult to determine. For example, climate variability might affect the timing and/or magnitude of the spring bloom, the effects of which then propagate through the food web to influence the timing, composition, and biomass of summer-fall zooplankton, with consequences for juvenile salmon feeding success and growth rate (Denman et al. 1989; Gargett, 1997). The target zooplankton species in GLOBEC-CGOA (Coastal Gulf of Alaska) studies, Calanoid copepods and euphausiids (see Table 1 in Fogarty and Powell this issue; Strub et al., this issue), were selected as critically important elements in the food web dynamics of this region.

In the NEP-GLOBEC program we are investigating how large-scale climate signals are manifested at the scale of the continental shelf ecosystem. Basin-or global-scale climatic signals are likely modified by regional processes, and it is this modified, local, signature that presumably affects the regional biological response to a given climate perturbation. The regional responses to climate perturbations in the GOA are strongly dependent on its high-latitude location and its geomorphology. Together these profoundly influence the meteorology, hydrology, and the response of this shelf ecosystem to climate variability.

The geomorphology of the GOA shelf reflects past (and present) glacial and tectonic processes. These have carved a convoluted coastline and punctuated this relatively deep (>150 m) shelf with numerous troughs, canyons, and banks. Tectonic uplift has formed an extensive ring of coastal mountains around the gulf. The mountains are covered by the Earth's third largest glacial field (Meier, 1984), with these being

both a freshwater reservoir and a sediment source for the shelf.

Climate variability in the GOA might be expressed in a number of ways. Atmospheric-induced variations could alter the wind and thermal regime both over the shelf and the basin and/or perturb the hydrologic cycle

through changes in precipitation rates or patterns or by altering the mass balance of the glaciers and the seasonal snowpack. Alternatively, ocean currents might efficiently carry remote climate perturbation signals into this region. In developing an understanding of how climate variability affects the CGOA ecosystem, a key challenge is to explain the physical basis of biological production on this shelf. The CGOA is paradoxical because the high biological productivity (as indicated by the magnitude of commercial fish landings) occurs in the face of both strong downwelling and a massive, nitrate-poor coastal freshwater discharge.

Solving this intriguing problem and understanding how production processes might be altered by climate change is a key focus of GLOBEC studies in the CGOA.

## Physical Setting

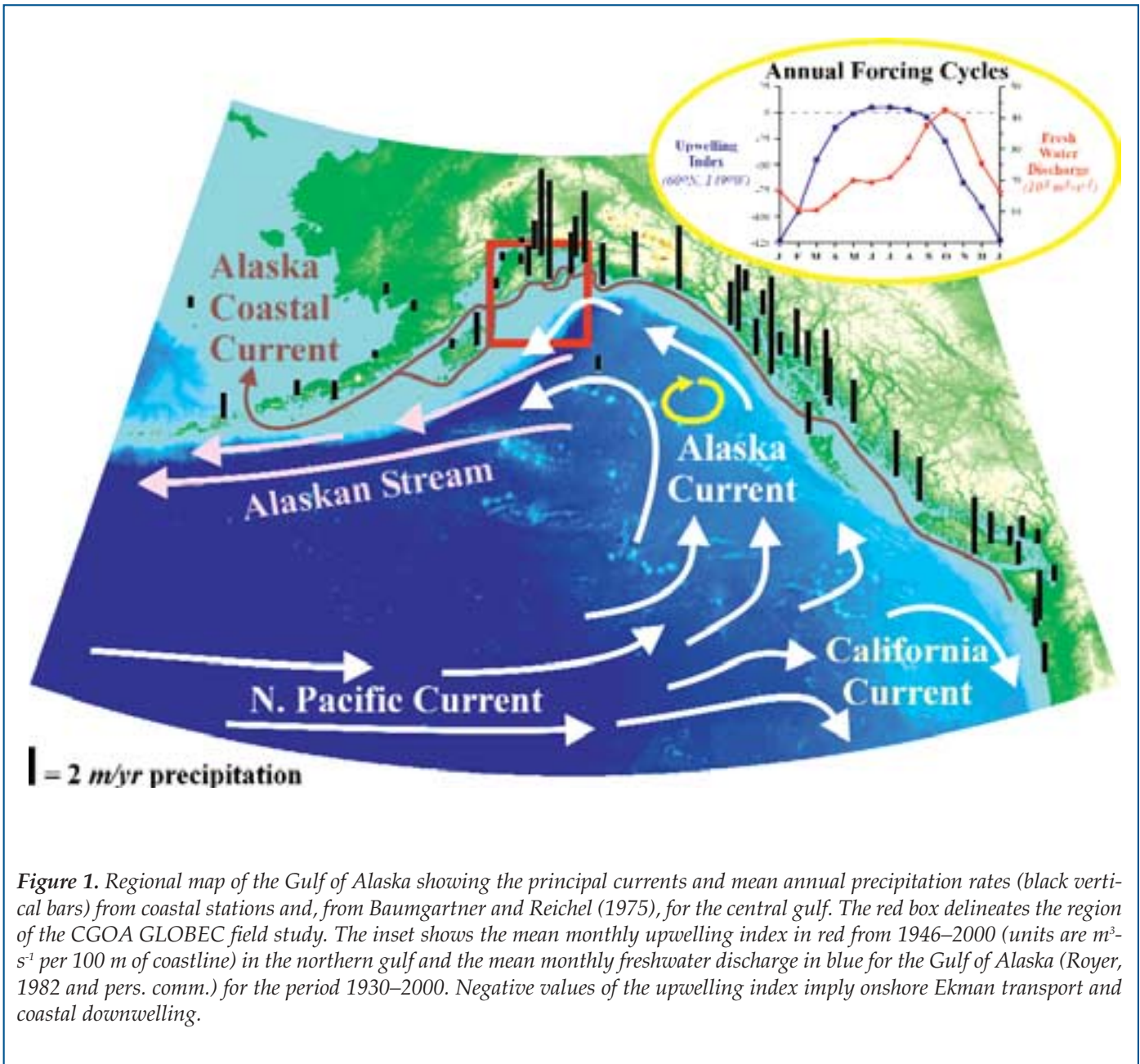
The dominant circulation features over the GOA shelf and slope are the Alaska Coastal Current (ACC) on the inner shelf and, along the continental slope, the Alaska Current in the eastern gulf and its transformation into the Alaskan Stream in the northwestern gulf (Figure 1). These currents are extensive, cyclonic, and persist year-round. They flow over complicated bottom topography, so that mesoscale flow variations generated by flow-topography interactions are likely. The ACC spans an alongshore distance of ~2500 km from its origin on the British Columbian shelf (or perhaps even further south in winter) (Royer, 1998) to its termination in the western gulf where it enters the Bering Sea (Schumacher et al., 1982). It is a wind- and buoyancy-forced coastal current generally confined to within 40 km of the coast and bounded offshore by a salinity front whose strength and structure varies seasonally in response to variations in winds and freshwater discharge. The Alaska Current and Alaskan Stream are, respectively, the eastern and western boundary currents of the GOA and respond primarily to the cyclonic wind stress curl over this basin.

These currents comprise the poleward limb of the North Pacific Subarctic Gyre and provide the oceanic link between the GOA shelf and the North Pacific Ocean. In so doing, the boundary currents advect warm, lower latitude waters into the northern gulf and therefore play an important role in the regional heat budget. The Alaska Current is a broad (~300 km), sluggish (5–10 cm s<sup>-1</sup>) flow with weak horizontal and vertical velocity

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**Figure 1.** Regional map of the Gulf of Alaska showing the principal currents and mean annual precipitation rates (black vertical bars) from coastal stations and, from Baumgartner and Reichel (1975), for the central gulf. The red box delineates the region of the CGOA GLOBEC field study. The inset shows the mean monthly upwelling index in red from 1946–2000 (units are  $\text{m}^3\text{-s}^{-1}$  per 100 m of coastline) in the northern gulf and the mean monthly freshwater discharge in blue for the Gulf of Alaska (Royer, 1982 and pers. comm.) for the period 1930–2000. Negative values of the upwelling index imply onshore Ekman transport and coastal downwelling.

shears while the Alaskan Stream is narrow (~100 km) and swift (~100  $\text{cm s}^{-1}$ ) with large velocity shears (Reed and Schumacher, 1986). The transformation of the Alaska Current into the Alaskan Stream entails concomitant changes in the velocity and thermohaline gradients along the shelfbreak. Insofar as these gradients influence fluxes between the shelf and slope (Gawarkiewicz, 1991), this transformation, along with the varying slope topography, suggests that shelfbreak exchange mechanisms are probably not uniform around the gulf. Moreover, the effects of these exchanges on the shelf will also be influenced by the shelf width, which is  $\leq 25$  km in the eastern gulf but broadens to more than 200 km in the northwestern gulf.

Gulf of Alaska shelf water temperatures are mod-

erately low (mean annual sea surface temperature =  $7^\circ\text{C}$ ) and temperature gradients generally weak. Because of this, the large, but seasonally varying, coastal freshwater discharge results in salinity being the primary variable controlling horizontal and vertical density gradients throughout much of the year, but especially from fall through spring. Climate perturbations that affect the rates and timing of coastal discharge might play an important role in the seasonal evolution of density gradients and the shelf circulation.

Energetic storms associated with the Aleutian Low predominantly influence the regional meteorology. Storms develop in the western and central North Pacific Ocean and, as they propagate eastward, they intensify by absorbing heat and moisture from the

ocean surface. The strength, trajectory, and frequency of these lows are also influenced by both the Siberian and East Pacific High pressure systems (Wilson and Overland, 1986). The position and strength of these three climatological systems varies seasonally and interannually, leading to variations in wind velocity, cloud cover, precipitation, and runoff on equivalent time scales. The coastal mountains bordering the gulf inhibit the inland migration of storms so that lows often dissipate here. Consequently, the mean winds are cyclonic and impel an onshore surface Ekman transport over the slope and shelf, generating coastal convergence or downwelling. Downwelling favorable winds occur from September through May and are maximal in January, whereas winds are weakly upwelling in summer on average (Figure 1 inset). Although maximum cyclonic wind stress occurs in the northeastern gulf, the alongshore wind stress fluctuations are largely coherent around the gulf (Livingstone and Royer, 1980). The mountains force air masses upward, resulting in cooling, condensation and enhanced coastal precipitation (Figure 1). In most months this precipitation feeds the many small watersheds draining into the Gulf, but in winter, much of the precipitation is stored in snowfields and glaciers where it can remain for one or more seasons. Freshwater discharge is a minimum in winter when precipitation is stored as snow, increases rapidly through summer through melting, and attains its maximum in fall when precipitation rates are greatest (Royer, 1982; Figure 1 inset). Slightly more than half of the discharge enters in southeast Alaska (Royer, 1982) with the remainder entering along the south central coast. Although the freshwater is a significant buoyancy source for the shelf, the runoff is nitrate poor owing to its glacial and mountainous origin (Reeburgh and Kipphut, 1986). Both the spatial structure of the winds and the distributed nature of the coastal runoff suggest spatially coherent patterns of wind and buoyancy forcing over much of this shelf.

### The CGOA Sampling Program

The principal GLOBEC field effort in the CGOA entails two inter-related components: observational and process-oriented studies. The Long Term Observation Program (LTOP) is designed to provide a broader temporal and spatial context for interpretation of process studies and to measure key variables required in physical and biological models of this system. The process studies are designed to provide a mechanistic understanding of physical and biological rates and processes critical to ecosystem dynamics.

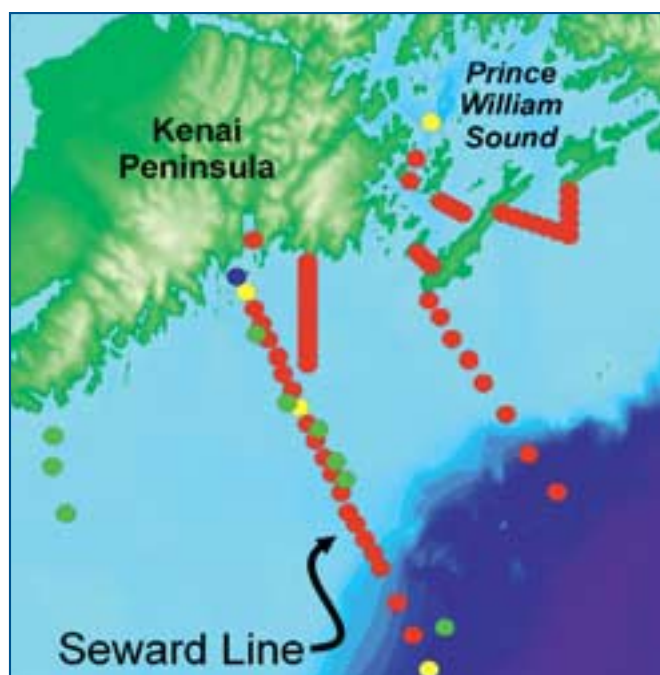
### The Long Term Observation Program (LTOP)

In the LTOP study we are quantifying the temporal (interannual and seasonal) and spatial variability of the physical environment, nutrient concentrations, phytoplankton production and abundance, and zooplankton and fish abundance and distribution. The LTOP pro-

gram began with an opportunistic cruise in October 1997 in response to the developing El Niño and then on a systemic basis in March 1998.

Sampling is mainly focused along the Seward Line, which extends ~250 km from the coast across the continental slope (see Figure 2). Additional sampling is conducted within Prince William Sound and at high spatial resolution within the ACC on a short transect along a relatively straight stretch of the coast between the sound and the Seward Line. The sampling activities in the LTOP and process components are timed to the principal biological and physical seasonal transitions occurring on this shelf (Table 1). The mooring array, deployed in spring 2001, spans the shelf and shelfbreak measuring temperature, salinity and currents. Several moorings include nitrate analyzers and fluorometers and one includes a bio-acoustic sensor to measure zooplankton biomass. Drifters, drogued at 40 m, are released periodically along the Seward Line to track broader-scale water movements and to provide information on mesoscale variability.

The 2002 field program will be augmented by Seaglider surveys (autonomous, telemetering underwater vehicles) that will make continuous high-resolution measurements at a horizontal resolution of approximately 1.2 km and profile between the surface and 10 m of the seabed. Seaglider sampling will continue throughout the year conducting 20-day repeat sur-



*Figure 2. Map showing location of moorings (green), LTOP stations (red, yellow, and blue). Stations colored yellow are also the zooplankton process stations occupied in 2001. The blue circle indicates station GAK 1 where nominally monthly CTD casts have been made since 1970.*

veys through the ACC between Prince William Sound and the Seward Line. Sampling will include temperature, conductivity, pressure, chlorophyll fluorescence, dissolved oxygen, optical backscatter, surface drift, and vertically averaged currents. Seaglider data will be periodically transmitted to the laboratory via the Iridium system.

Fish sampling is conducted as part of the LTOP surveys in Prince William Sound and along the Seward Line and as part of an annual Gulf-wide survey conducted from mid-July through early August, under the auspices of NOAA's Ocean Carrying Capacity (OCC) program. The latter effort involves trawling along eleven cross-shelf transects between Southeast Alaska and the western Gulf. Data from all fish surveys are used to determine salmon condition, distribution, size, age, diet, growth rate and genetic stock identification. Other fish species are counted and juvenile rockfish (*Sebastes* species) and sablefish (*Anoplopoma fimbria*) are frozen for additional laboratory analyses. The fish surveys also include the collection of oceanographic data including CTD casts, currents (VM-ADCP), continuous

surface salinity and temperature, chlorophyll, and zooplankton.

### Process Studies

The process studies focus on measuring feeding and growth rates of key organisms comprising the planktonic ecosystems (e.g. phytoplankton, heterotrophic protists, copepods, euphausiids,) as well as juvenile salmon. A variety of analytical approaches (microscopy, imaging-in-flow techniques, pigment biomarkers, chlorophyll size fractionation) are being employed in conjunction with feeding and growth experiments to elucidate trophic interactions among these groups. These process measurements are critical in order to make comparisons with the California continental shelf (CCS) ecosystem and for developing and evaluating regional ecosystem models having a prognostic capability. The process studies also include data obtained from drifters and moored instruments. Both techniques will provide high-resolution time series on the cross- and along-shore variations in the circulation. Most of the process studies began in the spring of 2001

**Table 1.** Sampling schedule and rationale for CGOA LTOP and process sampling. *Italicized months indicate time of process study cruises in 2001.*

<b>Month</b>	<b>Physical Rationale</b>	<b>Biological Rationale</b>
<b>March</b>	Strong downwelling and vertical mixing, low discharge, weak stratification	Zooplankton migrate from depth (at shelfbreak) & transported inshore
<b>April</b>	Moderate downwelling, discharge increasing, weak and spatially variable stratification	Phytoplankton bloom
<b>May</b>	Moderate-weak downwelling, moderate discharge, stratification increasing biomass	Phytoplankton bloom and maximum oceanic copepod
<b>July</b>	Weak up- and downwelling, discharge increasing, strong stratification	Maximum zooplankton abundance Juvenile salmon enter shelf
<b>August</b>	Weak up- and downwelling, moderate-strong discharge, strong stratification, deep onshore movement of nutrient-rich offshore waters	Maximum juvenile salmon abundance on shelf
<b>October</b>	Strong downwelling, maximal discharge, strong stratification	Juvenile salmon on shelf, possible fall phytoplankton bloom
<b>December</b>	Strong downwelling, decreasing discharge, weakening stratification	Fall-winter deep mixing, assess small zooplankton condition.

with the results from the first process field season still being synthesized.

## Scientific Highlights

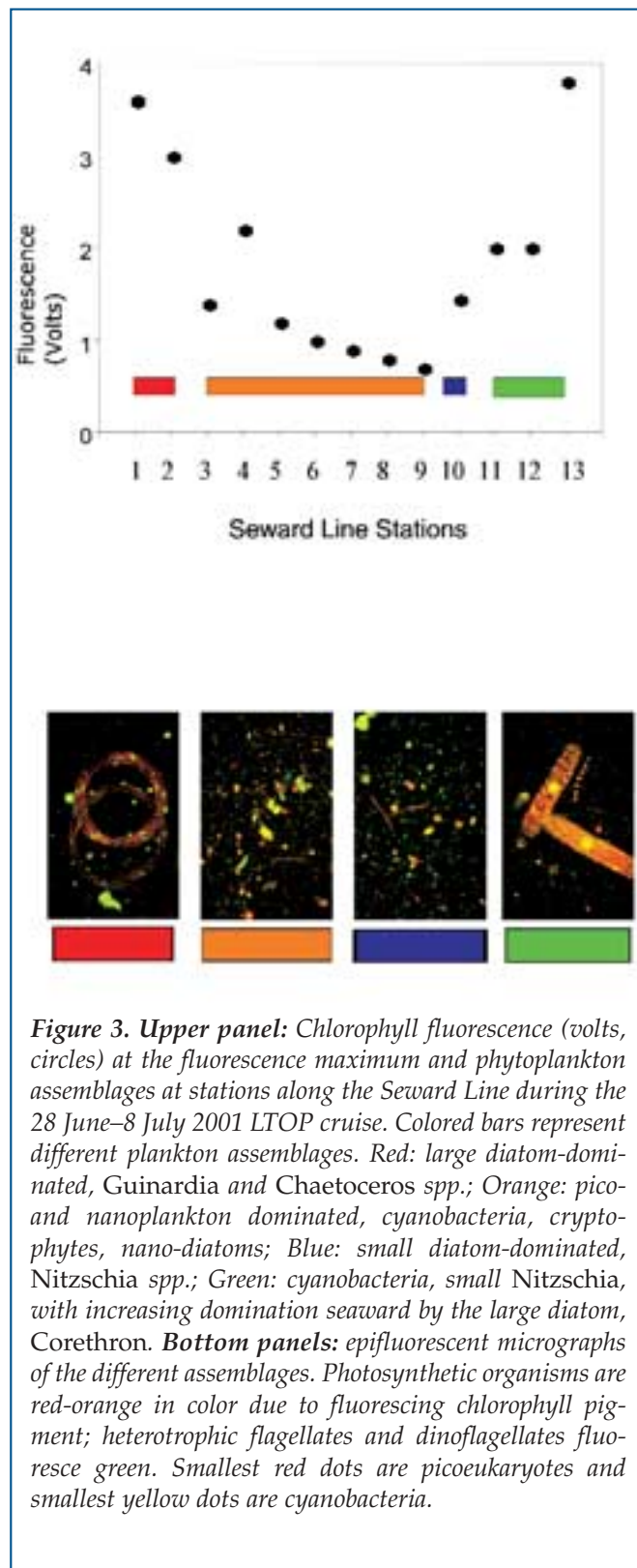
Accumulating field data and model results suggest that the CGOA shelf is roughly organized into three distinct physical regimes delineated by salinity fronts whose strength and position varies seasonally. The inner shelf is dominated by the low-salinity ACC; while the outer shelf, including the shelfbreak and inner slope, is influenced by saltier and (generally) more nutrient-rich oceanic waters advected within the boundary currents. The mid-shelf regime contains waters of intermediate salinity and a highly variable flow field that is weakly westward on average. These observations, along with the low cross-shelf correlation in along-shelf flow variability, suggests that distinctly different dynamics might apply to each regime. These physical regimes roughly delineate different biological habitats, as there are often distinct species assemblages found within each regime. Cross-shelf gradients in species assemblages are also evident; phytoplankton, microzooplankton and fish assemblages show a very heterogeneous cross-shelf distribution.

Shipboard measurements, current meter data, drifter trajectories, and SeaWiFS satellite imagery all suggest that considerable mesoscale variability is embedded within these various shelf regimes. In springtime, the cross-shelf de-correlation scale is 5–20 km as derived from zooplankton biomass distributions obtained from continuously recording, towed acoustic sensors. Similarly, cyanobacteria, picoeukaryotes, heterotrophic dinoflagellates and ciliates are all abundant (Figure 3) but show highly variable numbers and biomass over short (<10 km) distances. Process measurements made in spring and summer 2001 indicate that phytoplankton and zooplankton productivity rates can also vary widely over short spatial scales, even in mid-summer when low nitrate concentrations occur in the mixed layer.

Satellite altimeter data indicates that mesoscale spatial variability over the shelfbreak and slope is linked to meanders in the boundary flows or the large (>100 km diameter) anticyclonic eddies propagating along the continental slope (Okkonen et al., submitted). As these anticyclones propagate along the slope they induce upwelling at the leading and trailing edges of the eddy and downwelling over the eddy center with these effects reflected in chlorophyll biomass, rates of primary productivity, and zooplankton biomass.

## Nutrient Dynamics

The CGOA-GLOBEC program is concerned with identifying and quantifying the mechanisms by which nutrients are transferred onto the inner shelf and supplied to the euphotic zone. On an annual basis, salty, nutrient-rich water flows onshore when downwelling winds relax and weak upwelling begins in early sum-



**Figure 3. Upper panel:** Chlorophyll fluorescence (volts, circles) at the fluorescence maximum and phytoplankton assemblages at stations along the Seward Line during the 28 June–8 July 2001 LTOP cruise. Colored bars represent different plankton assemblages. Red: large diatom-dominated, *Guinardia* and *Chaetoceros* spp.; Orange: pico- and nanoplankton dominated, cyanobacteria, cryptophytes, nano-diatoms; Blue: small diatom-dominated, *Nitzschia* spp.; Green: cyanobacteria, small *Nitzschia*, with increasing domination seaward by the large diatom, *Corethron*. **Bottom panels:** epifluorescent micrographs of the different assemblages. Photosynthetic organisms are red-orange in color due to fluorescing chlorophyll pigment; heterotrophic flagellates and dinoflagellates fluoresce green. Smallest red dots are picoeukaryotes and smallest yellow dots are cyanobacteria.

mer. The summertime inflow of saline water onto the inner shelf is one means by which the slope and basin communicate directly with the inner shelf; this water is drawn from within the permanent halocline of the GOA. Although this is a potential source of nutrients for the phytoplankton, the bulk of this onshore flow

occurs at depths greater than 100 m and beneath the euphotic zone. Thus, upwelling in the CGOA differs from upwelling in the CCS in which nutrient-rich waters are brought into the euphotic zone. This difference is due to the weak upwelling winds and the distributed nature of the coastal runoff into the CGOA.

Modeling studies are showing that buoyant plumes associated with a point discharge (such as a single river) respond differently to upwelling winds from those formed by a distributed discharge. Plumes formed by the latter, which characterize the ACC, do not detach from the coast during weak upwelling as readily as plumes generated by a point discharge (Williams, pers. comm.). Thus, other mechanisms are required to bring nutrients into the surface layers in the CGOA. This could be accomplished in the following winter by deep mixing although some of the nutrients at depth are also transported offshore by return flows associated with downwelling. Other potential mechanisms include surface onshore Ekman transport in fall and winter, onshore flows up canyons that intersect the shelfbreak, topographically-induced upwelling, and exchanges fostered by eddies and meanders along the slope. However, the relative importance of these mechanisms has not been established.

## Interannual Variability and ENSO Effects

The LTOP program was fortunate enough to have captured both the 1997–98 El Niño and 1998–99 La Niña events. Comparisons of temperature, salinity, and nutrient concentrations along the Seward Line for April of both years provide examples of the interannual variability (Figure 4). Temperatures were substantially higher and salinity and nitrate concentrations lower in 1998 compared to 1999. Averaged over the upper 100 m and within 100 km of the coast temperatures were approximately 1.5°C higher, salinities 0.4 psu lower, and nitrate concentrations about 25% lower in April 1998 compared to April 1999.

These anomalies are a consequence of both atmospheric and oceanic forcing occurring over the previous summer and fall (Weingartner et al., in prep.). Unusually calm and cloud free conditions prevailed over the northern gulf in summer and early fall of 1997, resulting in above-normal near-surface water temperatures. Cyclonic winds were anomalously strong throughout the Northeast Pacific (including the CCS region), but particularly so in the northeastern gulf (and east of the CGOA study area). Through fall and winter the winds forced warm, low salinity surface waters shoreward, which then downwelled along the coast. The fresher conditions in April 1998 were also associated with greater precipitation and anomalously large freshwater discharge into the northeast Pacific during summer-fall 1997 and early winter 1998.

Moreover, because fall-winter air temperatures were also above normal over the GOA, the winter hydrologic regime was altered with more of the precipitation delivered as rainfall rather than snow. Therefore, in the months prior to spring 1998, the anomalously strong winds and runoff resulted in a freshening of the inner shelf. In contrast, the higher salinities observed in April 1999, were associated with anomalously weak freshwater discharge and cyclonic winds throughout the GOA during the preceding fall and winter.

The differences in forcing by the winds and runoff between these two years was also reflected in differences in the alongshore baroclinic transport within the ACC, as the transport in April 1998 was nearly twice that of April 1999. The stronger ACC transport in 1998 was also consistent with Strub and James' (in press) findings of anomalously strong cyclonic flow over the continental slope in 1998. Conceivably, the anomalously large alongshore transports in the ACC and the slope currents also contributed to the observed warming in 1998 through enhanced advection of warm waters from farther south.

The low nitrate concentrations observed in late winter 1998 are consistent with the anomalously high nutrient poor coastal discharge, although other mechanisms might also have contributed. For example, anomalously low winter nitrate concentrations were prevalent throughout the euphotic zone of the North Pacific in winter 1998 (Goes et al., 2001) and these low nitrate waters could have been advected into the Gulf by the slope currents and onshore by the cyclonic winds.

## Stratification

Interannual differences in the onset of stratification provide some insight into the complexities associated with the development of stratification on the GOA. While the shelf was unstratified in early May 1999, it was strongly stratified by early May 1998, with the stratification due solely to the vertical salinity gradients. In general, early spring water temperatures are fairly uniform throughout the water column and across the shelf. Density variations therefore depend on salinity differences. Stratification begins adjacent to the coast (where the runoff first enters the ocean) and then gradually spreads offshore. The offshore dispersal of low salinity water is dependent on both vertical mixing and the cross-shelf circulation field. Thus, initiation of spring blooms on the GOA shelf might not be as tightly in-phase with the annual solar cycle as on shelves where solar heating and vertical wind mixing exert the dominant control over upper ocean stratification. Second, mixed layer development in the CGOA depends upon processes operating over a range of time

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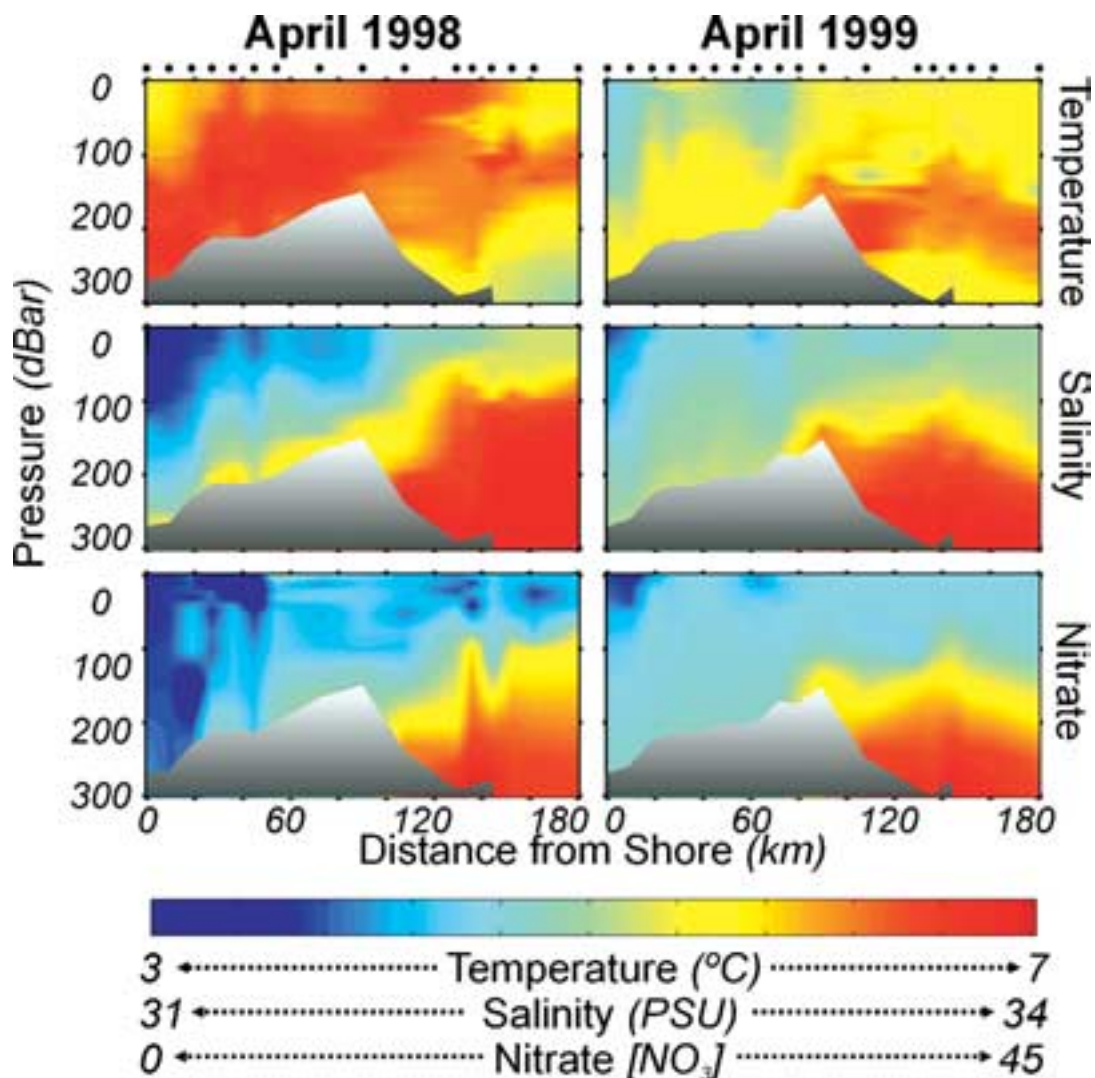


Figure 4. Temperature (top), salinity (middle) and nitrate (bottom) along the Seward Line in April 1998 (left) and 1999 (right). The coast is on the left and the continental slope on the right in each panel.

scales and involves several variables affecting both vertical mixing and the offshore flux of freshwater. These variables include the fractions of winter precipitation delivered to the coastal watershed as snow and rain, the timing and rate of spring snowmelt, and the wind velocity. The relevant time scales range from a few days (storm events) to the seasonal or longer where the longer time scales reflect the advective potential of the ACC to transport freshwater from the eastern GOA. We note that the development of stratification is not exclusively dependent on the addition of freshwater. We are finding, for example, that in the absence of any significant freshwater additions, the middle and outer shelf will stratify as solar radiation increases and wind speeds decrease through May.

Differences in the timing of springtime stratifica-

tion might impact the zooplankton. Due to the short growing season in the Gulf of Alaska zooplankton such as *Neocalanus* species that hibernate over winter at great depth must awaken and spawn in anticipation of the spring bloom. Properly timed, younger stages in surface waters may increase their weight by up to 10% per day, although this rate declines with development. If feeding early stage *Neocalanus* arrive at the surface prior to the bloom, growth will be slow and mortality will be high. Just such an impact was observed in March 2001 when zooplankton on the mid-shelf arrived prior to stratification and were growing poorly, while animals in Prince William Sound (which stratifies earlier than the shelf) were growing at healthy rates. Thus recruitment success of zooplankton, and by extension salmon, might depend upon physical



processes within the ACC that occur over one or more seasons and which ultimately affect nutrient supply, the onset of stratification in spring, and the timing of the spring bloom.

### Zooplankton Community Structure

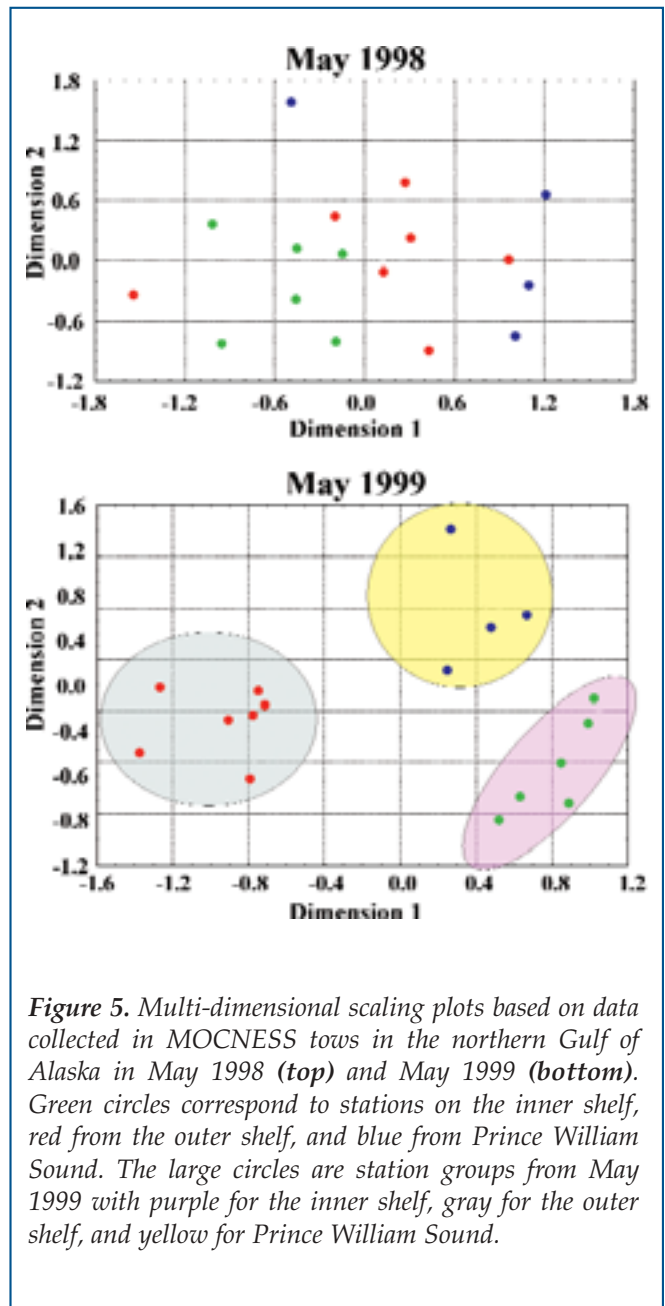
Interannual variability might also be reflected in different community structures. For example, the zooplankton community structure differed between May 1998 and 1999 according to groupings defined by multidimensional scaling based on the taxonomic composition and developmental stage of the most abundant taxa collected (Figure 5). Distinct station groupings were absent in May 1998, suggesting a fairly homogeneous zooplankton community structure on the GOA shelf. In May 1999 distinct zooplankton communities were observed in Prince William Sound, the inner portion of the shelf, and over the outer shelf and slope. A similar pattern emerged in 2000 (not shown). Enhanced ACC transport in 1998 might have increased the flushing rate of near-surface waters in Prince William Sound, thereby washing out endemic species and replacing them with zooplankton from the shelf.

### Phytoplankton Dynamics

Sampling during April, May and July 2001 illustrated the tremendous range in phytoplankton biomass that characterizes the CGOA. In 2001, chlorophyll biomass varied by more than a factor of 20 over spatial scales of 5 to 10 km. As has been observed for other planktonic ecosystems, increases in phytoplankton biomass (blooms) are typically associated with the build-up of large phytoplankton cells (Figure 6a). However, over the mid- and outer shelf episodic blooms of primarily small (<5 μm) phytoplankton cells occur episodically (lower left-hand corner of Figure 6a). These contrasting bloom modes lend further support to the idea that this shelf hosts broadly contrasting biological regimes with the boundary being the mid-shelf region. The reason(s) for the differences in bloom patterns is not clear but one possibility is that iron availability decreases seaward from the coast. Small phytoplankters are less susceptible to iron limitation than the large phytoplankton (Martin et al., 1989; Miller et al., 1991). We expect relatively high iron concentrations in the freshwater runoff and therefore on the inner shelf and the ACC, but relatively low concentrations in GOA basin waters flowing along the continental slope.

### Zooplankton Grazing

Seawater dilution assays confirmed that microzooplankton grazing consumed nearly all production by phytoplankton cells <20 μm (see also Strom et al., 2001). Microzooplankton consumption of large phytoplankton was highly variable, and preliminary observations show corresponding variation in the abundance of large heterotrophic dinoflagellates and ciliates that might be capable of consuming diatoms.



**Figure 5.** Multi-dimensional scaling plots based on data collected in MOCNESS tows in the northern Gulf of Alaska in May 1998 (top) and May 1999 (bottom). Green circles correspond to stations on the inner shelf, red from the outer shelf, and blue from Prince William Sound. The large circles are station groups from May 1999 with purple for the inner shelf, gray for the outer shelf, and yellow for Prince William Sound.

Understanding the source of this variability—food quality, temperature effects, top-down control of protist grazers—will be key to understanding how the transfer of primary production to larger animals is regulated. This transfer is also being examined through studies of egg production and hatching success in dominant copepod taxa (*Pseudocalanus*, *Metridia*, *Calanus*, *Eucalanus*) as a function of diet. It is now appreciated that microzooplankton are likely the dominant consumers of phytoplankton while planktonic copepods prey extensively on these forms. In turn, juvenile salmon prey on larger zooplankton and other species (including forage fishes), as they grow. Understanding these linkages is essential to determining how bottom-up effects might be mediated in this system.

Close coupling between copepods and microzooplankton, with consequent effects on planktonic food web structure, was also demonstrated in grazing experiments conducted and analyzed at sea in 2001 with the FlowCAM (Flow Cytometer and Microscope). This instrument detects particles in a flow chamber based on laser-induced fluorescence or light scattering. Particles in the 11–200  $\mu\text{m}$  size range are counted, their fluorescence and scattering intensity measured, and their image captured with a CCD camera, frame grabber and image processor system (Sieracki et al., 1998). The ability to generate particle size spectra (Figure 6b) and “picture galleries” (Figure 6c) in near real-time was a great help in planning experiments. When coupled with copepod grazing experiments, FlowCAM analysis revealed the targeting by *Neocalanus* and *Pseudocalanus* of particles in specific size ranges (Figures 6d and e). Apparent negative clearance rates on small particles, observed frequently during these experiments, suggest that removal of larger microzooplankton by copepods relieved grazing pressure on smaller cells, allowing them to increase more in the presence of copepods than in control bottles without copepods. Such “trophic cascades”, although hypothesized to be important in aquatic ecosystems, have proven difficult to demonstrate in the marine plankton. If widespread in the CGOA, these cascades indicate that top-down effects could have a large influence on food web structure and function, and a full understanding of climate effects on shelf production will require consideration of such effects.

### Retrospective Analysis

Retrospective studies provide important insights into variability over longer space and time scales than those covered by GLOBEC field programs. Catch data for GOA salmon during the 20<sup>th</sup> Century suggest strong relationships between salmon abundance and climate change as measured by the Pacific Decadal Oscillation (PDO) Index, an integrated measure of sea surface temperature in the North Pacific (Mantua et al., 1997). However, these records are too short to define the persistence and frequency of such relations. Moreover, human activities such as hatchery production, fishing and habitat alteration complicate the identification of climatic effects. To gain a long-term perspective on relationships between GOA salmon abundance and climatic change, retrospective studies were conducted to reconstruct salmon abundance prior to the onset of commercial fishing (ca.1880s). Long-term relationships between sockeye salmon (*Oncorhynchus nerka*) populations and climatic change can be evaluated by analyzing sediment cores from their nursery lakes (Finney et al., 2000). Following 2 to 3 years of feeding in the North Pacific, sockeye salmon return to their natal

lake/stream system to spawn and die (Burgner, 1991). The nutrients derived from spawned carcasses can be significant relative to other sources, and may be reconstructed from palaeolimnological records of  $\delta^{15}\text{N}$  (Finney et al., 2000). Salmon are enriched in  $\delta^{15}\text{N}$  relative to terrestrial nitrogen sources in Alaska. Periods of greater input of salmon-derived nutrients, and hence greater sockeye abundance, correspond to higher sedimentary  $\delta^{15}\text{N}$ .

Reconstructions of salmon abundance over the past 300 years reveal similar patterns for three lakes on Kodiak Island (GOA) (Finney et al., 2000), consistent with the hypothesis of common forcing as a result of climatic change. Regimes of anomalous abundance ( $\delta^{15}\text{N}$  anomalies) over this period occur in an irregular pattern on timescales of 30–100 years. A comparison of the GOA sockeye records to Northeast Pacific sea surface temperature as derived from analysis of coastal tree rings reveals changes at similar times (D’Arrigo et al., 1999). During certain time periods, the pattern observed during the 20<sup>th</sup> Century of higher salmon abundance during warm periods and lower salmon abundance during cooler periods is maintained. However, during the period from approximately 1840–1900, apparently high salmon

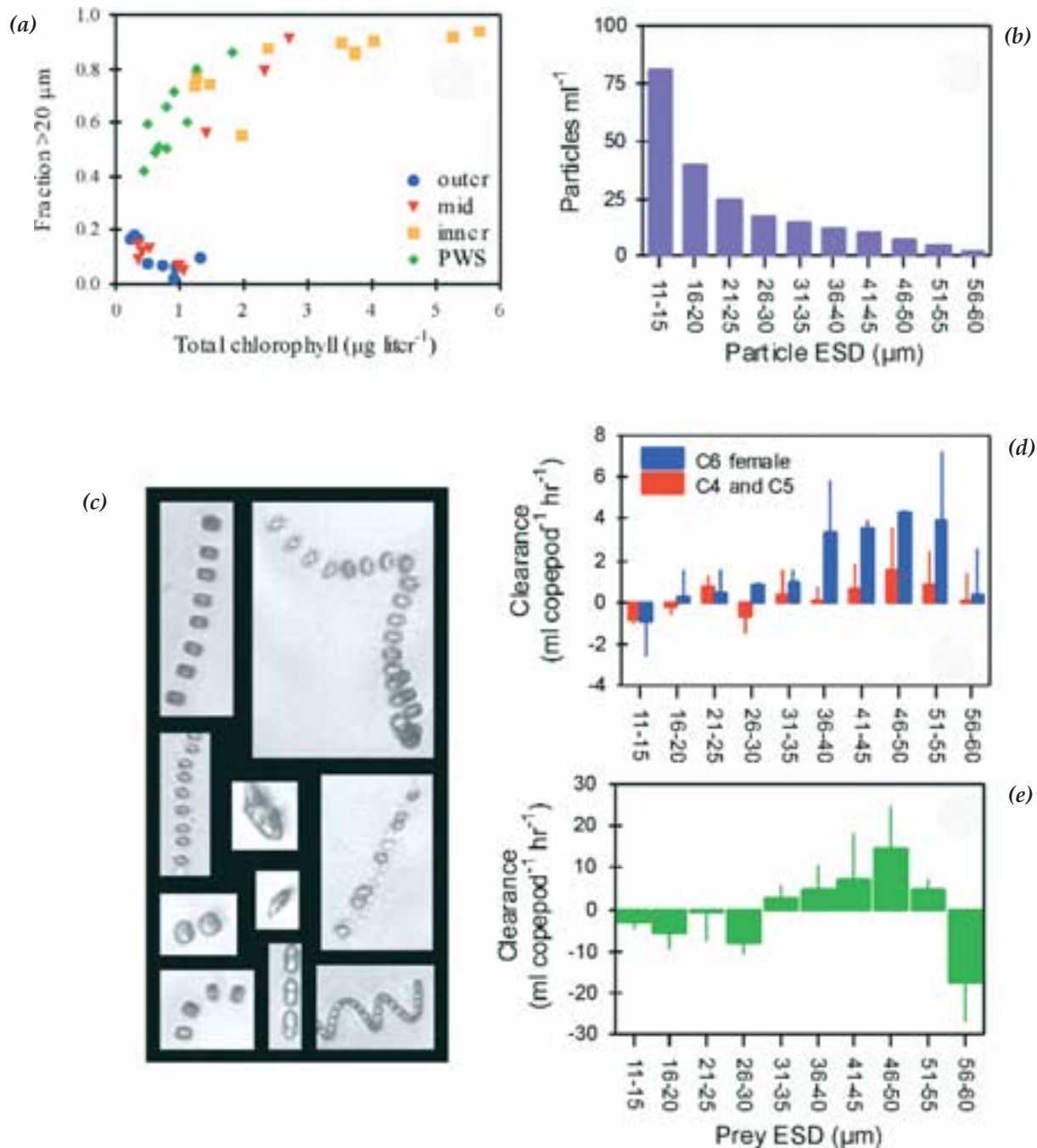
abundance occurred during a period of cool sea surface temperature. Analysis of tree rings from sites along the Northeast Pacific coast reveals two substantial periods over the past 400 years where spatial temperature patterns are not consistent with that of the PDO (Gedalov and Smith, 2000). One such period occurred between 1840 and 1920. This suggests that other modes of climate and ecosystem variability exist than revealed by 20<sup>th</sup> Century data. Although the reconstruction of long term abundance is only possible for salmon species such as sockeye that utilize freshwater lake habitats, historical records suggest that Kodiak sockeye abundance patterns are similar to those of GOA pink salmon and other salmon species.

In other retrospective analyses, Doyle et al. (in press) analyzed a 20-year time series of springtime oceanographic and ichthyoplankton data collected by the Alaska Fisheries Science Center in the northern GOA. The observed shallow to deep-water gradient in species occurrence and abundance reflects the habitat preference and spawning location of adult fish. At finer scales variations in this primary assemblage structure seems related to the local bathymetry and the prevailing current patterns. They also show that interannual variations in GOA larval fish densities exhibit long-term trends in species abundances similar to those reported by Anderson and Piatt (1999) for older age classes. In another study Bailey and Picquelle (in press) found that enhanced onshore larval transport might contribute to strong year-classes of Pacific halibut. Both

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*Catch data for GOA salmon during the 20<sup>th</sup> Century suggest strong relationships between salmon abundance and climate change*

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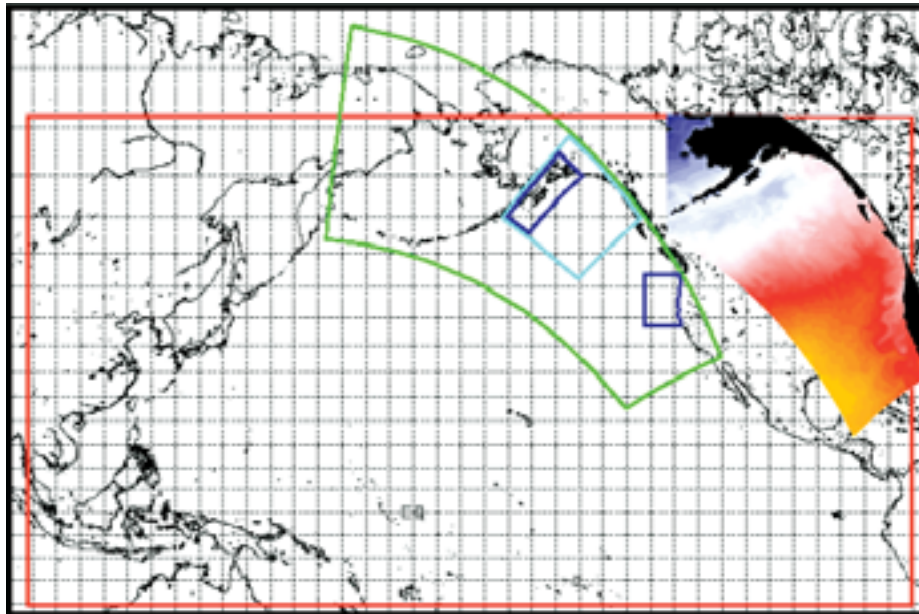


**Figure 6.** **a)** Total chlorophyll versus the fraction of total in cells  $>20 \mu\text{m}$  for the CGOA during April, May and July 2001, **b)** size spectrum (as equivalent spherical diameter, ESD) of particles in the phytoplankton bloom (total chlorophyll =  $5.3 \mu\text{g/liter}$ , 92%  $>20 \mu\text{m}$ ), **c)** Representative FlowCAM images from the bloom. The dominant diatom was *Thalassiosira* sp.; central image is *Gyrodinium* sp., a large heterotrophic dinoflagellates, **d)** and **e)** Size spectra of clearance rates (mean  $\pm 1$  sd) for copepod grazers *Pseudocalanus* **d)** and *Neocalanus* **e)**. Note the increase in clearance rates for larger-bodied stages and taxa, as well as the generally elevated clearance rates on 36 to 55  $\mu\text{m}$  particles. Negative clearance rates on smaller particles are interpreted as evidence for a trophic cascade involving top-down control of large microzooplankton grazers by copepods (see text).

studies suggest that interannual changes in plankton transport processes in the GOA might have a significant effect on the distributions and survival of fish larvae, some of which serve as prey for juvenile salmon.

## Models

Coupled biophysical models are being developed in order to understand and to predict how the CCS and CGOA ecosystems respond to climate variability. Results from the field and retrospective studies have



*Figure 7. The nested model domains that are currently in development for NEP-GLOBEC. The grid sizes are 20–40 km for the global grid (red), 10 km for the regional grid (green) and 3 km (light blue) and 1–2 km for the local grids (dark blue). The inset is the NEP-model temperature fields at 10 m depth for September 18, 2001.*

guided model development, and will be used to evaluate model performance using hindcasting studies and, eventually, data assimilative simulations. In addition, the models serve as useful interpretive tools in several ways with respect to the observations, which are limited both in space and time. The models are being used to examine

- 1) Interannual-to-decadal scale changes in the circulation, hydrography, and lower trophic level dynamics in the CGOA;
- 2) Differences in along- and cross-shelf transport as a function of location;
- 3) Spatial variation in tidal effects on mesoscale physical and biological properties; and
- 4) Effects of remote ocean forcing on CGOA ecosystem variability.

With these aims in mind we are developing a suite of nested physical and biological models (see article by Mantua et al., this issue).

### Numerical Hydrodynamic Models

The initial regional physical model of the CGOA and adjacent basin (henceforth referred to as GOA-1) was based on the S-Coordinate Rutgers University Model (SCRUM; Song and Haidvogel, 1994). More recently, we have reconfigured the modeling system so that each of the nested physical models is based on the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Hermann et al., in press).

The initial set of nested physical models included global, basin-scale, and regional grids (Figure 7), with the larger-scale models providing barotropic tidal and subtidal velocity information to the regional scale model. The global circulation model is driven by glob-

al winds. The regional physical model of the CGOA and adjacent basin (GOA-1) was configured with approximately 22 km resolution and 20 vertical levels on a telescoped grid and forced by monthly fields of runoff, daily heat fluxes, and daily wind stresses appropriate to specific years. We are now developing a new nested system at higher spatial resolution so that the new basin-scale model (NEP), extending from Baja California through the Bering Sea, will have 10 km resolution, and the regional CGOA model (GOA-2) will have a spatial resolution of 3 km.

The velocity and thermohaline fields of both the boundary currents and the ACC are easily identified in both the GOA-1 and NEP regional models (Figure 8). The models also indicate a summer weakening/reversal of the coastal current in the eastern CGOA, consistent with inferences based on altimeter data (Strub and James, in press). Interannual differences were evident among the years simulated with GOA-1; for instance, spring 1997 exhibited significantly higher sea surface temperature than spring 1995. Preliminary comparisons of a NEP hindcast with current meter data for 2001 along the Seward Line suggest a stronger correspondence between model and data in the fall (when the ACC is strongest), than in the summer (when the ACC is weak). The models are also capturing the substantial gradients in tidal energy, consistent with purely tidal models for this region (Foreman et al., 2000) across the northwestern shelf. These gradients might establish important biological gradients insofar as the NPZ model suggests that enhanced tidal mixing can substantially increase biological production.

Both the GOA-1 and NEP models also capture the large 200 km scale variability observed in the Gulf by

AVHRR imagery (Thomson and Gower, 1998) and altimeter data (Crawford and Whitney, 1999; Crawford et al., 2000), especially in Southeast Alaska where the isobaths veer northwestward. The models indicate that this eddy activity migrates slowly offshore from spring through winter.

### Coupled Biophysical Models

The physical modeling activity is also shedding light on biologically important aspects of the CGOA. Critical issues here include the source of zooplankton and nutrients for the shelf. Cooney (1986) suggested that, upon emergence from diapause, deep ocean zooplankton could be transferred by onshore surface Ekman transport onto the inner shelf, where they become an important component in juvenile salmon

diets. By seeding the model with “numerical floats” throughout the CGOA, we find that zooplankton over the slope and in the upper 5 m can indeed be transferred into the ACC (Stabeno et al., submitted). However, at greater depths (>40 m) the onshore transport is much weaker because the flow is steered alongshore by topographic influences. The model results further suggest that nutrients in the upper layer can also be supplied from offshore to the inner shelf by wind-driven cross-shelf transport, especially in fall and winter when the winds are strong and phytoplankton consumption of near-surface nutrients is negligible. The float studies also indicate the important role that alongshore advection plays in the CGOA. We find that the onshore flow preferentially occurs in the northeastern gulf (east of the CGOA study region) before the Alaska Current trans-

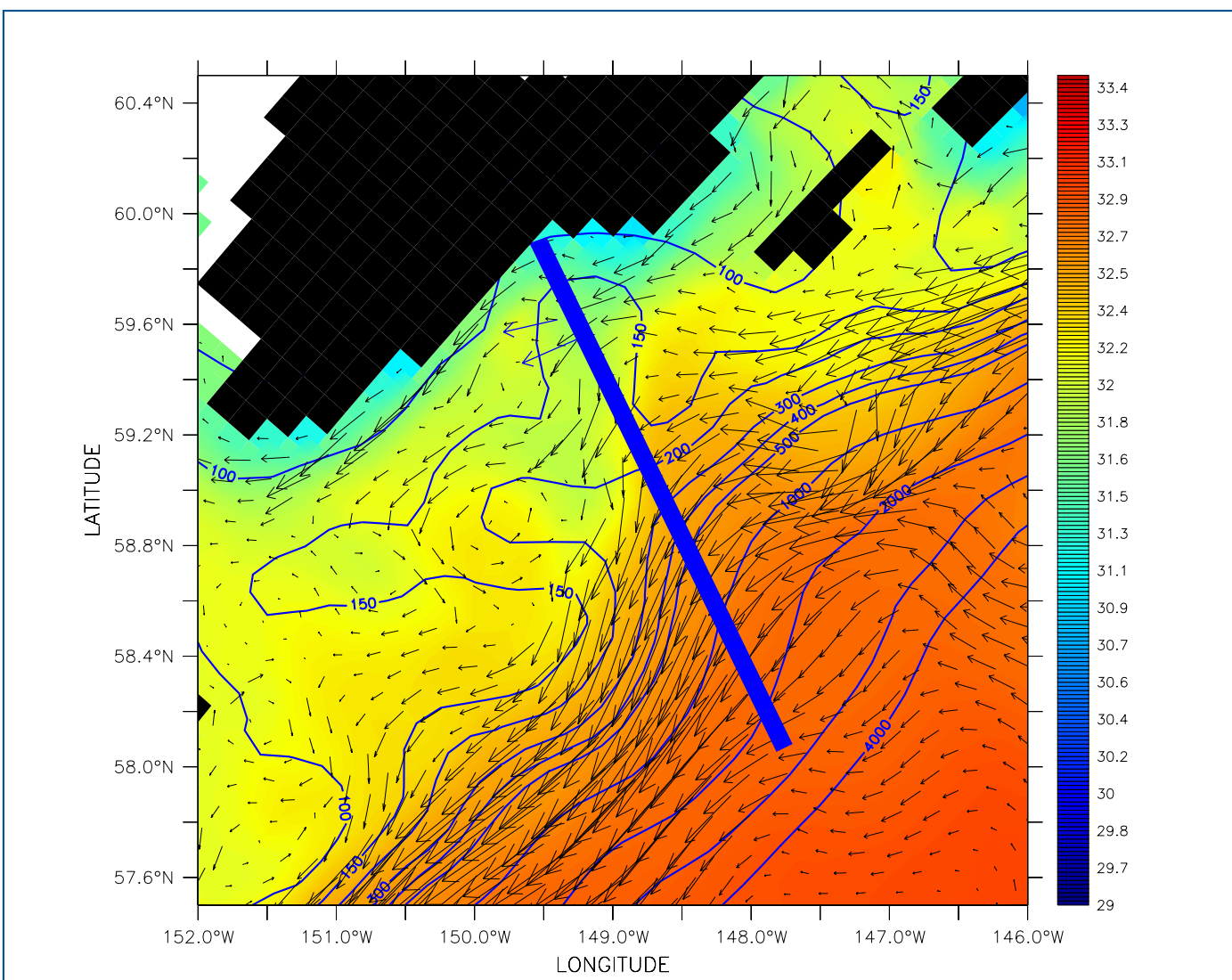


Figure 8. Detail from NEP model hindcast for September 18, 2001, showing salinity and velocity at 40 m depth in the vicinity of the GAK line. The Seward Line is the thick blue line. Measured velocities from current meter moorings and interpolated to 40 m depth are shown as blue vectors.

forms into the Alaskan Stream. Once onshore, the floats move alongshore within the ACC. These results suggest that variations in the velocity and density structure of the boundary currents (in conjunction with regional variations in the winds) are important in controlling shelf-basin exchange processes.

The CGOA NPZ model is being used to explore the biological sensitivity of this ecosystem to physical forcing. The results will be of particular value in understanding how environmental or biological variations affect the trophic structure and food availability for fish. The NPZ model was initially constructed to run as a one-dimensional model but recently was expanded to utilize the three dimensional circulation and thermohaline fields produced by the physical models. The CGOA NPZ model consists of twelve compartments. Nitrogen is modeled as both nitrate and ammonium to determine the proportion of new versus recycled production and the effects of nitrogen source on the zooplankton community. The phytoplankton community consists of two size fractions that differ in their use of nitrate vs. ammonium, and which can support different herbivore species complexes. The microzooplankton community includes small heterotrophic nanoflagellates, ciliates, medium sized dinoflagellates, and large heterotrophic dinoflagellates, because these groups are important components of the GOA coastal and oceanic ecosystems. Small copepods are represented by *Pseudocalanus* species and larger zooplankton are represented by *Neocalanus* species and euphausiids (*Euphausia pacifica*). A detrital component completes the model.

A typical run of the one-dimensional model illustrates the seasonal evolution of the lower trophic levels. The large-phytoplankton bloom occurs first in spring followed by the small-phytoplankton bloom. The temporal difference between these blooms occurs because the larger phytoplankton grow at lower temperatures, but are sensitive to nutrient depletion, whereas the small phytoplankton grow better under warmer temperatures and are less sensitive to low nutrient concentrations. Following the small-phytoplankton bloom, surface nutrients are depleted as observed (Childress, 2001; Napp et al., 1996). The evolution of these phytoplankton blooms affects seasonal transitions in the zooplankton community. Initially, heterotrophic dinoflagellates have higher densities than ciliates because the dinoflagellates consume both large and small phytoplankton. *Neocalanus* species increase through early summer but then decrease as they enter diapause. Euphausiid concentrations increase gradually from spring through late summer.

## Preliminary Conclusions and Future Directions

The CGOA-GLOBEC field program has occurred during a period of strong contrasts in physical and biological conditions related to the 1997–98 El Niño and

the 1998–99 La Niña events. The strong seasonality and distinct phasing of wind and runoff in this region, with their apparent effects on the oceanographic environment and biota, indicate a system highly susceptible to climate variability. We have also begun to recognize and better define what appear to be distinct bio-physical regimes on the CGOA shelf. While these different shelf domains must be linked to one another, we do not yet understand the nature of these connections, how they are brought about, and how they vary in time. The field, retrospective, and modeling components all indicate that there is considerable mesoscale variability within each regime that might exert important influences on species distribution and production. A further challenge is to understand how the time scales that govern physical forcing are linked to the apparently disparate time scales that govern biological production.

Among the key questions and results thus far in the CGOA-GLOBEC program are:

1) What are the mechanisms by which nutrients are supplied to the inner shelf? Are they advected across the shelf within the surface layers by the wind-driven Ekman transport, supplied at depth in summer and then mixed into the surface layers in winter, or are they preferentially channeled inshore and vertically through interactions between the bottom topography and the alongshore flow? Observations and modeling indicate that there might be preferred sites for onshelf transport of nutrients and zooplankton, some occurring upstream (east) of the GLOBEC CGOA study area. If this proves to be the case, it suggests that alongshore advection is important in influencing “downstream” productivity at all trophic levels on this shelf. Modeling exercises also indicate that gradients in tidal energy dissipation might also strongly influence spatial patterns shelf productivity.

2) How does the timing of juvenile salmon outmigration and their distribution on the shelf contribute to recruitment success in the CGOA? Juvenile pink salmon are generally most abundant within the ACC although it is not yet clear if this current is simply serving as a migratory corridor for these fish or if it provides a critical habitat in terms of both prey type and abundance. Further, the timing of juvenile pink salmon entry onto the shelf (August and September) is offset by several months from the spring phytoplankton bloom and zooplankton biomass peak (April and May). Is spring production retained within the system in some form that fuels late summer salmon growth or does this growth depend upon late summer primary and secondary production? If the latter proves to be the case then what are the physical and biological mechanisms that support biological production in summer?

3) How do the magnitude, timing and modes of the spring bloom(s) vary from year to year, and what impact do variations in rates and timing of these blooms have on zooplankton and salmon success? We have been struck by the complexity inherent in the

development of stratification in the spring and the different ways that freshwater and solar heating might bring about stratification. In this regard, springtime stratification develops as a consequence of three-dimensional circulation processes and probably does not develop uniformly in time and space over the GOA shelf. Such complexity is likely to directly influence planktonic community size structure, species composition, and function.

4) Retrospective studies are showing that the 20<sup>th</sup> Century pattern of higher salmon abundance during warm periods in the North Pacific Ocean and lower salmon abundance during cooler periods does not appear to have consistently held prior to 1900. This suggests that other modes of climate and ecosystem variability exist than revealed by 20<sup>th</sup> Century data. How do these modes of variability arise, and what is their effect on the CGOA ecosystem?

These are among the many critical issues that are being addressed by the CGOA-GLOBEC program. The answers will enable us to compare the CGOA and the CCS ecosystems, to identify efficient strategies by which to monitor long-term variability in these ecosystems, and to develop ecosystem models with a prognostic capability.

This is U.S. GLOBEC contribution Number 233. 

## Websites

Several websites are available that provide additional information on the NEP and CGOA-GLOBEC program. These serve to communicate the activities and results of this program to the scientific community and to the public at large. An overview of the NEP-GLOBEC program is at <http://globec.oce.orst.edu/groups/nep/index.html>. Material pertaining to modeling is at: <http://www.pmel.noaa.gov/~dobbins/nep.html>; <http://www.pmel.noaa.gov/~hermann/globec-2001/ms.pdf>. Further information on the LTOP program is at: <http://murphydome.ims.uaf.edu:8000/globec/intro/> and information related to the long-term time series at station GAK1 on the Seward Line is at: <http://www.ims.uaf.edu/gak1/>. Additional websites are under construction and can be found in the future through links with those listed.

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