Surface nutrients over the central Gulf of Alaska shelf in summer: Final report for project 030654 and 040654

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INTRODUCTION

The basic supplier of energy to a complicated ecosystem, such as the one found in the northern Gulf of Alaska (GOA), is the physical mechanism that governs the availability of food to the lowest trophic levels. If conditions of physical mixing, nutrient flux, or light availability change primary production or the timing and composition of the primary producers, the entire food web structure can be affected (Napp *et al.* 1996). For example, a climate-induced loss of nutrients and primary production along the west coast was thought to impact fish survival (Welch *et al.* 2000). In the northern GOA, strong evidence suggests that significant changes in fish abundance and composition are associated with environmental shifts (Merrick 1995; Shima 1996; Mueter 1999; Hollowed and Wooster 1995; Hollowed *et al.* 2001).

Approximately 600 million hatchery-reared and wild pink salmon (*Oncorynchus gorbuscha*) enter Prince William Sound (PWS) each year. Their entrance to salt water is timed to coincide with peaks in *Neocalanus* abundance in PWS (Cooney, et al., 2001). In summer, many of the juveniles begin to move out of PWS and are found in the Alaska Coastal Current (ACC) and across the middle shelf of the GOA; maximum numbers are observed on the Seward Line (also referred to as the GAK Line, Fig. 1) in August and September. Their survival rate is dependent on the extent of predation (top-down control) and prey availability (bottom-up control) in each of these regions (PWS, ACC, and the middle shelf).

To understand better how variations in atmospheric forcing and ocean conditions impact lower trophic levels of the ecosystem (bottom-up control), we collected physical, chemical and biological data from moorings, underway mapping systems, and hydrographic surveys as part of the Global Ocean Ecosystem Dynamics (GLOBEC) program, the Gulf Ecosystem Monitoring (GEM) program, the Fisheries-Oceanography Coordinated Investigations (FOCI) program, and the Steller Sea Lion program. Data from these programs are now being synthesized in an effort to address the following overarching hypotheses:

Summer phytoplankton and zooplankton production are crucial to sustaining food webs that support juvenile pink salmon over the GOA shelf, and there is substantial interannual variation in this lower-trophic level production, which can be attributed to the physical forcing.

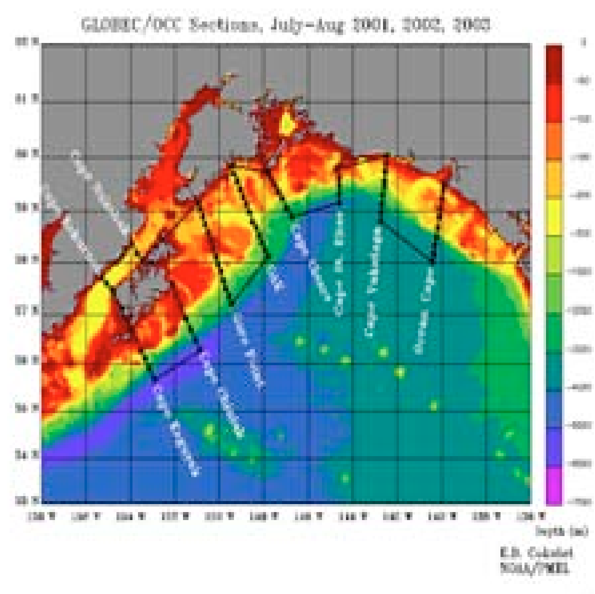

Figure 1. Study area and location of cross-shelf CTD transects.

The primary objective of the GEM component of this research was to map surface nutrients across the northern and central GOA as part of the large-scale Ocean Carrying Capacity/GLOBEC (OCC/GLOBEC) juvenile salmon survey in summer of 2003 and autumn 2004. These data sets, in conjunction with data from moored instruments deployed in 2002 and 2003, were used to better understand horizontal, vertical and temporal variability of summertime nitrate concentrations in the GOA.

METHODS

Hydrography / Underway measurements

Hydrographic transects across the GOA from Kodiak Island to Yakutat Bay were undertaken in July and August of 2002 (on the F/V *Great Pacific*) and 2003 (on the NOAA ship *Miller Freeman*). In 2004, the OCC-GLOBEC survey on the *Great Pacific* was moved to autumn, and due to bad weather, only a partial survey was completed. During the 2002 cruise, 83 CTD (conductivity, temperature, and depth) and fluorescence casts were taken using a Sea-Bird SBE-19, sampling the cross-shelf transect lines shown in Fig. 1. These same transects were again occupied during the 2003 cruise, when 98 CTD casts were taken with a Sea-Bird SBE-911 Plus system. In 2004, 29 CTD stations were completed using a Sea-Bird SBE-25.

An underway instrument suite was deployed during the OCC/GLOBEC juvenile salmon surveys in 2001-2004, consisting of a thermosalinograph and fluorometer measuring pumped water from the ship's sea chest. Here we will only discuss the underway data from 2003 and 2004 when an EnviroTech NAS-2E nitrate meter was added to this instrument suite. Discrete water samples were collected from Niskin bottles on the CTD-rosette for calibrating the CTD and fluorometer, and from the underway system for calibrating the underway instruments.

Moorings

As part of the GLOBEC program, a surface mooring was deployed at GB3 in the Gulf of Alaska on the Seward Line at GAK45, (location shown in Fig. 3). A NAS-2E nitrate meter was mounted at 16 meters below the surface with a Sea-Bird SeaCat (temperature, salinity, and fluorescence) mounted above (at 15 m) and an Aanderaa RCM-9 current meter mounted below (at 21 m in 2002 and 18 m in 2003). In 2002, the RCM-9 failed, but current measurements were available from an upward looking Acoustic Doppler Current Profiler (ADCP) moored 10 m off the bottom at an adjacent mooring. Although there was a meteorological package on the surface buoy, these instruments failed in 2002. For proper comparison, National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project winds at 10 m were interpolated to the mooring location. NCEP Reanalysis data was provided by the NOAA-CIRES ESRL/PSD Climate Diagnostics branch, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/, (Kalnay, et al., 1996).

Nutrients

The NAS-2E nitrate meter was installed as part of the underway instrument suite and on moorings in the GOA. This instrument uses standard wet chemistry techniques for measuring nitrate. The sample is passed through a column filled with copperized Cd-Ag wire where nitrate is reduced to nitrite. The nitrite is formed into a red azo dye by complexing with sulfanilamide and N-1-naphthylethylenediamine, and the absorbance of the complexed nitrite is measured spectrophotometrically. The underway nitrate meters were configured to sample about every 30 minutes and standards were analyzed every 4th sample (2003) or with every sample (2004). For the moored nitrate meters, seawater samples and calibration standards were analyzed at 6-hr intervals. In both modes, blanks were analyzed prior to each measurement, and consisted of measuring the absorbance of a standard or sample without reagents. Working standards were made in low-nutrient seawater (LNSW) with a known nitrate concentration and stabilized by pasteurization at 80°C for 6 hours according to Aminot and Kérouel (1998). To verify stability, standards were analyzed before mooring deployment and again after mooring recovery, and were typically found to be within 0.2 μM nitrate. Because the NAS-2E does not include separate measurements for nitrate and nitrite, results from these instruments are reported as nitrate+nitrite, (N+N).

Discrete nutrient samples were frozen at –20°C, and analyzed at PMEL within 8 months after collection. Samples were thawed in a cool water bath and immediately analyzed. Analytical methods were from Armstrong et al. (1967) and Atlas et al. (1971). Standardization and analysis procedures specified by Gordon et al. (1993) were closely followed including calibration of labware, preparation of primary and secondary standards, and corrections for blanks and refractive index.

RESULTS

Data from the 2002 and 2003 GB3 moorings appear in Fig. 2 along with interpolated NCEP winds (at 10 m). In both years, September was a period with increased storm activity (more frequent winds with speeds of 10 m s^{-1}). However, at the 95% confidence level, there was no significant difference between the 2002 and 2003 mean summertime (June 1 to September 15)

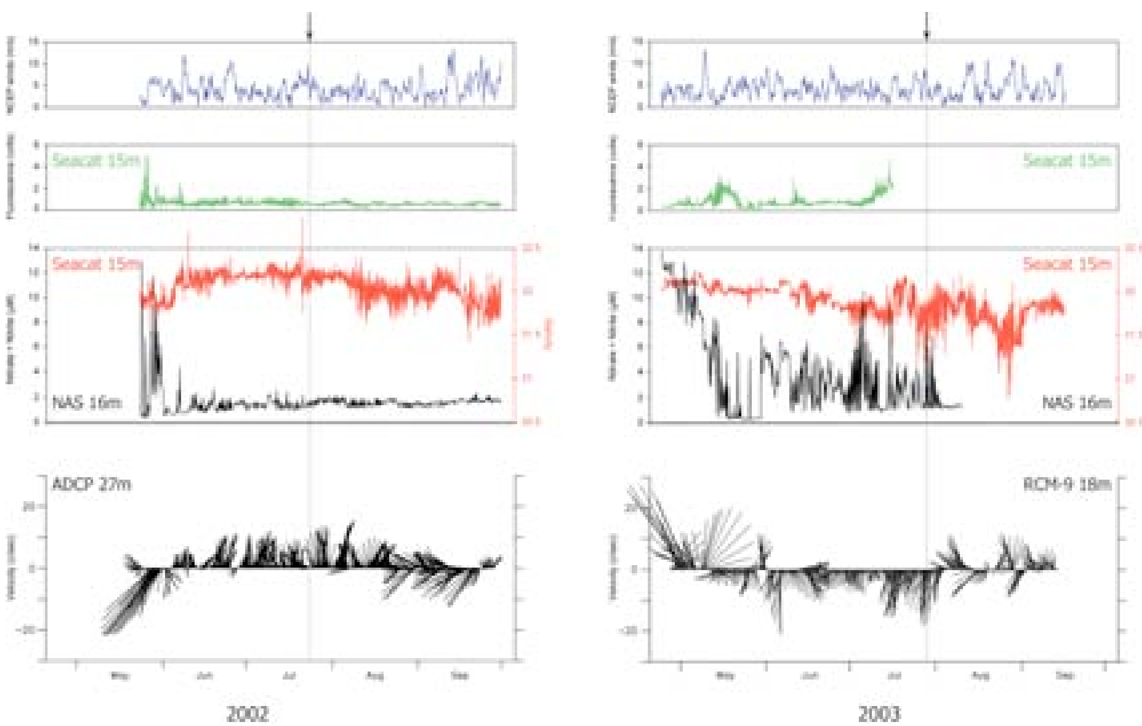

Figure 2. NCEP wind speed (blue) and results from surface moorings at GB3 in 2002 (left) and

2003 (right). Mooring results include chlorophyll fluorescence (green), salinity (red), nitrate+nitrite (black line) and current velocity vectors, (up is north). Vertical lines indicate the time of closest CTDs conducted on the OCC-GLOBEC survey cruises.

NCEP wind speed, nor was there a significant difference in the eastward- (or upwelling) component of the winds (-1.1 ± 0.2 m s^{-1} in 2002; -1.2 ± 0.2 m s^{-1} in 2003). Nonetheless, nearsurface oceanic flow at GB3, as determined by the moored current meters, varied seasonally and, in general, the direction of flow was opposite in 2002 and 2003 (Fig. 2, Table 1). In mid-summer, flow at GB3 was onshore in 2002 and offshore in 2003. Such seasonal and interannual variability of flow in the upper water column at GB3 may have resulted from variability in the strength and location of a shelf eddy/meander. In 2002, when more onshore flow dominated in mid-summer, there was relatively little variance in near-surface salinity, and N+N concentrations remained low. As a result of more offshore flow in mid-summer of 2003, fresher water from the ACC was evident in the salinity time series, and associated with this fresher offshore flow were relatively higher concentrations of subsurface N+N.

Table 1: Direction of near-surface flow in 2002 and 2003 at GB3

	2002	2003
Late Spring	Offshore	Onshore
Early to mid summer	Onshore	Offshore
Late summer	Offshore	Onshore

In general, surface maps show higher salinities over the slope and basin (~32-33 psu) and lower salinities over the shelf (20-32 psu) owing to freshwater dilution from the ACC (Fig. 3; fresher water in Shelikof Strait was a result of input from Cook Inlet). There were significant differences in the salinity maps between 2002 and 2003. In 2002, fresher water of the ACC was narrowly confined along the Seward Line in mid-summer when there was strong onshore surface flow. In 2003, offshore flow in mid-summer extended the influence of the ACC to GB3 as evidenced by fresher water on the Seward Line (Figs. 2 and 3). Opposite trends were observed along the Gore Point line where fresher water extended further offshore in 2002.

Vertical sections of sigma-t were also used to examine the seaward influence of the ACC along the Seward Line and to examine the depth of the mixed layer near the mooring (Fig. 3). In 2002, low salinity and a strong horizontal salinity gradient extended about 35 km offshore. In 2003 the same feature extended about 50 km offshore. At this time of the summer, the mixed layer depths at the mooring location were relatively shallow (< 10m); however, in 2002 the moored sensors at 15-16 m were in water that was more thermally stratified compared to 2003 when fresher water of the ACC was more prevalent at those depths.

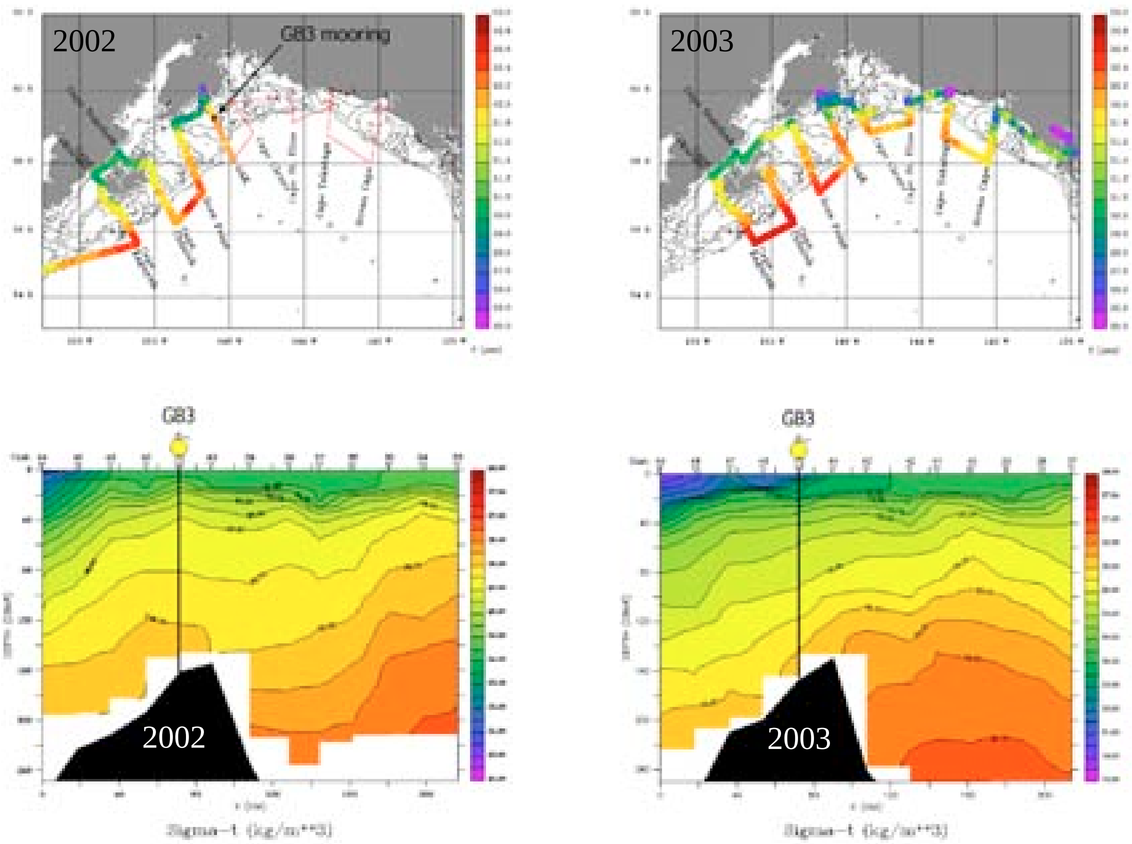

Figure 3. Underway maps of salinity (top) and vertical sections of sigma-t along the Seward Line (bottom) in 2002 (left) and 2003 (right). The instrument failed during the eastern portion of the survey in 2002; therefore, underway salinities along the Seward (GAK) line in 2002 were taken from the CTD casts. The **X** indicates the mooring location of GB3, and the vertical line in the lower panels indicates the mooring location of GB3.

Surface maps of chlorophyll show significant differences in its distribution in 2002 and 2003 (Fig. 4). In 2002, chlorophyll levels were higher in the eastern GOA, with the highest values generally found near the slope. This was counter to a 5 year satellite composite showing a strong chlorophyll front near the Gore Point Line with highest concentrations to the west (Stabeno et al., 2004). In 2003 the highest chlorophyll levels were found around the banks and troughs surrounding Kodiak Island, and especially over Portlock Bank suggesting nutrient replenishment subsequent to the spring bloom (discussed below).

Along the Seward Line, vertical sections show large differences in the magnitude of the sub-surface chlorophyll maximum (Fig. 4). In 2002, concentrations in the chlorophyll maximum were much lower and dispersed compared to 2003 when the sub-surface fluorescence was a strong band extending over much of the transect.

These observations are consistent with those from the time series at GB3. In 2002, the fluorescence signal at 15 m shows a nearly uniform, very low level of fluorescence throughout the summer. Likewise, the concentration of nitrate remains low for the entire summer, and salinities remain uniform indicating that the low levels of chlorophyll are probably the result of low levels of nitrate in the water. During the following year, 2003, there were pulses of nutrients concurrent with the influx of fresher water, and a concomitant increase in fluorescence suggesting the fresher water is bringing with it replenishing nutrients, enhancing the growth of the phytoplankton. This is counter of our current understanding of the relationship between nutrients and fresh water (Stabeno, et al., 2004).

Along the Gore Point Line, surface chlorophyll maps in the summer of 2002 and 2003 show higher chlorophyll over the area of Portlock Bank (Fig. 5a&b). Vertical sections along the Gore Point line show evidence of deep tidal mixing (breakdown of stratification), enrichment of nitrate, and plumes of chlorophyll extending from Portlock Bank. Hence, tidal mixing over shallow banks is a mechanism that provides for the injection of nutrients and sustaining new production throughout the summer.

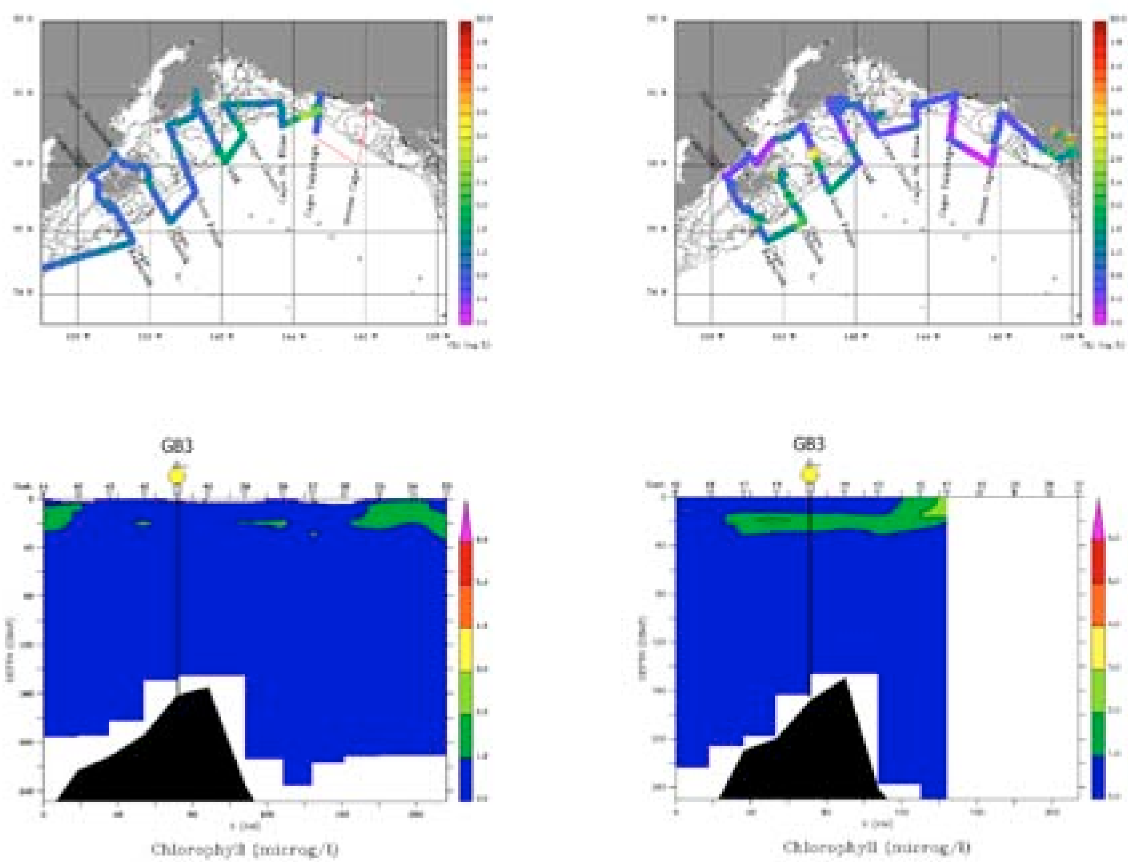

Figure 4. Underway maps (top) and vertical sections along the Seward Line (bottom) of chlorophyll concentration in 2002 (left) and 2003 (right)

The surface nitrate map in 2003 shows very low concentrations (at 5 m) over the shelf, but higher concentrations off of Kodiak Island (Fig. 6a). Most surprising were the low concentrations over Portlock Bank. A vertical section from 2002 found 5-10 μM surface nitrate in the vicinity of the bank (Fig. 5a), but higher concentrations were not observed during the summer of 2003 in this study. Higher concentrations were observed at the shelf break where phytoplankton growth is thought to be more iron limited, and nutrient concentrations more plentiful (Strom et al, 2006). A similar map for 2004 is inconclusive due to instrument failure during the portion of the cruise over Portlock Bank (Fig. 6b).

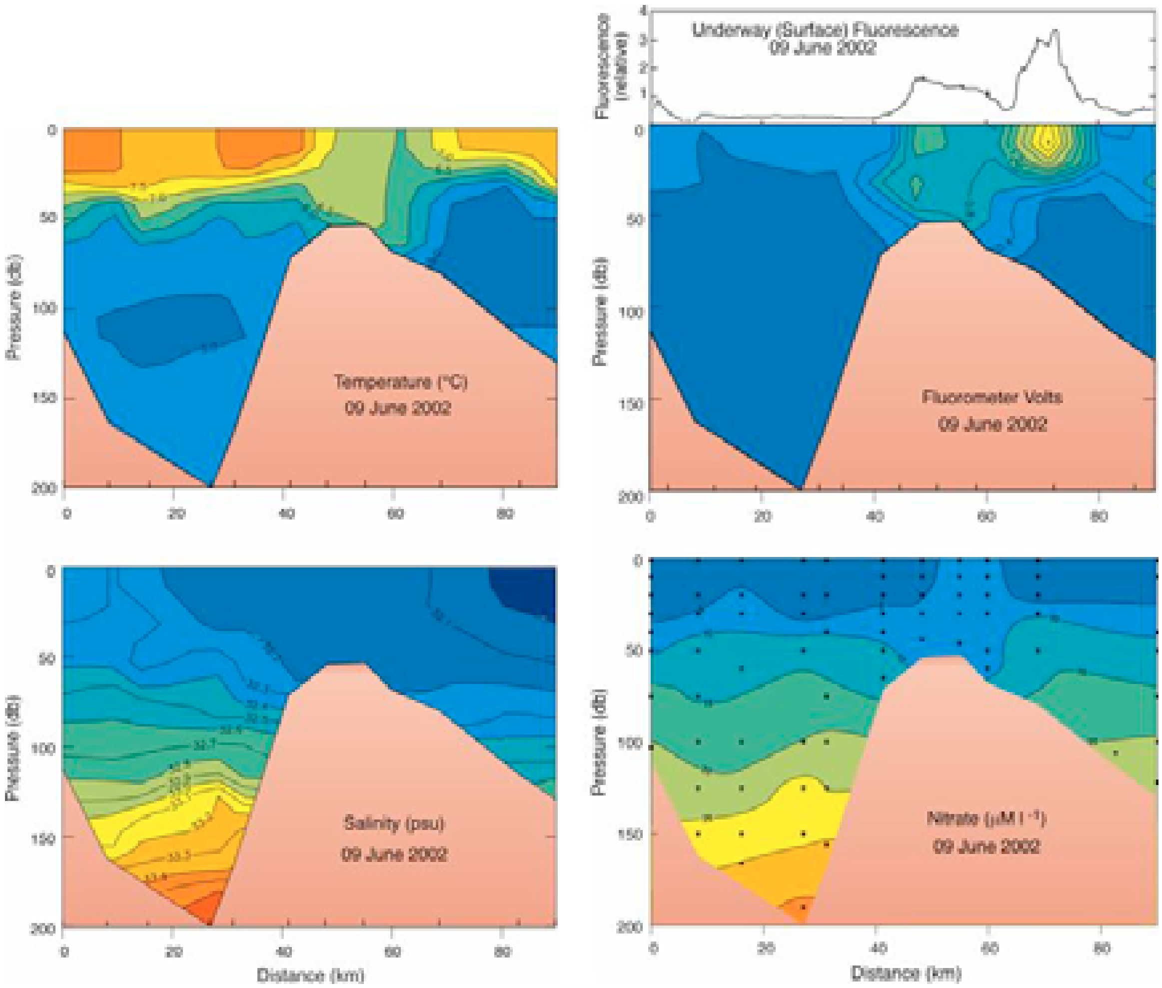

Figure 5a. Vertical sections along the Gore Point Line and over Portlock Bank on June 9, 2002

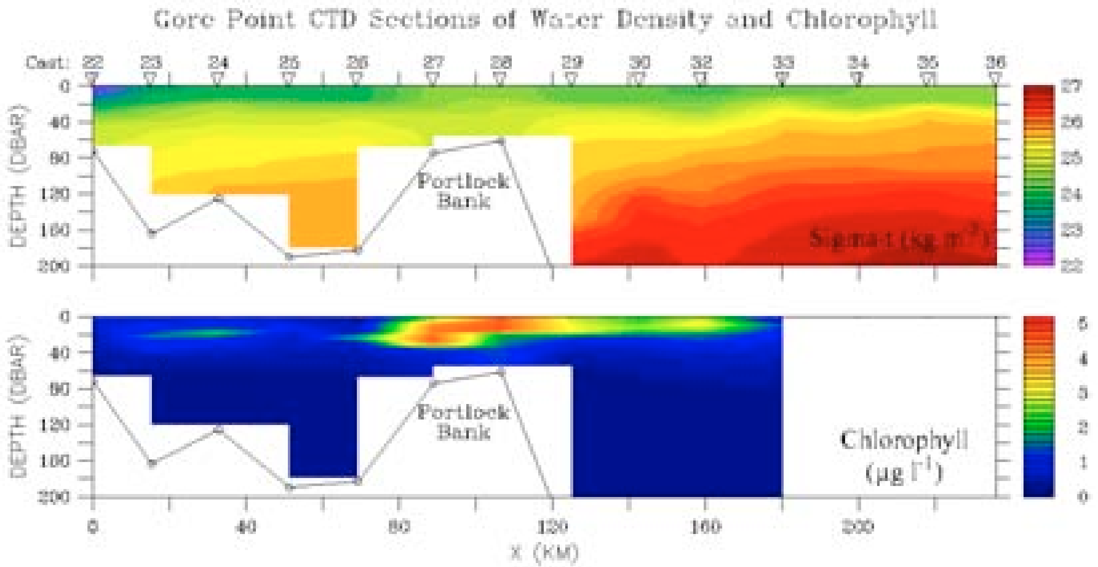

Figure 5b. Vertical sections along the Gore point line and over Portlock Bank in 2003

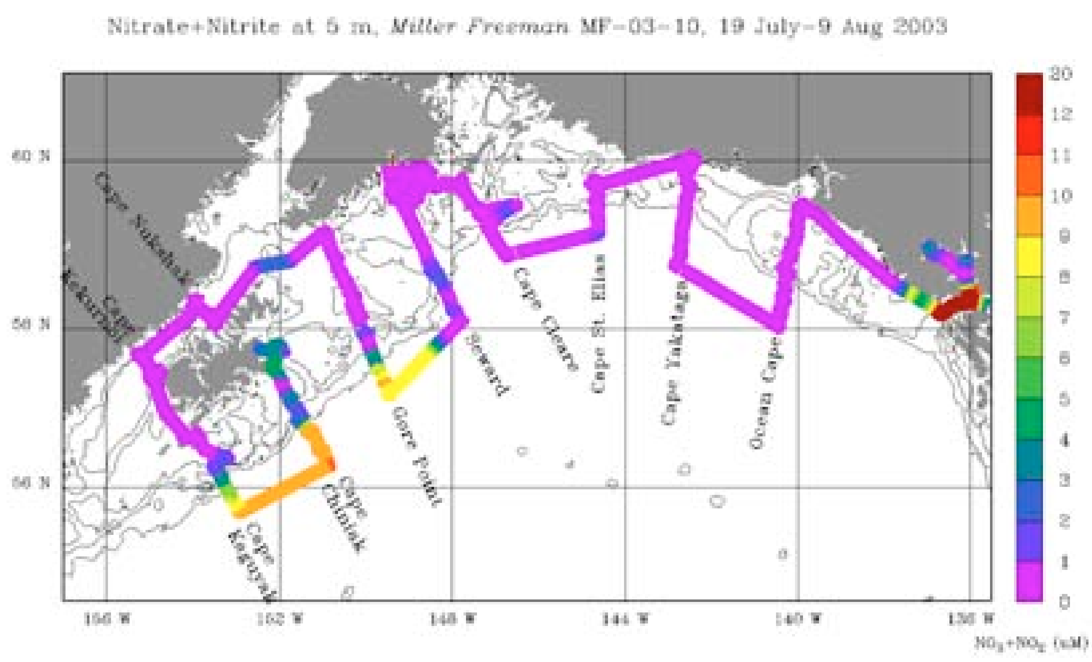

Figure 6a. Underway surface nutrients (N+N) from NAS-2E instrument installed in 2003 onboard the *Miller Freeman* at ~5m.

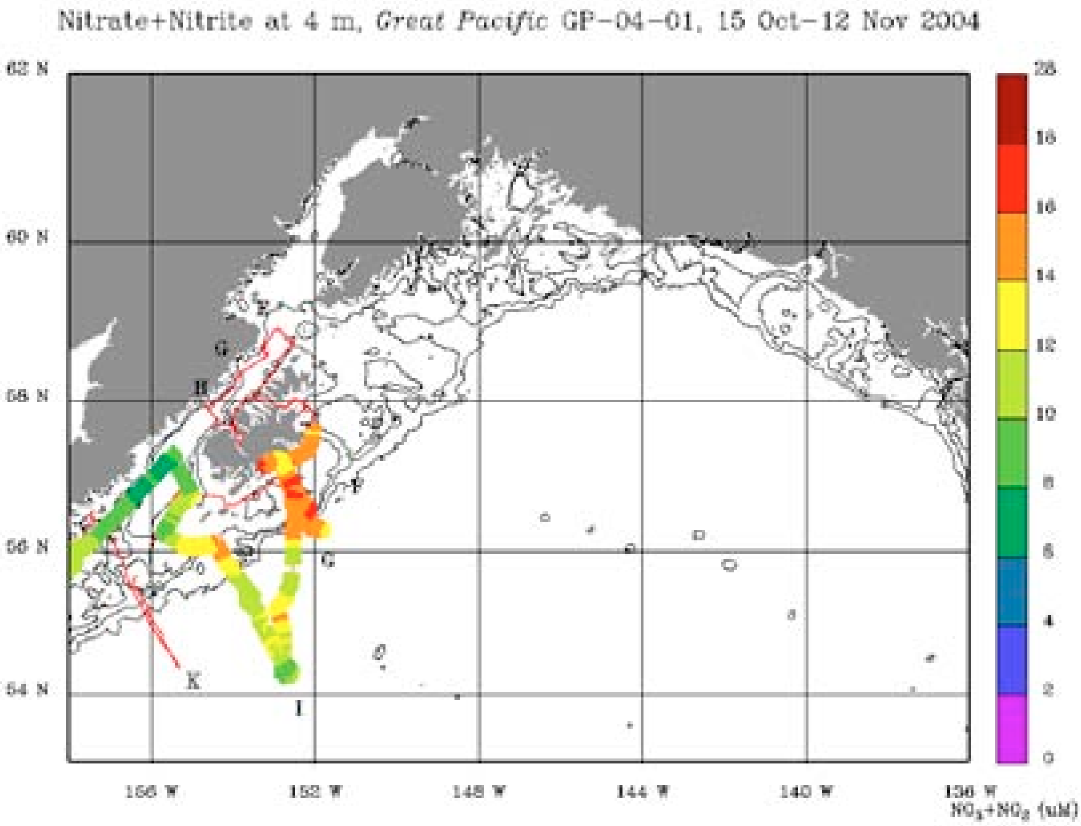

Figure 6b. Underway surface nutrients (N+N) from NAS-2E instrument installed in 2004 onboard the *Great Pacific* at ~4m.

DISCUSSION

Nutrient and Chlorophyll Distributions in the Gulf of Alaska

During winter, nutrients are introduced to the shelf from the basin to support the spring bloom. During summer, nutrients are introduced to the shelf through a variety of on-shelf mechanisms discussed above and in Stabeno *et al.* 2004. Wind mixing introduces nutrients to the euphotic zone over the whole shelf. Tidal mixing erodes summer water-column stratification from below, enhancing surface nutrients, especially over the banks. The asymmetry of mixing on the flood and ebb tides in canyons plays a role in mixing nutrients (Stabeno *et al.* 2005, Mordy *et al.* 2005). Intense vertical mixing that occurs as the water is pumped back and forth by tides in Kennedy and Stevenson Entrances enhances surface nutrient concentrations in Shelikof Strait. Mixing that occurs over the shallow banks during the ACC's transit past Kodiak Island enhances surface nutrient concentrations to the south of Kodiak. Meanders in the ACC determine the partitioning between inner and outer shelf domains. The horizontal and especially vertical shears associated with these features of the ACC promote the blending of fresh water rich in micronutrients from the inner shelf with saltier water rich in macronutrients from farther offshore, and from depth.

Associated with the bottom along the shelf break are higher salinities and nutrient concentrations, as shown in the very high correlation between moored nitrate and salinity at depth (Fig. 7) (Mordy *et al.* 2005). These are introduced to the shelf through bathymetric steering; mixing in the water column in the troughs and canyons then brings these nutrients to the euphotic zone.

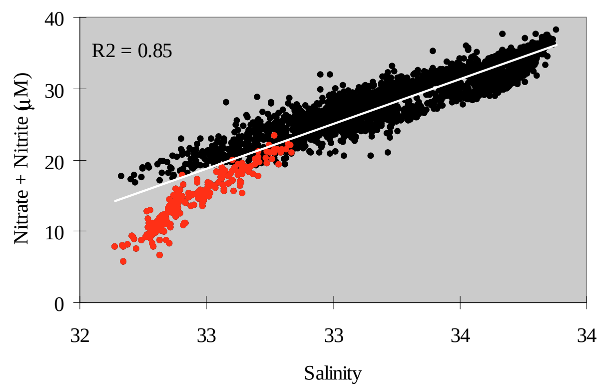

Figure 7. The relationship between nitrate + nitrite and salinity for the near bottom nitrate meters in the GOA. Data from Chiniak Trough are in red, and are not included in the linear fit.

There appears to be significant spatial variability in the post-bloom nutrient content of surface waters along the shelf. Over the less rugged bathymetry off the Kenai Peninsula, seasonal heating in late spring and summer stratify the upper 50 m, and associated with this stratification is the seasonal drawdown of nitrate and establishment of a sub-surface chlorophyll maximum. Data from the Northeast Pacific GLOBEC project centered off the Kenai Peninsula show a drop in surface nitrate concentrations from about 8-16 μM in spring to < 2 μM in October (data not shown). Similarly, nitrate concentrations in Shelikof Strait may be undetectable in late spring (Napp *et al.* 1996). In contrast, hydrographic sections taken across Portlock Bank in June 2002 showed the water column to be well-mixed or weakly stratified in both temperature and salinity (Fig. 5). This is likely a result of tidal mixing, which is enhanced over the banks. As a result of this mixing, near-surface nutrient concentrations over the banks are higher than in the surrounding water.

It is worth noting that unlike in the subarctic Pacific gyre where nitrate remains replete and iron limits primary production on the shelf (Martin *et al.* 1989), iron on the inner Coastal Gulf of Alaska (CGOA) shelf is sufficient to support generous biological production and the drawdown of nutrients. This means that macronutrients such as nitrate can govern primary production in shelf waters. Recent indirect evidence, however, suggests that iron limitation may be important where the offshore and shelf waters mix (Strom *et al.* 2005).

Phytoplankton

The spring phytoplankton bloom on the CGOA shelf is a series of individual blooms, each of a different water mass, potentially with different phytoplankton communities. The first to bloom is PWS where protection from the coastal winds and high freshwater runoff lead to early stabilization of the water column. In 2001, the GLOBEC Process program sampled the shelf spring phytoplankton blooms and found that the ACC bloomed before the mid-shelf region (Napp, pers. comm.). In general the bloom finishes in May due to nutrient depletion and microzooplankton grazing. Strom *et al*. (2005) observed macronutrient limitation of growth rates as early as late April along the Seward line with the onset of spring stratification. They also observed that while the summer phytoplankton community was generally dominated by small (<5 µm) cells, there were strong cross-shelf gradients in phytoplankton community structure and function, including overall biomass, cell size, species composition, nutrient utilization, growth rate, and degree of macronutrient limitation, and implicated progressively greater iron limitation with increasing distance from the coast.

Post-bloom production over the shelf has marked patterns of spatial variability, and these patterns of variability represent the shelf environment when juvenile salmon are entering the ocean. Chlorophyll concentrations vary spatially over the shelf and are clearly related to mesoscale features such as eddies and intrusions of slope water. On average, however, there is larger standing stock near Kodiak Island than there is near Seward Line (Fig. 4). This contributes to the "chlorophyll front", between the shelf off the Kenai Peninsula and the region just east of the northern tip of Kodiak Island. It appears to be a persistent feature of the summer chlorophyll distribution. The bathymetry on the high chlorophyll side of the "front" (southeast of Kodiak Island) is characterized by multiple banks and troughs. In this region, the highest chlorophyll concentrations appear to be centered over the shallow banks with slightly lower concentrations in the troughs. It appears that higher chlorophyll around Kodiak Island in summer stems from the interaction of bathymetry with flow over the shelf and basin.

Elevated biological production over the banks and in coastal waters off Kodiak Island (i.e., the chlorophyll front) appears to result from the interaction of circulation and mixing which enhance the nutrient flux and promote new phytoplankton production in summer. It is not known how the production off Kodiak, and its distribution, varies in relation to freshwater forcing (e.g. the location of the ACC), or varies on interannual and decadal temporal scales.

OBJECTIVES

An examination of the objectives in the original proposal in regards to this report.

Objective 1 Map surface nutrients across the northern and central GOA,

OCC-GLOBEC surveys were designed to sample the shelf and basin from south of Kodiak Island to Yakutat (see Fig. 1). Originally, these cruises were scheduled for summer on the NOAA chartered F/V *Great Pacific*. In 2003, the *Great Pacific* experienced engine failure, and the cruise was moved to the NOAA ship *Miller Freeman*. In 2004, the cruise was completed on the F/V *Great Pacific*; however, the cruise had to be delayed until fall, and was cut short due to bad weather. Furthermore, the nutrient analyzer in the underway system was operational only during the second leg of this cruise. The results of these surveys are shown in figures X and Y.

Objective 2 Identify mechanisms supplying nutrients to surface waters in summer,

In winter, the Gulf of Alaska is normally a downwelling favorable regime and nutrients are brought into the area from the surface of the basin (Stabeno et al., 2004). In summer, the prevailing winds are at times upwelling favorable, but these occurrences are much less frequent and weaker than for typical upwelling regimes. Hence upwelling winds have much less impact on the replenishment of the supply of nutrients to the surface waters of the GOA. Other mechanisms do have an effect on the replenishment of localized areas of the Gulf. Flow up troughs and canyons bring deep nutrients closer to the surface. Tides mix up nutrients over shallow banks. Seasonal eddies that move through the area appear to play a role in bringing nutrients up into the phototrophic zone on an ongoing basis, maintaining these regions at a higher production level than areas immediately adjacent (Ladd et al., 2005). In this study we were better able to understand mixing over shallow banks and in troughs and canyons, and their affect in injecting nutrients into the euphotic zone.

Objective 3 Parameterize the relationship of nutrient distributions with physics, chlorophyll, zooplankton and fish.

This work is ongoing. The synthesis of these relationships has just funded by GLOBEC

Objective 4 Provide a mesoscale context for moorings and process studies in the western GOA (FOCI, GLOBEC and the Steller Sea Lion Programs).

Results are presented in this report.

Objective 5 Initiate a long-term monitoring program of the nutritional status of the northern and central GOA to better understand the impact of interannual and decadal variability, and to provide nutritional forecasts to resource management teams.

A long-term monitoring program of the Gulf of Alaska has been initiated with the deployment of NAS-2E nitrate meters at several sites in the GOA. These meters have been deployed as part of both surface and subsurface moorings and are typically deployed and recovered twice each year, in the spring and autumn. An on-going study of the area is being conducted by the installation of an underway sampling on the Alaskan State Highway System Ferry M/V *Tustumena*. This package consists of an optical nitrate sensor in conjunction with salinity, temperature fluorescence, Colored Dissolved Organic material (CDOM), and turbidity measurements. These instruments, operating during the ferry’s regularly scheduled transits of the Gulf of Alaska between Kodiak Island and the mainland are providing a long-term, detailed record of the variations in the biophysical parameters associated with the ACC in the Gulf of Alaska.

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