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Mixed Layer Dynamics Along the Seward Line in the Northern Gulf of Alaska

Nandita Sarkar

Old Dominion University

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MIXED LAYER DYNAMICS ALONG THE SEWARD LINE IN THE NORTHERN GULF OF ALASKA

by

Nandita Sarkar
M.S. in Oceanography, Old Dominion University, August 2001

A Dissertation Submitted to the Faculty of Old Dominion University in Partial Fulfillment of the Requirement for the Degree of

DOCTOR OF PHILOSOPHY

OCEANOGRAPHY

OLD DOMINION UNIVERSITY
August 2007

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ABSTRACT

MIXED LAYER DYNAMICS ALONG THE SEWARD LINE IN THE NORTHERN GULF OF ALASKA

Nandita Sarkar
Old Dominion University, 2007
Director: Dr. Thomas C. Royer

The northern Gulf of Alaska marine ecosystem is very productive with a “nutrient paradox”. Primary producers require light and nutrients for photosynthesis. A primary source of nutrients is the deep ocean, while light is available in a relatively shallow layer in the upper ocean. In most productive parts of the world oceans, nutrients are brought to surface waters by upwelling. However, in the northern Gulf of Alaska, the winds are generally downwelling inducing and the mechanism(s) by which nutrients are brought to the euphotic zone are not known. One mechanism that might bring nutrients into the euphotic zone is the deepening of mixed layers. This dissertation is the first study of mixed layer depths (MLDs) across the continental shelf of the northern Gulf of Alaska. Hydrographic and nutrient data have been collected as part of the GLOBEC NEP (GLOBal ocean ECosystem dynamics North East Pacific) project along the Seward Line in the northern Gulf of Alaska. The Seward Line of hydrographic stations extends from the coast, across the continental shelf and beyond the shelf break. It intersects two major circulation features – the Alaska Coastal Current (ACC) on the inner shelf and the Alaska Current offshore of the shelf-break.

This dissertation contains calculations and descriptions of the across-shelf and temporal (seasonal and interannual) variability in the MLDs and assessments of the role of MLDs in providing nutrients to the euphotic zone. The MLDs across the shelf are deepest in late winter/early spring and shallowest in summer. In general, MLDs on the shelf are deeper than those offshelf, with deepest MLDs near the shelf-break. This annual cycle is primarily in response to freshwater discharge, winds and solar insolation. On longer timescales, four forcing mechanisms have been identified: the direct interaction of freshwater discharge and winds; an estuarine-type circulation controlled by freshwater discharge and winds; upwelling related to the curl of the wind stress; and interactions with anticyclonic eddies.
Interannually, deep winter MLDs show a deepening trend near the coast and a shoaling trend mid-shelf and at the shelf-break. This might lead to greater productivity near the coast and decreasing productivity offshore. A primary source of nutrients to the region is the deep ocean, but the coastal runoff might be a secondary source at the inner shelf. The nutrients correlate well with MLDs on the inner and mid-shelf, where they play a significant role in the supply of nutrients to the euphotic zone. However, at the shelf-break and beyond, other mechanisms might be more important for supplying nutrients. Further studies need to be done to include the effects of bathymetric interactions and horizontal advection and to resolve the episodic wind events that are possibly responsible for deep mixing.
To Isaac, Ian and my parents, Jyoti and Biswajit Sarkar
With love as always
ACKNOWLEDGMENTS

First of all, I would like to thank my advisors, Drs. Tom Royer and Chet Grosch, for their guidance over the years. You have taught me so much more than oceanography and I am truly grateful for your mentorship. I would also like to thank my committee members, Dr. John Klinck, Dr. Tom Weingartner and Dr. John Adam, for their valuable feedback, which have been incorporated into this document.

I would like to thank a number of people for sharing data and other information. Dr. Isaac Fine provided the FORTRAN codes for the Thomson and Fine algorithm. Nutrient data were provided by Dr. Terry Whitledge. Sea surface height anomaly data were provided by Dr. S. Okkonen. Dr. B. Finney at the University of Alaska provided insightful comments about marine derived nutrients. I would also like to thank all the people involved in the collection of the data used here, especially the crew of R/V Alpha Helix.

Thanks are also due to my many friends spread all over the world for their camaraderie and also to the friends at CCPO for all the late night companionship. Special thanks are due to Sinan Huseyoglu for often rescuing data I accidentally deleted.

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And finally, my heartfelt love to my parents, Jyoti and Biswajit Sarkar. This is your dream, and I could not have done it without you. Thank you.
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CHAPTER I
INTRODUCTION

I.1 THE IMPORTANCE OF THE SURFACE MIXED LAYER OF THE OCEAN

The oceanic surface mixed layer is the layer of almost uniform density resulting from the competition between stratifying and destratifying processes. Stratifying processes include surface heating, ice melting and freshwater influx including precipitation, while destratifying forces include wind forcing, surface cooling, evaporation, ice formation and turbulent mixing. The mixed layer depth (MLD) can vary from a few centimeters to thousands of meters in depth, as in the Labrador Sea.

The sea surface is in continuous interaction with the atmosphere above it. The ocean gains heat from the atmosphere primarily by absorption of short-wave radiation, and also by heat conduction and longwave back radiation. It loses heat to the atmosphere by short-wave reflection, by turbulent transfer, by latent heat loss due to evaporation and by long-wave radiation (Neumann and Pierson, 1966). Net absorption of short-wave solar radiation increases the temperature of the water. The increase is greatest in surface waters and diminishes rapidly with depth. This distribution is altered by convection, advection and stirring by wind waves. For mixing to take place in a stably stratified water column (lighter water overlying denser water), colder or saltier and hence denser water must be displaced upwards against gravity and warmer or fresher, lighter water displaced downwards against buoyancy forces. The energy required to accomplish this is reflected as a change in the potential energy of the water column (Mann and Lazier, 1996). Thus mixed layer formation, which varies spatially and temporally, is important from the point of view of energetics or dynamics of the water column.

The mixed layer is actively involved in the connection between the atmosphere and the oceanic interior. It is affected by and reflects the effects of atmospheric forcing and flux of heat, freshwater and atmospheric gases such as carbon dioxide and oxygen between the ocean and the atmosphere. Moreover, the high density and specific heat of water compared to air makes the ocean a greater reservoir of heat.

The journal model for this dissertation is Continental Shelf Research.
than the atmosphere (about 1000:1) (Levitus et al., 2005). For this reason mixed layers can play a significant role in climate and climate change.

The variation of MLDs plays a crucial role in controlling the biology in a region. However, the effect of MLDs on biology can be different in different systems. For primary production, the essential components are light and nutrients. While sunlight penetrates into the water column from the surface and generally decreases exponentially with depth (Mann and Lazier, 1996), nutrients are often made available from the depths of the ocean through vertical mixing. At low latitudes, where light is abundant throughout the year, deepening mixed layers can bring additional nutrients into the euphotic zone and increase new production. However, in high latitudes where light levels change seasonally and light angles are more oblique than at lower latitudes, deepening of the mixed layer can decrease new production since it mixes water and organisms into darker zones. Thus at higher latitudes, mixed layers can increase production through nutrient enhancement or decrease production by removing primary producers from optimal light conditions. Shallow mixed layers in all systems also may decrease net production by allowing higher rates of predation.

1.2 MIXED LAYER DEPTHS IN THE COASTAL GULF OF ALASKA

The high primary productivity on the northern continental shelf of the Gulf of Alaska (Sambrotto and Lorenzen, 1986) supports a number of important commercial fisheries, for example, salmon, pollock, herring and halibut (Rogers et al., 1986; Ware and McFarlane, 1989). How this primary productivity is sustained has been a topic of active research for a number of years. A number of hypotheses have been suggested for horizontal transport of nutrients onto the shelf, but most studies attribute the vertical transport of nutrients into the euphotic zone to deepening of mixed layers in the winter.

Very few studies have attempted to describe MLDs in the northern Gulf of Alaska, mostly due to lack of adequate datasets. At high latitudes in the Pacific Ocean, where temperatures are low and precipitation and freshwater discharge are high, salinity dominates the density calculation in the non-linear equation of state (UNESCO, 1981). Due to unavailability of salinity data, Polovina et al. (1995) calculated mixed layer depths in the Central and North Pacific based on water column temperature observations from 1960 to 1988. They found that the mixed layers in the Gulf of Alaska
were 20-30 percent shallower in 1977-88 than during 1960-76. They attributed this change to the intensification of the Aleutian Low and found strong direct correlations between the strength of the Aleutian Low (as given by the Aleutian Low Pressure Index) and salmon and zooplankton production. Freeland et al. (1997) found that from 1956 to 1994, there was a shoaling trend in MLD (based on temperature and salinity) at Ocean Station P, significant at the 95% confidence level. From this they computed a linear shoaling trend of 63 m/century, with a 95% confidence interval of ±28 m/century. The study also predicted that as the MLDs were shoaling, there should be a declining trend in upper mixed layer nitrate concentrations. The nutrient reduction is caused by reduced winter entrainment of deep waters with their high nutrient concentrations. Sarkar et al. (2005) applied the same method to hydrographic data from 1974 to 1998 at station GAK 1 (Fig. 1). However, they have found no significant trend at GAK 1 over this time period.

It has been suggested that there is an optimal stability window (Gargett, 1997; Gargett et al., 2001) of the MLD in the North Pacific within which primary production is maximized. According to this theory, as water column stability increases and MLDs shoal, northern (Alaskan) stocks of primary producers will shift towards optimal conditions of light and southern (northern California) stocks will shift away from optimal supply of nutrients. The opposite will be the case when water column stability decreases and MLDs deepen. Strom et al. (2006) report that in summer in the coastal Gulf of Alaska, phytoplankton growth is limited by nutrients, not by light, so deepening MLDs there should be associated with higher productivity.

1.3 BACKGROUND TO THE AREA

1.3.1 Geographical setting

The Gulf of Alaska is the northeastern extension of the Pacific Ocean, bounded by the 50°N latitude in the south, the landmass of North America on the east and north and the Aleutian Island chain on the west. Commercially, it is one of the most important marine ecosystems of the world.

The Seward Line of hydrographic stations (Fig. 1) was established in 1970 for tracking alongshore flows and cross shelf variability. This line consisted originally of 11 stations, GAK 1 to GAK 11, and later the stations were extended to GAK 15. The stations were approximately 18 km (10 nm) apart and later additional stations were
added to resolve better the cross-shelf variability. At present, there are 18 stations from GAK 1 to GAK 9, for example GAK 1, GAK 1i, GAK 2, GAK 2i, etc. These stations are nominally 9 km apart. Beyond GAK 9, the stations are 18 km apart and they consist of four stations, GAK 10 to GAK 13. Details about these hydrographic stations are given in Table 1.

The Seward Line of stations has been divided into four distinct regimes by Childers et al. (2005): (1) Inner shelf regime, (2) Middle shelf regime, (3) Shelf break regime, and (4) Slope regime. The inner shelf regime consists of the freshwater and wind driven Alaska Coastal Current (ACC) and generally extends to between 35 and 50 km from shore. The middle shelf regime is between the inner shelf regime and the shelf break regime. Variability in this regime is associated mainly with passage of mesoscale features like eddies and the variability in the ACC. The shelf break regime
Table 1

Location and bottom depths of the hydrographic stations along the Seward Line.

<table>
<thead>
<tr>
<th>Hydrographic Station</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Bottom Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAK 1</td>
<td>59.85</td>
<td>149.47</td>
<td>265</td>
</tr>
<tr>
<td>GAK 1i</td>
<td>59.77</td>
<td>149.39</td>
<td>250</td>
</tr>
<tr>
<td>GAK 2</td>
<td>59.69</td>
<td>149.32</td>
<td>220</td>
</tr>
<tr>
<td>GAK 2i</td>
<td>59.62</td>
<td>149.25</td>
<td>220</td>
</tr>
<tr>
<td>GAK 3</td>
<td>59.55</td>
<td>149.18</td>
<td>220</td>
</tr>
<tr>
<td>GAK 3i</td>
<td>59.48</td>
<td>149.11</td>
<td>210</td>
</tr>
<tr>
<td>GAK 4</td>
<td>59.40</td>
<td>149.04</td>
<td>200</td>
</tr>
<tr>
<td>GAK 4i</td>
<td>59.33</td>
<td>148.97</td>
<td>200</td>
</tr>
<tr>
<td>GAK 5</td>
<td>59.26</td>
<td>148.91</td>
<td>175</td>
</tr>
<tr>
<td>GAK 5i</td>
<td>59.19</td>
<td>148.83</td>
<td>150</td>
</tr>
<tr>
<td>GAK 6</td>
<td>59.11</td>
<td>148.77</td>
<td>145</td>
</tr>
<tr>
<td>GAK 6i</td>
<td>59.04</td>
<td>148.70</td>
<td>190</td>
</tr>
<tr>
<td>GAK 7</td>
<td>58.97</td>
<td>148.63</td>
<td>230</td>
</tr>
<tr>
<td>GAK 7i</td>
<td>58.88</td>
<td>148.56</td>
<td>260</td>
</tr>
<tr>
<td>GAK 8</td>
<td>58.79</td>
<td>148.49</td>
<td>290</td>
</tr>
<tr>
<td>GAK 8i</td>
<td>58.74</td>
<td>148.42</td>
<td>280</td>
</tr>
<tr>
<td>GAK 9</td>
<td>58.68</td>
<td>148.35</td>
<td>275</td>
</tr>
<tr>
<td>GAK 9i</td>
<td>58.61</td>
<td>148.27</td>
<td>700</td>
</tr>
<tr>
<td>GAK 10</td>
<td>58.54</td>
<td>148.21</td>
<td>1300</td>
</tr>
<tr>
<td>GAK 11</td>
<td>58.38</td>
<td>148.07</td>
<td>1400</td>
</tr>
<tr>
<td>GAK 12</td>
<td>58.24</td>
<td>147.93</td>
<td>1500</td>
</tr>
<tr>
<td>GAK 13</td>
<td>58.09</td>
<td>147.79</td>
<td>1525</td>
</tr>
</tbody>
</table>

extends approximately 135-160 km offshore, where the shelf falls steeply into the continental slope. Frontal dynamics, leading to shears, loops and meanders account for most of the variability here. The slope regime includes the Alaska Current/Stream. Anticyclonic eddies that are relatively fresh rather than warm have been observed in this regime (Okkonen et al., 2003). Thus the Seward Line is designed to capture the cross-shelf variability and includes the ACC on the inner shelf as well as the Alaska Current on the continental slope.

1.3.2 Bathymetry

The North American continent arc bordering the Gulf of Alaska stretches roughly east-west and has a complex coastline, with several significant embayments (eg. Prince William Sound, Cook Inlet) and major islands (eg. Kodiak Island, Kayak
Island, Hinchinbrook Island). The bathymetry is also correspondingly complex as
the shelf is dissected by many submarine canyons and sills (eg. Hinchinbrook Canyon
and Amatouli Trough to the east and west of the Seward Line, respectively).

The Seward Line extends from the mouth of the Resurrection Bay, an embayment
located between Prince William Sound and Cook Inlet. The depth of the shelf here
generally varies between 150 m and 250 m. Across the Seward Line, the bottom
depth inshore at GAK 1 is about 250 m, shoaling gradually offshore into a sill at
150 m depth, approximately 80 km from shore. The shelf break lies about 150 km
from shore, beyond which the continental rise has bottom depths of approximately
1500 m.

1.3.3 Atmospheric conditions

The most striking feature of the atmospheric conditions in the northern Gulf of
Alaska is the strong seasonality of wind events (Wilson and Overland, 1986). In the
summer, the Pacific High pressure system lies over the region, and the winds are
weak and variable. At the coast, there is relaxation of the downwelling or even weak
upwelling. However, in the winter, the Pacific High is replaced by the strong Aleutian
Low pressure system with strong westward winds at the coast. The Aleutian Low
dominate the weather patterns in the Gulf of Alaska. It pulls storm systems into the
Gulf of Alaska, and strong downwelling-inducing winds are associated with low sea
level pressure (SLP). In January, February and December from 2002 to 2004, there
were on average 7.2 days each month when the SLP at Buoy 46001 in the center of
the Gulf of Alaska was below 990 mb (Dr. Chester Grosch, personal communication).

This region is a major storm dissipation area (Royer, 1998). The tectonically
formed coastal ranges intercept these storm systems causing precipitation along a
narrow coastal strip. Precipitation rates in this area are very high, 2.4 m yr\(^{-1}\) (Luick
et al., 1987) (Fig. 2). There is a strong seasonality in the precipitation, with the
maximum at Seward, Alaska being in late September and staying elevated through
December. However, in winter most of this is locked up as snow or ice. When the
air temperatures are above freezing, the ice/snow can melt and drain into the Gulf
of Alaska through a fine network of small streams. Thus there are two peaks in the
freshwater discharge into the Gulf of Alaska - one in October, when the precipitation
is high, and another secondary one in May, which is meltwater induced.
I.3.4 Physical oceanography

The physical oceanography of the northern Gulf of Alaska is dominated by two systems: the subarctic cyclonic gyre which occupies the ocean basin and the Alaska Coastal Current on the continental shelf (Stabeno et al., 2004) (Fig. 2). The subarctic gyre is formed by the eastward flowing North Pacific Current bifurcating offshore of Queen Charlotte Island in British Columbia with a northward limb called the Alaska Current. In the east, it is a broad, relatively sluggish, typical eastern boundary current, with many loops and eddies. (Musgrave et al., 1992) reported a meander of radius 100 km which propagated downstream about 2 cm s\(^{-1}\). Typical current speeds at the offshore end of the Seward Line are about 10 cm s\(^{-1}\) (westward) (Reed and Schumacher, 1986; Stabeno et al., 2004). Near Kodiak Island, the Alaska Current becomes narrow due to western intensification and is steered by bathymetry so that it hugs the shelf. It is then called the Alaska Stream.

On the continental shelf, the flow pattern is dominated by the relatively narrow Alaska Coastal Current (ACC). This is a baroclinic jet driven by the cross-shelf gradient in freshwater discharge, whose strength is modified by winds. It is a swift
flowing current, with typical westward flow speeds of 20-30 cm s\(^{-1}\). There is an annual cycle in the flow speed of the ACC, which coincides with the annual cycle in the freshwater discharge. In October, when freshwater discharge is at its maximum, the ACC can be as swift as 100 cm s\(^{-1}\) (Reed and Schumacher, 1986). In September 1983, peak values of 180 cm s\(^{-1}\) have been measured in the ACC upstream of the Seward Line (Johnson et al., 1988). The width of the ACC varies according to wind direction and freshwater, but is generally between 35 and 50 km (Childers et al., 2005). The ACC generally stays close to the coastline, but is sometimes deflected due to bathymetric features.

Another aspect of the oceanography of the region is the presence of eddies of different spatial scales and longevity. In the vicinity of the Seward Line the eddies are generally associated with baroclinic instabilities in the Alaska Current (Cummins, 1989) and are more frequent during the phenomenon of El-Niño/Southern Oscillation (Okkonen et al., 2001).

### I.4 GLOBEC IN THE GULF OF ALASKA

US GLOBEC (GLOBal ocean ECosystem dynamics) NorthEast Pacific (NEP) program began in the California Current System (CCS) where the focus was on the interaction between mesoscale physical features and zooplankton, which are known to vary on ENSO (El-Niño - Southern Oscillation, 2-7 years) and multidecadal timescales (Strub et al., 2002). At this time it was recognized that the California and the Alaska Currents vary out of phase with each other on ENSO (Chelton and Davis, 1982) as well as decadal timescales, and these effects percolate up the ecosystem (Hollowed and Wooster, 1995).

In the design of the Coastal Gulf Of Alaska (CGOA) program, (pink) salmon was chosen as the target species, along with its food sources, for example, copepods and euphausiids. It was hypothesized (U.S.GLOBEC, 1996; Strub et al., 2002) that:

1. Production regimes in the CGOA and CCS covary, and are coupled through atmospheric and ocean forcing;
2. Spatial and temporal variability in mesoscale circulation constitutes the dominant physical forcing on zooplankton biomass, production, distribution, species interactions, retention and loss in coastal regions;
3. Ocean survival of salmon is primarily determined by survival of the juveniles in
coastal regions, and is affected by interannual and interdecadal changes in physical forcing and by changes in ecosystem food web dynamics."

In order to test these hypotheses, a Long Term Observing Program (LTOP) was set up in the area. The Seward Line is the primary set of hydrographic stations sampled during LTOP cruises. The Seward Line runs across the continental shelf and beyond. It crosses the Alaska Coastal Current as well as the Alaska Current. During GLOBEC LTOP cruises, each station was sampled for depth profiles of hydrographic parameters (temperature and salinity), nutrients, phytoplankton as well as zooplankton. The Seward Line was sampled approximately seven times each year; the sampling schedule and rationale are elaborated in Table 2.

I.5 RESEARCH OBJECTIVES

This study is a part of the GLOBEC CGOA program. The research objectives of this study are the following:

1. To establish a seasonal climatology of MLDs along the Seward Line and understand cross-shelf variability of MLDs;
2. To understand the interannual variability of the MLDs in relation to atmospheric and oceanic forcing;
3. To describe the stratification and energetics of the water column along the Seward Line;
4. To explore the relationship between MLDs and nutrients along the Seward Line.
# Table 2

Sampling schedule and rationale for CGOA LTOP sampling of the Seward Line (after Weingartner et al., 2002).

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

II.1 INTRODUCTION

Although mixing has been recognized as a crucial process in bringing the deep pool of nutrients on the northern continental shelf of the Gulf of Alaska into the euphotic zone, there has been only one study of the mixed layer depths in the region. Sarkar et al. (2005) discuss the mixed layers at hydrographic station GAK 1 from 1974 to 1998 (pre-GLOBEC period), that vary seasonally from a depth of 40 m in the summer (August) to over 160 m in winter (January). The variability is highest in the winter, when they attribute it to the episodic nature of the storm events that lead to deep mixing. Spectral analysis of the MLDs shows that the MLDs vary on ENSO (El-Niño- Southern Oscillation) (2-7 years) and decadal timescales.

This dissertation extends that earlier study by Sarkar et al. (2005). A distinction is made here between local and remote formation of mixed layers, and each is addressed separately. The local mixed layer is the immediately formed mixed layer, due to local processes. They reflect the atmospheric and hydrographic conditions at that location, close to the time the observations were made. For this reason, they are not good time-integrators of regional or seasonal conditions and long term trends. However, they reflect the mixing conditions of the moment that include the effects of atmospheric and oceanic forcing, for example, winds, freshwater, state of ENSO and PDO (Pacific Decadal Oscillation) and eddies.

II.2 DATA

The hydrographic data used here were collected during the CGOA GLOBEC LTOP cruises (https://penguin.sfos.uaf.edu) as described in section I.3.1. Over the period from October 1997 to December 2004, there were 45 LTOP cruises that collected temperature and salinity profiles at hydrographic stations along the Seward Line along with other interdisciplinary oceanographic data. Data were collected approximately 7 times a year onboard R/V Alpha Helix, in the months of March, April, May, July, August, October and December.
Two critical forcing functions of the ocean here are freshwater discharge and winds. Freshwater discharge and freshwater discharge anomaly are from the Royer model (Royer, 1982) and obtained from Dr. T. C. Royer at Old Dominion University. The freshwater discharge into the Gulf of Alaska is higher than the discharge of the Mississippi River (Sarkar et al., 2005). The discharge into the gulf from numerous small streams and glaciers all along the coast is quantified using the Royer model (Royer, 1982), which is the only available estimate of freshwater discharge in the region. This is a very simplistic model of freshwater discharge, which uses the precipitation and air temperature from the southern border of Alaska (near British Columbia) to Cook Inlet, obtained from the National Weather Service. It does not include data from either British Columbia or any region to the south of it. It also does not include any river discharge data as they are not available. Thus, the freshwater discharges obtained from this model are underestimations of the true discharge into the Gulf of Alaska. Recently, however, the model has been upgraded to include the meltwater due to increased glacial ablation (Arendt et al., 2002).

Wind data are from two sources. The Upwelling Index (UI) data are for site 60°N, 149°W (http://www.pfeg.noaa.gov). The UI (Bakun, 1973) is derived from the onshore-offshore component of the Ekman transport, which in turn is calculated from the mean geostrophic component of the wind stress as determined from the atmospheric horizontal pressure gradient. Timeseries of UI are calculated on a 3° × 3° grid. Wind data derived from satellite scatterometers (QuikSCAT) are also used. The QuikSCAT wind timeseries are daily means of the ascending and descending passes of the satellite in a continuous 1800 km band, with a wind vector resolution of 25 km (Schroeder, 2007). The data are processed by the Jet Propulsion Laboratory and maintained at their website (http://podaac.jpl.nasa.gov/ovw). For this study, winds at a location near GAK 4 (Q4) have been used. Q4 is located approximately 50 km offshore. QuikSCAT data are available since August 1999 so the seasonal cycles of both UI and Q4 are constructed using data from August 1999 to December 2004 to aid comparison. QuikSCAT data products have been provided by Dr. I. D. Schroeder at Old Dominion University.

Although winds and freshwater are the primary forcing functions for the oceans in the region, other factors also play a role in causing ocean variability. In the northern Gulf of Alaska, such secondary factors include ENSO, PDO (http://jisao.washington.edu/pdo) and eddies. The Southern Oscillation Index (SOI)
Fig. 3. Coastline and bathymetry in northern Gulf of Alaska, showing ascending pass A62 of TOPEX and JASON satellites. The Seward Line is also plotted, with stations GAK 1, 4, 9 and 13 marked on the plot.

(http://www.pfeg.noaa.gov) is used to represent ENSO.

Information about eddies is derived from altimetry data from TOPEX and JASON satellites (http://podaac.jpl.nasa.gov). TOPEX altimetry data are available until June 2001, with JASON altimetry data replacing it since June 2001. Data preprocessing details are described by Okkonen et al. (2003). The ascending pass (A62) along track gridded SSHA data have been used here (Fig. 3). The SSHA data have been provided by Dr. S. Okkonen at the University of Alaska.

II.3 THE SPLIT AND MERGE ALGORITHM

A number of methods exist to calculate MLDs. A popular method of calculating the local MLD is by using a density (or, most often, temperature) threshold, that is, a density (temperature) difference between the surface waters and those at depth. An
example of this method is the Kara et al. (2000) method. However, these algorithms are very sensitive to the threshold value chosen. To avoid this problem, the Split and Merge (SM) algorithm (Thomson and Fine, 2003) was chosen to calculate the local mixed layers.

The SM algorithm fits a curve to the profile by using piecewise polynomial fitting functions. It proceeds in a number of steps. Initially, the algorithm decomposes the curve into \( n \) number of polynomial segments of order \( m \). \( n \) is the minimum number of segments required to keep the error norm below a chosen error limit \( \varepsilon \). The error norm tests the fit between the segment and the curve it approximates and can be any statistical measure of the fit; in this case it is the RMS (root mean square difference) between the two. The maximum value of \( m \) used is 2, and since the mixed layer is considered homogenous, the value of \( m \) here is 1. Thus each segment is associated with a maximum of two coefficients. The algorithm then merges together adjacent segments with similar coefficients such that the error norm is still within the error limit. The algorithm then tries to minimize the error norm by relocating the boundaries between segments. Once the minimum error norm is found, there is no change with further iterations, and the algorithm terminates.

The value of the error norm used in this study is 0.05, the minimum depth is 10 m, maximum depth is 1 m above bottom depth. The SM algorithm is not very sensitive to the value of the error norm (one of the advantages of this method) and so the difference in MLDs due to changing the error norm by even an order of magnitude is not significant. The minimum depth of 10 m eliminates problems with surface noise. If the SM method returns an MLD of 10 m, this implies an actual MLD value between the surface and 10 m.

II.4 SEASONAL CYCLES

Seasonal cycles are constructed by using the mean value for each month. Data from October 1997 to December 2004 have been used to calculate mean values for most of the forcing and MLDs. The exceptions are the wind data, for which seasonal cycles have been contructed with data from August 1999.
II.4.1 Freshwater discharge and winds

The freshwater discharge (Fig. 4) is at its maximum in October when the precipitation is highest and the air temperatures are still above freezing, allowing meltwater runoff. In winter, temperatures drop and the freshwater is locked up as snow or ice. Thus freshwater discharge reaches its annual minimum in March (late winter). With spring warming comes the thaw so freshwater discharge increases through the summer. The variability in the freshwater discharge (denoted by error bars on Fig. 4) is high in winter because of the dependence on air temperature and in fall because of the episodic nature of the storm induced precipitation.

The climatology of winds using UI and Q4 are constructed in two ways (Fig. 5). Fig. 5a shows the eastward (upwelling inducing) as well as westward (downwelling inducing) wind events 14 days before each cruise. The seasonal cycle of UI shows negative values for most of the year, which implies downwelling inducing (westward) winds. This is the period when the Aleutian Low is over the Gulf of Alaska, which results in strong cyclonic circulation and downwelling inducing winds at the coast. In the summer, the cyclonic circulation weakens considerably and sometimes is replaced by an anticyclonic circulation driven by the Pacific High. This causes relaxation in the downwelling winds or even some upwelling (eastward winds) along the coast in the summer months. This is denoted by small positive values of the UI around July. The seasonal cycle of Q4 winds has a similar shape, but some significant differences compared to the UI. The winter values (December-January) are not as
Fig. 5. Seasonal cycle of mean daily Upwelling Index (UI) and QuikSCAT winds near location GAK 4 (Q4), from August 1999 to December 2004, integrated over 14 days before each monthly cruise averaged in two ways: (a) including both upwelling and downwelling events; (b) including downwelling events only.

strongly downwelling inducing, while the summer values are small but negative. Thus Q4 winds do not show as strong downwelling in the winter, nor does it show upwelling in the summer.

Since downwelling is the dominant process rather than the upwelling, another climatology is constructed using only the downwelling inducing (westward) wind events 14 days before each cruise (Fig. 5b). These values were then averaged to obtain monthly means for the seven cruises each year. Once again, there are significant differences in the values between UI and Q4, even though the cycles are similar, with greater downwelling in the winter and less downwelling in summer. Q4 shows greater downwelling in all months, and especially in December. In the summer, UI shows weaker downwelling, but not upwelling. There is a distinct difference between the states of weak or relaxed downwelling and active upwelling, as has been stressed by
II.4.2 Mixed layer depths

There is a strong seasonal variability in the MLDs along the Seward Line (Fig. 6). Deepest mixed layers occur in March or April (late winter/early spring). At GAK 1 and 1i, the deepest mean mixed layers are less than 100 m, GAK 2i to 4 have average March/April MLDs deeper than 100 m, GAK 4i to 6 again have shallower values (around 100 m). Stations GAK 6i to 8 have March/April mean MLDs of almost 150 m, with GAK 8 having the deepest average MLD along the Seward Line - 150 m. Beyond GAK 8 up to the shelf break (GAK 8i, 9), the deepest mean MLDs are again shallower, approximately 100 m. Beyond the continental shelf, on the shelf break and offshore, the mixed layers are shallow, from 40 m at GAK 10 to 50 m at GAK 13 in April.

Increasing insolation and meltwater through spring and summer increase the vertical stratification and the mixed layers shoal. Since the seasonal cycle of freshwater discharge has a secondary peak in May due to meltwater released from snow/ice fields due to higher air temperatures and as a result of increased solar influx, the mixed layers on the shelf are shallower than the previous month by approximately 50 m. Offshelf they are shallower by 30 m. Except between GAK 6 and 7 where the average May MLDs range from 75 to 100 m, the average May MLDs on the shelf vary between 20 and 50 m. Offshelf (beyond GAK 9i) the mixed layers are approximately 20 m deep.

In July and August (summer) the insolation is high due to the higher angle of the sun's rays, longer days and less cloud cover due to the presence of the Pacific High over the area. The freshwater discharge continues to be high, adding to the stratification near the coast. At stations GAK 1 to 3, the mixed layers are within the surface layer (10 m) and beyond GAK 3, the mixed layers are less than 20 m. Mean summer mixed layers are deepest offshore.

By October, the insolation has decreased significantly as the overhead position of the sun has shifted southward. Freshwater discharge has its annual peak at this time. As the Pacific High begins its retreat southward, the number of storm days increases. Mixed layers at stations GAK 1 to 2 are still shallow (10 m or less) due to the increased stratification caused by high rates of freshwater discharge. However, offshore, the mixed layers deepen. The deepest mean mixed layers in October are...
Fig. 6. Monthly average MLDs along the Seward Line using the SM algorithm.
found at stations GAK 6i to 9 on the outer shelf. Off the shelf, the mixed layers are shallower – approximately 20 m.

December is the month of transition into winter conditions. The Aleutian Low pressure system consists of strong storm systems, which mix the water column, leading to deeper mixed layers. Near the coast, the MLDs are close to 50 m, and become deeper in the offshore direction. The December mean MLD is deepest at GAK 6i. Beyond GAK 7, the MLDs shoal rapidly to approximately 50 m on the outer shelf and 35-40 m beyond the shelf-break.

Offshore of GAK 9, the stations have a very different seasonal cycle of MLDs (Fig. 7). These stations are situated off the shelf - GAK 9i is on the continental slope while GAK 10-13 are on the continental rise. While the basic shape is the same, with deeper values in winter and shallower values in summer, the seasonal cycle is much smaller, with maximum values being 50 m or less. In the summer, the deepest average mixed layers are found in the offshore region, while at other times of the year, the deepest mixed layers are found in the vicinity of GAK 6-8.

Variabilities of the MLDs (depicted by the error bars) are high in March, April, May and December. The variabilities in May and December are high because these are the transitional months between summer and winter conditions. The variabilities are high in April and May because the mixed layers are achieved by storm events, which are episodic in nature and the minimal density stratification allows quicker changes in MLDs. The shelf near GAK 5i-6 is shallow due to the presence of a sill and the bottom depth is less than 150 m. The high variability in this region shows that in some years, mixing occurs down to the bottom at these stations. In the offshore region, the variabilities in MLDs are also low throughout the year, but the maximum variability in the year occurs in May.

II.5 INTERANNUAL VARIABILITY

II.5.1 Ambient atmospheric and oceanic conditions

The interannual variability in the freshwater discharge, winds, state of ENSO and PDO and SSHA (Fig. 8) shows a vast range of climatic conditions over the seven years of NEP GLOBEC LTOP data collection. El-Niño - Southern Oscillation (ENSO) is a coupled ocean-atmosphere phenomenon (Neelin et al., 1998) with periodicities ranging from 2 to 7 years (Rasmusson et al., 1990). In a high latitude system like the
Fig. 7. Seasonal cycle of MLDs at each station along the Seward Line.
Gulf of Alaska, ENSO may be manifest as an atmospheric sea level pressure or wind stress variability (Subbotina et al., 2001) or as a coastally trapped Kelvin wave with a propagation speed of 2-3 m s\(^{-1}\) (Meyers et al., 1998). Latif and Graham (1992) have reported an oceanic subsurface thermal structure associated with ENSO. Royer (2005) reported that while there was no evidence of an atmospheric ENSO signal at GAK 1, the arrival of a thermal signal in the subsurface layer was consistent with the Kelvin wave speed reported previously by Johnson and O’Brien (1990). There are a number of indices used to represent El-Niño/La Niña phenomena. The Southern Oscillation Index (SOI) (Bjerknes, 1969), which is the normalized sea level pressure difference between Tahiti and Darwin (Australia), is used here as a measure of El-Niño/La Niña conditions. Positive SOI values denote La Niña conditions, associated with stronger Trade winds, cooler surface waters off the Peru-Chile coast, and warmer SSTs near Australia in the Pacific Ocean. Negative SOI values signify El-Niño conditions, with opposite conditions to those described above. In 1997, there was a strong El-Niño event, which lasted into the first part of 1998. This was followed by very strong La Niña conditions from 1998 to 2000. Moderate El-Niño conditions were again present from 2002 to 2004.

Ocean and atmospheric variability in the north Pacific Ocean on decadal and multi-decadal scales is attributed to the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Zhang et al., 1997), which is defined as the first EOF mode of SSTs in the Pacific Ocean, north of 20°N. It is a spatial pattern of SSTs such that the positive phase of PDO coincides with the cold phase of SOI and vice versa. SOI and PDO are not independent of each other but correlated with a coefficient of -0.33 and significance of 0.99 over the time period 1900 to 2000 (Sarkar et al., 2005). The change between positive and negative phases has been called a regime shift (Mantua et al., 1997). A regime shift from warm to positive (cool) phase of the PDO may have occurred in 1998 (Peterson and Schwing, 2003). PDO is not a forcing function but a pattern of SST and is used as a proxy for interannual thermal forcing (Sarkar et al., 2005).

The interannual variabilities in the freshwater discharge and winds are obtained by removing the mean annual signal from their timeseries. Positive discharge anomaly values denote higher than monthly average discharge and negative values denote lower than monthly average discharge. The highest positive discharge anomaly during 1997-2004 was in early 2001 and the second highest positive anomaly was in December...
Fig. 8. Atmospheric and oceanic conditions in the Gulf of Alaska from October 1997 to December 2004. The timeseries include (from left to right): sea surface height anomalies; freshwater discharge anomalies; QuikSCAT (Q4) wind anomalies and the cube of the wind speed; UI anomalies; SOI and PDO. Start dates of cruises are shown as horizontal dotted lines. The vertical dotted line in the SSHA figure is the approximate position of the closest approach to the Seward Line.
1997. Highest negative anomalies were in end-1998, spring 2002 and summer 2004. Anomalies in the wind field are shown by QuikSCAT and UI anomalies. These anomalies are constructed from wind data with downwelling inducing winds only. Negative anomalies denote higher westward winds (downwelling inducing) than normal and positive winds denote lower than normal westward winds. The QuikSCAT anomalies and UI anomalies appear different from each other because QuikSCAT winds are wind measurements while UI is calculated from the horizontal atmospheric pressure gradient. Further discussion about the differences between the two is by Schroeder (2007). In this dissertation, QuikSCAT values are generally used for wind information, but UI values are included for comparison and also because readers are more familiar with the UI index rather than QuikSCAT data.

Another source of interannual variability is related to the passage of eddies. Anticyclonic eddies cross the Seward Line in most years in spring (Okkonen et al., 2003). These eddies strengthen the shelf-break front as they approach, and are associated with upwelling. As the eddy passes, the shelf-break front moves offshore and weakens, spreading freshwater into the Gulf. The retreating eddy re-establishes a stronger shelf-break front and upwelling zone. Such eddies were seen in all years of sampling except spring 1998.

II.5.2 Mixed layer depths

The potential causes of interannual variability in the MLDs are investigated through the use of MLD anomalies (Fig. 9). The anomalies of the MLDs are the timeseries of MLDs with the mean seasonal cycle removed. Positive anomalies denote deeper than normal MLDs and negative anomalies denote shallower than normal MLDs. The interannual variability in the mixed layers is explained by addressing several examples.

In early 1998, the SOI was strongly negative, indicating an El-Niño event. Water temperatures were higher than normal. High precipitation and high runoff (due to temperatures being higher, most of the precipitation was in the form of rainfall) caused high freshwater discharge in the inshore region. The regional winds were strongly downwelling inducing (Weingartner et al., 2002) (Fig. 8). These conditions resulted in the water column being warmer and fresher, but uniform due to the strong downwelling inducing winds (Fig. 10). This resulted in deeper than normal mixed layers on the inner shelf (Fig. 9).
Fig. 9. MLD anomalies (m) from October 1997 to December 2004. Negative values denote shallower than normal values and positive numbers denote deeper than normal values. Black dots are used to show where data have been obtained by interpolation. Horizontal dotted lines show start dates of GLOBEC LTOP cruises.
In March 2003, the freshwater discharge was higher than normal, leading to a fresher water column (negative salinity anomalies) (Fig. 11). The winds at this time are anomalously less downwelling inducing than normal (Fig. 8). This spread out the freshwater on the surface of the water column, forming a cap of stratification (Fig. 11), which resulted in shallower than normal mixed layers in the inner and mid-shelf regions. According to Williams (2003), in the absence of downwelling winds, extensive freshwater spreading over the shelf occurs due to eddy freshwater flux. However, this process by itself cannot account for the rapidity of the offshore movement of freshwater.

In March 2004, the freshwater discharge was average. The salinity field on the shelf showed fresher than normal waters overlying saltier than normal waters and this is reflected in the density anomaly also (Fig. 12). The winds 14 days before the
Fig. 11. Hydrographic conditions in March 2003.

...cruise were less downwelling inducing. The freshwater was spread out on the shelf and the mixed layers were shallow.

Near the outer shelf and shelf-break region, the MLDs also interact with eddies that frequently pass through the region. MLD-eddy interaction is characterized by the doming of the density structure (Ferrari and Boccaletti, 2004). A good example of this type of interaction along the Seward Line is found in April 2002 (Fig. 8). At this time, the passage of an anticyclonic eddy across the Seward Line caused the doming of isopycnals in the vicinity of GAK 7 to 8i (Fig. 13).

Beyond the shelf-break, the spatial pattern of MLDs is very different from the MLDs on the shelf. MLDs off the shelf are probably affected by different processes than those on the shelf. The passage of eddies tend to have an effect on the MLDs at the outer stations of the Seward Line, as in March 1999, when an eddy caused...

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Fig. 12. Hydrographic conditions in March 2004.

Fig. 13. MLDs along the Seward Line in April 2002.
doming of the pycnocline and shoaling of MLDs near GAK 11 (not shown). Near GAK 11, the MLDs are highly correlated with UI. Correlation of MLDs at each station with the UI (not shown) show very low correlation values, which are not significant. The only exception is at GAK 11. The correlation of the anomalies of UI with the anomalies of MLDs at GAK 11 is 0.6 at a significance level of 0.95. One explanation for this high correlation at this particular location may be the estuarine type of circulation proposed by Royer (2005). In this study, Royer (2005) speculates that the relaxation of the downwelling winds in summer would allow high salinity deep water to intrude onto the shelf. The annual high in freshwater discharge occurs in October, when the upper water salinities are lowest. The resulting flow due to the injection of the freshwater along the coast would have an ageostrophic component flowing offshore. By the process of entrainment, an onshore flow would occur in the bottom layer and the resulting onshore-offshore flow in the two layers would be reminiscent of the two-layer flow in an estuary. In support of this theory, Schroeder (2007) finds the hydrography at the outer stations to be highly correlated to an onshore-offshore mode of freshwater discharge. Beyond GAK 11, at GAK 12 and 13, the MLDs are more influenced by open ocean processes and the Alaska Current.

II.6 CONCLUSIONS

The seasonal cycle of MLDs varies with insolation and wind events and is modified by freshwater discharge on the inner shelf. The deepest MLDs on the shelf are in late winter/early spring (March/April) when a number of storm events occur in the region and temperatures and freshwater discharge are low. With spring melting and summer warming, MLDs shoal and are shallowest in the summer. In October, the MLDs in the mid-shelf and offshore begin to deepen in response to fall storms and cooling. However, near the coast, where the freshwater discharge has its seasonal peak at this time, the MLDs remain shallow and eventually deepen in December. The maximum depth of the mixed layer (150 m) on the shelf occurs in the vicinity of GAK 8 in March/April. The seasonal cycle of MLDs beyond the shelf-break is different from the MLD cycle on the shelf. The seasonal cycle off the shelf is much smaller, with deep MLDs in summer (~20 m) and with shallower MLDs in winter (~50 m) compared to those on the shelf. The variability associated with the mean MLDs is higher in winter due to the episodic nature of winter storm mixing. The
variability is also high during transitional months between summer and winter.

The seven years of GLOBEC data collection encompass a wide variety of atmospheric and oceanic conditions, including two El-Niño events, a La-Niña event, a possible regime shift and several mesoscale anticyclonic eddies passing through the outer Seward Line. These factors cause interannual variations in the MLDs in complicated ways. At the inner shelf, there is a complex response of the MLDs to the combined effects of winds and freshwater discharge. The fate of the freshwater (and thus the stratification) depends on the winds. With strong downwelling winds, the freshwater is held adjacent to the coast and mixed downward, resulting in deeper mixed layers. When downwelling winds are weak, secondary processes that are not well understood, spread the freshwater across the shelf, increasing stratification and causing shallow mixed layers even as far offshore as GAK 4. On the outer shelf and beyond, the direct influence of the freshwater is less, but the process of mixing is complicated by the passage of anticyclonic eddies that can cause doming of isopycnals and thus create shallower mixed layers. Also, freshwater discharge may be indirectly linked with the MLDs on the outer shelf by the estuarine-type circulation moving fresh surface layers offshore. In the offshelf region, MLDs respond to different forcing than on the shelf as is evident from the difference in their seasonal cycles. MLDs offshelf are probably more connected to open ocean processes rather than shelf processes. This link with open ocean processes would be provided by the Alaska Current which flows westward along the shelf-break.

So far the treatment of the MLDs along the Seward Line has been two dimensional, but in reality ocean processes have another horizontal component. Horizontal advection is an important process in this region especially in the vicinities of the ACC and the Alaska Current. Thus these processes needs to be considered to get a more complete picture of the MLDs in the region.
CHAPTER III
STRATIFICATION, ENERGY AND MLDS

III.1 INFLUENCE OF TEMPERATURE AND SALINITY ON DENSITY

III.1.1 Introduction

At high latitudes, where water temperatures are low, salinity can play a greater role in the determination of density than temperature, as the equation of state is non-linear. This should be especially true in a region like the northern Gulf of Alaska, where the amount of freshwater is especially high. While the assumption that salinity plays a greater role than temperature in determining density is acceptable for initial understanding of the system, the effects of temperature and salinity on density need to be evaluated separately as there may be specific locations or times of year where temperature may play a greater role than salinity in determining density.

III.1.2 Method

The stability of the water column can be expressed as the sum of the two terms in the density gradient (Freeland et al., 1997; Sarkar et al., 2005), i.e.:

$$\frac{d\sigma_t}{dz} = \frac{\partial\sigma_t}{\partial T} \frac{\partial T}{\partial z} + \frac{\partial\sigma_t}{\partial S} \frac{\partial S}{\partial z}$$

where $\sigma_t$ is the water density, $z$ is the depth, $T$ is the temperature and $S$ is the salinity. The two terms on the right hand side give the temperature and salinity influences on density, respectively. A ratio $R$ of these two terms then gives the relative contributions of salinity and temperature gradients to the density gradient.

$$R = \frac{\partial\sigma_t}{\partial T} \frac{\partial S}{\partial S}$$

To calculate $R$ we need to obtain vertical gradients of temperature and salinity ($\frac{\partial T}{\partial z}, \frac{\partial S}{\partial z}$) and multiply by the corresponding density for each temperature and salinity value ($\frac{\partial\sigma_t}{\partial T}, \frac{\partial\sigma_t}{\partial S}$) using the equation of state (UNESCO, 1981). Instead, an alternate $\tilde{R}$ value has been used, which is the ratio of the range of density values using the range of temperature values for the mean salinity, to the range of density values using the range of salinity values and mean temperature. Mean, maximum and minimum
temperatures \((T_{\text{mean}}, T_{\max}, T_{\min})\) and salinities \((S_{\text{mean}}, S_{\max}, S_{\min})\) are calculated for each month.

\[
\tilde{R} = \frac{\sigma_t(T_{\min}, S_{\text{mean}}) - \sigma_t(T_{\max}, S_{\text{mean}})}{\sigma_t(T_{\text{mean}}, S_{\max}) - \sigma_t(T_{\text{mean}}, S_{\min})}
\]

Thus \(\tilde{R}\) values represent the ratio of the maximum change in density due to the range of temperature, to change in density due to the range of salinity at each station, for each month that hydrographic data are available, at a depth resolution of 1 m (Fig. 14). An \(\tilde{R}\) of unity indicates equal influence of salinity and temperature on density, a value greater than unity indicates greater influence of temperature and a value less than unity indicates greater influence of salinity.

### III.1.3 Results and discussion

As expected, salinity plays a dominant role in the determination of density along the Seward Line. However, there are exceptions at certain locations and in certain seasons. On the shelf, there are some small pockets of greater temperature influence on the inner shelf, at depths of 100 m. The biggest of these pockets is at GAK 1, and this maybe related to the temperature inversion found across the shelf in winter. In April, the pattern is similar across the shelf, but the magnitude of the area where temperature effects dominate is smaller and deeper (300-400 m). In May, with the beginning of surface stratification due to increasing insolation, the pockets of higher temperature effects on the shelf move upwards, while the offshelf region of higher temperature effects is at the annual minimum. In July, again the offshelf region of high temperature influence on density is stronger and more extensive. In August, there is a subsurface layer (around 50 m) of higher temperature influence, that becomes most extensive in October. This is in response to increased solar insolation in the summer. At the surface the salinity is low enough that it can suppress the effect of temperature on density. Also in October, the offshelf area of temperature dominance begins to move offshore from its August location, and has the most offshore location in December. By December, the subsurface region of temperature control over density begins to dissipate.

In March, offshore of the shelf break, there is an extensive area between the depths of 150-250 m where temperature dominates the density calculation. The region is most extensive in March and July and smallest in May. It also migrates from the shelf-break in August to farther offshore in December. This region of higher

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Fig. 14. Seasonal cycle of $R$ ratio showing temperature and salinity effects on density. Dark shaded areas have $R > 1$ and indicate areas where temperature effects dominate. Light shaded areas have $R < 1$ and indicate areas where salinity dominates over density.
temperature influence may be related to the bottom of the permanent halocline, where temperature decreases rapidly with depth (Royer, 1975).

III.2 STRATIFICATION

III.2.1 Dynamical importance of stratification

Stratification can play an important role in ocean dynamics. Under stable conditions in the ocean, less dense fluid overlies more dense fluid, minimizing potential energy of the water column. The energy supplied to mix the water column increases the potential energy of the water column by moving denser water upwards and lighter water downwards in the water column. Thus the increase in potential energy is at the expense of kinetic energy. To compare the dynamical importance of stratification, we need to compare the potential and kinetic energy of the system as a dimensionless ratio, $\sigma$ (Cushman-Roisin, 1994):

$$\sigma = \frac{\frac{1}{2} \rho_0 U^2}{\Delta \rho g H}$$

where $\rho_0$ is the average water density, $U$ is the geostrophic speed, $\frac{1}{2} \rho_0 U^2$ is the kinetic energy per unit volume, $\Delta \rho$ is the change in density, $g$ is the acceleration due to gravity and $\Delta \rho g H$ is the change in the potential energy per unit volume due to a change in depth $H$.

A $\sigma$ value of the order of unity implies that a significant portion of the kinetic energy is required to break through the stratification and increase the potential energy of the water column. When $\sigma$ is much less than unity, there is insufficient kinetic energy to modify the stratification. In both these cases stratification is dynamically important. However, if the $\sigma$ value is much greater than unity, the kinetic energy in the system is much higher than the potential energy. In this case, the kinetic energy can easily overcome the stratification and therefore stratification is not dynamically important.

A first order calculation for the Seward Line in the Gulf of Alaska showed that the $\sigma$ ratio here is very small – essentially zero. Within the ACC and some of the eddies, the $\sigma$ ratio sometimes assumes a small number, $\sim 0.02$. The amount of kinetic energy within the system was sufficient to mix the water to a depth of only 2-5 m. This means that stratification is very important in the dynamics of the region and it constrains the flow significantly. Nevertheless, this does not mean that there is no
energy in the system to mix the water column. For example, if the water column is mixed by highly episodic wind events, it would not be resolved by the present hydrographic sampling frequency.

III.2.2 Seasonal and interannual variability of the potential energy in the Alaska Coastal Current

Since stratification plays an important part in the dynamics of the region, the variability in the potential energy of the ACC is investigated further.

The ACC is defined in this section as the region of westward geostrophic velocities of 10 cm s\(^{-1}\) and above on the inner shelf (GAK 1 to GAK 3). The potential energy, \(P\), of the ACC is defined as the energy required to mix the water column from the 'reference' depth to the depth 'k':

\[
P_k = P_{k-1} + g\Delta z\left[\rho_{ref} - \left(\frac{\rho_{k-1} + \rho_k}{2}\right)\right]
\]

where \(\Delta z\) is the depth resolution, in this case 1 m; \(P_{k-1}\) is the potential energy of the depth level above \(k\); \(g\) is the acceleration due to gravity and \(\rho\) is the density. The reference density, \(\rho_{ref}\), is chosen to be the density 1026.724 kg m\(^{-3}\) corresponding to a temperature, \(T\), of 5°C and salinity, \(S\), of 33.8 which is generally considered to be the dominate deep, oceanic watermass in the region (Royer, 1975; Weingartner et al., 2005).

The temporal variability of the potential energy in the ACC (Fig. 15) has both seasonal and interannual components. Small absolute values of total potential energy denote a less stratified water column, while a higher absolute value denotes greater stratification. Greatest stratification of the year generally occurs in December. December of 1999 and 2001 are exceptions. In these years the maximum seasonal stratification is in October. Progressing through winter, the ACC loses potential energy, such that minimum seasonal stratification usually occurs in May. In 1999, the minimum stratification occurs in April. In both 1998 and 2000, the ACC was highly stratified in May, and minimum stratification occurred later in the year – in July in 1998 and in August in 2000. 1998 was warmer and fresher due to the effect of the strong 1997-98 El-Niño and this is reflected in the higher and earlier (May) stratification. However, freshwater discharge was low during the moderate 2002 El-Niño (Fig. 8), and this is reflected in the low stratification in that year. The 1999 La Niña also had a similar effect of lowering stratification due to less freshwater discharge.
The interannual variability in the seasonal cycle (based on the spread of the values for each month, in Fig. 15) is maximum in December and minimum in July. Variabilities in May and October are also high. This is related to the variability in the freshwater discharge, which shows a similar seasonal cycle.

To understand how the stratification covaries with the freshwater discharge, the potential energy anomaly in the ACC is correlated with freshwater discharge anomaly using Spearman’s method (Kendall and Gibbons, 1990; Press et al., 1992). The anomaly of a timeseries is constructed by removing a mean seasonal cycle from the timeseries. In this case, seven years of data are used to construct the mean seasonal cycle. For the months that the cruise started after the 20th (date), the freshwater discharge of the same month was used in the construction of the freshwater timeseries. In the months that the cruise started before the 20th, the freshwater discharge of the previous month was used. This reduced the time lags related to sampling differences. The timeseries of potential energy in the ACC and freshwater discharge anomalies (Fig. 16) have been normalized (timeseries divided by its standard deviation) for ease of comparison and viewing.

Spearman’s method is a rank-correlation, non-parametric technique to find if two timeseries covary. The Spearman’s method returns a correlation coefficient, $C$, which varies between $-1$ and 1. $C = 1$ implies that both timeseries increase or decrease at the same time. $C = -1$ implies a perfect opposite relationship, that is, while one timeseries increases, the other decreases. $C = 0$ implies no correlation. The correlation can also be computed at several lag times, such that one timeseries follows the
Fig. 16. Timeseries of potential energy anomaly and freshwater discharge anomaly, normalized by their standard deviations, for the months of March through August. The phasing of the freshwater discharge anomaly is explained in the text.

pattern of the other after an interval of a given number of time units. The Spearman’s method also returns a probability, $p$, of the correlation being by chance. The significance or confidence of the $C$ value is thus computed by $1 - p$. The Spearman’s method, like any correlation technique, can only indicate covariation and cannot establish a cause-effect relationship.

In the months from March to August (late winter to summer), the anomalies of potential energy in the ACC are correlated to freshwater discharge anomaly with a correlation of 0.52 and a significance of 0.99. The correlation is positive, so that high stratification accompanies high discharge. In the months of October and December, the correlation between the potential energy anomaly in the ACC and the freshwater discharge anomaly is low and not significant (data not shown).

Anomalies of potential energy in the ACC were also correlated with anomalies in QuikSCAT winds (shown in Fig 8), but the analysis did not yield any significant, high correlations (data not shown). In spite of this, winds may play an important role in determining stratification of the ACC by modifying the freshwater discharge. In the months of October and December, the winds become strongly downwelling inducing as the Aleutian Low brings storms through the area. These high velocity, intermittent wind events can interact with the freshwater discharge to cause the stratification, but this interaction would not be reflected in the correlations of the potential energy anomalies either with the winds or the discharge.
III.3 INTERANNUAL VARIATIONS IN THE DEEPEST WINTER MIXED LAYERS

III.3.1 Introduction

The SM algorithm discussed in the previous chapter provides the instantaneous or local mixed layer of the density profile. Underlying this mixed layer, there may exist one or more "fossil", "relic" or remote mixed layer(s). According to Sprintall and Roemmich (1999), this layer contains the memory of the three dimensional ocean system by retaining evidence of prior stratification. According to Polovina et al. (1995), the decadal variability is in these annual maximum mixed layers.

The Freeland et al. (1997) method is useful for locating the depth of the relic or the annual maximum mixed layer. This method conserves the potential energy of the water column by conserving the integrated mass and is thus a powerful method, especially useful for model intercomparison.

III.3.2 Methods

The Freeland et al. (1997) method locates the relic or remote mixed layer by using a best-fit that minimizes the residual mean square (RMS) difference of a two-step function obtained by least-squares techniques to the prescribed upper ocean density structure. The vertical extent of the upper layer is user defined. Freeland et al. (1997) report that the method is not sensitive to a depth range between 200 and 500 m. In this study, 300 m or bottom depth has been used, whichever is shallower. The algorithm returns the depth of the "step" as the depth of the deepest mixed layer, which is created usually late winter or early spring (December-May) (Freeland et al., 1997; Sarkar et al., 2005), when upper water column density stratification is minimum.

The Freeland et al. (1997) algorithm (henceforth Freeland method) was applied to the stations of the Seward Line for the seven winters from October 1997 to April 2004. Each winter, by definition, provides one MLD for the timeseries. The MLD for the winter of 2004-2005 was not calculated since the last cruise was in December 2004. Stations GAK 6i and GAK 7i were only sampled four of these years, so these stations have not been included in this analysis.

The deepening or shallowing trend of the deepest winter MLDs along the Seward Line could, as noted above, be an indicator of climatic changes taking place in
the region. The timeseries of deepest winter mixed layers obtained at each station were examined for trends using a rank correlation technique called the Daniel's test (Kendall and Gibbons, 1990). Based on Spearman's correlation technique (discussed in the previous section), this test returns a Spearman's \( r \) value ranging from \(-1\) to \(+1\) and a significance level \((1 - p)\), where \( p \) is the probability of the relation occurring by chance) that varies between 0 and 1. In this analysis, significance values of 0.9 and above are considered significant while those between 0.85 and 0.9 are marginal. Below a significance value of 0.85 the correlation is considered to be by chance and is rejected. Student's \( t \) test is used to compute confidence limits on the linear slope at the 0.9 significance level. If the range of the slope with its confidence limits includes a zero value, the trend is not accepted; whereas, if the range of the slope is always positive or always negative, the linear trend is accepted as truly significant.

### III.3.3 Results

The deepest winter MLDs across the Seward Line (Fig. 17) lie in the depth range between 100 and 200 m for all stations. There are a few outliers (winter of 1997-1998, GAK 4i; winter of 1998-1999, GAK 8). In the mid shelf region around GAK 6, where the bathymetry is shallow, there is a possibility that the mixed layers interact with the bottom, enhancing turbulence and mixing in the near bottom portion of the water column.

At stations GAK 2, 4i and 13, the linear trend appears positive, i.e., deepening with time (Fig. 17). Of these, the only significant trend is at GAK 4i. The other stations all have negative trends (MLDs shoal with time). Of these, GAK 6 has a very high correlation \((-0.92\) with a 0.99 significance. The trend at GAK 8 also shows a high correlation \((-0.79\) significant at 0.95 level.

### III.3.4 Discussion

Though seven years of data are marginally sufficient to predict a climatological trend, the trends of the winter MLDs along the Seward line do demonstrate some patterns. Positive trends at stations GAK 4i in the mid-shelf region contrast with a significant negative trend at Ocean Station P located in the center of the Alaskan gyre (Freeland et al., 1997). The cyclonic circulation of the Alaskan gyre accompanies upwelling at the center and downwelling at the coast. Deepening mixed layers at the
Fig. 17. Deepest winter mixed layer using the Freeland method (see text). MLDs are indicated by solid circles and the linear trends are shown by solid lines. Abbreviated years are shown on the horizontal axes.
Fig. 18. Correlation coefficients (left panel) and significance levels (right panel) of temporal trends of the deepest winter MLDs along the Seward Line from October 1997 to December 2004. Station numbers are displayed on the horizontal axes.

cost and shoaling mixed layers in the center suggest the possibility that the gyre may be getting stronger Sarkar et al. (2005).

Farther offshore, (GAK 6 and 8) positive trends may be related to increased upwelling in the area. Royer and Grosch (2006) report that over the period from November 1997 to December 2005, the number of storm events in the Gulf of Alaska has significantly increased compared to the period between November 1974 and June 1996. Means of daily winter (January-April) vertical velocities derived from Ekman pumping due to the curl of the wind stress at a QuikSCAT location near GAK 7, shows an increasing trend (correlation 0.9; significance 0.96) between January 2000 and December 2004 (Schroeder, 2007). Increasing vertical upwelling velocities can cause MLDs to be shallower over time.
III.4 CONCLUSIONS

Salinity, rather than temperature, dominates the density determination at most times and most locations along the Seward Line. Notable exceptions are in the subsurface region on the shelf in the summer months, in response to high solar insolation. The effect of temperature is suppressed at the surface by low salinity because of high freshwater discharge.

The stratification of the water column plays an important role in the dynamics of the region by constraining the flow significantly. Within the ACC, the potential energy of the water column is related to the freshwater discharge from March to August. In October and December, the winds possibly interact with the freshwater in a complex manner to modify stratification. These interactions take place at different temporal and spatial scales, and include effects such as the mixing or spreading of freshwater by the prevailing winds and an estuarine type circulation set up by freshwater flowing offshore at the surface and deep water flowing inshore at the bottom, due to relaxation of downwelling winds.

The deepest winter mixed layers along the Seward Line vary between 100 and 200 m. Increasing trends near the coast might be an indication of gyre spin-up when contrasted with the shoaling at Ocean Station P in the center of the gyre (Freeland et al., 1997). Increased upwelling in the mid-shelf/outer-shelf region due to the curl of the wind stress (Schroeder, 2007) might be responsible for the significant shallowing of the mixed layers in this area.

Royer and Grosch (2006) indicate freshening and warming trends in GAK 1 ocean properties. This would lead to shallower MLDs near the coast. The observation of deepening winter MLDs near the coast suggest that they may be forced by atmospheric effects like increasing storminess in the region (Royer and Grosch, 2006).
CHAPTER IV
NUTRIENTS, HYDROGRAPHY AND MLDS

IV.1 INTRODUCTION

The central Gulf of Alaska is known as an HNLC (high nutrient, low chlorophyll) region and is iron limited (Freeland et al., 1997). On the continental shelf, iron may not be a limiting factor for primary productivity as it is believed to be provided from land sources (Burrell, 1986; Stabeno et al., 2004). The primary source of nutrients (nitrate, phosphate, silicate) is the deep ocean (Cooney, 2005) but how are these nutrients made available to primary producers in the upper layers of the northern continental shelf? While it is no longer believed that the winds in the region are strictly downwelling inducing (Schroeder, 2007), the mechanism of nutrient transport to the shelf has not been resolved. Possibly, there are multiple methods of nutrient transport from the deep ocean onto the shelf, for example, horizontal advection, eddy and frontal activity or flow along submarine canyons. Many authors have discussed the possibility of nutrients being brought up to the surface in the center of the gulf through the process of upwelling and then transported to the shelf in the Ekman layer (Stabeno et al., 2004; Weingartner et al., 2002). Strom et al. (2006) have noted the role of horizontal advection on the inner shelf. Childers et al. (2005) observed significantly enhanced nutrients in May 1999 on the outer shelf associated with the passage of an anticyclonic eddy. If the nutrients are brought onto the shelf at depth, vertical mixing might be responsible for lifting the nutrients into the euphotic zone and making them available for primary production. Of these theories of onshore transport of nutrients, the only ones supported by evidence so far is the transport of nutrients onto the shelf at depth in summer, when the downwelling is weak and preferential flow of nutrient-rich deep water up submarine canyons (Childers et al., 2005).

IV.2 DATA

Macronutrients (nitrate, phosphate and silicate) were sampled and analyzed at most stations along the Seward Line, for the years 1998 to 2001. Nutrient data were collected as part of GLOBEC LTOP in the Gulf of Alaska for all seven years, but
only four years data have been analyzed (1998-2001) and have been provided by Dr. T. E. Whitledge at the University of Alaska, Fairbanks. Twenty-five cruises were conducted in this time period (1998-2001). The chemical analyses of these samples are described in Childers (2005). An analysis of the nutrient distributions on the shelf of the northern Gulf of Alaska has been discussed by Childers et al. (2005). Ammonium will not be discussed here as Childers et al. (2005) have found that most of the primary productivity in the region is based on "new" (nitrate, nitrite) forms of nitrogen. In the euphotic zone, nutrient concentrations are affected not only by physical mechanisms of transport, but also by biological processes such as phytoplankton uptake and remineralization of organic detritus. To avoid complications due to biological uptake in the euphotic zone, the nutrient values used here are nutrients in the depth range of either 75 m to 300 m (or bottom depth for stations on the continental shelf) (for the correlation between nutrients and MLDs) or in the depth range between 150 m and 300 m. For the correlation analysis between MLDs and nutrients, the shallow depth of 75 m was chosen since the depth of 75 m made a good distinguishing point between the somewhat arbitrarily defined shallow and deep MLDs. 75 m is deep enough to be out of the euphotic zone and below the subsurface chlorophyll maximum, which, in the northern Gulf of Alaska, generally lies at depths between 10 and 25 m (Strom et al., 2006). However, it may not be completely out of the depth range of biological activity (Childers et al., 2005), though 150 m depth certainly is.

IV.3 METHODS

Methods used in this section are primarily correlation techniques using Spearman's method described in Chapter III. The nutrients are correlated with temperature and salinity fields across the Seward Line to visualize the pattern of correlation so that possible mechanisms of nutrient transport may be identified. Correlation techniques cannot identify cause-effect relationships. However, they can help to identify the possible mechanisms that might be of greater significance than others or even eliminate certain possibilities. Nutrients have been correlated to the timeseries of temperature and salinity and the anomalies of the nutrients have been correlated with the anomalies of temperature and salinity. The anomalies are obtained by removing the mean seasonal cycle. All the correlations reported here are at lag zero.
The correlations and significances were found to be highest when the data sets are temporally in phase with each other.

Hydrographic parameters at every 5 m depth interval are used. As mentioned above, nutrient data in the upper layers of the water column are affected by biological processes, and to avoid this complication, nutrient data below a certain depth have been used. For example, at station GAK 1, the nutrients in a chosen depth range (say 150-250 m) are averaged to yield a single number for total nutrients in that depth range for GAK 1. The average value is used because not all standard depths have been sampled for every cruise. This number is then correlated with a hydrographic parameter (temperature or salinity) at GAK 1 at 5 m depth intervals. This process is repeated for each combination of nutrient and hydrographic parameter, for each station. Similarly, MLDs are also correlated to the total "deep" nutrient at each station.

To test whether nutrients vary with the depth of the mixed layer, MLDs have been correlated with nutrients. Nutrients have been correlated to the MLDs obtained by both the SM algorithm as well as the Freeland method. The Freeland method supplies an annually occurring deepest winter MLD. The correlation analysis has only four data points in the timeseries for each station (representing the four winters/springs: 1997-98, 1998-99, 1999-2000 and 2000-01). This analysis was conducted since it has been hypothesized that the maximum winter MLDs set up a nutrient pool for the spring bloom. However, because of the short length of the timeseries (few data points), the analysis did not yield any meaningful results and the results have not been discussed. The SM algorithm returns an MLD for every cruise in the timeseries at each station, so a timeseries of 45 MLDs is available for correlation with nutrients at corresponding stations.

IV.4 RESULTS

IV.4.1 Correlation between hydrography and nutrients

The correlation between nutrients (nitrate/silicate/phosphate) and salinity across the Seward line and with depth (Figs. 19, 20, 21) show very similar patterns. At the inner and mid-shelf, below depths of approximately 75 m, nutrients show a highly significant (0.95 and above) positive correlation with salinity. Offshelf, silicate (Fig. 20) and phosphate (Fig. 21) have highly significant positive correlations throughout the
upper water column (to a depth of 500 m), but nitrate (Fig. 19) has significant high positive correlation at depths of 250 m and deeper. On the inner shelf, near the surface (to a maximum depth of 50 m), the nutrients have a significant negative correlation with salinity. This suggests that increases in freshwater (decreased salinity) are accompanied by increases in nutrients. This correlation is seen between GAK 1 and 1i for nitrate and GAK 1 to 3i for phosphate and silicate.

The nutrients are slightly more varied in their correlation pattern with temperature (Figs. 22, 23, 24). All three show a significant positive correlation with temperature near the surface on the inner and mid-shelf (from GAK 1 to between stations GAK 5i and 6). For nitrate (Fig. 22), the maximum depth of this pattern is 75 m near the coast and shallower offshore; for silicate (Fig. 23) the depth is almost 150 m and
for phosphate (Fig. 24) the depth is 150 m at GAK 1 and reaches the bottom near GAK 4i. In the offshelf region, nitrate has pockets of significant negative correlation (depths 150-200 m and 350-450 m at GAK 12). Silicate and phosphate have more extensive significant correlation with temperature. However, for phosphate these correlations are below a depth of 150 m.

While high correlations exist between the hydrographic properties and nutrients on a seasonal time scale, the only links might be the general seasonal fluctuations in the marine ecosystem. To delve further into the nutrient-hydrography relationship, the seasonal cycle of temperature, salinity and nutrients have been removed to yield anomalies. The nutrient anomalies differ in their patterns of correlation with salinity anomalies (Figs. 25, 26, 27). Nitrate anomalies have significant positive correlations with salinity anomalies at the inner shelf, throughout the water column (Fig. 25).
Fig. 21. Spearman’s rank correlation and significance between salinity and phosphate at depths 150-300 m.

This pattern extends from GAK 2 to GAK 2i at the surface, but up to GAK 4 at depths at and below 50 m. In the offshelf/slope region, high positive correlations are below a depth of 200 m with the core at GAK 10, around 300 m.

Silicate has positive significant correlations with salinity anomalies at depths below 150 m on the inner and mid shelf (GAK 1 to 6) (Fig. 26). Between GAK 5 and 6, there is also a region of high correlation at depths 50-100 m. Offshelf, significant positive correlations are at depths greater than 250 m, with the core between GAK 10 and 11, at around 300-350 m water depth. Phosphate shows no significant high correlations on the shelf, but significant positive correlations offshelf from the surface to 500 m.

The patterns of correlation between the nutrient anomalies and temperature anomalies are also different from each other (Figs. 28, 29, 30) and from the patterns of correlation of the nutrients with temperature. Nitrate anomalies have significant
negative correlations with temperature anomalies in the mid-shelf region (GAK 2 to 4) below a depth of 50 m (Fig. 28). Significant negative correlations are also seen from GAK 8 to 13, from the surface to a depth between 50 and 100 m for different stations. A small area of high negative correlation is between GAK 12 and 13, around 150 m.

Silicate anomalies are highly negatively correlated with temperature anomalies between GAK 4i and 6, almost all through the water column (Fig. 29). They are also highly correlated to temperature anomalies below 150 m near GAK 1i. On the slope, they are negatively significantly correlated below 100 m, offshore of GAK 11.

Again, phosphate and temperature anomalies show no significant high correlation on the shelf. However, a significant negative correlation exists offshelf through all the upper water column (500 m) at GAK 13, but only between 200 and 350 m from

Fig. 22. Spearman’s rank correlation and significance between temperature and nitrate at depths 150-300 m.
Fig. 23. Spearman's rank correlation and significance between temperature and silicate at depths 150-300 m.

GAK 10 to 12 (Fig. 30).

IV.4.2 Correlation between MLDs and nutrients

All the correlations are reported at zero lag, that have the highest significant correlations. MLDs are significantly (0.9 level and above) negatively correlated with nitrate (Fig. 31a, b), with values of $-0.4$ to $-0.75$ at many stations on the shelf at depths 75-300 m. Notable exceptions are GAK 2, 4, 4i, 5i-6i and 7i. GAK 2 has a very different pattern of correlation compared to all other Seward stations. This may be because it is located in the core of the ACC and is thus affected by different processes that are contained within the ACC. In general, correlations and significance drop off towards offshore, and they drop sharply at and beyond the shelf break. Phosphate is negatively correlated (correlations vary between $-0.4$ and
Fig. 24. Spearman's rank correlation and significance between temperature and phosphate at depths 150-300 m.

-0.65) which are significant at most stations on the inner and mid shelf (Fig. 31c, d). Stations GAK 6i and 7i also have highly significant correlations, but these stations have only seven observations. Silicate is significantly negatively correlated (−0.4 to −0.65) with MLDs at GAK 1i on the inner shelf and GAK 3i-5 on the middle shelf (Fig. 31e, f).

IV.5 DISCUSSION

Sub-halocline deep waters in the northern Gulf of Alaska have a low temperature (2 − 4°C) and high salinity (34.2-34.6) signature (Musgrave et al., 1992). Highly significant correlations of nutrients at depths between 150 m and 300 m with low temperature (negative correlation) and high salinity (positive correlation) across the shelf suggests that the nutrients on the shelf are from the deep ocean. This is seen in
Fig. 25. Spearman’s rank correlation and significance between salinity and nitrate anomalies at depths 150-300 m.

both the correlation of the nutrients and hydrography, as well as in the correlation of the anomalies. The nutrients are probably transported along the bottom of the shelf until they are brought up into the euphotic zone by some physical mechanism. This is supported by the correlation pattern of silicate and salinity anomalies (Fig. 26). Silicate acts more conservatively than nitrate or phosphate as it is used only in the inner shelf (Strom et al., 2006) or within eddies by diatoms (Ladd et al., 2007). Thus it is a relatively good proxy as a tracer offshore from the inner shelf.

The correlation of nutrients with the hydrography shows that the nutrients in the inner and mid-shelf region are significantly correlated with low salinity (negative correlation) and high temperature (positive correlation) in the surface waters. This significant correlation is not seen in the correlation of the anomalies. This suggests
that there may possibly be a separate source of nutrients in the inner and mid shelf region, replenished annually, associated with a low salinity and high temperature signal. This suggests various possibilities. Since these are the deep nutrients (150-300 m) which correlate highly with surface low salinity and high temperature, it might mean that high stratification increases deep nutrients by reducing removal to upper layers. This scenario does not yield any information about the source of these deep nutrients. Another possibility is related to the ACC. In the winter, the ACC is associated with cooler waters compared to the waters of the inner shelf and the ACC is slightly saltier than its summer/fall values. However, in the summer, the ACC advects warm, fresh waters into the inner shelf. So enhanced summer flows of the ACC might be a source of nutrients on the inner and mid-shelf regions. There is some evidence that deep nutrients are brought on the shelf preferentially at

Fig. 26. Spearman’s rank correlation and significance between salinity and silicate anomalies at depths 150-300 m.
Fig. 27. Spearman’s rank correlation and significance between salinity and phosphate anomalies at depths 150-300 m.

particular locations (e.g., up submarine canyons) and such upstream injections may be transported to the Seward Line by the ACC (Weingartner et al., 2002). Another possible source of nutrients is coastal runoff. Since the coastal terrain bordering the northern Gulf of Alaska is rocky and not cultivated, runoff is usually assumed to be nutrient poor (for example, Childers et al., 2005) but according to Burrell (1986), runoff may be a source of iron and silicate. Another source of nutrients in the runoff is marine derived nitrate and phosphate from salmon carcasses (Finney, 1998). This enrichment takes place in late summer and is remineralized within a few weeks in the euphotic zone (Dr. B. Finney, personal communication). The timing of this source is consistent with the low salinity, high temperature signature of the ACC at this time.
The negative correlations between MLDs and nutrients in the inner and mid-shelf regions implies that when MLDs are shallow, deep nutrients at depths between 75 m and 300 m are higher. In contrast, deep MLDs mix nutrients upwards, thus decreasing their concentration at depth. Even though the correlations are significant, in most cases, the values of the correlations are in the range of 0.4 to 0.7, which does not signify a very high degree of correlation. However, this may be because of the short length of the timeseries (4 years; maximum of 25 data points) and, in addition, the timeseries contains a lot of noise.

In the inner shelf, phytoplankton are dominated by diatoms (that require silicate) and spring and summer blooms are generally driven by new nitrogen (nitrate, nitrite). In addition, nitrate is generally understood to be limiting on the inner and mid shelf, sometimes as early as April and through the summer months (Strom et al., 2006).
Therefore mixing plays a significant role in providing silicate to diatom communities in the inner shelf. Mixing also provides nitrate and phosphate to phytoplankton communities in the inner and mid-shelf regions. According to Strom et al. (2006), phosphate is always present in excess of the Redfield ratio and is not considered to be limiting but according to Childers et al. (2005), all the nutrients are depleted if not actually limiting by April. At the shelf-break and offshore, nutrients are decoupled from MLDs. Other mechanisms would be of greater importance in bringing nutrients to the euphotic zone. Such mechanisms include advection by the Alaska Current, eddies and movements and mixing by fronts. Lateral advection is probably a very significant process but has not been studied much. Even in the inner and mid-shelf regions, advection plays an active role in transporting nutrients, as noted by Strom et al. (2006).
**IV.6 CONCLUSIONS**

High significant correlations between nutrients at depths of 150-300 m with high salinity and low temperatures strongly suggests that the source of nutrients to the shelf is the deep waters of the Gulf of Alaska. The nutrients are likely transported horizontally inwards along the bottom and not in the Ekman layer as proposed by Stabeno et al. (2004). A secondary source may be the Alaska Coastal Current during the late summer/early fall peak of freshwater discharge.

MLDs might not be the only significant mechanism for the vertical transport of nutrients on the shelf, as previously assumed. It is possible that the vertical transport of nutrients might be related to the relaxation of the downwelling winds. Royer (2005) suggests a two-layer system analogous to an estuarine system of onshore
Fig. 31. Spearman's rank correlation and significance between mixed layer depths and nutrients at depths 75 to 300 m. Horizontal axes show Seward Line station number.
flow in the bottom layer and offshore flow in the surface layer. This flow structure can be explained primarily by the relaxation of downwelling winds in the summer (Schroeder, 2007) and secondarily by the forcing due to the freshwater discharge near the surface at the coast, which is highest in early fall (October) (Weingartner et al., 2005). This theory is supported by observations by Childers et al. (2005) that the deep nutrients on the shelf are highest in summer. In this case, the nutrients would be transported inshore in the lower layer, brought to the upper layer near the coast and then transported out again in the upper layer.

Another mechanism by which winds may provide nutrients in the upper layers is by the mechanism of upwelling due to the curl of wind stress (Schroeder, 2007). This mechanism would be active near the mid-shelf, being strongest at GAK 3-5i. However, this upwelling is seen deeper in the water column (below 50 m) and does not bring nutrients to the surface (Schroeder, 2007; Weingartner et al., 2002). This deep upwelling differentiates this system from traditional upwelling regions like the California Current system (Weingartner et al., 2002). It also means that another vertical mixing mechanism, like deepening MLDs, may be required to make these deep upwelled nutrients available to primary producers.
CHAPTER V

CONCLUSIONS

The NEP GLOBEC program includes two target areas - the California Current System (CCS) and the Coastal Gulf of Alaska (CGOA). In this program, they are linked together by an out-of-phase relationship in their fish stock which is a result of an out-of-phase relationship in the atmospheric forcing (Mantua et al., 1997). However, the biological productivities of the two systems are sustained in entirely different ways. The CCS is sustained by equatorward winds, which lead to offshore Ekman transport and upwelling of deep, nutrient-rich waters to the euphotic zone. This supply of nutrients maintains a biologically rich ecosystem (Batchelder et al., 2002). In the CGOA, the winds are primarily downwelling inducing and the mechanisms(s) of nutrient transport to the highly productive ecosystem are not understood. The primary source of nutrients to the area is from the deep ocean and there are a number of potential pathways by which these nutrients can reach the shelf. These include (1) transport of nutrients from the upwelling region in the center of the gulf to the shelf in the Ekman layer and (2) transport along the bottom, possibly up submarine canyons. Most studies in the CGOA seeking to address how deep nutrients might be made available to primary producers in the euphotic zone refer to MLDs as the responsible mechanism (eg. Stabeno et al. (2004); Childers et al. (2005); Weingartner et al. (2005)). However, this is the first systematic study of the MLDs in the northern Gulf of Alaska that describes the temporal and across-shelf variability of MLDs along the Seward Line, the primary set of hydrographic stations sampled by the GLOBEC program.

Another major contribution of this study is that while MLDs are correlated with nutrients on the inner and mid-shelf, they are not associated with nutrients near the shelf-break and offshore. Thus other mechanisms are needed to explain the high productivity here. These possibly include the upwelling due to the curl of the wind stress and the estuarine-type circulation set up due to the relaxation of the downwelling winds. The anticyclonic eddies that frequent the area bring in some nutrients (Childers et al., 2005) but these eddies are probably too irregular in frequency to sustain such a stable ecosystem by themselves.

The deep ocean is the primary source of nutrients to the region, but a secondary
source might be the coastal runoff. Nutrients in the runoff could be from land sources (iron and silicate, Burrell (1986)) or marine derived (nitrate and phosphate, Finney (1998)). Marine derived nutrients in this particular region would probably include carcasses of pink and chum species of salmon, which are more prevalent in the area (Dr. B. Finney, personal communication). However, nutrients might also be advected by the ACC from farther upstream.

The lack of kinetic energy in the wind timeseries compared to the potential energy provided by the stratification leads to the speculation that the wind energy for deep mixing must be from storm events. Sambrotto et al. (1986) have shown that deep mixing is achieved by winter storms and this had significant effects on the timing and type of spring blooms in the Bering Sea. As discussed previously, MLDs seem to be responding to atmospheric forcing rather than oceanic forcing. The increased number of storms in the rapidly changing climate regime reported by Royer and Grosch (2006) would increase the deepening at the coast and the shoaling experienced at the mid-shelf.

The shelf has been treated primarily as a two dimensional system in this study. Across-shelf variability along the Seward Line has been addressed, but not the horizontal advection in the along-shore direction. The only horizontal advection addressed is that associated with anticlonic eddies which frequently intersect the Seward Line. The Alaska Coastal Current (ACC) on the inner shelf and the Alaska Current beyond the shelf-break are both major circulation features. The role of the ACC in advecting watermasses across the Seward Line has been noted by Strom et al. (2006). To understand the role that horizontal advection plays, data is required upstream of the Seward Line.

Interactions of the MLDs with bathymetric features have also not been addressed. On the mid-shelf, where the bathymetry is relatively shallow (150 m), mixing often takes place to the bottom. Flow interactions with the bottom could increase turbulence and enhance mixing. Bottom interaction has further implications for the nutrients also, especially iron. Iron is a micro-nutrient believed to be limiting in the North Pacific, making it an HNLC (high nutrient low chlorophyll) region (Freeland et al., 1997). It is believed that iron might not be limiting along the coast, since runoff is a source of iron (Burrell, 1986; Stabeno et al., 2004). Interactions of mixed layers with the shelf bottom may be another mechanism providing iron on the shelf.

The IPCC (2007) report confirms that current trends in climate should lead to a
warming and freshening in the CGOA. The question is, how would this trend affect MLDs (and primary productivity) in this area? Analysis of deepest winter MLDs shows a deepening trend near the coast and a shoaling trend offshore. Increasing insolation acts as the trigger for spring blooms, so deepened MLDs would delay the onset of the bloom and shoaled MLDs would lead to an earlier bloom. However, in late spring/summer, Strom et al. (2006) report that the system is not as light limited as previously believed (Gargett, 1997). Nutrients are possibly limiting at this time (Childers et al., 2005). Deepened MLDs would increase/elongate the period of bloom and shoaled MLDs would shorten/decrease the bloom.

Moreover, indirect effects of warming and freshening also need to be considered. These include, but are not limited to, changes in cloudiness, storm strength and frequency, and changes in circulation. To understand these complex interactions, further studies are required. Future sampling programs need to focus their efforts on long timeseries. An extensive sampling program might not be possible, but to understand and possibly predict long-term changes, long timeseries are required at least at a few strategic locations. Data collection is also required at specific sites to address specific research questions. These should include sampling near submarine canyons to understand the inflow of nutrient-rich deep water onto the shelf and high frequency sampling of hydrography, currents and nutrients to study the effect of the intense, episodic storms on MLDs and their relation to the nutrient transport into the euphotic zone.
REFERENCES


APPENDIX A

TIMESERIES OF MLDS ALONG THE SEWARD LINE
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