University of Alberta

Investigation of Mixed Layer Depths along Line P and thoughout the Gulf of Alaska using Historical Data and Argo Floats

by

Jing Li ©

A thesis submitted to the Faculty of Graduate Studies in partial fulfilment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

Edmonton, Alberta
Spring 2005

Your file Votre référence
ISBN: 0-494-08113-9
Our file Notre référence
ISBN: 0-494-08113-9

University of Alberta

Library Release Form

Name of Author: *Jing Li*

Title of Thesis: *Investigation of Mixed Layer Depths along Line P and thoughout the Gulf of Alaska using Historical Data and Argo Floats*

Degree: *Master of Science*

Year this Degree Granted: *2005*

Signature

Dec 22 2004

Abstract

Mixed layer depths are computed, based upon a new method proposed by Kara et al. (2000), for historical measurements along Line P, in the Gulf of Alaska. Forty- six years of data are used for the monthly climatological calculations. To examine variability, the data are divided into two periods, based around the changes that occurred in the 1970s, except at Station P, where a sufficient abundance of data permits the examination of monthly mixed layer changes over 5 year pentads. These results are also compared with the main modes of climate variability in the Pacific, such as PNA (Pacific/North American) and WP (West Pacific) to see which of those climate modes is driving the Station P MLD (mixed layer depth) variability in a given season.

Mixed layer depths are also computed from Argo floats and mapped onto the Line P stations using an objective analysis method. Argo data from 2001, 2002 and 2003 are used. Using the historical measurements for validation, the mixed layer depths estimated from the Argo floats agree well with the shipboard observations. The 2003 data show reduced mixed layer depths that occurred in winter 03/04. Furthermore, the objective analysis scheme is used to map the Argo mixed layer depths throughout the Gulf of Alaska. Finally, the correlation coeffcients between monthly average MLD in the Gulf of Alaska and Ekman pumping are calculated. The extreme r value is -0.64 which shows the Ekman pumping is a key contributor to MLD variability in the Gulf of Alaska.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 General Review

Ocean waters are arranged in a sequence of horizontal layers of increasing density from the surface to the ocean bottom. The upper region of the ocean usually displays a surface mixed layer that is of uniform or nearly uniform density. The depth of the mixed layer varies from a few metres to several hundred metres depending on the time of year (season) and location. The mixed layer is the link between the atmosphere and the deep ocean and directly affects the air-sea exchange of heat, momentum and gases. Moreover, turbulent flows in the mixed layer affect biological productivity by controlling both the supply of nutrients to the upper sunlit layer and the light exposure of phytoplankton. The turbulent mixing in the mixed layer is primarily driven by the surface wind stress and convective buoyancy flux (Segar, 1998). Weak turbulence leads to a shallow mixed layer, and a well stratified layer acting as barrier to vertical mixing of disolved gases and upwelling of nutrients below. Shallow mixed layers are usually associated with poor, or low productivity, and vice versa for deep mixed layers.

Since 1999, Alaska salmon stocks have experienced dramatic population declines. This has raised a strong interest in studying the salmon's complicated life history, such as its varied habitats, its numerous prey and predators, to enhance our understanding of the factors driving the population oscillations of this economically important fish. One significant potential factor has been ignored until recently. After smolts (young salmon) migrate to ocean, they will spend one to four years in the upper ocean becoming adult salmon (http://www.fish.washington.edu/hatchery/salmon.html). This is an important facet of salmon life history. Thus over the last 50 years, have they lived in a high productivity environment or a low productivity environment? We are now in a good position to explore the question of mixed layer depth variability and other significant physical variables (such as temperature, salinity) in this region. Moreover, obtaining information on the variations of the mixed layer depth on seasonal and longer time scales in the Gulf of Alaska is essential for understanding the ocean's link to the Aleutian Low (and possible climate variations) and can also be used as guidance in numerical modelling of the upper ocean.

Argo is a program proposed by an international team of scientists, which began in 2000. It will deliver a global array of 3,000 free-drifting robotic floats to observe the ocean's upper and intermediate layers and report the results in real time through satellites. Argo floats can be deployed from a variety of ships and aircraft. The great advantage of the floats is that after deployment they will continue to operate unattended. Argo floats drift at depths between 1km and 2km. Every 10 days each float surfaces and measures a profile of temperature and salinity. These data and the float's position are transmitted to satellites and the float then dives to start a new cycle. The global Argo data set is available on the http://www-argo.ucsd.edu/. Currently 50% of planned Argo floats are in place with completion expected by the end of 2006. Until now, Canada has contributed 86 floats, through the Department of Fisheries and Ocean, Canada.

1.2 Literature Review

West of British Columbia and south of Alaska lies the Gulf of Alaska, a large open body of water part of the general North Pacific Ocean. The large-scale circulation within the basin is mainly wind-driven and cyclonic, part of the larger sub-polar gyre circulation. The southern branch of the gyre is the Subarctic Current at 50° (Musgrave et al., 1992), which bifurcates as it approaches the North American coast (Fig. 1.1). The northern branch of this bifurcation flows northward as the Alaska Current (as a broad and diffusive flow - Musgrave et al., 1992).

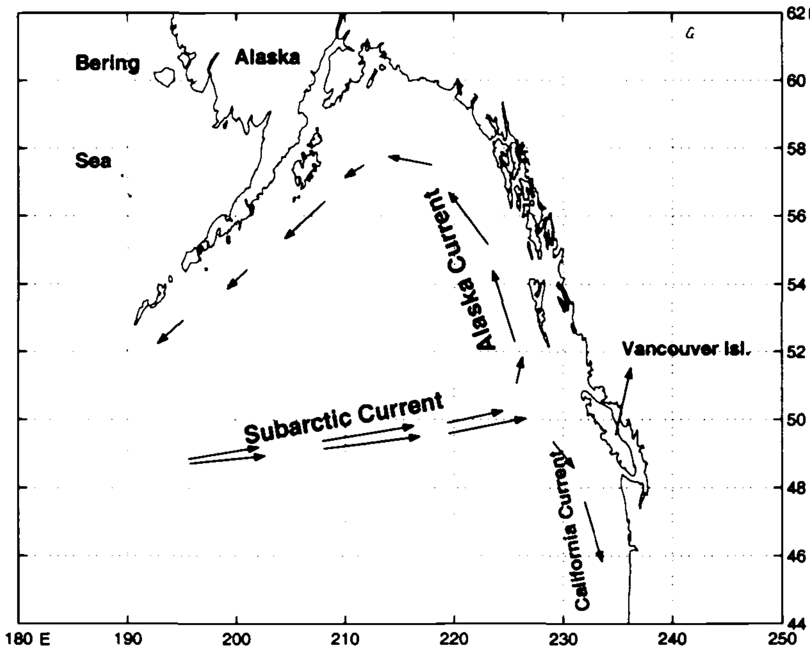

Figure 1.1: Map of the Gulf of Alaska with the main currents

As the Alaska Current reaches the head of the Gulf of Alaska, it turns westward and intensifies. The narrow intense jet that is formed is often referred to as the Alaskan Stream. The transport of the stream has been estimated to be 12 Sv ($10^6 m^3 s^{-1}$), referenced to 1500 db, with little longshore variability (Reed et al., 1980) and 12-18 Sv, also referenced to 1500 db, by Musgrave et al. (1992). Myers and Weaver (1997) estimated the transport as 20 Sv using a diagnostic finite element model. Although this transport estimate was larger than the previous observational estimates, Reed et al. (1980) and Reed (1984) noted that the choice of a reference level at 1500 db underestimates the baroclinic transport by 3-8 Sv, depending on location.

West of 158° the transport increases, with a recirculation region south of the stream (Reed, 1984). West of 180° 12-15 Sv is estimated to flow into the Bering Sea, while the rest of the Alaskan Gyre recirculates south of the Aleutians (Reed, 1984). At 175°W, Warren and Owens (1988) computed a transport of 28 Sv, while the diagnostic study of Myers and Weaver (1997) estimated 30-35 Sv. Warren and Owens (1988) also found an eastward flowing deep current over the Aleutian Rise and Aleutian Trench.

Within the gyre, Ocean Station P (50 00°N , 145 00°W, depth 4220 metres) was operated as an ocean weather station from 19 December, 1949 through 20 June, 1981 (Tabata and Weichselbaumer, 1992). Connecting Station P to the mainland (southern tip of Vancouver Island) is a 1500 km oceanographic section called Line P (Fig. 1.2), occupied at approximately 6 week intervals between April 1959 and June 1981 by Canadian weather ships and then subsequently at irregular intervals by research vessels (Whitney and Freeland, 1999). Initially 13 stations were established along Line P, with additional stations being gradually added over time with, in general, 26 or 27 stations now taken along the line (Tabata, 1991).

Located near where the Subarctic Current bifurcates, the transport across Line P

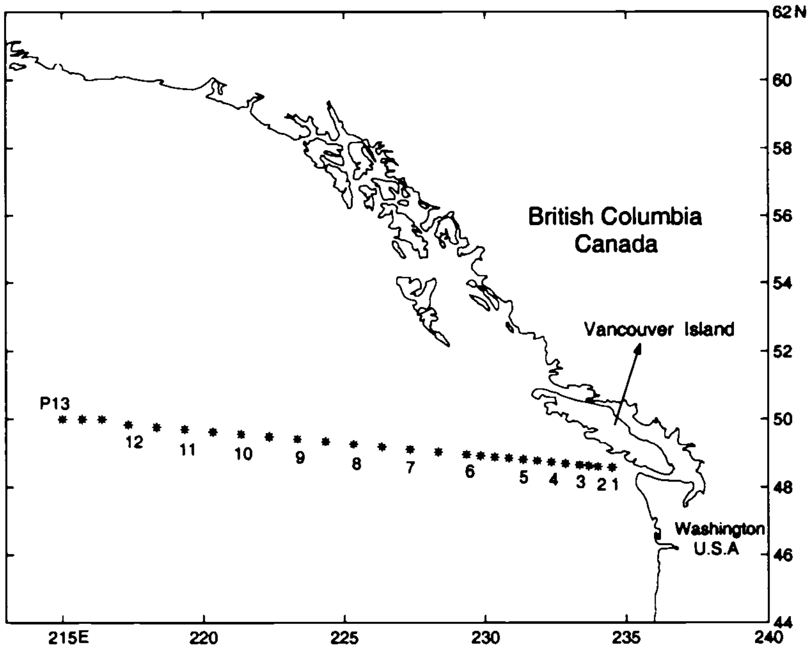

Figure 1.2: Map of the western Gulf of Alaska, showing Line P with original 13 stations indicated.

represents that of the Alaska Current (or at least a significant portion of it). Tabata (1991) found that of about 10 Sv total northward transport, 5.0 ± 1.8 Sv crossed Line P (with little intra-annual variability), relative to 1000 db, with the transport increasing linearly to at least 1200 db and with still more transport possible deeper in the water column, up to 1500 db. From their diagnostic model, Myers and Weaver (1997) estimated just under 8 Sv crossing Line P, as part of a 10 Sv total transport north into the Gulf of Alaska.

Many studies have shown the existence of low frequency variability in the upper ocean in the Gulf of Alaska. Mysak (1986) showed how the position of the Subarctic front and the temperature structure along the British Columbia coastline changes in accordance with ENSO (El Niño Southern Oscillation). Royer (1981) noted that interannual variations in the transport of the Alaskan Stream could be as large as 30% and later that very low frequency fluctuations (of 1-3 decade duration) occurred in sea surface temperature north of 55°N (Royer, 1989). Tabata et al. (1986) described annual and interannual variability of thermosteric, halosteric and total steric heights along Line P, while Tabata (1991) found interannual variability in the transport across Line P (both the entire line and also the western half) with a period of 3-4 years (and with events often having a persistence of at least 4 years). More recently, many studies have shown that upper ocean variability in the Gulf of Alaska is generated by fluctuations of the Aleutian Low (Lagerloef, 1995; Miller et al., 1994).

Trenberth and Hurrell (1994) described an abrupt climatic shift that occurred in the mid-1970's, associated with a deepening of the Aleutian Low, deeper mixed layers and lower sea surface temperatures in the central northern Pacific and higher sea surface temperatures along the coast. This led to a shift of the Alaskan Gyre to the east, with a stronger circulation (Lagerloef, 1995). This was followed by an increase in sea surface temperatures during the 1980's. It was additionally noted that much of the upper ocean climatic variability was wind forced, driven by fluctuations of the Aleutian Low (Lagerloef, 1995; Miller et al., 1994). Deser et al. (1996) examined the vertical structure of thermal anomalies between the surface and 400 m between

1970-1991, noting the origination of cold pulses at the surface that descended with time into the main thermocline. They (Deser et al., 1996) found that these changes were associated with changes in the mixed layer depth, but the spatial patterns of the changes were not the same as for sea surface temperature. Variability in the depth of the pycnocline was seen at Station P by Freeland et al. (1997), with a shoaling from 1957-1994. Changes in upper ocean temperature in the Gulf of Alaska were also noted by White and Cayan (1998), as part of their global study. Tourre et al. (1999) noted that inter-decadal variability in sea level pressure and sea surface temperature was coherent and quasi-periodic, related to a decade(s) long cycle, which included the regime shift previously seen in the Gulf of Alaska in the mid-70's. Cummins and Lagerloef (2002) showed that a large percentage of the pycnocline depth variability, at least at Station P, could be explained by the integrated response to local Ekman pumping. Capotondi et al. (2004) extended the previous work, to show using an ocean general circulation model, that a large fraction of the pycnocline variability could be explained by the local Ekman pumping, over much of the Gulf of Alaska.

In the first part of my research, the variability of mixed layer depth along the entirety of Line P (the original 13 stations) has been examined by using all available ship-based data. We focus on both the seasonal cycle and the long term variability, examining periods before and after the proposed regime shift of 1976/77. In the second part, the Argo data are validated through a comparison with ship-based Line

P data. We then map mixed layer depths throughout the Gulf of Alaska using an objective analysis scheme. We also consider factors that set the mixed layer depths through the Gulf of Alaska, and how representative values along Line P (e.g. Station P) are in comparison to the rest of the gyre.

Chapter 2

Data and Methods

2.1 Data Summary

The mixed layer depth at the 13 original Line P stations has been estimated with temperature and salinity data from 1956-2002 (Fig. 1.2). Only these 13 old stations have been used because they have the longest historical records. The use of these 13 stations can also avoid a bias resulting from a strong sampling frequency oscillation, as the frequency of sampling significantly declined when the numbers of stations was increased to 26 (Whitney and Freeland, 1999). The main information provided by the CTD and Argo floats are pressure, temperature and salinity in the upper water column. Density is calculated using the algorithms suggested by Fofonoff and Millard (1983).

To get the monthly and seasonal mean mixed layer depth from these data, average quantities must be computed in each case to avoid a bias from frequency oscillation (Whitney and Freeland, 1999). Calculations are made on individual profiles and then monthly unbiased statistics are computed for each station. This deals with the issue that for some stations very limited data coverage exists in some months. For all of the Line P stations, Station P was the richest in data coverage.

Argo data are available in near real-time through the Argo data servers. Based on software created by Dr. Howard Freeland at the Institute of Ocean Sciences, we have created an Argo data mirror here at the University of Alberta that updates our local database with all relevant float data for our study region. Our study region includes the Gulf of Alaska, from 46°N and 200°E to the North American coastline.

Finally for the Ekman pumping calculations, the monthly wind speed, SST (sea surface temperature) and air temperature data in Gulf of Alaska area have been downloaded from the NCEP/NCAR Reanalysis Data website (http://www.cdc.noaa.gov/). Wind stress was calculated from these data. Then Ekman pumping velocity from wind stress was computed.

2.2 Method of MLD calculation

A number of different methods have been used to estimate mixed layer depth or isothermal layer depth. For example, threshold methods, which use a gradient criterion, define the surface layer as the depth h at which the (potential) density difference in the upper ocean exceeds some surface reference value, usually $0.01 - 0.03 kgm^{-3}$. Another popular method is the integral method, which is also called the trapping depth. It can be described by the following equation (Freeland et al., 1997).

$$h = H \frac{\sigma_H - \sigma_m}{\sigma_H - \sigma_0} \tag{2.1}$$

where, σ_0 and σ_H are the value of σ_t (density) at the surface and at the reference depth H which can be chosen arbitrarily between 200 to 500 metres. And σ_m is the average value of σ_t between the surface and reference depth H. Although this method is insensitive to the choice of H between 200 to 500 metres, it requires deeper profiles. Unfortunately, deep profile data do not always exist.

Recently, Kara et al. (2000) developed a new method for estimation of mixed layer depth. They used an absolute change in $\Delta\sigma_t$ (or ΔT) with respect to an approximately uniform region of density (or temperature) just below the surface. They also showed this method is able to estimate the mixed layer depth more accurately than the gradient criterion.

Firstly, choose the density (σ_t) at 10 metres as the initial reference density value (σ_t^{ref}). Then determine a threshold $\Delta\sigma_t$ from the corresponding temperature change ΔT:

$$\Delta\sigma_t = \sigma_t(T + \Delta T, S, P) - \sigma_t(T, S, P) \tag{2.2}$$

Currently used values for ΔT range over 0.2°, 0.5°, 0.8°, and 1.0°C. This scheme then defines a uniform region such that the difference between any pair of density values at adjacent depths in the profile must be smaller than one-tenth $\Delta\sigma_t$. All pairs of density values (σ_n and σ_{n+1}) at adjacent depths (h_n and h_{n+1}) in the profile are compared to see if the difference is less than one-tenth of a density difference criterion $\Delta\sigma_t$. If so, then the density value σ_t at the shallower depth h_n is used to update σ_t^{ref}. This is done for every pair of density values in the uniform region. Thus the reference density is always at the base of the uniform layer. If the adjacent density values do not meet the criterion, then the density for the base of the mixed layer is determined by:

$$\sigma_t^b = \sigma_t^{ref} + \Delta\sigma_t \tag{2.3}$$

Finally, the depth of σ_t^b is found by linear interpolation from the profile depths. This depth is our mixed layer depth. If we can't find the depth of σ_t^b, then we begin the search from the reference depth at 10 metres.

In this paper, $\Delta T = 0.8$ has been chosen such that it gave an optimal estimate of MLD in the North Pacific (consistent with Kara et al. (2000)). Using an absolute change of density in the upper uniform region can avoid problems with oscillations in the upper layer's data in the profile. From equation (2) and (3), to get $\Delta\sigma_t$, this method considers not only salinity variation, but temperature change as well. This is the big difference compared with other methods. Mixed layer depth computed using more traditional methods was calculated, but the results were found to compare poorly with estimates of MLD determined by visual inspection of profiles.

2.3 Method of data gridding

To map the Argo data over the Gulf of Alaska as well as to project it to fixed locations, such as the Line P stations, we have to grid these irregular data using an objective analysis technique based on the modification of a technique of successive corrections (Levitus, 1982). The scheme is described as follows:

$$S = S_{guess} + \frac{\sum W_i Q_i}{\sum W_i} \tag{2.4}$$

$$Q_i = S_i - S_{guess} \tag{2.5}$$

$$W_i = 0 \qquad r_i > R \tag{2.6}$$

$$W_i = \exp(-\frac{4{r_i}^2}{R^2}) \qquad r_i \leq R \tag{2.7}$$

where r_i is the spatial distance between the observation S_i which denotes MLD and a grid point. Effectively the scheme works by correcting an initial guess S_{guess} by the weighted mean of the difference between that value and all measurements of S_i that are within a given influence radius R. The corrected value S can then be used as a new initial guess when repeating the procedure with a smaller influence radius. We used 8 iterations, based on radii of influence descending from 800km to 100km in steps of 100km to grid the Argo data along Line P. For gridding the Argo data over the entire Gulf of Alaska, we used 5 interations with an initial radius 500km and decreasing steps of 100km.

2.4 Method for determining Ekman Pumping

In the ocean, upwelling occurs when there is a divergent flow at the ocean surface. Upwelling occurs along the equator, in sub-polar regions, and along some coastlines, such as the Peru and California coastline. These regions are associated with high biological productivity, as high-nutrient deep water is brought to the surface. This phenomenon of mid-ocean divergence is called Ekman pumping. The upwelling velocity W_e can be given by

$$W_e = \frac{1}{\rho f}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right) \tag{2.8}$$

τ_x and τ_y are the wind stress components in x and in y directions. The term $\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}$ is the curl of the wind stress. When it is positive, there is divergence, and upwelling, and vice versa. Where $\rho = 1 \times 10^3 kgm^{-3}$, $f = 2\Omega \sin \varphi$, φ is latitude and

$\Omega = 7.27 \times 10^{-5} s^{-1}$.

Wind stress can be calculated from following formular:

$$\vec{\tau} = \rho_a C_D \vec{v}_a \sqrt{u_a^2 + v_a^2} \tag{2.9}$$

where C_D is the quadratic bottom drag coefficient (Haidvogel and Beckmann, 1999). $\vec{v_a}$ is the atmospheric wind over the sea surface and u_a, v_a are the wind component. ρ_a is the air density. The monthly mean wind data are from NCEP/NCAR Reanalysis website (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html).

Chapter 3

Results

3.1 Mixed layer along Line P

First, the long term climatological mixed layer depth are presented, for each station and month, along Line P. as well as a more detailed representation of the annual cycle at several stations (Fig. 3.1). MLD increases with increasing distance from the coast where haline effects are dominant and the MLD is shallow year round, to those further offshore, where a pronounced seasonal cycle is visible. Under strong winter thermal forcing, long term average mixed layer depths reach 110 m at Station P. Except in certain spring and autumn months, mixed layer depth always increases as one moves offshore. There is little difference in summer mixed layer depth anywhere along the line.

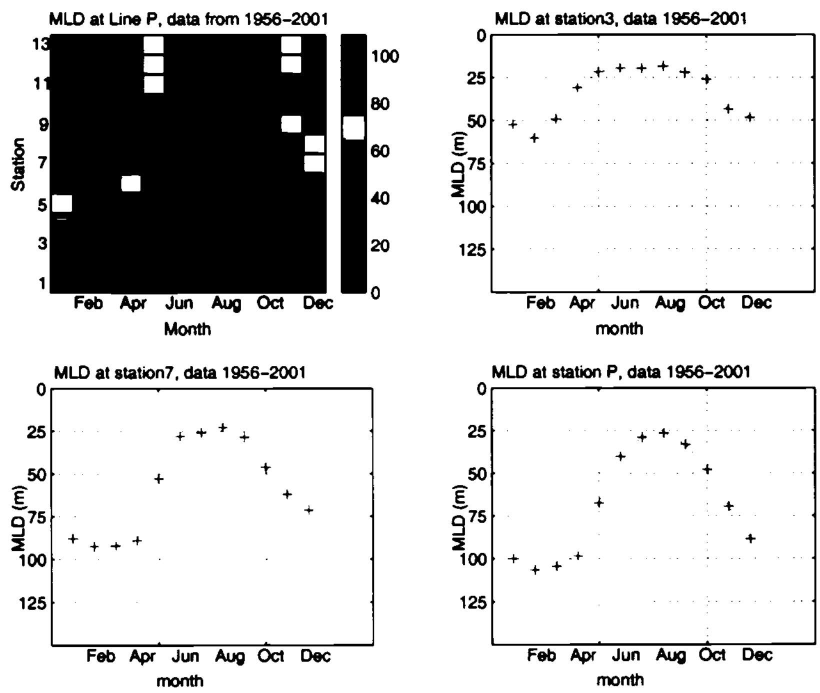

Figure 3.1: a) Mixed layer depth, at each of 13 stations along Line P, averaged over 1956-2001, for each month of the year; b) c) and d) show the long term average annual cycles of mixed layer depth at stations 3, 7 and P respectively. Unit: metre

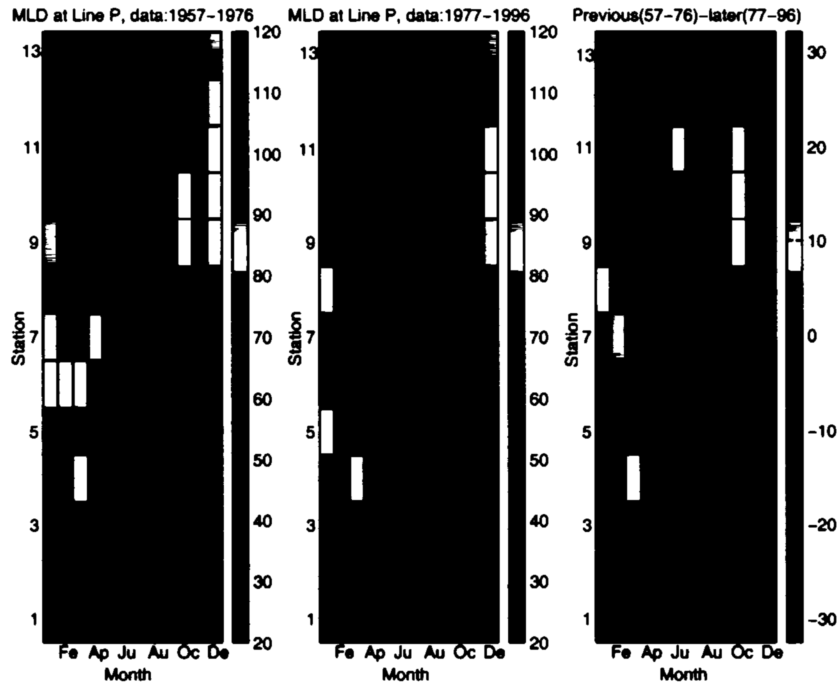

Figure 3.2: Average annual cycles of MLD along Line P in two successive time periods. White blocks indicate where we were lacking data for the analysis. The third figure is a difference plot between the two time periods. MLD unit: metre

Many authors have discussed the possible regime shift that occurred in the Gulf of Alaska between 1976/77 (Trenberth, 1994). As such a change would have left a significant signature on mixed layer depths, This field over two period has been estimated, 1957-1976 and 1977-1996 (Fig. 3.2). Averaged periods have been considered and not each individual year due to a data sparcity in many months and years.

If one were just to calculate the average MLD over all stations and months in each period, one would find little difference, with 49.9 m for 1957-1976 and 52.1 m for 1977-1996. The changes instead are more local in both space and time. For the stations just off the edge of the continental shelf (i.e. 4 and 5), there has been a deepening of the maximum winter mixed layer from 66.6 m to 84.9 m, combined with a phase shift to maximum mixed layer depths later in the spring. As one moves farther offshore along Line P, one does find a general shoaling of the mixed layer depth in late fall (December onwards) through to February. However, through the 1977-1996 period, there is a phase shift in the end of winter, with little decrease in mixed layer depth through April and substantially deeper mixed layer, 60-75 m, at the offshore stations, through May. For some stations, such as 9 and 11, the data are also suggestive that the deepest mixed layers are now being seen as late in the year as April.

Only Station P, has enough data to allow us to examine the changes in mixed layer depth over shorter time periods. Here 5 year pentads have been considered, from 1956-1960 through to 1996-2000 and examine each season (Fig. 3.3). These results show significant higher frequency variability in the mixed layer depth, and suggest that more complicated processes than a simple regime shift may be at work here. Even between 1970-75 and 1975-1980, the mixed layer behavior is not consistent through all seasons. The greatest variability is seen in spring. These results at Station P are consistent with those from the two period analysis in that there was a significant deepening in spring over most of the recent pentads. However, this deepening was not uniform, reaching a maximum in 1991-1995 and then shoaling. The wintertime mixed layer depths do not show any trend, instead with a more pronounced decadal

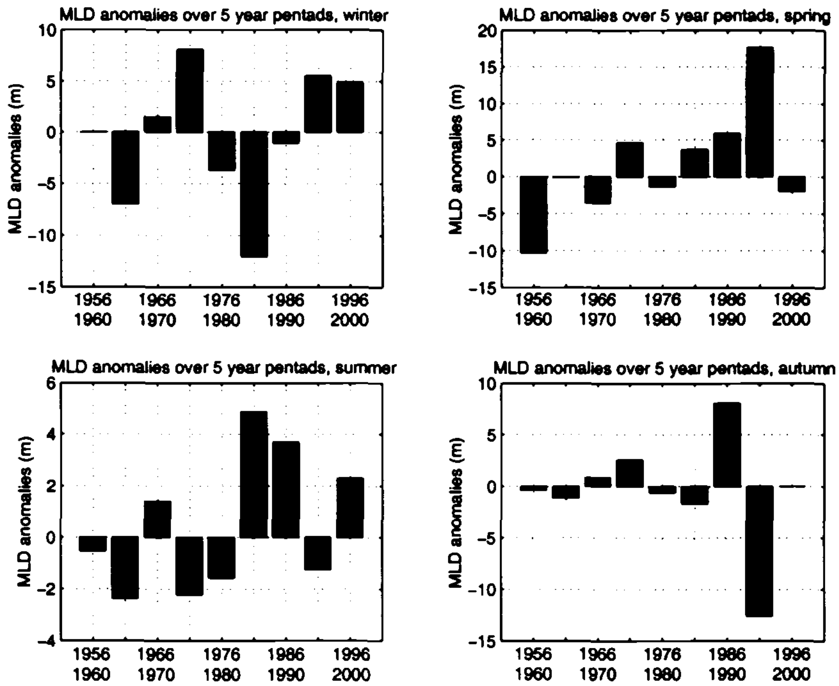

Figure 3.3: MLD anomalies at Station P of average annual cycles over 5 years pentads in different seasons. The last pentad in autumn is missing data rather than zero. Winter: Jan. to Mar., Spring: Apr. to June, Summer: July to Sept., Autumn: Oct. to Dec.

variability.

Table 3.1: Correlation coefficient of the main climate modes and seasonal MLD anomalies at Station P

Corr. Coef.	NAO	WP	EP	NP	PNA	PT	ENSO
Spring MLD	0.17	0.18	-0.31	0.36	0.18	-0.29	0.52
Summer MLD	-0.05	-0.36	0.50	-0.11	0.27	0.56	0.05
Autumn MLD	—	—	—	—	—	—	—
Winter MLD	0.31	0.01	0.02	0.44	-0.36	—	-0.27

To attempt to clarify the driving mechanisms for the variability in mixed layer depth along Line P, we correlate our seasonal pentadal time series at Station P with similar seasonal pentadal timeseries of major climatic indices (based on data available from the NOAA Climate Prediction Centre, www.cpc.noaa.gov). Spring mixed layer depths correlate with ENSO, with an r value of 0.52. The summer time MLD best correlates with the Pacific Transition Pattern (PT), with an r value of 0.56. This summer pattern showed two of its most pronounced negative phases during July of 1992 and 1993, leading to above normal 500 mb heights above the Gulf of Alaska during this period, leading to weaker winds and shallower summer mixed layers. The winter MLD depths do not correlate as well with any atmospheric pattern, with an extreme r of -0.36 with the Pacific/North American Pattern (PNA). This is most evident during the 1976-88 period when the PNA pattern was persistently positive and the MLDs through the Gulf of Alaska were persistently shallow.

3.2 MLD from Argo Data

Before using the Argo data to map MLD throughout the Gulf of Alaska, we must validate it against existing ship-based data. In fig. 3.4, we compare MLD along Line P during two months (August 2001, February 2002) with MLD depths obtained from Argo floats during those months, and then mapped onto the location of the Line P stations. The comparisions in August 2001 are poor, but we must remember that the Argo program was only initiated in 2000, and thus this analysis is based on a very limited number of floats (i.e we only had 20 floats available in the Gulf of Alaska for

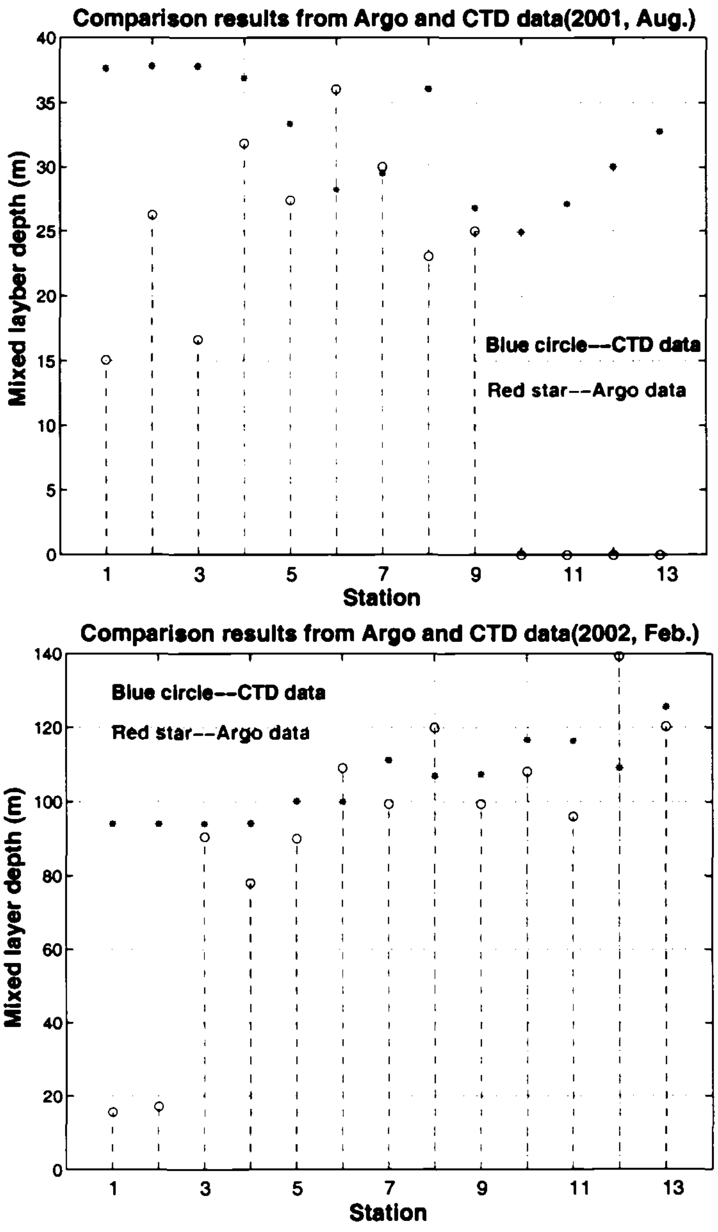

Figure 3.4: Comparison of CTD and Argo MLDs in two different months. Where a value of zero is given, no data were available.

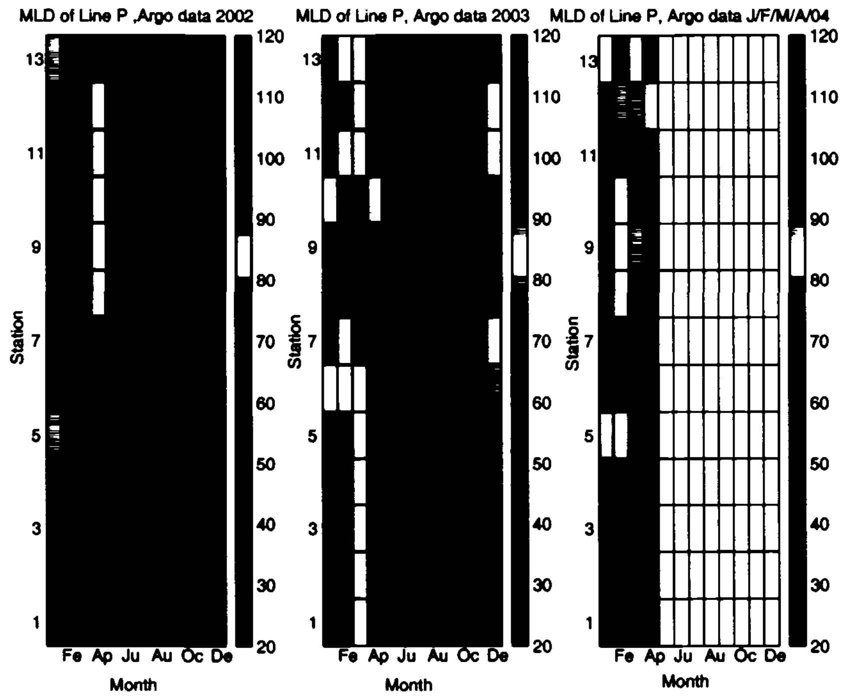

Figure 3.5: MLD projected along Line P from January 2002 to April 2004 computed from Argo floats, MLD unit: metre. Stars denote the location of the grid points.

the objective analysis in Aug. 2001). The errors are significantly reduced by February 2002 as more floats were deployed and more profiles became available. And there is no systematic over or underestimation bias with the Argo floats based MLDs. The significant overestimate of the MLD has been noted at stations 1 and 2 as compared to the ship data is because these two stations are coastal (in 120 metres and 114 metres of water respectively) and thus one would not expect an agreement with deep water Argo profiles mapped to these location.

Fig. 3.5 reprents the winter time MLDs from the Argo data declined precipitously from 2002 to 2003. But the MLDs start to deepen again through the winter of

2003/2004. There is also a location shift for the deepest MLDs. Deep MLDs ($> 100m$) occured through Jan. to Mar. 2002 in several offshore stations(i.e. Station 7, 10, 12, 13), but MLDs ($> 100m$) only occured at Station 9 in Feb. 2003. A year later, the MLDs are greater than in the previous year but are still shallow (only $> 100m$ at Station 11, and then only in March). These patterns can be observed from the edge of the continental shelf, all the way out to Station P. In 2002, deepest MLDs occur in February and March, with a rapid shoaling through April and May. In 2003, the core shallow MLDs are seen throughout the entire winter, reaching a maximum for many stations in April. MLDs are generally deeper in 2004 than 2003, especially among the stations closest to Station P. At these stations deepest MLD generally reached in February, but there is little shoaling through the end of April.

For mapping the MLD throughout the Gulf of Alaska, a grid point resolution of 6 degree in the zonal direction and 3 degree in the meridional direction has been used. Setting the grid point resolution depends on the float density in the study area. Choosing the coarse resolution is because of the relatively low density of float coverage in the first few years of the Argo project. Again the MLD results are gridded by an objective analysis technique, using an initial search radius of 500km with decreasing steps of 100km.

Fig. 3.6 shows the MLDs mapped through the Gulf of Alaska for winters 01/02 to

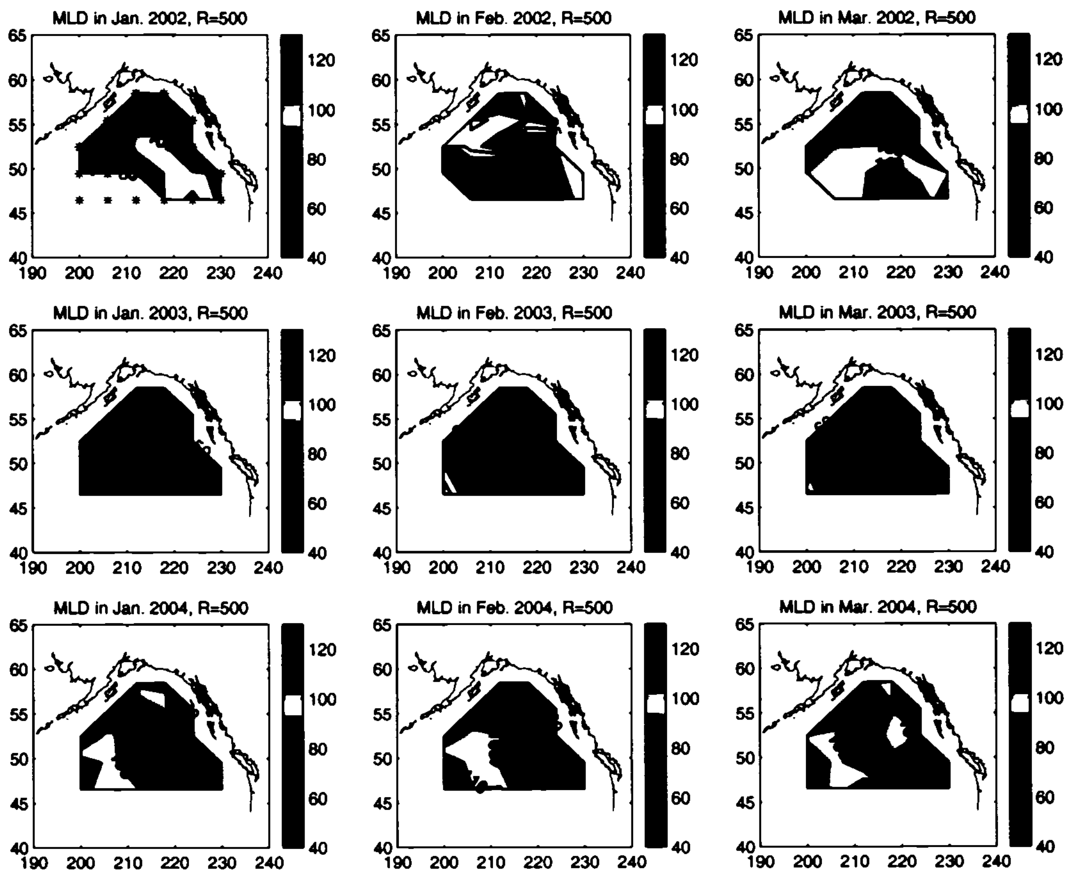

Figure 3.6: MLD mapped from Argo data for three winters (2002-2004) in the Gulf of Alaska. MLD unit:metre

03/04. White regions in the winter of 2002 are due to a lack of data. As before, the strong shoaling of the MLD throughout the region in the winter of 02/03 is clearly visible. These results show that this phenomenon is basin wide, although there is spatial structure in the shoaling patterns. Maximum wintertime mixed layer depths decrease towards the north and east, with large tongues of shallow MLD extending from the British Columbia and Alaska coasts in the winter of 2003.

Although the MLDs are deeper in the winter of 03/04 than for the winter of 02/03, a similar spatial pattern is seen, with a decrease in MLD towards the north and east. In the winter of 01/02, besides having the deepest MLDs of the three winterss, the spatial pattern is also different-with a significant slope in maximum MLD upwards from the south to the north. Additionally, unlike the two later winters when the maximum MLD occurs in March/April for the central Gulf of Alaska, in the winter of 01/02 the maximum MLD is earlier in winter, in February.

For the early spring (April) in 2002, in the center of the Gulf of Alaska, the MLDs are quite deep although shallower than earlier in winter and surrounded by shallow depths (Fig. 3.7). Suprisingly, the MLDs are deeper over much of the region in April 2003, even though the MLDs were much shallower in winter 02/03 (e.g. MLDs reach 70m in May 2003). From Fig. 3.8, we can see there are quite uniform MLDs of 20 to 40 metres throughout the Alaska Gyre in summer of these two years. Later on, in

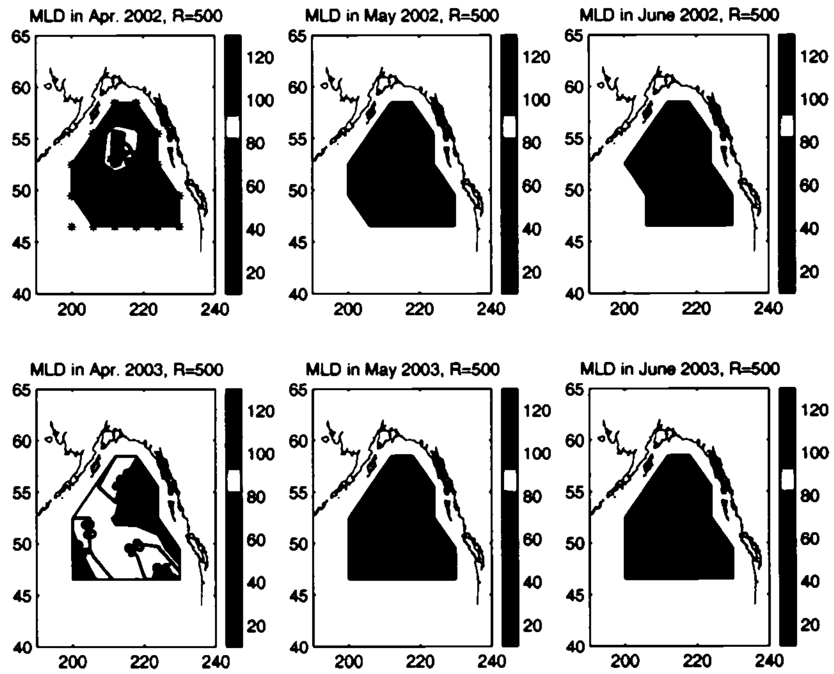

Figure 3.7: MLD mapped from Argo data for two springs (2002,2003) in the Gulf of Alaska. MLD unit: metre

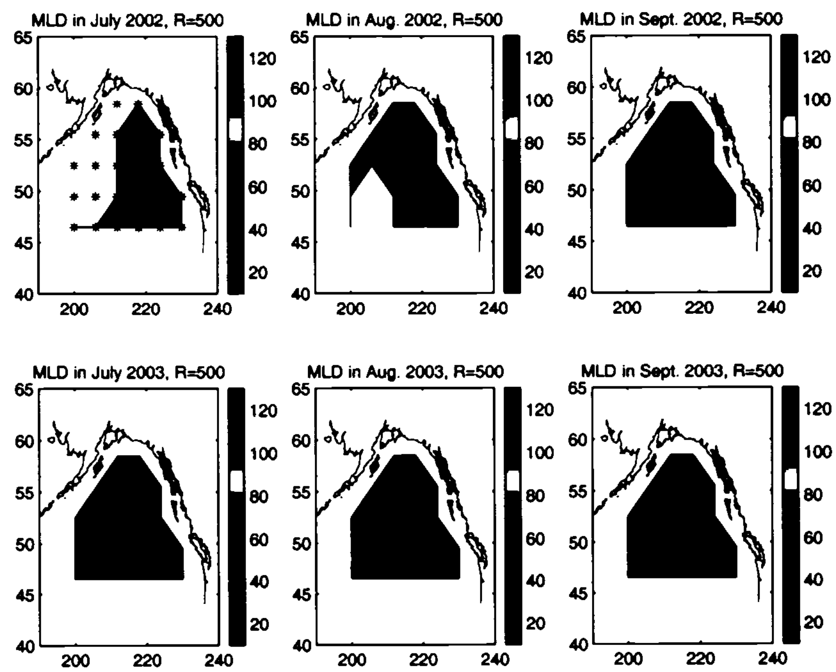

Figure 3.8: MLD mapped Argo data for two summers (2002,2003) in the Gulf of Alaska. MLD unit: metre

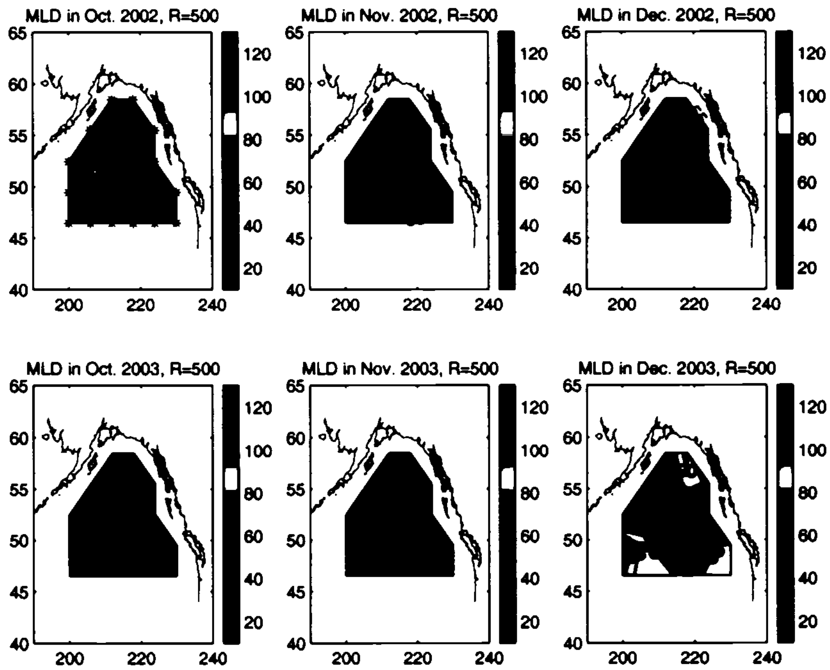

Figure 3.9: MLD from mapped Argo data for two autumns (2002,2003) in the Gulf of Alaska. MLD unit: metre

autumn (Fig. 3.9), we see little deepening of MLDs in 2002, but a rapid deepening in November and December of 2003. The deepening first occurs in the coastal eastern and south eastern parts of the gulf, with the shallowest MLDs in the late fall being found in the center of the Gulf, near the location of Station P.

Monthly MLDs of Gulf of Alaska from January 2002 to Arpil 2004 have been calculated by averaging MLD at all grid points in the basin (Fig. 3.10). The annual variability of MLD in the Alaska Gyre has been showed and the results are consistent with the localized results along Line P (e.g. Fig. 3.1). The deepest MLDs occur in Feb. 2002, April 2003 and March 2004. Again MLDs depths are deepest in the

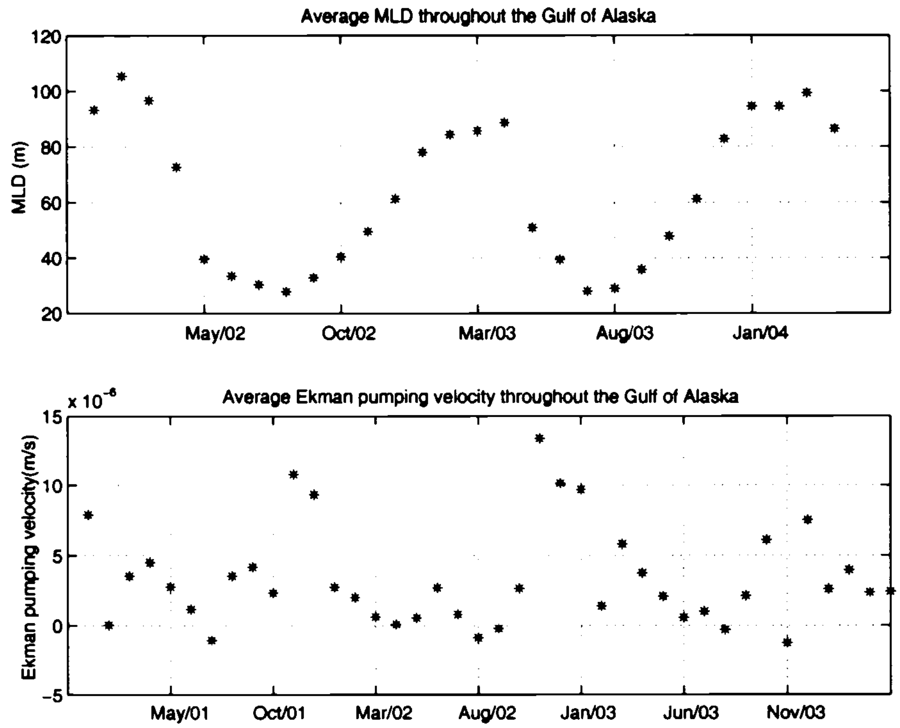

Figure 3.10: Monthly average MLD and Ekman pumping velocity over the Gulf of Alaska. Note the temporal lag between the two figures

winter of 01/02 but fall away rapidly by April. When we look at the corresponding Ekman Pumping Velocity plot (Fig. 3.10), focussing on the time up to one year in advance of our study period, we can see that positive Ekman Pumping (upwelling) is dominant over the Gulf of Alaska. It also shows a similar shape to the MLD's with a single maximum of 2/3 month duration each year. The strongest Ekman pumping velocities occured in Nov. 2001, Nov. 2002 and Dec. 2003, with weakest (linked to deepest MLDs) occuring in July 2001, August 2002 and Nov. 2004.

To examine the linkage between Ekman pumping and the mixed layer depths,

(Fig. 3.10), the correlation coefficients have been calculated with different time lags (Table. 3.2) for the two time series. The extreme r value is -0.64 with a 8 months lag. The negative relationship between Ekman Pumping and MLD occurs because when there is downward Ekman Pumping, the MLD deepens. We find mixed layer depth variability over the whole of the Gulf of Alaska is partially driven by the Ekman Pumping, with an 8 months lag.

Capotondi et al. (2004) found in a numerical model that the Ekman pumping variations always led pycnocline depth variations with lags ranging from 6-8 months in the central part of Gulf of Alaska to values as large as 10-15 months in the northern portion of the Gulf of Alaska and close to the southeastern corner of domain. Since at these latitudes density is largely controlled by salinity, the low-frequency variability of pycnocline depth indicates the variability of MLD. Our results of an 8 month lag between Ekman Pumping and MLD based on data comfirms the previous model based hypothesis is valid for the Gulf of Alaska.

Our results do also show other factors seeming to set the MLD in our study region. Fig. 3.11 shows the propagation of a MLD anomaly in the coastal boundary current through the fall and winter at 03/04. Deeper MLDs are first seen southwest of Vancouver Island in Oct. 2003, and then this region travels to the north in the Alaska Current reaching the Queen Charlotte Islands in December. By December

Table 3.2: Correlation coefficient between Ekman pumping velocity and MLD, both averaged over the Gulf of Alaska with different lags in months

Corr. Coef	Lag [months]	Corr. Coef	Lag [months]
0.24	12	-0.01	11
-0.21	10	-0.47	9
-0.64	8	-0.61	7
-0.41	6	-0.02	5
0.30	4	0.56	3
0.55	2	0.42	1
0.20	0		

2003, this feature had reached the most northerly part of the Gulf of Alaska where it seemed to stall. Obviously, this MLD variability was not related with the local Ekman pumping, instead it would seem to be an anti-cyclonic eddy propogation in the boundary currents.

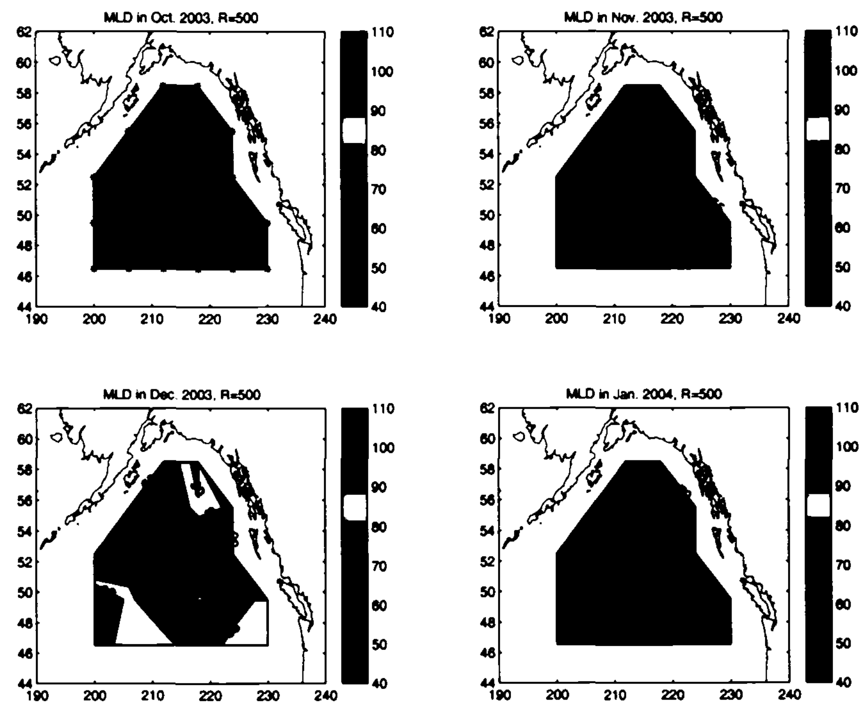

Figure 3.11: MLD variability along the main currents

Chapter 4

Summary

Historical mixed layer depths have been examined along Line P in the Gulf of Alaska. 13 stations with data existing from 1956 through 2001 have been examined. Monthly unbiased climatological mixed layer depths have been calculated based upon a method of Kara et al. (2000). The data have been then broken down into two periods, pre and post 1976. Rather than showing a consistent regime shift, as documented by other authors, we find little change in the mixed layer depth averaged over each station and month. Instead we find more localized behavior, with a deepening of the coastal MLDs in the post 1976 and a shift in the date of deepest MLD offshore (approaching Station P) towards the late winter/early spring. A point for possible speculation is that although there may be a general slow shallowing of the mixed layer depth in the Gulf of Alaska (Freeland et al., 1997), in terms of impact on nutrients and the biology, is the absolute reduction in mixed layer depth possibly offset by the increased period of 'deep winter' mixed layers (now extending well into April)?

Seasonal pentadal analysis of MLDs at Station P has been performed. Significant variability has been seen in all seasons, but the variability did not correlate strongly (no correlation coefficient above 0.55) with any of the identified North Pacific patterns of climate variability.

Mixed layer depths have been also computed from Argo floats over three recent years (2002, 2003, 2004) and mapped onto Line P. This computation showing no systematic biases, suggest that mapped Argo MLDs are as reliable as those based off shipborne-observations. These results show mixed layer depths along Line P in 2003 are much shallower than those in 2002 (Fig. 3.5). Furthermore, we find a similiar situation thoughout the Gulf of Alaska. The winter (Jan. to Mar.) MLDs in the Gulf of Alaska in 2003 are much shallower than those in 2002 and 2004 (Fig. 3.6). After calculating the correlation coefficients between monthly averaged MLD and Ekman Pumping Velocity, we find an extreme r value of -0.64 with 8 months lag. The Ekman Pumping thus has a significant effect on the MLD variability in the central part of the Gulf of Alaska. These observationally based results validate similar ideas suggested by Cummins and Lagerloef (2002) and Capotondi et al. (2004) from model based studies.

This study is the first to map the annual cycle of mixed layer depth along the whole length of Line P. This also allows the output of the Argo float program to be compared and validated against the large body of observations collected over time along Line P. Additionally, calculations of mapped MLD are provided for the entire Gulf of Alaska, much of which is not regularly observed using ship-borne instruments. In the future, these derived mixed layer depths could be used for validation of a basic physical model of the mixed layer embedded with simple biology/chemistry models as part of an additional following research project.

Bibliography

Capotondi, A., M. A. Alexander, C. Deser, and A. J. Miller, 2004: Low-frequency pycnocline variability in the Northeast Pacific. *J. Physical Oceanography*, submitted.

Cummins, P. F. and G. S. E. Lagerloef, 2002: Low frequency pycnocline depth variability at station p in the northeast pacific. *J. Physical Oceanography*, 3207–3215.

Deser, C., M. A. Alexander, and M. S. Timlin, 1996: Upper-ocean thermal variations in the north pacific during 1970-1991. *Journal of Climate*, **9**, 1840–1855.

Fofonoff, N. P. and R. C. Millard, Jr., 1983: Algorithms for computation of fundamental properties of seawater. Technical Report UNESCO Technical Papers in Marine Science 44, UNESCO.

Freeland, H. J., K. L. Denman, C. S. Wong, F. Whitney, and R. Jacques, 1997: Evidence of change in the winter mixed layer in the northeast pacific ocean. *Deep Sea Research"*, **I 44**, 2117–2129.

Haidvogel, D. B. and A. Beckmann, 1999: *Numerical Ocean Circulation Modeling*. Imperial College Press, 246 pp.

Kara, A. B., P. A. Rochford, and H. E. Hurlburt, 2000: An optimal definition for ocean mixed layer depth. *J. Geophysical Research*, **105**, 16803–16821.

Lagerloef, G. S. E., 1995: Interdecadal variations in the alaska gyre. *J. Physical Oceanography*, **25**, 2242–2258.

Levitus, S., 1982: Climatological atlas of the world ocean. *NOAA Prof. Pap. 13, Natl. Oceanic and Atmos. Admin., Washington D.C.*.

Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber, 1994: Interdecada variability of the pacific ocean: model response to observed heat flux and windstress anomalies. *Climate Dynamics*, **9**, 287–302.

Musgrave, D. L., T. J. Weingartner, and T. C. Royer, 1992: Circulation and hydrography in the northwester gulf of alaska. *Deep Sea Research"*, **39**, 1499–1519.

Myers, P. G. and A. J. Weaver, 1997: On the circulation of the north pacific ocean: Climatology, seasonal cycle and interpentadal variability. *Progress in Oceanography*, **38**, 1–49.

Mysak, L. A., 1986: El niño, interannual variability and fisheries in the northeast Pacific Ocean. **43**, 464–497.

Reed, R. K., 1984: Flow of the alaskan stream and its variation. **31**, 369–386.

Reed, R. K., R. D. Muench, and J. D. Schumacher, 1980: On baroclinic transport of the alaska stream near kodiak island. *Deep Sea Research"*, **27**, 509–523.

Royer, T. C., 1981: Baroclinic transport in the gulf of alaska part i. seasonal variations of the alaska current. *J. Mar. Res.*, **39**, 239–250.

— 1989: Upper ocean temperature variability in the Northeast Pacific Ocean: Is it an indicator of global warming. *J. Geophysical Research*, **94**, 18175–18183.

Segar, D. A., 1998: *Introduction to Ocean Sciences*. Wadsworth Publishing Company, chapter 8.

Tabata, S., 1991: Annual and interannual variability of baroclinic transports across line p in the northeast pacific ocean. *Deep Sea Research"*, **38**, 221–245.

Tabata, S., B. Thomas, and D. Ramsden, 1986: Annual and interannual variability of steric sea level along line p in the northeast pacific ocean. *J. Physical Oceanography*, **16**, 1378–1398.

Tabata, S. and W. E. Weichselbaumer, 1992: History of oceanographic sampling at ocean weather Station Papa and line p. Technical Report Canadian Data Report of Hydrography and Ocean Sciences, 107, Institute of Ocean Sciences.

Tourre, Y. M., M. Kushnir, and W. B. White, 1999: Evolution of interdecadal variability in sea level pressure, sea surface temperature and upper ocean temperature over the pacific ocean. *J. Physical Oceanography*, **29**, 1528–1541.

Trenberth, K. E., 1994: Decadal variability and climate change in large-scale interaction between the atmosphere and the ocean. *Contribution to IPCC 1995 assessment, Chapter 7*.

Trenberth, K. E. and J. W. Hurrell, 1994: Decadal atmosphere-ocean variations in the pacific. *Climate Dynamics*, **9**, 303–319.

Warren, B. A. and W. B. Owens, 1988: Deep currents in the central subarctic pacific ocean. *J. Physical Oceanography*, **18**, 529–551.

White, W. B. and D. R. Cayan, 1998: Quasi-periodicity and global symmetries in interdecadal upper ocean temperature variability. *J. Geophysical Research*, **103**, 21335–21354.

Whitney, F. A. and H. J. Freeland, 1999: Variability in upper-ocean water properties in the ne pacific ocean. *Deep-Sea Research*, **II 46**, 2351–2370.