An examination of historical mixed layer depths along Line P in the Gulf of Alaska

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[1] Mixed layer depth (MLD) is computed, based upon 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, pre and post 1976. Mixed layers deepen in winter post 1976 in a number of coastal stations. Offshore, including at Station P, shoaling after 1976 is observed in February, but there is also a phase shift with the deepest winter mixed layers occurring in April during the same period (and reaching depths comparable to those seen in February prior to 1976). A pentadal analysis of MLDs at Station P is also carried out and no obvious regime shift in MLD is seen. Significant variability is seen in all seasons, but the variability does not correlate strongly with any of the identified North Pacific patterns of climate variability. **Citation:** Li, M., P. G. Myers, and H. Freeland (2005), An examination of historical mixed layer depths along Line P in the Gulf of Alaska, *Geophys. Res. Lett.*, *32*, L05613, doi:10.1029/2004GL021911.

1. Introduction

[2] The upper ocean is characterized by its homogeneous nature, with well mixed fields of temperature, salinity and density. It is produced by a combination of buoyancy forcing and turbulent mixing due to the wind stress at the ocean surface and undergoes variability on temporal scales ranging from diurnal to interannual and longer [*de Boyer Montégut et al.*, 2004]. The mixed layer is important as a link between the atmosphere (and its variability) and the upper ocean, including biology [*Polovina et al.*, 1995]. With its long term measurement history, the Gulf of Alaska is an ideal region for high resolution studies of MLD and its variability.

[3] 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. Connecting Station P to the mainland (southern tip of Vancouver Island) is a 1500 km oceanographic section called Line P (Figure 1), 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].

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[4] *Polovina et al.* [1995] used temperature data to examine MLD changes through the Pacific Ocean between 1960–76 and 1977–88. They found a 20–30% shoaling of the mean winter and spring MLD from the earlier to the later period through much of the Gulf of Alaska but the results also suggested a deepening with time in the vicinity of Station P. *Freeland et al.* [1997] pointed out that in the vicinity of Station P, the winter MLD is primarily determined by salinity and thus determining MLD from temperature alone in the Gulf of Alaska is not appropriate. Using a pair of density based criteria, *Freeland et al.* [1997] showed that the mid-winter MLD exhibited a steady decline between 1956 and 1994. *Whitney and Freeland* [1999] examined trends in surface properties along Line P but only examined the climatological annual cycle of MLD at Station P.

[5] Thus, despite the existence of significant long term data along Line P, no historical study of MLD and its variability along the entire length of Line P has ever been carried out. Here the variability of MLD along the entirety of Line P (13 stations) is examined, using all available data. We focus upon both the seasonal cycle and the long term variability. The data and the scheme used to evaluate the MLD are presented in section 2. One question that is focussed on is what information can the Line P MLD tell us about low-frequency variability and the proposed regime shift of 1976/77 in the Gulf of Alaska?

[6] Many studies have shown the existence of low frequency variability in the upper ocean in the Gulf of Alaska. *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 (SST) 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 with a period of 3–4 years.

[7] *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 SST in the central northern Pacific and higher SST 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 SST 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

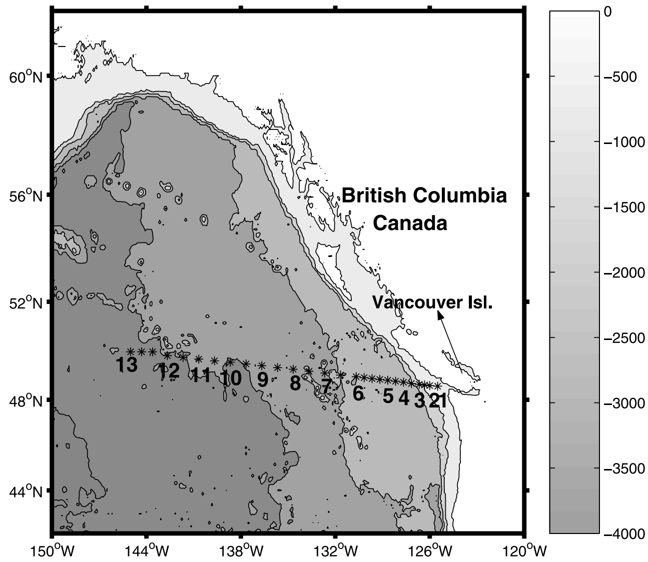

Figure 1. Map of the western Gulf of Alaska, showing Line P and its stations.

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 found that these changes were associated with changes in the MLD, but the spatial patterns of the changes was not the same as for SST 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 SST 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. A. Capotondi et al. (Low-frequency pycnocline variability in the northeast Pacific, submitted to *Journal of Physical Oceanography*, 2004, hereinafter referred to as Capotondi et al., submitted manuscript, 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.

2. Data and Methods

[8] Several recent studies [*Kara et al.*, 2003; *de Boyer Montégut et al.*, 2004] have taken advantage of the recent increases in ocean data to produce mixed layer climatologies at basin and global scale. These studies have also highlighted the question of what actually is MLD and the fact that no single definition of it is used or accepted globally (e.g., see *Kara et al.* [2000b] or *de Boyer Montégut et al.* [2004] for discussion of these issues, including typical criteria).

[9] We estimate MLD at the 13 original IOS (Institute of Ocean Sciences) Line P stations using temperature and salinity data from 1956–2001 (Figure 1). We only use the 13 original stations because they have the longest historical records. By doing this, a strong sampling frequency bias is avoided, as the frequency of sampling significantly declined when the number of stations was increased to 26 [*Whitney and Freeland*, 1999]. As discussed by *Whitney and Freeland* [1999], this data set is believed to be internally consistent and suitable for examining rates of changes in properties.

[10] Density is calculated using the algorithms suggested by *Fofonoff and Millard* [1983]. We estimate MLD using a method proposed by *Kara et al.* [2000b]. *Kara et al.* [2000b] suggest that this method accurately represents the depth to which turbulent mixing has penetrated, and validate the method using 11 stations along Line P. Such an approach also avoids problems with barrier layers and differences between isothermal and mixed layer depths [*Kara et al.*, 2000a]. We use a temperature difference criterion of 0.8°C, as suggested by *Kara et al.* [2000b], which then leads to a variable density criterion. We find the results are more robust than if recalculated using a more conventional threshold method (using a $\delta\sigma_t$ of 0.01 for winter (Nov.–Apr.) and 0.03 for summer (May–Oct.)). To produce long term averages, MLDs were calculated for each profile and then averaged for each month within a year, before longer period averaging was carried out (to avoid a bias towards the earlier part of the period when more frequent sampling was carried out).

3. Results

[11] First the long term climatological MLDs, for each station and month, along Line P, are presented, as well as a more detailed representation of the annual cycle at several stations (Figure 2). MLD increases from the coastal stations, where haline effects such as riverine freshwater discharge are dominant and the layer depth is shallow year round, to those further offshore, where a pronounced seasonal cycle is visible. For stations 6 through 13 significant winter deepening occurs, with long term average MLDs exceeding 100 m at Station P. The winter deepening is driven by both thermal forcing and Ekman pumping, with a lag of 8 months [*Cummins and Lagerloef*, 2002; *Li*, 2005]. Spring restrati-

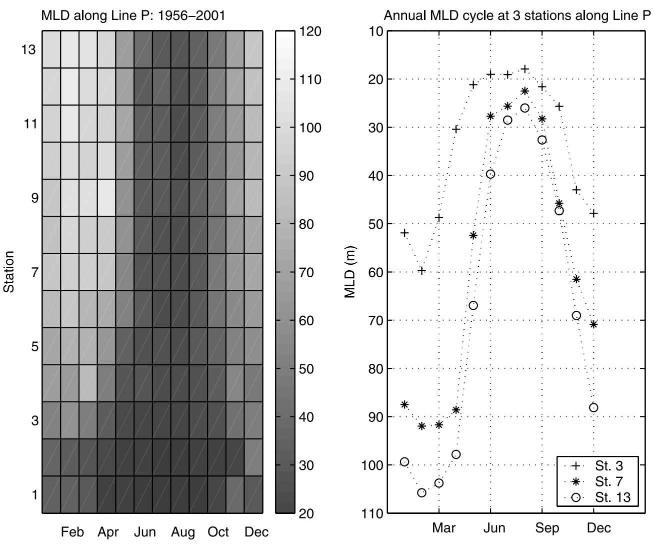

Figure 2. MLD at each of 13 stations along Line P, averaged over 1956–2001, for each month of the year (top left); and the long term mean annual cycle of MLD at stations 3, 7 and P respectively.

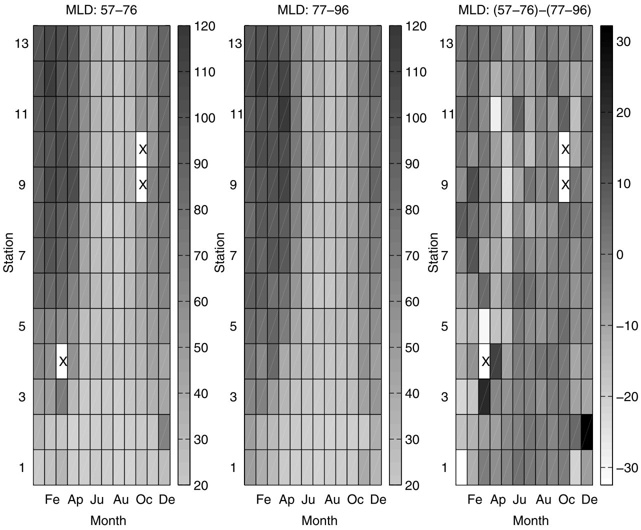

Figure 3. Average annual cycles of MLD of Line P in two successive time periods. White blocks with an x in them indicate a lack of data for the analysis. The third plot is a difference plot between the two time periods.

fication is then related to a shift away from downwelling favourable winds. Except in certain spring and autumn months, MLD always increases as one moves offshore as the effects of lateral advection of coastal freshwater diminish. There is little difference in summer MLD anywhere along the line.

[12] Many authors have discussed the possible regime shift that occurred in the Gulf of Alaska between 1976/77 [e.g., *Trenberth and Hurrell*, 1994]. As discussed by Capotondi et al. (submitted manuscript, 2004), while SST variations are significantly affected by high-frequency variations, pycnocline depth changes in the Gulf of Alaska are more representative of the low-frequency oceanic response to atmospheric forcing and thus are a better measure to detect long term climate variations. Thus MLDs over two periods, 1957–1976 and 1977–1996 (Figure 3) are examined. We consider averaged periods and not each individual year due to a data sparcity in many months and years.

[13] 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 are instead more local in both space and time. For the stations just off the edge of the continental shelf (i.e. stations 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 MLDs later in the spring. This deepening in the coastal band is consistent with the modelling study of Capotondi et al. (submitted manuscript, 2004), who suggested a deepening of the pycnocline in a broad band along the coast associated with changes in Ekman pumping, pre and post 1977. As one moves farther offshore along Line P, one does find a general shoaling of the MLD in late fall (December onwards) through to February, consistent with *Freeland et al.* [1997]. However, through the 1977–1996 period, there is a phase shift in the end of winter, with little decrease in MLD through April and substantially deeper MLDs of 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. Although based on a very limited number of cruises (except at Station P), this change is consistent with MLDs mapped from Argo floats over 2002–04 [*Li*, 2005]. This is also consistent with *Whitney and Freeland* [1999] who found that the period of maximum surface sigma-t extended through April all along Line P (and was linked to the SST structure).

[14] Only at Station P is there really enough data to allow us to examine the changes in MLD over shorter time periods. Five year pentads, from 1956–1960 through to 1996–2000 are considered and examined in each season (Figure 4). Although the winter MLDs do change in sign between the 1971–75 and 1976–80 pentads, they shoal over the period 1976–88, inconsistent with the idea of a regime shift discussed by *Trenberth and Hurrell* [1994]. The different variability in each of the four seasons seen between 1970–75 and 1976–80 is also inconsistent with the idea of a simple regime shift. Additionally, it can be noted that between 1971–75 and 1981–85, the spring/summer and summer/autumn MLD anomalies are of opposite sign while during the intervening period of 1976–80 all the anomalies are of the same sign (and have small magnitudes). The reasoning for this is still under investigation.

[15] 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, the deepening is not uniform, reaching a maximum in 1991–1995 and then shoaling.

[16] We point out that these spring deepening results are not inconsistent with *Freeland et al.* [1997]. Even though they included April in their winter definition, they weighted all observations equally over each winter, masking the very limited number of observations available in April. The variability in winter MLDs at Station P are also consistent with those examined by Capotondi et al. (submitted manuscript, 2004), who used a similar definition of winter, and

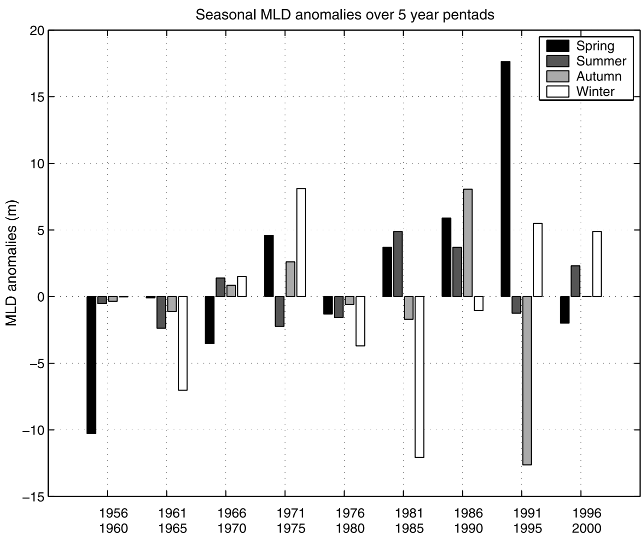

Figure 4. MLD anomalies at Station P of average annual cycles over 5 years pentads in different seasons. The last pentad in autumn is missing data rather than zero.

who then attributed a significant portion to the variability to local Ekman pumping in their model.

[17] To attempt to clarify the driving mechanisms for the variability in MLD along Line P, correlations of our seasonal pentadal time series at Station P are calculated with similar seasonal pentadal time series of major climatic indices (based on data available from the NOAA Climate Prediction Centre, www.cpc.noaa.gov). Spring MLDs correlate with ENSO, with an r value of 0.52 (significant at the 90% level). The summer time MLD best correlates with the Pacific Transition Pattern (PT), with an r value of 0.56 (significant at the 90% level). 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), which is not statistically significant. It is also noted that local forcing issues are not considered here.

4. Summary

[18] Historical MLDs are examined along Line P in the Gulf of Alaska. 13 stations with data existing from 1956 through 2001 are examined. Monthly unbiased climatological MLDs are calculated based upon a method of *Kara et al.* [2000b]. The data are then broken down into two periods, pre and post 1976. Mixed layers deepen in winter post 1976 in a number of coastal stations. Offshore, including at Station P, shoaling after 1976 is observed in February, but there is also a phase shift with the deepest winter mixed layers occurring in April during the same period (and reaching depths comparable to those seen in February prior to 1976). A pentadal analysis of MLDs at Station P is also carried out and no obvious regime shift during the mid 1970's is seen in MLD. While our February data coverage is adequate to have revealed a MLD regime shift if it occurred, if only the deepest winter MLD (occurring in April post 1976) would be a proper indicator of a regime shift, our data coverage is then inadequate.

[19] Does this work then disprove the commonly held idea of a Pacific regime shift during the 1970's? The answer to that is no. The best that can be said is that no such shift was seen in MLD at Station P. Although Ekman pumping (related to the large scale Aleutian Low pressure system) is the dominant factor in driving variability in MLD in the Gulf of Alaska [*Cummins and Lagerloef*, 2002], others factors are significant. The most likely opposing factor to us would be upper layer salinity changes, which would act to shoal the MLD even if forced with a comparable winter time buoyancy loss from surface cooling. A number of authors have noted freshening of the sub-polar oceans, including in the Gulf of Alaska [*Whitney and Freeland*, 1999]. This is obviously a topic for much further research.

[20] Significant variability is seen in all seasons, but the variability does not correlate strongly (no correlation coefficient above 0.56) with any of the identified North Pacific patterns of climate variability. A point for possible speculation is that whether or not there may be a general slow shallowing of the MLD in the Gulf of Alaska [*Freeland et al.*, 1997], in terms of impact on nutrients and the biology, is the absolute reduction in MLD possibly offset by the increased period of 'deep winter' mixed layers (now extending well into April)?

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