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Argo: A new tool for environmental monitoring and assessment of the world's oceans, an example from the N.E. Pacific

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Abstract

Argo is an international project that is deploying profiling drifters in all of the oceans of the world, with the exception of the Arctic Ocean. Though still in its implementation phase the Argo array is now supplying an impressive amount of data which offers new opportunities to assess and monitor the environmental status of many regions of the world oceans. Recently, changes in the Gulf of Alaska have been documented by other means that suggest large changes in the T/S relationships and related changes in nutrient supply and productivity. This paper examines these unusual changes to demonstrate the use of the Argo database to determine the physical status of an ecosystem. While the methods of analysis are general, they are here specifically applied to the N.E. Pacific Ocean. We show how it is possible to monitor the baroclinic geostrophic circulation fields in near real-time and correlate these changes with alterations in the stratification of the upper water column.

Regional Index Terms: Pacific Ocean; Gulf of Alaska

Keywords: Argo; Circulation; Geostrophic flow; Density stratification; Ecosystems

1. Introduction

Several papers have been published recently concerning the unusual conditions in the Gulf of Alaska and the California Current System during the summer and fall of 2002. A consensus appeared that there was an

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unusual subarctic influence in the California Current System (Bograd & Lynn, 2003; Freeland, Gatien, Huyer, & Smith, 2003; Kosro, 2003; Strub & James, 2003). This likely was forced by large-scale changes in the wind patterns (Murphree, Bograd, Schwing, & Ford, 2003) and was accompanied by elevated nutrients in regions close to the coast (Wheeler, Huyer, & Fleischbein, 2003) and increased primary production (Thomas, Strub, & Brickley, 2003; Wheeler et al., 2003).

The circulation in the Gulf of Alaska is dominated by the eastward flowing North Pacific Current (NPC) which bifurcates near the latitude of Vancouver Island with a north-flowing branch forming the Alaska Current, and a south-flowing branch forming the California Current. The Alaska Current is renamed the Alaska Stream after it rounds the top of the Gulf of Alaska and becomes a narrow western boundary current. The paper by Bograd and Lynn (2003) in particular suggests that there was a southward shift of the NPC bifurcation during 2002. Potentially such shifts could result in fluctuations in the California and Alaskan Currents that are 180° out-of-phase with each other (Chelton & Davis, 1982) and such shifts could easily have significant impacts on ecosystems of the two current systems. Additionally several of the papers referred to above reported increases in the southward transport of the California Current. These two observations (increase in transport of the California Current and a southward shift of the NPC bifurcation) appear to be questions especially well suited to analysis using the Argo array.

This paper uses the Argo array in the Gulf of Alaska to explore the general circulation of the region. The Argo array is being deployed by a consortium, which, at the time of writing, includes representation of 18 nations, that is creating a global ocean climate monitoring array (Roemmich et al., 2001). Typically, each Argo float is programmed to drift at a depth of 2000 dbar for a 10 day interval, and then adjust its buoyancy to float to the sea surface. Some variations from the standard duty cycle do occur, notably the so-called ''park 'n profile'' mode of operation, but these differences are not critical. During the ascent phase the float records the temperature and salinity structure of the ocean from 2000 dbar to the sea surface which is reported to a land station via a satellite. The float then descends for another 10-day drift and profile. The Gulf of Alaska was the first major ocean region to reach the target density of instrumentation and so makes an excellent case study for how Argo might be used in the future to assess changes in the climatic state of an oceanic region.

In the following pages we will outline the evolution of the Argo array in the N.E. Pacific and follow with a review of the unusual events observed in the N.E. Pacific from the beginning of 2002 to 2003 with special emphasis on the view afforded by the Argo array. This will show that the large changes in the scalar fields were accompanied by changes in the large-scale circulation of the Gulf of Alaska; a simple analysis method allows routine monitoring of the geostrophic circulation of the Gulf of Alaska. Evidence will then be shown that the changes in the circulation observed were associated with alterations in the upper-ocean stratification in the Gulf. The changes in the circulation involved large fluctuations in the latitude of the bifurcation of the North Pacific Current, strength of the circulation in the Gulf of Alaska, and substantial changes in the southward flow in the California Current.

2. The evolution of the Argo array in the Gulf of Alaska

Deployments in support of Argo began in early 2001, but it was some time before there were sufficient floats in discrete areas to allow plausible maps of ocean conditions to be constructed. In the Gulf of Alaska the first deployments were along Line-P (see Fig. 1) and by late 2001 a distinct area of coverage existed that allowed the synoptic mapping of the horizontal variation of properties. The strategy of the early deployments was to maintain the sampling along Line-P, but gradually to increase the density of floats in the Gulf of Alaska to the north and south of Line-P using Canadian resources. By early 2003 US floats were de-

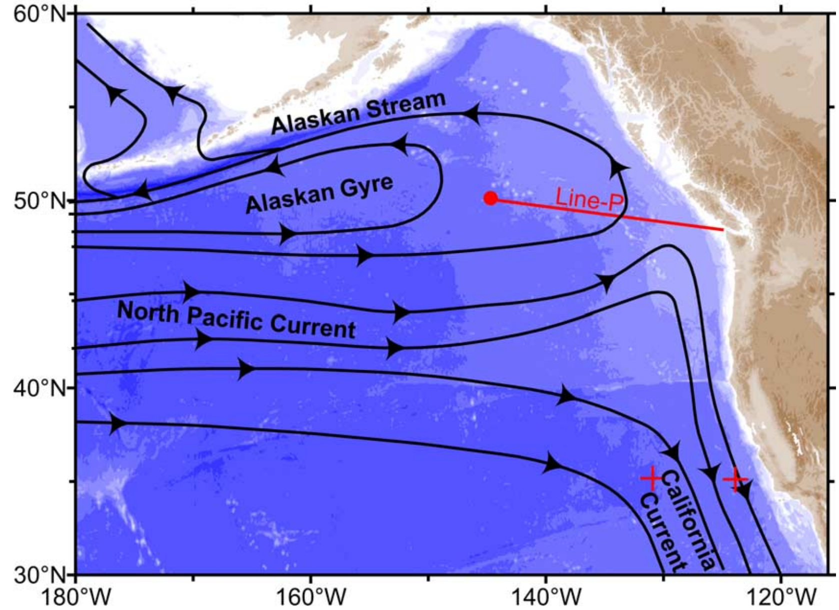

Fig. 1. A schematic presentation of the background flow in the Gulf of Alaska based on Dodimead et al. (1963). Also indicated are the locations of Line-P and Ocean Station Papa. The area covered by this map is identical with subsequent maps in this paper. The two red "+" symbols are locations used later in the paper to monitor the baroclinic transport in the California Current.

ployed farther to the south of Line-P and floats were deployed in the Bering Sea. Meanwhile, Japanese agencies had begun deploying floats in the western Pacific and over time some of these entered the eastern Pacific. Gradually, from collaborative resources, the Gulf of Alaska has been filled with profiling floats. In Fig. 2, we contour estimates of the density of floats and add the float locations for the month in question. According to the Argo implementation plan (Argo Science Team, 1998), the aim is to deploy an array of floats with an approximate spacing of 3° in latitude and longitude which is interpreted here roughly as a nearest-neighbour spacing of about 300 km. To calculate the local float density the following process was used:

1. A reference array of floats was created by scanning the Etopo2 database and placing a hypothetical reference float in a 100 km × 100 km array wherever water depth was equal to or greater than 2000 m. This reference array has 9 times the float density of the Argo target.
2. To calculate the current density of Argo floats at any given latitude and longitude (ϕ_0, λ_0) we count the number of Argo floats (N_a) within a large circular region of radius 400 km and centred on (ϕ_0, λ_0) then count the number of reference floats (N_r) within the same circle.
3. The density at location (ϕ_0, λ_0) is estimated as $9N_a/N_r$.

Fig. 2 shows the evolution of the float array from March 2002 to September 2003. Some small regions had achieved the target density (density = 1.0) as early as March 2002 though large regions of the Gulf contain no floats at all. By late 2003 almost all parts of the Gulf of Alaska were being sampled by floats in the Argo array, and many large regions have a float density over 0.6 of the target density. Though more deployments are still required, this average density is sufficient to begin the task of developing and applying operational tools for the assessment of the state of the Gulf of Alaska.

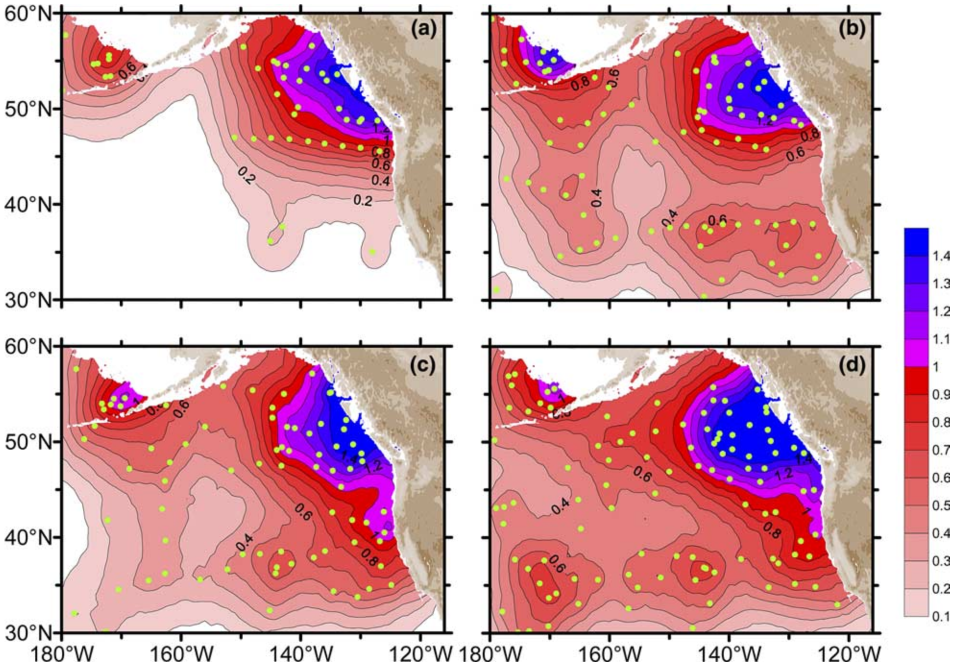

Fig. 2. The evolution of the Argo array showing float density (see text) and the locations of floats (green dots) for: (a) March 2002; (b) September 2002; (c) March 2003; and (d) September 2003.

3. The geostrophic circulation of the N.E. Pacific in real time

Monthly mean maps of the dynamic height distribution in the N.E. Pacific were computed. In every case the map is centred on the 15th day of each month (t_c) and data are accepted from any float reporting between the dateline and the coast of North America, anywhere north of 30°N, and within the time window $t_c \pm 15$ days. In most cases each float examined will report 3 times during that interval, and occasionally a float will report four times. If a float is launched during the month being examined then it will report fewer than three profiles. For each profile the dynamic height at the surface is computed relative to 1000 dbar. Since in almost all cases the floats drift an imperceptible distance in 10 days, repeat observations from a single float are averaged together. This ensures that an old float reporting three or 4 times in this time window is not given greater weight in the mapping algorithm than a new float in a distinct region that reports only once or twice.

A simple objective analysis scheme (e.g., Freeland & Gould, 1976) could be used to map the circulation, but such a scheme would not make use of all of the information available; in particular, it would not use the fact that there is no flow through coastal boundaries. Methods have been developed (Bennett, 1992; Golnaraghi, 1993) that allow boundary conditions to be imposed on an objective analysis scheme. However, we propose applying boundary conditions by fitting the observations to a set of empirical orthogonal functions derived from a dynamical model. This method has enormous advantages over objective analysis. In particular the method outlined here permits the inclusion of a thin boundary layer along the western boundary which arises due to the β effect. This would be very difficult to achieve in an objective analysis scheme.

The empirical orthogonal functions (EOFs) were determined from a numerical simulation with a reduced gravity quasi-geostrophic model described in Cummins and Lagerloef (2004); specifically, the modes are based on results from experiment 3 of that study. The model was driven by Ekman pumping anomalies derived from the NCEP reanalysis wind stresses (Kalnay et al., 1996) in a 56-year integration extending from 1948 to 2003. The EOFs were calculated for the northeast Pacific region at a resolution of 1° in the E–W direction and 1/3° in the N–S direction. The enhanced N–S resolution is to ensure that the thin western boundary layer found along the north Gulf of Alaska and Aleutian Islands is represented. However, the Bering Sea is not represented and the modes do not allow for representation of flow through gaps in the Aleutian Island chain. Tests have shown that the use of modes defined at a uniform lateral resolution of 1° has little effect on the inferred circulation patterns within the interior of the basin, away from the western boundary region, although they fail to resolve the western boundary current.

A set of 20 EOFs, ordered by eigenvalue, was computed from the simulated surface stream-function field. To compute the synoptic maps of the dynamic height field the following steps were followed:

(a) For any particular month the Argo archives were scanned for any profiles found in the Gulf of Alaska during that month. Some quality control checks were also imposed in addition to the automated and delayed-mode QC checks developed for the standardised Argo data management procedures.
(b) The areal mean value of dynamic height was computed from the data selected in (a) and subtracted from the observations.
(c) The variance left over after removal of the mean, was computed and considered to be the variance to be accounted for (σ_0^2) by a mapping.
(d) Each EOF was fitted in turn to the zero-mean observations and a weight computed for each EOF.
(e) A mapped field was then computed by summing the product of EOFs and the fitted weights then adding in the areal mean value.
(f) The residual variance (σ_r^2) was computed and in the maps that follow we estimate the fraction of variance accounted for as $(\sigma_0^2 - \sigma_\mathrm{r}^2)/\sigma_0^2$.

Fig. 3 shows four views of the circulation of the Gulf of Alaska in July 2003 to demonstrate the performance of the mapping system. Panel (a) shows the observations from July 2003 mapped as described above. The resulting contour map accounts for 91% of the variance in the system resulting from 299 profiles. For panel (b) the same procedures have been used, but data selection was restricted to the top right hand corner. This was tried because the Argo array in the Gulf of Alaska gradually filled from that region; we wanted to determine whether the mapping was stable when large areas of the Gulf have no observations. The resulting map has evident similarities to the full mapping in (a) and suggests that the location of the bifurcation might indeed be mapped from the more restricted data set which in this case includes only 84 profiles. However, it is also clear that the flow of the California Current system and the broad sweep of the North Pacific Current are not represented correctly. Not surprisingly, the mapping does well where data exist and performs badly in regions that have no observations. Panels (c) and (d) use the same data as in panel (a) but are mapped using only 4 and 8 EOFs, respectively. The mapping in panel (c) shows minor discrepancies from the full mapping and accounts for 85% of the original variance, the mapping in panel (d) shows barely perceptible discrepancies and accounts for 89% of the variance. Apparently, the first few EOFs derived from the quasi-geostrophic model can be used to provide an almost complete description of the circulation field. This is more clearly illustrated in Fig. 4 which shows the cumulative variance reduction as a function of the EOF added, as well as the amount of variance reduction associated with each mode. The amount of information added by modes beyond number 8 is extremely small, but despite this, we chose to use all 20 EOFs in the maps to be presented in the following analyses.

The method allows us to map the strength of the Alaska Stream along the Aleutian coast, even when we have no observations actually acquired inside the Stream. This occurs because the remainder of the circulation of the Gulf of Alaska is mapped successfully and the flows towards or away from the Aleutian island chain must, by continuity, be related to accelerating and decelerating regions of the Alaska Stream. Thus, this stream is represented because it is necessary for dynamical consistency. We note also that a few Argo

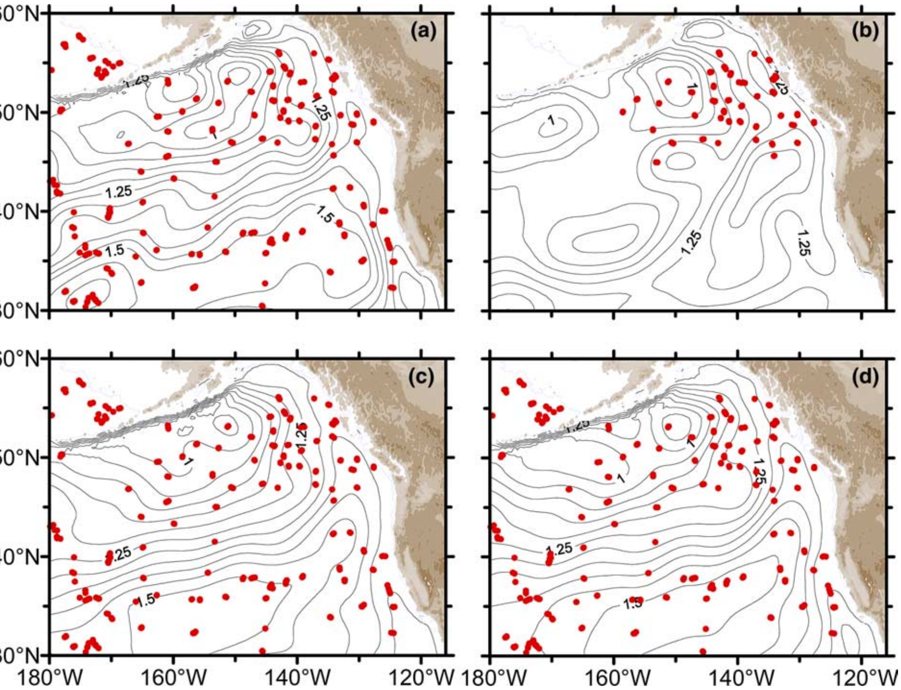

Fig. 3. The circulation of the Gulf of Alaska in July 2003 mapped as above but with four variations (see text) to test the sensitivity of the mapping process.

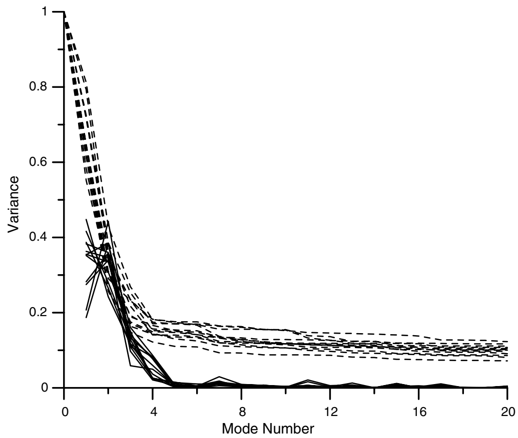

Fig. 4. The variance accounted for by each EOF in turn (solid lines) and the cumulative reduction in total variance after adding the first N EOFs (dashed lines). In each case the lines represent the spectrum of variance reduction for each of 12 months in 2003.

floats have in fact been advected into the Alaska Stream and these show some of the highest velocities observed anywhere in the Pacific Ocean.

This method also allows the user to examine the difference between dynamic height computed at individual float locations and the estimate from the dynamic fits. Hence, the method allows the construction

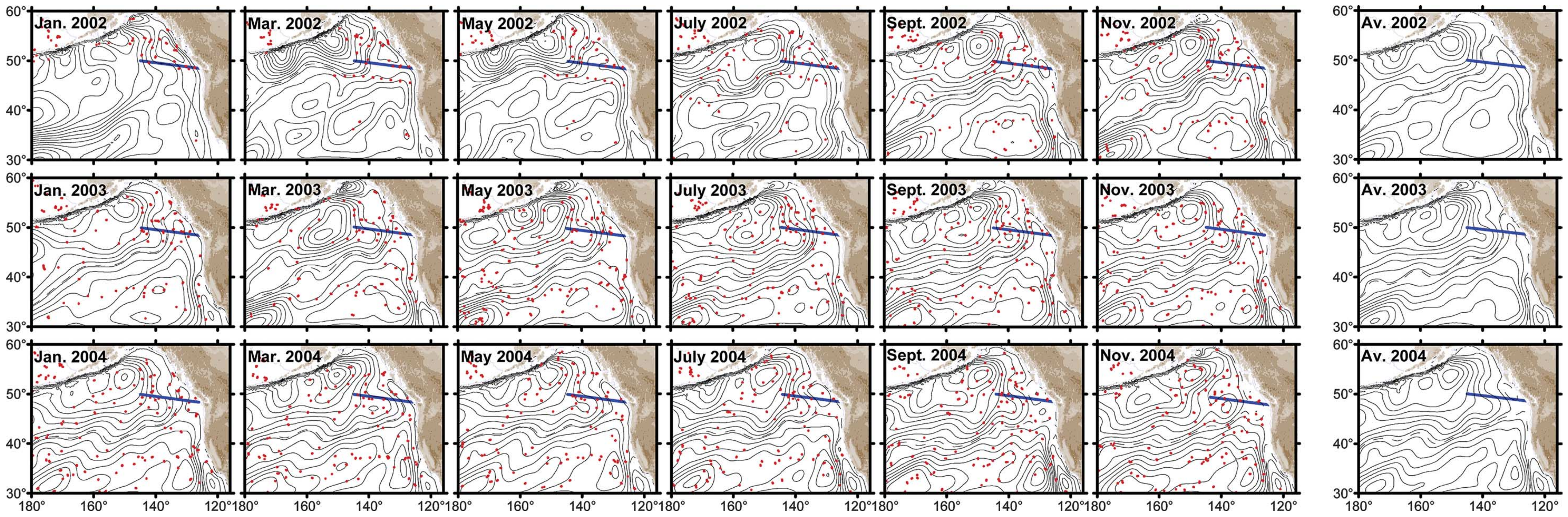

Fig. 5. The surface circulation of the Gulf of Alaska at two-month intervals, computed as described in this section, and in the right-hand column the annual average circulation. The red dots on the monthly maps indicate the locations of floats used in the computation, and the blue line is Line-P, for reference.

CYAN MAGENTA YELLOW BLACK

of an error map. In all cases the maps presented fit a large fraction of the total variance; in most cases the amount of variance accounted for lies between 87% and 92%. Individual maps with variances explained do exist down to 85% and as high as 96%. While no such error maps are presented here, a large number of maps at monthly intervals, including velocity component maps and error field maps, are available at a site on the world wide web: http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/argo/Dhgts_e.htm.

Fig. 5 shows maps of the surface circulation of the Gulf of Alaska at intervals of two months running through 2002, 2003, and 2004 together with the averages over all months available for each of those years. One can see both the evolution of the Argo array in the Gulf of Alaska through this period, and the changing circulation field. There are a number of unusual features in these maps that warrant closer inspection. Firstly, the maps shown for March, May and September 2003 show an unusual anticyclonic recirculation in the most northerly part of the Gulf of Alaska. In fact, examination of the monthly maps shows this feature present in the last few months of 2002, February through July and September 2003, inclusive. We have not seen mention of this anticyclonic recirculation published elsewhere, however, both Phyllis Stabeno and Tom Royer (personal communications) indicate that such recirculation has been observed in their surveys.

Farther to the south the California Current varies, but without exception it appears to leave the coast at some point with a recirculation between the California Current and the coast. There is considerable evidence from other sources that the California Current does actually separate from the coast near the location indicated in Fig. 5 (Huyer, Barth, Kosro, Shearman, & Smith, 1998) and the recirculation has also been reported. This lends some confidence that the maps are representing the circulation systems in a plausible manner. Further, since the amount of variance accounted for always exceeds 85% and in most cases exceeds 90% we are also confident that the maps owe more to the Argo database than to the analysis method.

The blue line on each of the panels comprising Fig. 5 indicates the location of Line-P, and the dashed line indicates our estimate of the dividing streamline. Thus, any parcel of water to the north of the dividing streamline will eventually flow northwards into the Alaska Current system, anything to the south of the dividing streamline will eventually flow southwards in the California Current System, provided that the fields vary slowly. Bograd and Lynn (2003) suggested that there was an anomalous southward shift of the NPC bifurcation during 2002. Examination of these maps in fact suggests exactly the contrary. Comparison of any pair of maps separated by 12 months, with the single exception of January, suggests rather that the North Pacific Current was much farther to the north in 2002 than it was in 2003. It is apparent from the maps in Fig. 5 that, contrary to the conclusions of Bograd and Lynn (2003), the bifurcation in the North Pacific Current to be anomalously far to the north in 2002 compared with what we believe to be normal, compared with historical estimates (e.g., Fig. 1) and compared with 2003 and 2004. Early in 2002, the distribution of float observations is far from being uniform, and this might be having a significant effect on the apparent location of the axis of the NPC. However, by July of 2002 we do have floats covering most regions of the Gulf and these also show a northward displacement of the NPC compared with maps a year later.

To quantify the anomalous displacement of the North Pacific Current, the latitude of the maximum N/S gradient in the dynamic height field along 145°W (the longitude of Ocean Station Papa) and along 150°W were computed for every month from 2002 to the end of 2004. These are plotted in Fig. 6.

These results, plotted in Fig. 6, indicate that profound changes took place in the nature of the NPC system between 2002 and the end of 2003. By the middle of 2003, the current appears to be at roughly the latitude that traditional estimates of its location would indicate. Indeed, we wish that we could map the current fields earlier than 2002, but the Argo array was just too early in its development and these maps cannot reasonably be computed. The available evidence suggests that as it became possible to map the circulation fields, they were already in an anomalous state associated with the unusual climate anomalies observed and reported during 2002.

The surface waters along Line-P were unusually warm during 2002 and extending well into 2003. These maps would suggest that during this period Line-P was lying entirely within the California Current System.

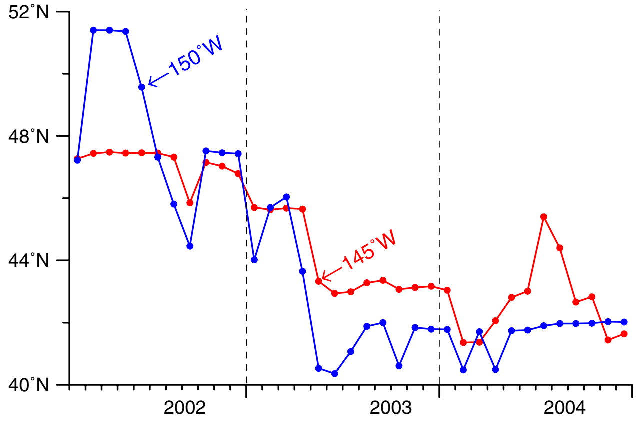

Fig. 6. The latitude of the axis of the North Pacific Current at 145°W (blue line) and along 150°W (red line) versus month through 2002, 2003 and 2004.

By the end of 2003 most of Line-P appears to lie within the Alaska current system; the eastern third of the line being found within a stagnation region that is really in neither current system. Dodimead, Favorite, and Hirano (1963) referred to this region as the *transitional domain*.

It was also reported in the various analyses of the 2002–2003 anomaly that there was an associated increase in the southward transport of the California Current. We examined each of the maps and computed the difference in dynamic height at 35°N and between longitudes 131° and 125°W (see Fig. 1). These two locations almost always appear to bracket the California Current. The dynamic height differences are shown plotted in Fig. 7, one entry per month from January 2002 onwards, and colour coded by calendar year. It is apparent that the dynamic height differences were substantially larger in early 2002 compared with the later periods, in agreement with the observations of Bograd and Lynn (2003) and others. The differences are appreciable and over this horizontal distance of 550 km correspond to average surface flows of 8.6 cm/s during the first 8 months of 2002 and an average of 5.4 cm/s during 2003 and 2004.

In a series of papers, Lagerloef (1995) and Cummins and Lagerloef (2002, 2004) showed that a simple Markov model of the N.E. Pacific Ocean driven by Ekman upwelling could account for much of the ob-

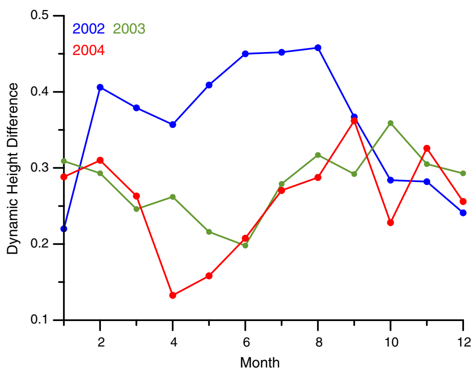

Fig. 7. The dynamic height difference across the California Current.

served upper-ocean variability in the over the region. Specifically, following Hasselman (1976) and Frankignoul and Hasselmann (1977) they assumed a model for pycnocline depth variability of the form

$$\frac{dh}{dt} = w - \lambda h, \tag{1}$$

where h represents the isopycnal displacement anomaly and w is the Ekman pumping velocity. The Ekman pumping velocity is itself driven by atmospheric processes, essentially a white-noise process. The decay parameter λ specifies the timescale (λ^{-1}) over which fluctuations in h are damped. Cummins and Lagerloef (2002) found an optimal fit to observed variability at Ocean Station Papa with a time scale (λ^{-1}) of 1.5 years. Rewriting Eq. (1) in finite difference form

$$\frac{(h_{m+1} - h_m)}{\Delta t} = w_m - \lambda h_m,$$

it can readily be shown that the covariance between h_{m+n} and h_m is

$$\mathrm{Cov}(n\Delta t) = \langle h_{m+n} h_m \rangle = (1 - \lambda\Delta t)^n \langle h_m^2 \rangle,$$

provided that the correlation $\langle w_m h_m \rangle = 0$. Thus, the correlation coefficient is given by

$$\mathrm{Cor}(n\Delta t) = \exp(-n\Delta t/T_0),$$

where

$$\exp(-\Delta t/T_0) = (1 - \lambda\Delta t).$$

For time scales significantly larger than Δt, we find that very closely $T_0 = \lambda^{-1}$. So far we have only about 36 maps of the baroclinic circulation field available. However, correlating dynamic height maps out to a maximum lag of 15 months (despite the short time series) produces the correlation estimates shown in Fig. 8.

We appreciate that, with only 36 maps available to us, correlations to a maximum lag of 15 months involves unwarranted optimism. However, we felt that this optimism was rewarding as it does show the likely presence of an annual cycle. Discussion of an annual cycle and its residuals is left for a later paper. As expected the monthly maps do show substantial autocorrelation, but a steady decline is evident. The best fit (in a least squares sense) exponential suggests a decay scale of 15 months. This is surprisingly close to the

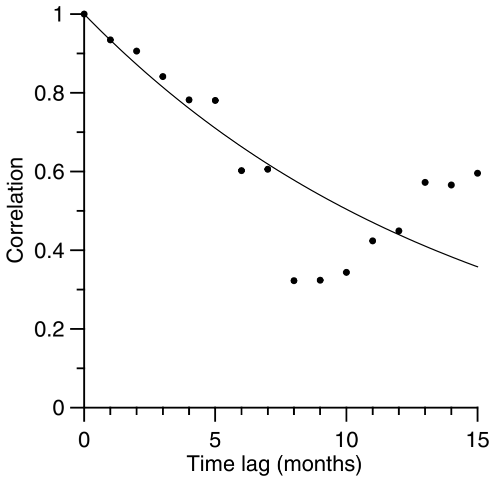

Fig. 8. The correlation coefficient between successive maps (see Fig. 5) of the dynamic height field in the Gulf of Alaska. The solid line is an exponential best fit.

model estimate of 18 months found by Lagerloef (1995) and Cummins and Lagerloef (2002, 2004). However, this result should be treated as only general guidance that the time scales indicated by the dynamic height fields we are computing are not in substantial disagreement with the model results and should be re-examined when substantially more maps are available.

It is worth comparing the oceanic time scale implied by the correlations of about 15 months with the time required to survey the ocean. The surveys as outlined here can be completed at monthly intervals using the Argo array and this is sufficient to resolve the dominant variability in a process with time scale of around 12 months. In principle such maps could be computed every 10 days, but this leaves no redundancy in the estimates of dynamic height from a given float, i.e., a single bad profile would have large impact on a map. It is interesting to enquire how we would have managed using traditional ship-borne methods. In 1955 a multinational effort took place to survey the climatic state of the North Pacific Ocean. While the NORPAC surveys (NORPAC Committee, 1960) occupied the entire North Pacific, surveys within the region bounded by the dateline to North America, and the Aleutians to 30°N have almost exactly the same number of stations as is currently being acquired by Argo in one month. However, the 1955 survey occupied 242 ship-days of survey time on seven research vessels. Such a massive effort could only be mounted very rarely, so apparently traditional survey methods are poorly suited of providing a synoptic survey or of resolving the dominant variability of this ocean basin.

4. Impacts on the waters of the Gulf of Alaska

It is apparent from the preceding discussions that the anomalous warming of the surface waters of the Gulf of Alaska was associated with impressive changes in the geostrophic baroclinic circulation of the North Pacific Ocean. During this period of very high temperatures along Line-P the NPC was anomalously far to the north, sufficiently far that Line-P actually fell within the California Current system. This resulted in surface flows from subtropical regions and presumably accounts for the anomalously high temperatures observed.

There was no significant salinity anomaly associated with the surface warming, thus the excess warming contributed to a stabilisation of the water columns along Line-P. In contrast, the subsurface cold event was associated with a decrease in salinity such that temperature and salinity were, almost exactly, compensating in their contributions to density. Thus, that event, unlike the surface event, had virtually no effect on the stratification of the upper ocean.

To examine the effect of the surface warming on the waters of the Gulf of Alaska, we examined the profiles reported by all Argo floats in a large disc surrounding Ocean Station Papa. Data were examined from any float within 1000 km of Station Papa, and properties were mapped using objective techniques (using a Gaussian covariance function with a decay scale of 150 km) to produce a set of simulated CTD profiles at Ocean Station Papa (50°N, 145°W) at 5-day intervals. Since the duty cycle of Argo floats is 10-days, data were accepted in a 10-day interval centred on times that were separated by 5 days. Thus, consecutive profiles have about 50% of the input data in common. We then computed the difference in σ_t between the surface and a pressure of 75 dbar. The resulting time series is shown in Fig. 9.

The red line is the expected annual cycle of the stratification with the 95% confidence bounds. The expected value and confidence bounds were calculated from all previous observations, CTD and bottle observations, at Station Papa. All existing pre-Argo profiles were examined and the density differences calculated between the surface and 75 dbar; for some months over 1000 estimates were available. For each month the density differences were ordered from the smallest value to the largest value. The expected stratification was then determined as the median value, and the 95% confidence bounds estimated by the simple expedient of counting the highest and lowest 2.5% of observations. So the confidence levels are bootstrapped from the historical archive.

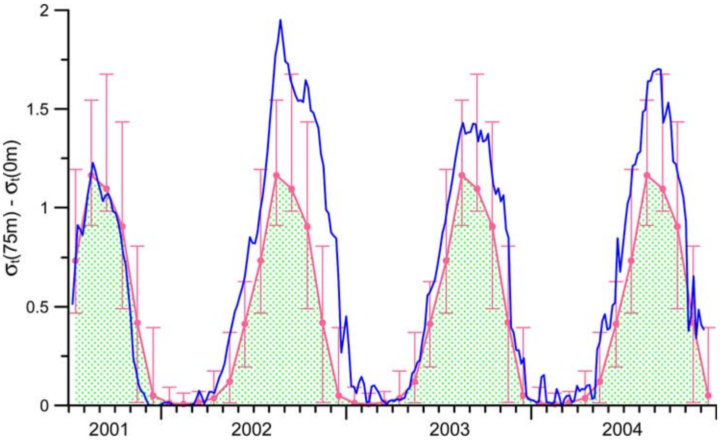

Fig. 9. The stratification of the upper ocean, computed as a σ_t difference between 75 dbar and the surface, at Ocean Station Papa. The blue line is a time series of stratification derived from Argo floats, the red points and the bars are expected differences and 95% confidence bounds.

In the second half of 2001 and in the early months of 2002 near-surface stratification at Ocean Station Papa was very close to the historical average. However, as the spring stratification began to develop in the spring of 2002 it began to exceed normal values significantly and by August was at record high levels. Though the stratification did decline in the fall of 2002 it remained extremely high, in most cases well above the upper 95% confidence bounds and at record high levels. The plots in Fig. 9 suggest that stratification was reduced to normal levels in the winter of 2002/03, but this is highly dependent on the measure of stratification used. In a normal winter, we expect the upper ocean at Station Papa to be well mixed at least down to 110 dbar, so the disappearance of stratification over the top 75 dbar is not a surprise even in this unusual winter. At the time of writing, December 2004, the near-surface stratification appears to be returning to normal.

The residual heat in the upper water column was distributed over a larger depth during the mixing events of the 2002/03 winter, but excess upper-ocean stratification remained and as the spring of 2003 started the warming was rapid and the stratification remained large. Throughout 2003 stratification remained larger than normal, but in this case the deviations remained within the 95% confidence bounds. During the mid-summer of 2004 and to the time of writing the stratification became exceptionally large once again.

The excess near-surface stratification must serve as an obstacle to deep mixing. The greatest depth at which mixing can take place during winter storms is determined by a balance between the rate of working by winds at the surface, injecting turbulent kinetic energy at the surface, and the work done to raise the potential energy of a water column. If the rate of working by winds is lower than normal, or if the initial state is one of anomalously low potential energy, then the increase in potential energy must be reduced. In other words, mid-winter mixing takes place to progressively shallower depths. In this case we know that the water column at Station Papa in the autumns of 2002 and 2003 was in a state of unusually low potential energy. We do not have wind measurements at Station Papa, but winds are measured at three locations about 500 km offshore from the coast of British Columbia, the buoys called North, South and Middle Nomad, Gower (1996). The mean-cube wind speed averaged over the period from November to March was found to be 1210, 1046, 1014 and 1052 m^3/s^3 for the winters of 2000/01, 2001/02, 2002/03 and 2003/04, respectively. Thus, the rate of working on the sea surface was indeed least in recent years during the winter of 2002/03, but the difference is extremely small.

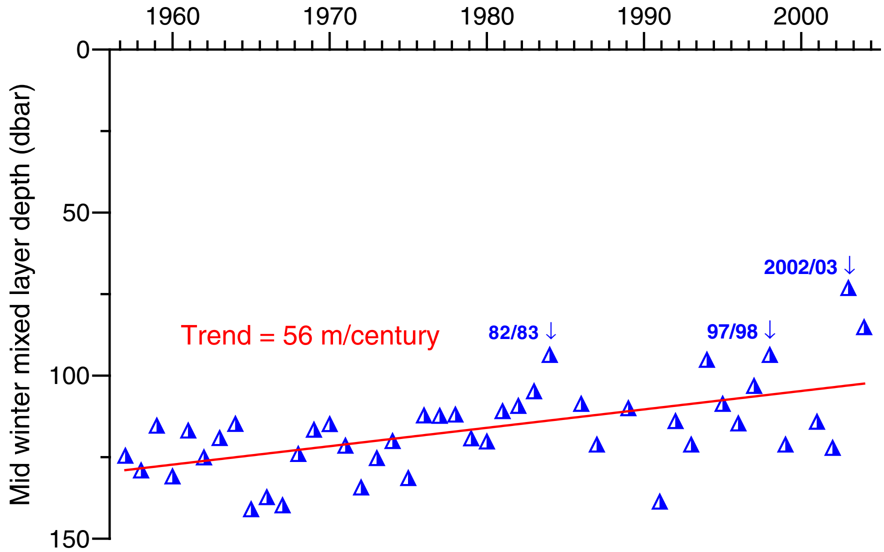

Fig. 10. The greatest depth to which winter mixing takes place at Ocean Station Papa (following Freeland et al., 1997).

Freeland, Denman, Wong, Whitney, and Jacques (1997) showed evidence of progressive warming and freshening of the upper water of the Gulf of Alaska and showed how this had to result in shallowing mixed layers. That paper presented an objective method for estimating the depth of mid-winter mixing and showed that the mid-winter mixing depths were getting progressively shallower.

The diagram originally presented in the paper by Freeland et al. (1997) has been extended to the present time and is presented in Fig. 10. In this diagram three years are highlighted, the winters of 1982/83 and 1997/98, both of which were influenced by warming associated with intense El Niño events. The third year highlighted is the winter of 2002/03 which has provided us with the shallowest mixed layers observed in the history of observations at Ocean Station Papa. This is purported to have been a period during which we experienced a minor El Niño event. The second shallowest mixing on record occurred during the winter of 2003/04 (observations actually in February 2004) and is not associated with any El Niño event. The trend towards shallower mixing is evident, as is the considerable amount of variability. Cummins and Lagerloef (2002) demonstrated that a Markov model driven by local Ekman pumping is capable of accounting for the trend and most of the interannual variability in Fig. 10. However, this model does not account for the anomalously shallow mixed layer of 2002/03.

5. Discussion

We have shown that the unusual climate anomalies seen in 2002 are associated with large-scale changes in the structure of the circulation of the Gulf of Alaska. Associated with these changes there was an intense warming of the surface waters of the Gulf which also stabilised the upper ocean against mixing, and this in turn led to much shallower mid-winter mixing. Such a reduction in the maximum depth of mixing must inevitably lead to a reduction in the supply of both macro and micro nutrients to the upper ocean. The shallower mixing also means that phytoplankton are cycled by turbulence to significantly smaller depths in the spring implying an increased exposure to light. This leads to the possibility of both a reduced supply of nutrients and an increased demand, which could affect the ecosystem.

Nitrates are rarely if ever limiting at Ocean Station Papa. It seems likely that nitrate supply was reduced, but this is not relevant to the health of the ecosystem if the amount available is not limiting. Silicate can, however, be limiting at Station Papa and observations suggest (Whitney, private communication) that the nitrate/silicate ratio was substantially altered as a result of the increased stabilisation of the water column, with a significantly lower concentration of dissolved silicates. A change was also observed in the plankton populations with an evolution towards smaller plankton and a striking absence of diatoms.

The events of 2002 were peculiar to the Gulf of Alaska, but the Argo array is global and there seems to be no obvious reason why the type of analysis described here could not be carried for any other ocean basin, with the exception, perhaps, of the Arctic Ocean which remains a problem for Argo-like explorations. Notwithstanding this difficulty, the Argo array now readily allows ocean scientists to carry out real-time assessments of the physical state of the upper 2000 dbar of the ocean, on the scale of ocean basins.

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