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An examination of advection in the northeast Pacific Ocean, 2001–2005

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[1] Horizontal advection has been assumed negligible within the Alaskan Gyre (AG). With the recently available Argo data this assumption can be tested. To estimate advection, the observed heat content (estimated from Argo data) was compared to the expected (based on surface heat fluxes) and the difference between these was defined as advection. Four stations were investigated. Our proxy suggests periods of greater advection than previously estimated. Most periods of strong advection were associated with oceanographic events such as the migration of the North Pacific Current and the passage of eddies. However, there were also periods of significant advection that were not expected, for example a region-wide event was observed in the winter of 2004–05. These results show that although advection is minimal in the AG, there are periods in which use of 1-D models for studies of short (monthly) scale processes is questionable. **Citation:** Jackson, J. M., P. G. Myers, and D. Ianson (2006), An examination of advection in the northeast Pacific Ocean, 2001–2005, *Geophys. Res. Lett.*, *33*, L15601, doi:10.1029/2006GL026278.

1. Introduction

[2] Ocean Station Papa (OSP, 50°N, 145°W) is a station that has almost 50 years of oceanographic data and has been used to represent conditions in the Gulf of Alaska (Figure 1) [*Whitney and Freeland*, 1999]. The interior of the Alaska Gyre has been considered an ideal location for 1-D mixed layer (ML) models as there is minimal horizontal advection [e.g., *Denman and Miyake*, 1973]. In addition, 1-D models driven by the divergence of the Ekman transport have been able to account for interannual variability [e.g., *Lagerloef*, 1995; *Cummins and Lagerloef*, 2002, 2004; *Capotondi et al.*, 2005]. However, processes that increase advection at OSP, such as the northward migration of the North Pacific Current (NPC) [*Freeland and Cummins*, 2005] have recently been documented. The relatively high spatial and temporal resolution of Argo and satellite data allows us to test the 1-D assumption over shorter time-scales (e.g., weeks).

[3] Previous estimates of the change in heat content due to horizontal advection ranged from 0.26–0.78°C per month [*Tabata*, 1965; *Denman and Miyake*, 1973]. We re-examine the magnitude of changes in heat content from advection and test the assumption of negligible advection at four stations: OSP, Station 16 (S16, 49°17N, 134°40W), located along Line P which is on the southeastern edge of the Alaskan Gyre, station CAG located at 55°N, 145°W in the center of the Alaskan Gyre and station NSG located at 40°N, 145°W along the northern edge of the subtropical gyre (Figure 1). We use real-time, continuous temperature profiles from Argo floats [*Gould et al.*, 2004] and the NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996] to calculate the monthly change of heat content. Current estimates of surface heat flux are more accurate than freshwater flux estimates [*Taylor*, 2002] so local changes in heat content were used (rather than salt content) as a proxy for advection.

2. Data and Methods

[4] Temperature and salinity data from the Argo data set [*Gould et al.*, 2004] was interpolated as by *Freeland and Cummins* [2005] to our 4 stations. We studied OSP, S16 and CAG from July 2001–July 2005 and NSG from April 2002–July 2005 because NSG was limited by the availability of Argo data prior to this period [*Freeland and Cummins*, 2005]. Outside of this period at NSG, float density was close to or above the target density (nearest neighbour spacing of 300 km, ibid) at all stations and sufficient for our analysis. The little temporal variability in the float locations between months [*Freeland and Cummins*, 2005, Figure 5] suggests that we should not expect a distribution bias in our heat content estimates. Daily average surface heat fluxes from the NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996] were linearly interpolated to our 4 stations and then summed to calculate the total surface heat fluxes (Q_{SF}) at each station.

[5] Heat content (Q_{HC}) was calculated as:

$$Q_{HC} = \rho_o C_p \int T \, dz \tag{1}$$

where ρ_o (reference density) is 1026.95 kg m^{-3}, C_p (specific heat of seawater) is 3986 Jkg^{-1}°C^{-1} and T is the temperature interpolated in 1 m intervals. A comparison between the Argo float derived heat contents with those from Line P cruises during 2003 reveals that the estimates in heat content differ by less than 10% - note also that our Argo estimates are monthly averages while the cruise measurements are effectively instantaneous.

[6] Advection is expected to affect the heat budget only after several weeks [*Denman and Miyake*, 1973]. Thus, once a month, Q_{HC} was integrated over the three depth ranges: an upper zone - UZ (0–100 m), a halocline zone - HZ (0–200 m) and a lower zone - LZ (0–250 m). The vertical flux through the bottom of each layer was assumed to be zero. It is possible that upwelling and downwelling could influence the heat content in the UZ because wind stress influences

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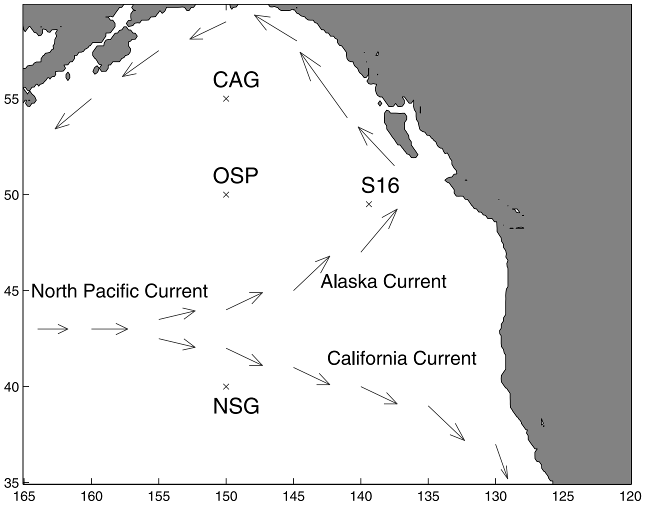

Figure 1. A map of the North Pacific Ocean with surface currents and stations used in this experiment. The NPC separates the Alaskan gyre (to the north) from the subtropical gyre (to the south).

temperatures in the Gulf of Alaska to 150 m [*Murphee et al.*, 2003]. We compared the magnitudes of the $w\frac{\partial T}{\partial z}$ and $v\frac{\partial T}{\partial y}$ terms of the temperature conservation equation, where w was estimated by integrating the basic Sverdrup vorticity balance $\beta v = f\,\frac{\partial w}{\partial z}$ from a level where the vertical velocity is assumed zero, which boils the comparison down to the ratio $\frac{L\beta}{f}$. A horizontal length scale of 500 km has been chosen as the distance a patch of water with a given temperature anomaly may cover in a month, assuming a horizontal velocity of 0.2 m/s.

[7] This simple scaling argument suggests that vertical advection is one order of magnitude smaller than horizontal in the Gulf of Alaska, especially through the base of our deepest box, the LZ layer.

[8] The observed heat content at the beginning of the month (Q_{HCobs1}) and the surface heat fluxes during that month (Q_{SF}) were subtracted from the observed heat content at the end of the month (Q_{HCobs2}) to yield an estimate of change in heat content due to advection during that month (Q_{AD}):

$$Q_{AD} = Q_{HCobs2} - (Q_{HCobs1} - Q_{SF}) \tag{2}$$

Monthly Q_{AD} is considered significant when it is greater than one standard deviation from the mean of the absolute value of all Q_{AD} at that location. Although the heat content estimates are significantly larger than the heat flux term, a global error in temperature of 0.1°C through an entire profile would lead to an error in heat content that is significantly less than the associated heat change due to the surface fluxes.

3. Results and Discussion

[9] All stations underwent no net heat change or small net heat loss due to horizontal advection throughout the study period (Table 1). OSP had the greatest heat loss, with a monthly average temperature change through the upper water column (zone LZ) of −0.1 ± 0.3°C while CAG had the smallest heat loss with temperature changes of −0.0 ± 0.2°C. Although NSG had a similar average as OSP, it had the largest standard deviation (0.4), suggesting that monthly advection with larger heat gains and losses were occurring. The result at OSP is consistent with *Large* [1996], who pointed out that there isn't a simple balance between heat fluxes and storage at that location. Additionally, we find little difference in the year-to-year change in temperature due to advection at all stations and in all layers (not shown), suggesting little variability in advection at the inter-annual timescale in the Gulf of Alaska during our study period, consistent with the findings of *Cummins and Lagerloef* [2002, 2004].

[10] The NPC was displaced north through OSP in February 2002 to 51.5°N, where the main axis resided from March–May and then returned to a more southerly location in June 2002 [*Freeland and Cummins*, 2005]. The signature of this migration can be seen in our results (Figure 2a). The largest advective heat loss was seen in March, with a maximum change in temperature of −0.5°C, −0.4°C and −0.4°C in the UZ, HZ and LZ, respectively. Constant heat loss with depth suggests that the main axis of the current was near OSP (otherwise a strong advective signal would only have been seen in the upper layer), with the NPC transporting cold water into the region. (A heat gain would have implied that the subarctic front had migrated as far north as OSP.) During this period, very little advective heat change occurred at any of the other stations, suggesting that no basin wide process was responsible for advection at OSP. Additionally, the arrival of the subsurface cold water anomaly [*Crawford et al.*, 2005] was not observed as there was no significant heat loss in the HZ at OSP and S16 during the summer of 2002. We suggest that the anomalous water mass was already present in the summer of 2002 at OSP and was a remnant of migration of the NPC. At OSP, there was a significant heat loss in December 2002 (−1.2°C) in the UZ. This significant heat loss was restricted to the UZ, and may have resulted from a reduction in Ekman pumping associated with a relaxation of the unusually strong winds the previous January (2002). Starting in November 2004, Q_{AD} oscillated from heating to cooling until July 2005. Significant values occurred in November (1.3°C), February (−0.8°C), April (−1.2°C) and July (−1.2°C) with the largest heat gain was seen in the LZ.

[11] Events of large Q_{AD} at S16 was generally in phase with Q_{AD} at OSP (Figure 2b), with sporadic periods of significant advection that were associated with a heat loss until the winter of 2004–2005. The first period of signif-

Table 1. Average Monthly Temperature Change and Standard Deviation at Each Level From August 2001 to July 2005 at OSP, S16, and CAG and From August 2002 to July 2005 at NSG[a]

	OSP	S16	CAG	NSG
100 m	−0.2 ± 0.4	−0.2 ± 0.4	−0.0 ± 0.4	−0.2 ± 0.7
200 m	−0.1 ± 0.3	−0.1 ± 0.2	−0.0 ± 0.3	−0.1 ± 0.4
250 m	−0.1 ± 0.3	−0.1 ± 0.2	−0.0 ± 0.2	−0.1 ± 0.4

[a]Negative values indicate a heat loss. Values are in °C; n = 48 at OSP, S16, and CAG and n = 36 at NSG.

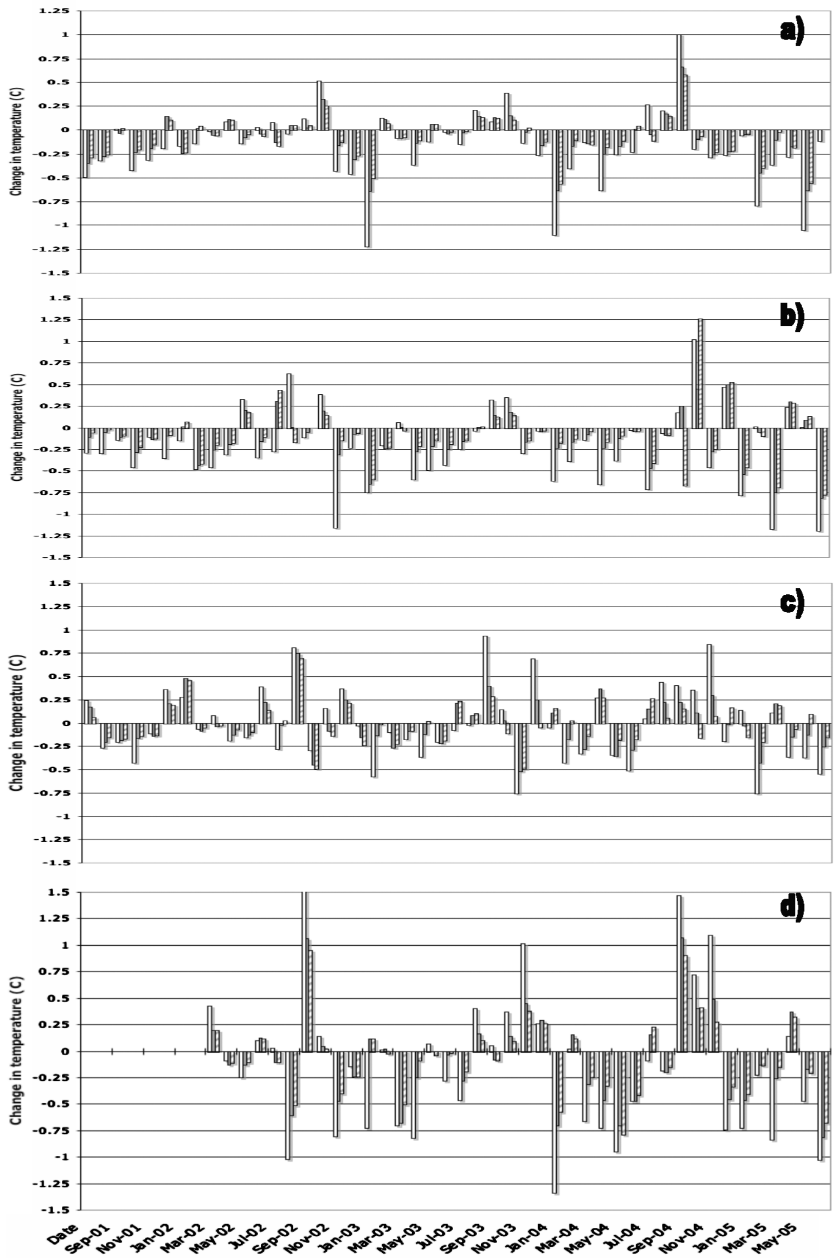

Figure 2. Calculated change in temperature from advection at (a) OSP, (b) S16, (c) CAG, and (d) NSG. White bars represent temperature change to 100 m, gray bars represent temperature change to 200 m and bars with gray diagonal lines represent temperature change to 250 m. Maximum value at NSG in October 2002 is 1.57°C.

icant change in heat content was in February 2003, with a heat loss of −1.2°C. Increased southward flow into the California Current and decreased northward flow into the AC from the NPC [*Freeland et al.*, 2003] may have caused this loss. Most of the advection was in the UZ so it is likely that the main axis of the surface intensified AC was not close to S16. Similarly in February 2004, there was a heat loss (−1.1°C) that was primarily in the UZ so we suggest that this was again caused by the close proximity of the AC to S16. Significant advection occurred in October 2004, March 2005 and June 2005 with values of 1.0°C, −0.8°C and −1.0°C, respectively. The heat gain occurred 1 month earlier at S16 than at OSP and was found primarily in the UZ instead of the LZ. Aside from the heat gain in October, there were no rapid temperature gains and losses through the winter of 2004–2005 at S16.

[12] At CAG (Figure 2c), significant advection associated with a temperature gain of 0.8°C, 0.7°C and 0.7°C in the UZ, HZ and LZ in September 2002 was followed by enhanced advection and heat loss in October. Based on altimetry data (W. Crawford and F. Whitney, Graphic images of the Haida eddy, available at http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/HaidaEddy/default_e.htm) we suggest that passage of a Haida Eddy and the associated depressing/raising of the thermocline caused this heat gain and subsequent loss. The following September, there was a similar heat gain (0.94°C) principally in the UZ again followed by the heat loss (−0.8°C) in November 2003

and then a heat gain of 0.7°C in December 2003 consistent with passage of a warm-core eddy or some other anomalous water mass. However, there were no observed eddies in the region during these months (Crawford and Whitney, Graphic images of the Haida eddy). In November 2004 significant advection that was associated with a heat gain (0.8°C) was followed by a heat loss in February 2005 (−0.8°C). Again, we see a similar pattern at CAG with a significant heat gain in November yet there were no observed eddies near CAG during this period.

[13] NSG was more variable than stations in the Alaska gyre (Figure 2d). The first period of significant advection was September, October and December 2002 with oscillatory monthly Q_{AD} (−1.0°C, 1.6°C and −0.8°C) in the UZ. We know that the NPC did not return to the region of NSG until much later [*Freeland and Cummins*, 2005] so another mechanism must have caused these oscillations. Significant cooling (−0.8°C) in May 2003, primarily in the UZ accompanied the return of the NPC. In December 2003 and February 2004 significant advection with a heat gain of 1.0°C was followed by a heat loss of −1.3°C. The reversal from the temperature gain to temperature loss in January is concurrent with the movement of the NPC [*Freeland and Cummins*, 2005]. We suggest that significant heat loss in June 2004 in all layers (−0.9°C in the UZ) was also caused by motion of the NPC. More oscillatory heat gains and losses occurred in October 2004, December 2004, April 2005 and June 2005 with temperature changes of 1.5°C, 1.1°C, −0.8°C and −1.0°C, respectively.

[14] A significant heat gain from horizontal advection occurred at all observed stations in the northeast Pacific during the fall of 2004 followed by a period of a significant advective heat loss in the spring, suggesting that a basin-scale process was responsible.

4. Summary and Implications

[15] Horizontal advection is assumed negligible in the Gulf of Alaska so many 1-D ML models have been used in the Gulf, particularly at OSP. Recent events such as the northern migration of the NPC show that atypical processes arise, thereby creating a need to verify the accuracy of this assumption, especially on short time scales. In this study, advection was estimated from the difference between the observed heat content and the expected heat content (based on surface heat fluxes) and discussed in context with documented atmospheric and oceanographic events that may have influenced advection. Estimated changes in heat content were usually within the same order of magnitude as the surface heat fluxes.

[16] OSP, where previous calculations have shown that the maximum monthly heat change from advection was 0.78°C [*Tabata*, 1965], experienced 7 out of 48 months (5 of which occurred during 2005) where the advection was significantly greater than the mean, with a maximum advective temperature change of 1.3°C in November 2004. S16 also experienced 6 months (4 during 2005) where the change in heat content due to advection was significantly greater than the mean with a maximum of −1.2°C in February 2003. We suggest that aside from the heat gain seen in October 2004, the meandering of the AC caused the advection. At CAG, there were 7 months where the change in heat content was significantly greater than the mean. However, a number of these events were only marginally significant and since the mean advection was smaller at this station, smaller anomalies were needed to produce ‘significant’ events. The maximum was 0.9°C in September 2003. It is likely that the passage of eddies through the Alaska Gyre caused these changes. Overall, our proxy showed that NSG had the strongest advection and the most number of months, 11 out of 36, with large advective temperature changes with a maximum of 1.6°C in October 2002. This advection was likely caused by its proximity to the NPC, a poor location for 1-D models. All stations experienced a significant amount of heat gain in the fall of 2004 followed by significant heat loss in early 2005. We are unsure what mechanisms caused these anomalies, although they appear to operate region-wide.

[17] Thus, our results show that while stations in the Gulf of Alaska experienced negligible advection most of the time (consistent with the historical limits of *Tabata* [1965]), as well as on inter-annual time scales, events occurred that increased the advection and would be expected to affect ML calculations and results of 1-D coupled models on monthly timescales. Thus if one were interested in short timescale processes (e.g., phytoplankton blooms), then there will be periods of time when the 1-D assumption fails. Of the stations studied, CAG would be the best location to use a 1-D ML model as anticipated as it is in the center of the gyre away from boundary currents. However, there were still several months when horizontal transport was significant. We suggest that heat budgets are estimated when 1-D models are used to ensure that the horizontal advection assumption is reasonable. The availability of CTD data from Argo floats makes such model checks possible.

[18] **Acknowledgments.** Special thanks to Howard Freeland for helping interpolated the Argo data and to Bill Crawford and Pat Cummins for interesting insight in preparation of this manuscript. The Argo data was collected and made freely available by the International Argo Project and the national programmes that contribute to it (http://www.argo.ucsd.edu). The NOAA-CIRES Climate Diagnostics Centre at UCAR for the freely available NCEP/NCAP Reanalysis data. This work was funded by an NSERC grant awarded to PGM.

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