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Recent western South Atlantic bottom water warming

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[1] Potential temperature differences are computed from hydrographic sections transiting the western basins of the South Atlantic Ocean from 60°S to the equator in 2005/2003 and 1989/1995. While warming is observed throughout much of the water column, the most statistically significant warming is about +0.04°C in the bottom 1500 dbar of the Brazil Basin, with similar (but less statistically significant) warming signals in the abyssal Argentine Basin and Scotia Sea. These abyssal waters of Antarctic origin spread northward in the South Atlantic. The observed abyssal Argentine Basin warming is of a similar magnitude to that previously reported between 1980 and 1989. The Brazil Basin abyssal warming is similar in size to and consistent in timing with previously reported changes in abyssal southern inflow and northern outflow. The temperature changes reported here, if they were to hold throughout the abyssal world ocean, would contribute substantially to global ocean heat budgets. **Citation:** Johnson, G. C., and S. C. Doney (2006), Recent western South Atlantic bottom water warming, *Geophys. Res. Lett.*, *33*, L14614, doi:10.1029/2006GL026769.

1. Introduction

[2] Bottom waters formed around Antarctica spread northward to cover much of the world ocean floor, with the exception of the Arctic and North Atlantic [*Mantyla and Reid*, 1983]. These bottom waters gradually warm by mixing as they spread into deep basins, with more abrupt property changes at sills between basins. These waters are often collectively referred to as Antarctic Bottom Water (AABW). Variations in the hydrographic and chemical tracer properties of these waters are of interest as a possible indicator of variations in their transport or formation properties.

[3] The coldest, densest bottom waters entering the deep basins of the western South Atlantic are referred to as Weddell Sea Deep Water (WSDW) for potential temperatures $\theta < 0°C$, and Lower Circumpolar Water (LCPW) for warmer temperatures. North of the Subantarctic Front in these basins there are strong vertical property gradients centered around $\theta = 1.5°C$ between the northward spreading LCPW and the southward spreading North Atlantic Deep Water (NADW) [*Tsuchiya et al.*, 1994]. These gradients are centered on 4000 dbar in the Brazil Basin, and shoal southward in the Argentine Basin. Changes in bottom water properties from the 1970s through the 1990s have been previously described in this region. Here we add to this description by comparing data from a 2005 hydrographic section with 1989 and 1995 section data. Decadal reoccupations of basin-spanning full-depth hydrographic sections such as those made by the U.S. CLIVAR/CO_2 Repeat Hydrography Program [http://ushydro.ucsd.edu/] provide much of the data for study of abyssal property variations.

[4] Closest to the source of AABW, in the Weddell Sea, analysis of hydrographic data suggests that Weddell Sea Bottom Water (WSBW; $\theta < -0.6°C$) clearly has warmed by $+0.003°C\ yr^{-1}$ during the 1990s [*Fahrbach et al.*, 2004]. A warming trend in the WSDW within the Weddell Sea from the 1970s to the 1990s is not statistically significant given interannual variability [*Robinson et al.*, 2002]. However, the overlying Warm Deep Water (WDW; $\theta > 0°C$) there exhibits a statistically significant warming trend of +0.012 (±0.007) $°C\ yr^{-1}$ from the 1970s to the 1990s [*Robinson et al.*, 2002], with a reversal from 1998 to 2002 [*Fahrbach et al.*, 2004].

[5] Downstream, in the Argentine Basin, a volumetric comparison of hydrographic data from 1988–1989 with data collected mostly around 8–10 years earlier revealed a substantial reduction in the coldest ($\theta < -0.2°C$) bottom waters in the basin [*Coles et al.*, 1996]. Reported concomitant abyssal freshening in that basin has been disputed as arising from systematic inter-cruise salinity errors [*Gouretski and Janke*, 2001].

[6] The primary conduit for bottom water flow from the Argentine Basin northward into the Brazil Basin is the Vema Channel [*Speer and Zenk*, 1993]. Bottom water temperatures in the Vema Channel appear to be nearly constant at $\theta = -0.18°C$ from 1972 through 1991, with an abrupt warming to about −0.15°C in 1992 that holds through 1996 [*Hogg and Zenk*, 1997], and no associated freshening.

[7] On the equator, between the Brazil Basin and the Guiana Basin to the north, a moored array deployed from Oct. 1992–May 1994 suggested warming rates of +0.098 and $+0.016°C\ yr^{-1}$ within the AABW at 4100 and 4300 m, respectively [*Hall et al.*, 1997], and a possible decreasing northward AABW volume transport. A redeployment of this array from Apr. 1999–Jan. 2003 suggested no statistically significant trend in AABW temperatures or transports during this later period [*Limeburner et al.*, 2005]. These authors suggested that the warming reported for the first deployment of the array be reinterpreted as a 25–40-m descent of isotherms in a stratified region over the more homogenous layer of AABW located below the instrument locations. CTD section data from mooring deployment and recovery cruises [*Limeburner et al.*, 2005, their Figure 3] do suggest decadal warming in the bottom water. The 0.6°C isotherm present from 0.5°S to 0.5°N about 100 m above the bottom in 1992 is almost absent in 1994 and completely gone in 1999, 2001, and 2003. Analysis of other equatorial CTD sections along 35°W show warming at the greatest sampled pressures from 0.55°C in 1993 to 0.65°C in 1999,

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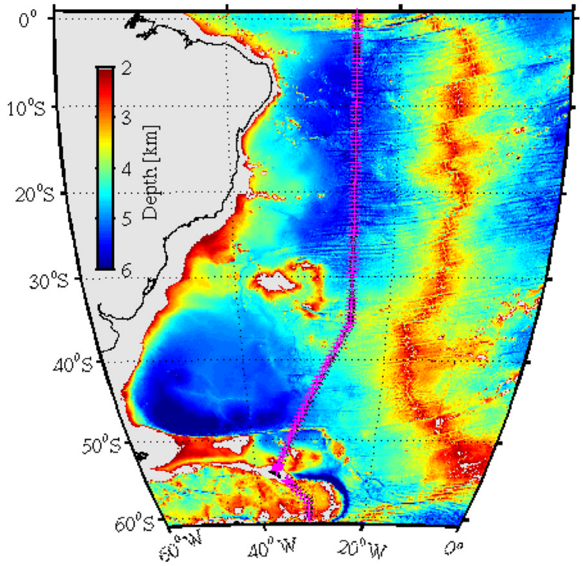

Figure 1. Combined 2005/2003 section station locations (maroon plusses) plotted over 1989/1995 locations (black crosses) and satellite bathymetry [*Smith and Sandwell*, 1997] color contoured (inset color bar) from deep (6 km) to relatively shallow (2 km) values with shallower waters indicated by light grey and the coastline by a black contour.

with intermediate values in 1995 and 1996 [*Andrié et al.*, 2003].

2. Data

[8] In Jan.–Feb. 2005, a hydrographic section [*Wanninkhof and Doney*, 2005; http://cchdo.ucsd.edu/] was occupied in the western basins of the South Atlantic Ocean (Figure 1) as part of the U.S. CLIVAR/CO_2 Repeat Hydrography Program. The section started from 60°S near the South Scotia Ridge, headed northwestward across the Scotia Sea to South Georgia Island at about 55°S, from there turned northeastward across the South Georgia Basin to the Falkland Ridge, continued across the eastern Argentine Basin, turned northward east of the Rio Grande Plateau to transit the central Brazil Basin, and almost reached the mid-Atlantic Ridge where it ended at 2.3°S. High-quality Conductivity-Temperature-Depth (CTD) instrument data were collected from the surface to the bottom at stations 0.5° lat. apart or closer (over steep bathymetry). The CTD data were calibrated to bottle salinity samples standardized with IAPSO Standard Seawater Batch P143. A few of the southernmost stations from the U.S. CLIVAR/CO_2 Repeat Hydrography Program 2003 reoccupation of A16N were appended to extend coverage to the equator and the mid-Atlantic Ridge. The combined section is referred to here as 2005/2003. The southern end of the 2005 cruise (to South Georgia Island) repeated a portion of WOCE section A23, previously occupied in Mar.–May 1995 [*Heywood and King*, 2002]. The northern end of the 2005 cruise repeated WOCE sections A16S and A16C, previously occupied in Feb.–Apr. 1989 [*Tsuchiya et al.*, 1994]. These authors have carefully analyzed regional water mass distributions and circulations from these previous sections, which are referred to here in combination as 1989/1995.

[9] Here the 2-dbar CTD temperature and salinity (S) data from these cruises are analyzed. Potential temperature referenced to the surface (θ), potential density referenced to 4000 dbar (σ_4), and planetary potential vorticity (Q; the Coriolis parameter divided by the in situ density and multiplied by a locally referenced vertical potential density gradient) are computed. These fields are low-passed vertically with a 40-dbar (80-dbar for Q) half-width Hanning filter. The results are then subsampled at 10-dbar intervals for analysis. The vertically filtered station data from each section are put on an evenly spaced latitudinal grid using a shape-preserving piecewise cubic Hermite interpolant.

3. Results

[10] The mean Q and θ fields (Figure 2) reveal a great deal about the regional ocean structure. As noted previously,

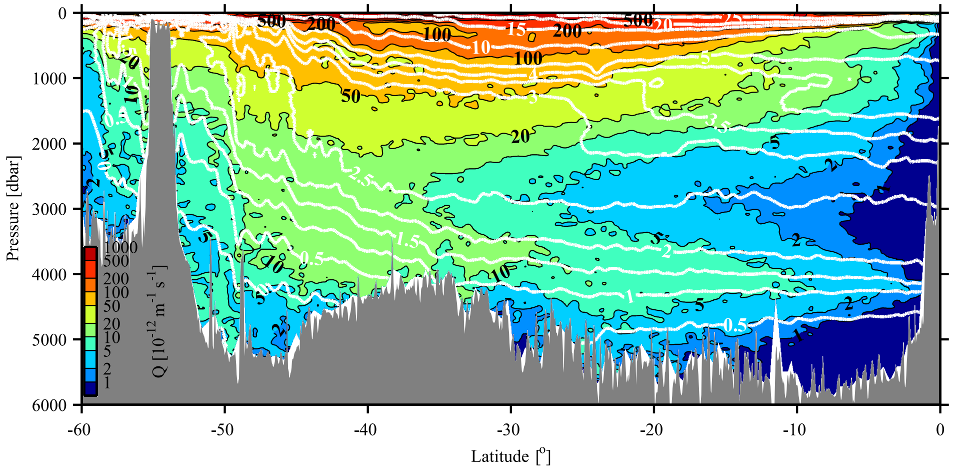

Figure 2. Mean Potential Vorticity (Q) magnitude from the average of the 2005/2003 and the 1989/1995 combined section data (Figure 1). Mean Q magnitude is color contoured (inset color bar) at roughly logarithmic intervals from low (1×10^{-12} m^{-1} s^{-1}) to high (1000×10^{-12} m^{-1} s^{-1}) values. Mean potential temperature (θ) is contoured (thick white lines) at 0.5°C intervals at and below 4°C, and 5°C intervals at and above 5°C.

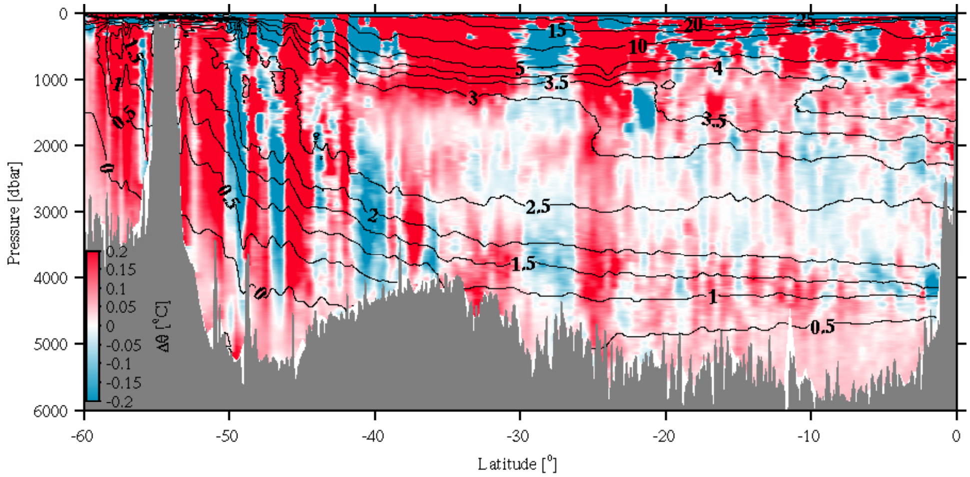

Figure 3. Differences in potential temperature, Δθ [°C], resulting from subtracting the 1989/1995 from the 2005/2003 combined section data (Figure 1). Values of Δθ are color contoured (inset color bar) from −0.2°C to +0.2°C to accentuate deep changes, despite some larger variations. Mean θ is contoured (black lines) as detailed in Figure 2.

a relatively strong maximum in Q centered around θ = 1.5°C divides the AABW from the NADW. Below that maximum, Q generally decreases in magnitude toward the bottom in the deepest 1000–2000 dbar of the deep basins, reflecting the relative lack of stratification in the bottom waters. In the Brazil Basin (here from about 34°S to the equator) deep isotherms are relatively level, and bottom waters are relatively uniform in θ (~0.2°C) north of about 27°S, but are slightly warmer (~0.7°C) south of that latitude, likely because of bathymetry that isolates the southeastern portion of the basin from the coldest bottom waters (Figure 1). In the Argentine and South Georgia Basins, as well as the Scotia Sea, the isotherms shoal to the south, mainly in a series of fronts associated with strong eastward geostrophic currents (including the Antarctic Circumpolar Current) increasing toward the surface, but evident to the bottom. Bottom Q (hence stratification) is low in these regions as well. Bottom θ reaches values as cold as −0.2°C in the southern Argentine Basin, below −0.5°C in the South Georgia Basin, and then only −0.4°C in the shallower Scotia Sea.

[11] The difference in potential temperature when the 1989/1995 combined section data are subtracted from the 2005/2003 values (Δθ; Figure 3) reveals predominant warming in the weakly stratified bottom 1000–2000 dbar of the abyssal ocean. Shallower in the water column, but still deeper than 1000 dbar, Δθ oscillations in sign and larger magnitude changes are evident at scales of a degree or two in latitude, especially in the southern basins. These Δθ oscillations suggest the influence of eddies or perhaps meridional shifts in frontal locations. Within the thermocline (in the upper km), very large Δθ oscillations are evident with somewhat longer meridional scales.

[12] Ascertaining the statistical significance of Δθ changes requires estimates of the effective number of degrees of freedom in Δθ fields. Integral spatial scales for Δθ are estimated using the horizontally interpolated fields at each pressure level. These fields are detrended by removing a linear fit versus latitude. To determine the integral spatial scales at each pressure level the autocovariances of these detrended fields are integrated from zero lag out to the first zero crossing [*Emery and Thomson*, 1998, pp. 261–263]. The resulting scales (not shown) are as large as 1.8° lat. above 1100 dbar and are generally ≤0.5° lat. below 1100 dbar, except for a peak approaching 0.9° lat. within 3800–4200 dbar. The effective number of degrees of freedom at each level, estimated as latitude range sampled divided by the integral spatial scale, is used throughout the error analysis, including application of Student's t-test for 95% confidence limits.

[13] Profiles of average Δθ in each basin (Figure 4) reveal overall warming except in the upper 100 dbar. Near-surface differences are likely influenced by sampling slightly different phases of the seasonal cycle. In the Scotia Sea (Figure 4a), warming increases with decreasing pressure, starting at +0.05°C near 3500 dbar and reaching about +0.2°C by 1000 dbar. The smallest confidence intervals are in the relatively homogenous and cold waters deeper than 2000 dbar. However, nowhere in this basin are Δθ values significantly different from zero at the 95% confidence level on isobars. In the South Georgia and Argentine Basins (Figure 4b), warming is smallest near 4000 dbar, and increases both shallower and deeper, reaching +0.15°C by 1000 dbar, and exceeding +0.05°C around 5000 dbar. The smallest confidence intervals are again found in the relatively homogenous and cold abyssal waters, deeper than 4000 dbar. However, only Δθ values around 5000 dbar are statistically significant in these two basins. In the Brazil Basin, warming is near zero from 1500–3500 dbar, and increases both above and below, reaching +0.1°C by 1000 dbar, and about +0.04°C at 4000 dbar and deeper. However, only the small warming in the coldest and most homogenous abyssal waters (deeper than 4500 dbar) is significantly different from zero at 95% confidence limits on isobars.

[14] The average deep θ-S curves for each basin (not shown) agree to within salinities of ±0.003 (PSS-78) or less in the AABW and nearly up to the NADW salinity maximum. Given variation among IAPSO Standard Seawater Batches and other factors, this level of agreement is likely within the uncertainty of salinity calibrations among indi-

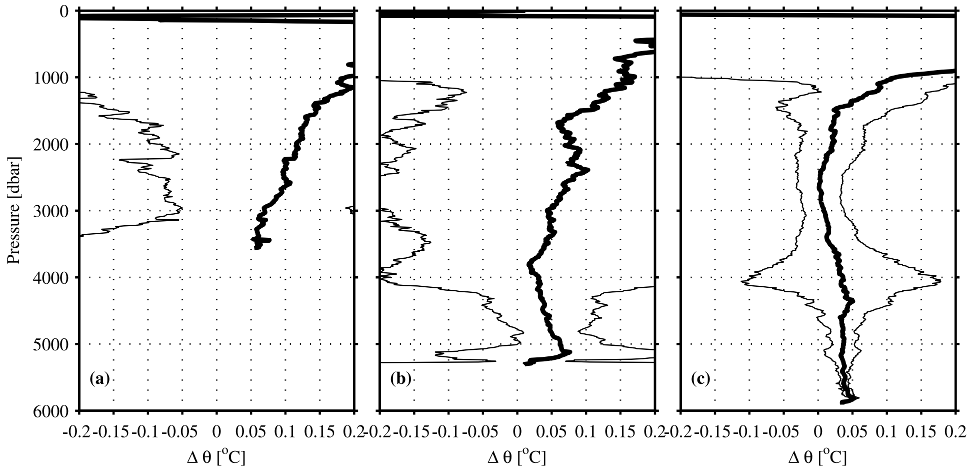

Figure 4. Mean differences (thick lines) of potential temperature, $\Delta\theta$ [°C], resulting from subtracting the 1989/1995 from the 2005/2003 combined section data averaged by deep basins as function of latitude and pressure with 95% confidence intervals (thin lines) for (a) the Scotia Sea (60°S–54.75°S), (b) the South Georgia and Argentine Basins (54.5°S–35.75°S), and (c) the Brazil Basin (35.75°S–0.75°S).

vidual cruises. The AABW warming appears uncompensated by salinity changes.

4. Discussion

[15] The most statistically significant differences in potential temperature in the western basins of the South Atlantic Ocean when 1989/1995 combined section data are subtracted from the 2005/2003 values are generally in the bottom 1000–2000 dbar of each basin where the coldest, most homogenous bottom waters are found. These bottom waters, which are of Antarctic origin and spread northward throughout these basins, have generally warmed by ~+0.04°C or more in each of the basins (Figures 3 and 4) between 1989/1995 and 2005/2003. Although only the warming in the Brazil Basin is significantly different from zero at 95% confidence, the warming in AABW is observed in all three basins. In contrast, the overlying NADW, at least in the Brazil Basin, shows no discernible change.

[16] In the Scotia Sea, this warming of abyssal waters is of the right size to have originated from the Weddell Sea, where warming of WSBW and WDW over recent decades is of a similar magnitude [*Robinson et al.*, 2002; *Fahrbach et al.*, 2004]. Alternately, southward shifts in the positions of the multiple deep-reaching fronts of the Antarctic Circumpolar Current [*Gille*, 2002] could also cause some of the observed abyssal warming in the Scotia Sea, South Georgia Basin, and Argentine Basin. This hypothesis might be consistent with the observed pattern of surface-intensified warming in these basins (Figure 4). However, the warming reported here in the Scotia Sea is not by itself significantly different from zero at 95% confidence limits (Figure 4a).

[17] In the South Georgia and Argentine Basins, the previously reported warming of abyssal waters between around 1980 and 1989 [*Coles et al.*, 1996], appears to have continued between 1989 and 2005 (Figure 4b) with as much as +0.05°C of warming in the AABW (some of it significantly different from zero at 95% confidence) over the past 16 years.

[18] The observed warming of abyssal waters by about +0.04°C from 1989 to 2005 in the interior of the Brazil Basin is highly statistically significant (Figure 4c), and contrasts with little change in the overlying NADW. This observation of abyssal warming is consistent with a +0.03°C warming in 1992 in the coldest AABW entering the Brazil Basin through the Vema Channel [*Hogg and Zenk*, 1997], and a warming of similar, but slightly larger magnitude at the equatorial exit point from the Brazil Basin between 1992 and 1999 [*Hall et al.*, 1997; *Andrié et al.*, 2003]. The AABW entry and exit points for the Brazil Basin are both fed by relatively rapid (0.03–0.08 m s^{-1}) western boundary currents, so water may take only 1–3 years to transit the basin [*Sandoval and Weatherly*, 2001].

[19] However, for the observed interior changes of Brazil Basin abyssal waters, a mass and density budget for $\theta <$ 0.8°C suggests a warming rate of only +0.001°C yr^{-1} after a +0.03°C increase in AABW entering the basin, with all else being equal [*Morris et al.*, 2001]. The observed lower bound (the warming could have happened more quickly than the 16-year interval between sections) of +0.0025°C yr^{-1} (Figure 4c) on the interior warming rate is a few times the previous estimate. This discrepancy may imply dynamical adjustment in addition to a change in the temperature of AABW flowing into the basin. Zonal gradients of bottom θ predominate near the longitude of WOCE section A16S in the Brazil Basin, and are about 5×10^{-8} C m^{-1} [*Morris et al.*, 2001], implying that bottom isotherms moved westward by about 800 km over 16 years, resulting in a lower bound on retreat rate of about -1.6 mm s^{-1}. In addition, the abyssal thermocline between the AABW and the NADW has deepened by about 20 m over this time interval, but this deepening is not statistically different from zero at 95% confidence.

[20] While the rate of change in abyssal temperature observed here seems small, it suggests the abyssal oceans could have a substantial impact on ocean heat budgets. Estimates of ocean heat content changes have shown that on global scales, 0–700 m multi-decadal heat content changes are about 75% of 0–3000 m changes [*Levitus et al.*, 2005].

That work indicates that ocean heat changes may be mostly concentrated in the upper portions of the water column. The volume-averaged rate of temperature increase for the upper 750 m from 1993 to 2003 for the global ocean [*Willis et al.*, 2004] is about +0.0085°C yr^{-1}. While the contribution of the observed +0.0025°C yr^{-1} warming rates in the bottom 1500 dbar of the western South Atlantic to the global heat budget is small, if such warming rates were found throughout the bottom 1500 dbar of the global ocean with a depth exceeding 3000 m, they would amount to almost 50% of the 1993–2003 upper ocean (0–750 m) changes.

[21] Whether the decadal bottom water warming trend observed here is natural variability or a human-induced trend cannot be deduced directly from the analysis of a few repeat hydrographic sections alone. However, anthropogenic climate change simulations do project similar patterns of a poleward shift in the Antarctic Circumpolar Current [*Fyfe and Saenko*, 2005] and deep and bottom water warming [*Huang et al.*, 2003; *Gent et al.*, 2006].

[22] The abyssal warming reported here for the western South Atlantic is not likely to be global. However, recently a smaller warming has been reported in the abyssal North Pacific, very far from the Antarctic [*Fukasawa et al.*, 2004]. Quantification of decadal abyssal temperature changes in other basins ventilated by AABW is certainly warranted. Argo [http://www.argo.net] is now measuring the upper portion of the water column with an array of profiling CTD floats approaching 3° × 3° lat.-long. spatial scales at 10-day intervals. At present, the abyssal ocean is only measured at roughly 10-year intervals with at best a few sections across each deep basin [http://ioc.unesco.org/ioccp/Prog_Hydro.htm]. Given the potential contributions of the deep ocean to the global ocean heat budget, and the possibility of detectable anthropogenic changes in the abyss, better-resolved deep sampling should be a priority.

[23] **Acknowledgments.** The 2005 and 2003 cruises on the NOAA Ship *Ronald Brown* are part of the NOAA/NSF funded U.S. CLIVAR/CO_2 Repeat Hydrography Program. The NOAA Office of Oceanic and Atmospheric Research and the NOAA Climate Program Office further supported GCJ. The hard work of all who contributed to the collection and processing of the data from the 1989, 1995, 2003, and 2005 hydrographic sections is gratefully acknowledged. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Oceanic and Atmospheric Administration. This is Pacific Marine Environmental Laboratory contribution 2924.

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