Recent Bottom Water Warming in the Pacific Ocean*

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ABSTRACT

Decadal changes of abyssal temperature in the Pacific Ocean are analyzed using high-quality, full-depth hydrographic sections, each occupied at least twice between 1984 and 2006. The deep warming found over this time period agrees with previous analyses. The analysis presented here suggests it may have occurred after 1991, at least in the North Pacific. Mean temperature changes for the three zonal and three meridional hydrographic sections analyzed here exhibit abyssal warming often significantly different from zero at 95% confidence limits for this time period. Warming rates are generally larger to the south, and smaller to the north. This pattern is consistent with changes being attenuated with distance from the source of bottom water for the Pacific Ocean, which enters the main deep basins of this ocean southeast of New Zealand. Rough estimates of the change in ocean heat content suggest that the abyssal warming may amount to a significant fraction of upper World Ocean heat gain over the past few decades.

1. Introduction

Since the bulk of the heating of the earth by greenhouse gas warming appears to have been taken up by the World Ocean (Levitus et al. 2005), estimates of interannual World Ocean heat storage changes (Willis et al. 2004; Levitus et al. 2005) are very important in evaluating climate model performance (Barnett et al. 2005), understanding the energy imbalance of the earth associated with global warming, and estimating the earth's climate sensitivity to changes in greenhouse gas concentrations and other climate forcing (Hansen et al. 2005).

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Most estimates of changes in World Ocean heat storage have been limited to the upper 750 m (Willis et al. 2004), or at most the upper 3000 m (Levitus et al. 2005), because historical temperature data become very sparse below the 750-m depth limit of most expendable bathythermographs (XBTs). The growing array of Argo floats (more information is available online at http://www.argo.net) promises to enhance routine ocean measurements of the ice-free World Ocean compared to the past XBT-based system by achieving even global coverage, adding measurements of ocean salinity to those of temperature, sampling to 2000 m, and sampling throughout the annual cycle. All of these things provide a great improvement for climate science, but data for estimates of deep (>2000 m) ocean heat storage changes will still be very sparse.

As might initially be expected for the case where heat is simply mixed down from the surface of a stratified fluid like the ocean, heat content changes do appear to be surface-intensified (Willis et al. 2004; Levitus et al. 2005). For example, simple linear fits to World Ocean heat content variations for 0–300-m and 0–700-m analyses of Levitus et al. (2005) between 1955 and 1998 have, respectively, slopes that are 35% and 59% of the slope for the 0–3000-m analysis (not shown), even though those layers span only 10% and 23% of the depth of the 0–3000-m layer, respectively.

However, the ocean is not ventilated solely by mixing from a shallow surface mixed layer into the thermocline. At high latitudes in locations such as the Labrador Sea (Lazier et al. 2002) and the Greenland Sea (Karstensen et al. 2005), very dense waters occasionally form where cooling in the open ocean is sufficiently strong to overcome the weak local stratification and create a surface mixed layer that extends deep into the water column, thus locally exposing the abyss to surface forcing. In addition, very dense waters are formed on ocean shelves around Antarctica, which then cascade down into the abyss (Orsi et al. 1999). Combinations of these North Atlantic Deep Waters and Antarctic Bottom Waters ventilate the cold deep abyss, mixing with waters above them (Mantyla and Reid 1983). As a result, while middepth waters in the Pacific and Indian Oceans are some of the "oldest" waters in the world in terms of the time since they have last been exposed to the surface (or ventilated), the bottom waters are significantly newer (England 1995).

Abyssal cooling of about 0.02°C has been reported in the southwest Pacific Ocean in 1990/91 relative to 1968/69 (Johnson and Orsi 1997). It should be borne in mind that the deep stations they analyzed were widely spaced in the horizontal, not all these deep stations were occupied all the way to the bottom, the 1968/69 stations had about 500-m vertical spacing between samples in the abyss, and 0.01°C is about the best instrumental accuracy expected for the reversing thermometers (Emery and Thomson 1998) that were used in 1968/69. In contrast, more recent analyses of modern closely sampled high-quality repeat hydrographic section data taken over the last decade or so reveal an abyssal warming of 0.005°–0.01°C at decadal intervals in the very coldest, nearly vertically homogenous abyssal waters of the main deep basins of the Pacific Ocean that are ventilated from the south (Fukasawa et al. 2004; Kawano et al. 2006b).

Here deep ocean temperature differences are presented from analyses of modern high-accuracy closely spaced hydrographic section data taken in the Pacific Ocean from the Antarctic Circumpolar Current to the Alaskan Stream and occupied at least twice during the past few decades (Fig. 1). Some of these differences are new and some are previously reported but are reanalyzed here in a slightly different way. The results presented here add to and confirm pioneering findings of abyssal Pacific Ocean warming in recent decades (Fukasawa et al. 2004; Kawano et al. 2006b). The warming is estimated to be statistically significant in many locations. Furthermore, the potential contribution of this abyssal warming to the global heat budget is discussed.

2. Data and processing

High-quality temperature (T), salinity (S), and pressure (P) data collected in the Pacific Ocean using conductivity–temperature–depth (CTD) instruments during hydrographic stations occupied first as part of the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) in the 1980s and 1990s, and more recently in support of Climate Variability and Predictability (CLIVAR) and CO_2 programs are analyzed here (Fig. 1 and Table 1). Data from sections nominally along 47°N, 30°N, and 32°S are reanalyzed, but in a slightly different manner than in Fukasawa et al. (2004) and Kawano et al. (2006b). In addition, new analyses are presented from sections along 150°W in both hemispheres and 170°W in the Southern Hemisphere. The carefully calibrated CTD data from all these sections are thought to be accurate to at least 0.002°C or better in temperature, and 0.003 PSS-78 in salinity (which is reported on the 1978 Practical Salinity Scale). At most stations, data were collected from near the ocean surface to within about 10 m of the ocean bottom. The initial sections were occupied from 1984 to 1996, and the more recent occupations were made from 1999 to 2006 (Table 1).

Station spacing is important for resolving the signals analyzed here, but is difficult to summarize in a tabular form and so is discussed here. The first occupation of WOCE section P01 (Talley et al. 1991), a primarily zonal section nominally along 47°N, had station spacing near 85 km, and as for all sections analyzed here, station spacing was closer over rapidly changing bathymetry. Thus for P01, closer stations are found near the eastern and western ends of the basin, as well as the crossing of the Emperor Seamount Chain near 170°E. The second occupation of P01 (Fukasawa et al. 2004) had similar station spacing.

The first occupation of WOCE section P02 (more information is available online at http://cchdo.ucsd.edu), a primarily zonal section nominally along 30°N, was a 3-ship operation extending over 2 calendar years with combined interior station spacing at distances of 56 and 88 km, with a few intervals around 250 km. The U.S. CLIVAR/CO_2 reoccupation of this section had station spacing mostly at distances of 56 and 73 km, with a few 110-km intervals.

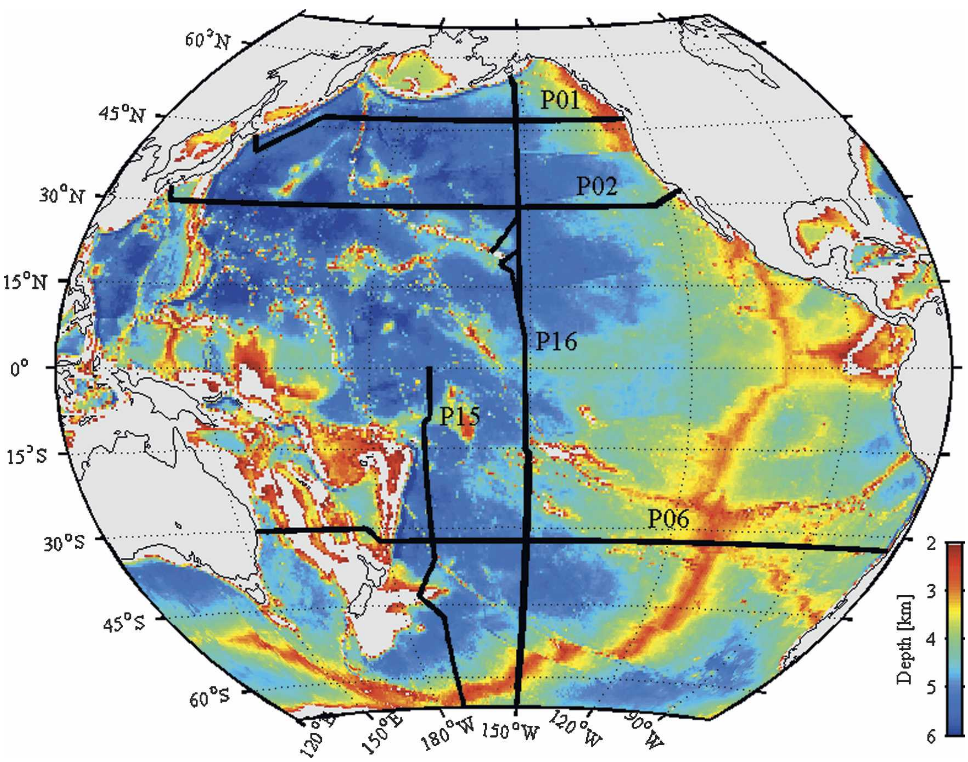

FIG. 1. Locations of hydrographic sections (thick black lines) with WOCE designators P01 (47°N), P02 (30°N), P06 (32°S), P16 (150°W), and P15 (170°W). Designator labels are located above zonal sections and to the right of meridional sections. Bathymetry is color shaded from 6 km (blue) to 2 km (red) with shallower depths in gray (see color bar) and coastlines drawn as thin black lines.

The first occupation of WOCE section P06 (Tsimplis et al. 1998), a primarily zonal section nominally along 32°S, had interior station spacing at distances of 48, 63, and 78 km, with a few short sections around 94 km. The reoccupation (Kawano et al. 2006b), done as part of the Japanese Blue Earth Global Expedition (BEAGLE) 2003, had station spacing like the original.

The first occupation of the Southern Hemisphere portion of WOCE section P15 (McTaggart and Johnson 1997), a primarily meridional section occupied nominally along longitude 170°W known as P15S, had interior station spacing (67°–5°S) of generally 56 km; it increased to 111 km from 5°S to the equator. The second occupation (more information is available online at http://www.marine.csiro.au/nationalfacility/franklin/plans/2001/fr0501s.html) was made along the same

TABLE 1. WOCE designator, nominal latitude or longitude, year of initial occupation, year(s) of subsequent occupation(s), time interval, and heat flux estimates (see text and footnotes).

WOCE/WHP designation	Nominal lat or lon	Initial occupation months and year(s)	Subsequent occupation months and year(s)	Time interval (years)	Heat flux (W m^{-2})*
P01	47°N	Aug–Sep 1985	May–Jun 1999 Aug–Oct 1999	13–14	0.011
P02	30°N	Aug–Nov 1993 Jan–Feb 1994	Jun–Aug 2004	10	0.028
P06	32°S	May–Jul 1992	Aug–Oct 2003	11	0.020
P15S	170°W	Jan–Mar 1996	May–Jul 2001	5	0.061
P16N	150°W	Feb–Apr 1991 May–Jun 1984**	Mar 2006	12–15	0.015
P16S/C	150°W	Aug–Sep 1991 Oct 1992	Jan–Feb 2005 Feb–Mar 2006	12–15	0.042

* Average heat gain rates as a function of depth for each section first normalized by global hypsometry and then depth integrated below 3000 m (4000 m for P06) as described in section 4.

** The 1984 occupation of P16 as part of the Marathon II expedition was limited to the portion of the section north of Hawaii, designated P16N.

track from 49.5°S to the equator as part of the Australian Deep-Ocean time series sections (DOTSS), with stations at locations similar to WOCE P15S.

The first occupation of the portion of WOCE section P16 north of Hawaii (Talley et al. 1991), a primarily meridional section nominally along longitude 152°W known as P16N, had full water column interior stations spaced for the most part at 80- and 100-km intervals. The second (WOCE) occupation (McTaggart and Mangum 1995) had stations for the most part occupied at 75-km intervals, with one 460-km gap between 48.3° and 52.4°N. The third (U.S. CLIVAR/CO_2) occupation had stations that were almost always spaced at 111 km, with one 222-km gap between 42.0° and 44.0°N.

The first occupations of the portions of WOCE section P16 (Johnson and Talley 1997) between Hawaii and Tahiti (P16C) and south of Tahiti (P16S) had full water column station spacing of generally 56 km, with 18-km spacing from 3°S to 3°N. The second (U.S. CLIVAR/CO_2) occupations had 55-km station spacing south of 16°S and from 2°S to 2°N, and 111-km station spacing elsewhere.

Here the 1-dbar or 2-dbar T, S, and P data from CTD stations occupied during these cruises are analyzed. First, T data reported on the 1990 International Temperature Scale (ITS-90) are converted to the 1968 International Practical Temperature Scale (IPTS-68) using a simple linear formula (Saunders 1991) since the 1980 Equation of State (EOS-80) was formulated using IPTS-68, not ITS-90. Then potential temperature referenced to the surface (θ) is computed using EOS-80. All fields from each CTD profile are low-passed vertically with a 40-dbar half-width Hanning filter. The results are then subsampled at 10-dbar intervals for analysis.

The vertically filtered station data from each section are interpolated onto an evenly spaced latitudinal or longitudinal grid (depending on section orientation) at 0.033° spacing using a shape-preserving piecewise cubic Hermite interpolant at each pressure level. This spacing matches that of a high-resolution bathymetric dataset generated by merging satellite altimetry data with bathymetric soundings (Smith and Sandwell 1997) that is used here. The bathymetry along each section is used as a mask to eliminate data that have been interpolated to locations below the ocean floor.

In section 3, latitude-pressure or longitude-pressure differences of gridded θ fields from the various hydrographic cruises are analyzed. Where gridded data from either cruise are missing, no difference is computed, or where cruise tracks diverge by more than 1° of longitude or latitude, data are not used in the difference analysis. Most prominently, the 1984 occupation of P16N deviated in position significantly from the 1991 and 2006 occupations between Hawaii and 27°N, so differences in that region are not computed. This step ensures that only closely collocated repeat measurements are used. In addition, the large gap in the 1991 occupation of P16N between 48.3° and 52.4°N was excised since it is simply too great a distance over which to interpolate. All other gaps were filled in with interpolation.

3. Analysis

In all the $\Delta\theta$ sections (e.g., Fig. 2), there is a good deal of vertically banded structure, with temperature difference fields sometimes alternating sign from band to band over at least parts of the water column. Generally the amplitude of these variations increases from the bottom to the surface. This pattern might be anticipated in the ocean for vertical excursions associated with eddies, waves, tides, or meanders, where vertical stratification generally increases toward the surface.

Differences of potential temperature fields ($\Delta\theta$) among the three P16N occupations between Hawaii and Kodiak Island show that for 2006–1984, much of the deeper water column has warmed measurably throughout all but the northernmost reaches (Fig. 2a), both in the very weakly stratified region of $\theta < 1.2$°C ($P > 3500$ dbar) and in the increasingly (but still weakly) stratified regions as shallow as 2000 dbar. Strong bottom-reaching subpolar currents, including the Alaskan Stream (Warren and Owens 1988) over the Aleutian Trench near 56°N and an offshore counterflow over the Aleutian Rise to the south, may be associated with significant variability on time scales much shorter than decadal, so temperature changes estimated there from differences of snapshots separated by many years may not be representative of long-term changes. For 2006–1991 (Fig. 2b) warming is also evident over much of the section for $\theta < 1.2$°C, but both warming and cooling tend to alternate above that level. In contrast, for 1991–84 differences (Fig. 2c) warming again appears dominant for $\theta > 1.2$°C, but below that level warming is not obvious since there are also bands of cooling. This result suggests that abyssal warming may have commenced here sometime after 1991, subject to the assumption that basin-scale abyssal variations are dominated by decadal and longer time scales. However, the fact that the time interval for the 1991–84 difference is less than half that for the 2006–1991 estimate makes detecting abyssal temperature changes over the earlier time period more difficult.

Ascertaining the statistical significance of $\Delta\theta$ changes requires estimates of the effective number of degrees of

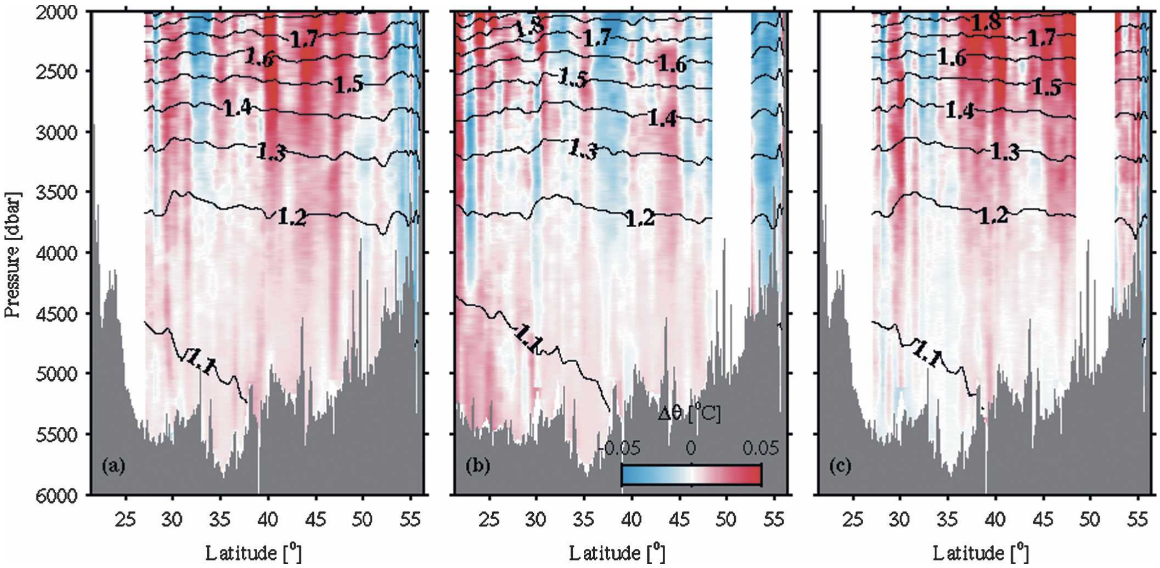

FIG. 2. Sections of potential temperature difference ($\Delta\theta$, °C) for P16N (nominally along 152°W) between Hawaii and Kodiak Island, color shaded as a function of latitude and pressure. (a) 2006–1984, (b) 2006–1991, and (c) 1991–84. Red areas indicate warming and blue areas indicate cooling, with color saturation at ±0.05°C. Mean potential temperatures from all the data (black lines) are contoured. Portions of the sections with either large data gaps [from 48.3°–52.4°N in (b) and (c)] or where section longitudes diverged at a given latitude [south of 27°N in (a) and (c)] are blanked out.

freedom in $\Delta\theta$ fields. Integral spatial scales for $\Delta\theta$ are estimated from autocovariances (e.g., von Storch and Zwiers 2001). Here the effective number of degrees of freedom at each level, estimated as the latitude or longitude range sampled at each level (which varies because of topography) divided by the integral spatial scale for that level, is used throughout the error analysis, including application of Student's t test for 95% confidence limits.

When latitudinal averages are computed for the $\Delta\theta$ fields along P16N (omitting regions with large data gaps and where the sections diverge by more than 1° longitude) they show abyssal warming of about 0.004°C between 2006 and 1984 (generally approaching statistically significant differences from zero at 95% confidence limits only for $P > 4500$ dbar), as well as between 2006 and 1991, but not between 1991 and 1984 (Fig. 3). Again, these results suggest that most of the warming

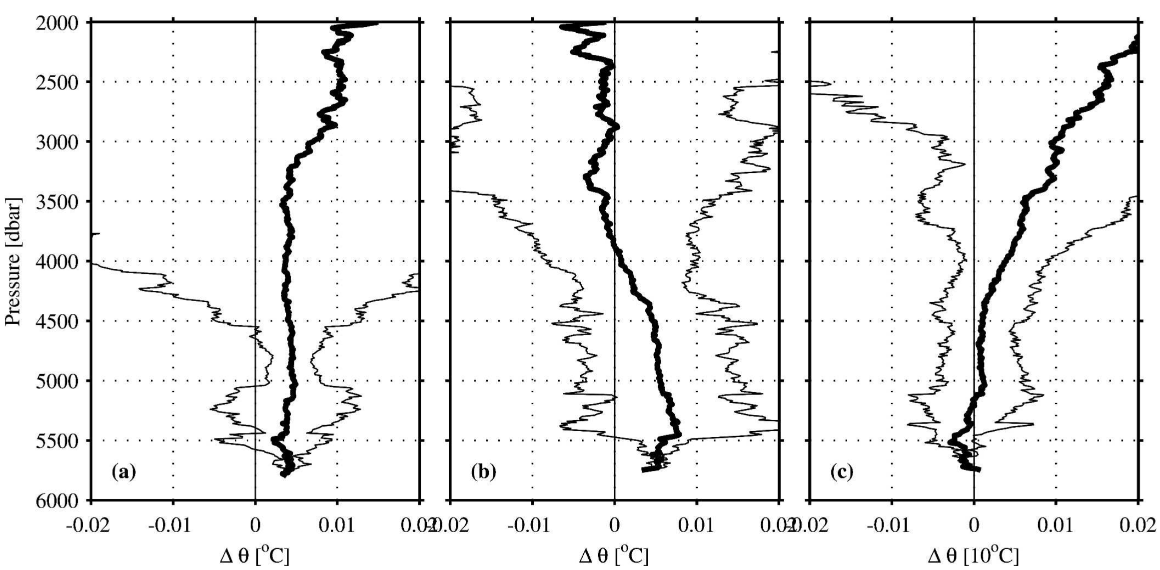

FIG. 3. Section-mean differences of potential temperature differences ($\Delta\theta$, °C, thick lines) for P16N (nominally along 152°W) between 27°N/Hawaii and Kodiak Island with 95% confidence limits (thin lines). (a) 2006–1984, (b) 2006–1991, and (c) 1991–84.

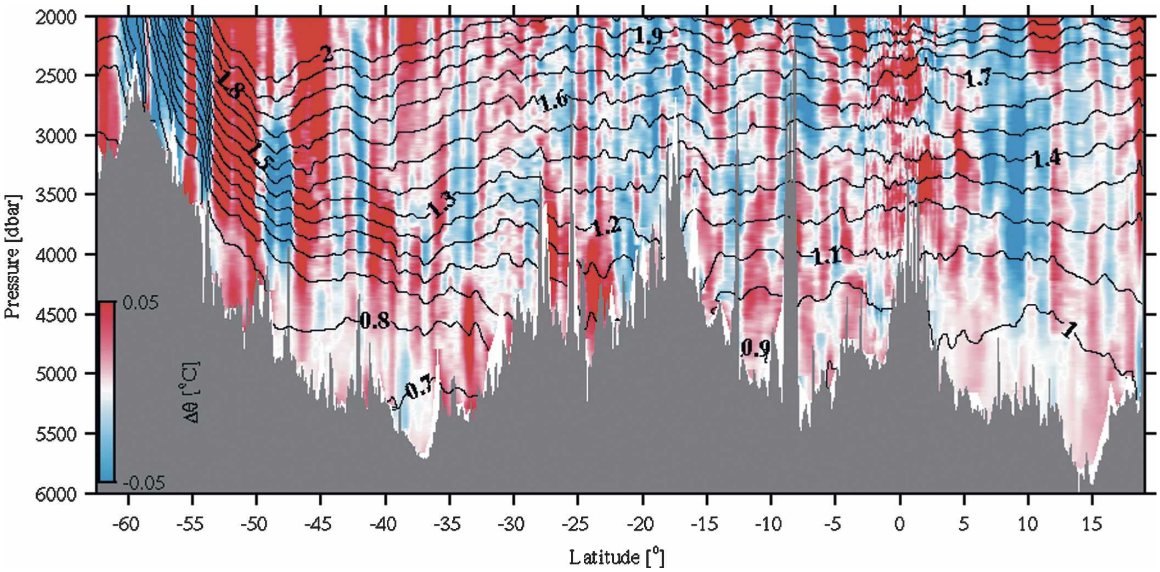

FIG. 4. Section of potential temperature difference ($\Delta\theta$, °C) for P16S/C (nominally along 150°W south of Hawaii) color shaded as a function of latitude and pressure using 2005/06–1991/92 data. Details are the same as in Fig. 2.

observed in the abyss along P16N occurred after 1991. However, the differing latitudinal ranges used for these averages because of gaps or excessive zonal separation of the sections (Fig. 2) may affect these difference estimates if the temperature changes are not uniformly distributed in latitude. As might be expected from the vertical banding noted above, uncertainties increase with decreasing pressure. The $\Delta\theta$ fields from 2005/06 to 1991/92 for the portion of P16 south of Hawaii (P16S and P16C) generally warm in the weakly stratified abyssal layers (Fig. 4). This pattern persists throughout the entire section, even with mean abyssal temperatures generally increasing from south to north. Once again there are stronger variations above the abyss. A mean of the $\Delta\theta$ field for this section between the Pacific–Antarctic Ridge and Hawaii (Fig. 5) shows abyssal warming of about 0.004°–0.01°C, increasing from near zero for P = 3000 dbar, but it is only statistically different from zero at 95% confidence for $P > 5500$ dbar. The large uncertainty around 5300 dbar is caused by an isolated region of cooling near 39°S (Fig. 4).

WOCE section P15S lies nominally along 170°W (Fig. 1). Again, a very consistent pattern of warming in the weakly stratified abyssal layer is evident in the $\Delta\theta$ field for P15S (Fig. 6). While warming appears stronger in the southern portion of the section, south of the Chatham Rise near 43°S, abyssal warming persists throughout the entire section. The mean $\Delta\theta$ for this section is about 0.003°–0.01°C, but is only statistically significantly different from zero at the 95% confidence

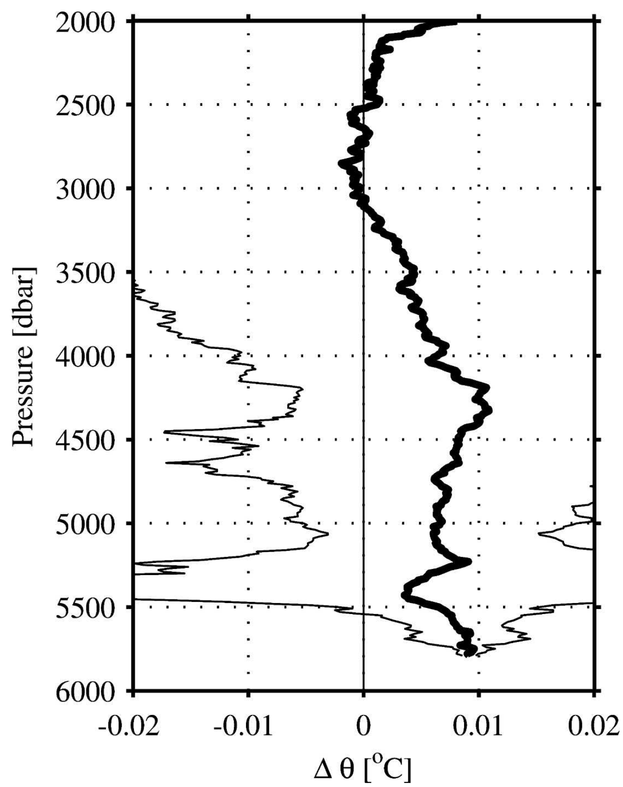

FIG. 5. Section-mean potential temperature differences ($\Delta\theta$, °C, thick lines) for P16S/C (nominally along 150°W) between the Pacific–Antarctic Ridge (near 59.5°S) and Hawaii (near 19°N) with 95% confidence limits (thin lines) using 2005/06–1991/92 data.

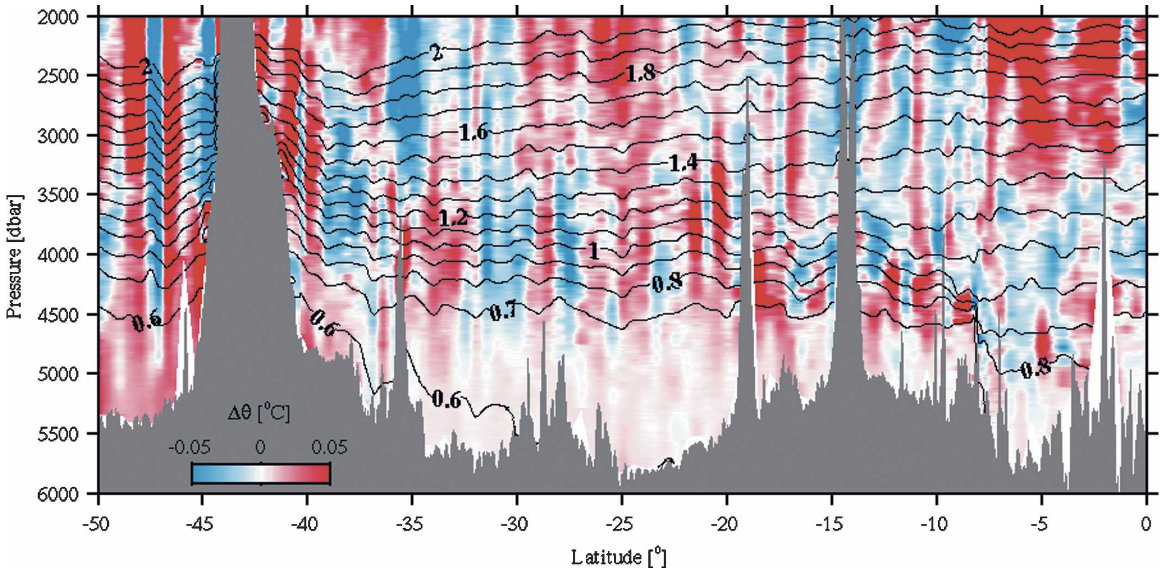

FIG. 6. Section of potential temperature difference ($\Delta\theta$, °C) for P15S (nominally along 170°W, south of the equator) color shaded as a function of latitude and pressure using 2001–1996 data. Details are the same as in Fig. 2.

level around $P = 5500$ dbar (Fig. 7). The time interval for this difference is much shorter than for the other sections, and since the mean warming signal is similar a faster rate of change is implied. The faster warming along P15S is perhaps the result of the section being closest to the entry of abyssal waters into the Pacific Ocean (Mantyla and Reid 1983), and is also consistent with the largest warming observed in this section being at its southern end.

These results are in close accord with those previously reported for differences of zonal sections at 47°N, 30°N, and 32°S (Fukasawa et al. 2004; Kawano et al. 2006b), all of which show slight but consistent warming over the past few decades in the weakly stratified abyss. Excellent sections of $\Delta\theta$ fields for those sections have already been presented in these previous studies, and so are not reproduced here. Suffice it to say that in the difference sections for P01 and P02 at 47° and 30°N, slight warming is present throughout the abyss, and in that for P06 at 32°S the abyss primarily warms, although weak cooling is observed in the South Fiji Basin, a small, relatively isolated deep basin just west of the date line, and relative strong warming is observed in the northern reaches of the Tasman Basin sampled by this section. The section-mean results reported below are all in agreement with the changes in areas between deep isotherms previously reported (Fukasawa et al. 2004; Kawano et al. 2006b). Here the analysis is slightly different, being presented as temperature differences on pressure surfaces with 95% confidence limits estimated.

Simply using the 32°S section as a whole to estimate mean $\Delta\theta$ values for this latitude suggests warming for $P > 4000$ dbar, with significant warming for $P > 5200$ dbar between 2003 and 1992, again in the weakly stratified abyss (Fig. 8a). The mean differences of about 0.01°C for $P > 5000$ dbar are larger than any other section-mean differences reported here, again consistent with the relative proximity of the section to the entry point for abyssal waters into the Pacific Ocean from the south. The abyssal warming seen here may be highly significant statistically because it is localized in the deepest portion of the southwest Pacific Basin, where the abyssal waters are relatively uniform in temperature both zonally and vertically.

Much further to the north, the P02 section along 30°N has positive mean $\Delta\theta$ values between 2004 and 1993/94 (Fig. 8b) for $P > 2000$ dbar. There is a relative minimum in section-averaged $\Delta\theta$ near $P = 4000$ dbar, and an increase toward the bottom, reaching around 0.008°C by 6000 dbar. Only the very deepest differences are statistically different from zero at the 95% confidence level.

Finally, the P01 section along 47°N has positive abyssal section-averaged $\Delta\theta$ values between 1999 and 1985 (Fig. 8c) for $P > 3500$ dbar. These differences are nearly statistically different from zero at 95% confidence for $P > 4800$ dbar, with a magnitude approaching 0.005°C near 6000 dbar. These relatively small temperature changes over a relatively long time interval are consistent with the northern location of this section being farthest from the abyssal source waters, and there-

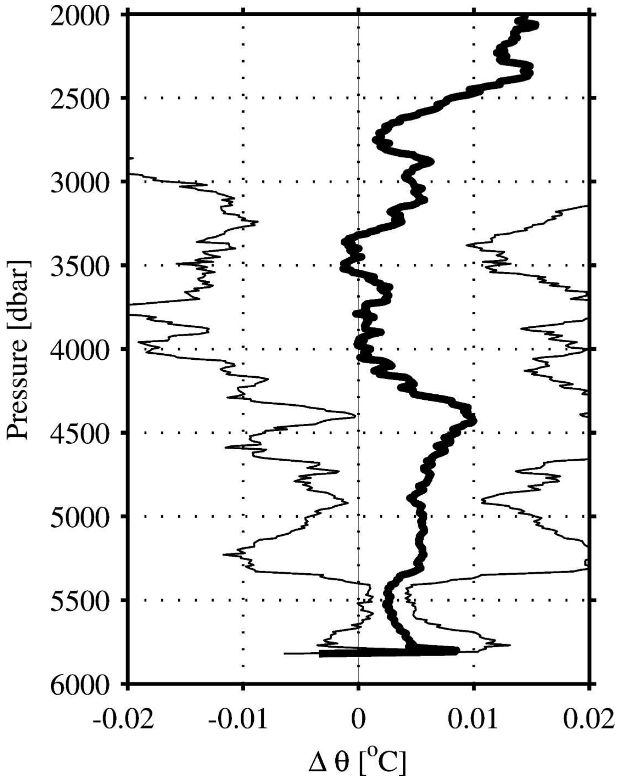

FIG. 7. Section-mean potential temperature differences ($\Delta\theta$, °C, thick lines) for P15S (nominally along 170°W, south of the equator) with 95% confidence limits (thin lines) using 2001–1996 data.

fore the most buffered of the sections analyzed here in terms of abyssal variability. In addition, this buffering appears to result in very small error bars, again because of zonal and vertical gradients in deep potential temperatures that are very small, even compared with the rest of the abyssal Pacific.

4. Summary and discussion

Temperature differences have been analyzed for five repeat hydrographic sections, mostly between the decades of the 1990s and the 2000s. Three of these sections are zonal, and two meridional (Fig. 1, Table 1). They span much of the Pacific Ocean, albeit sparsely. Warming in the weakly stratified abyss is consistently present in all of the section differences except one: the 1991–84 abyssal section-mean $\Delta\theta$ values along 150°W north of Hawaii are near zero, although the 2006–1991 abyssal differences there are positive. Most of the section differences in potential temperature are statistically different from zero at the 95% confidence limit over some abyssal pressure range. Section-mean $\Delta\theta$ values generally increase toward the bottom from values near zero around 3000–4000 dbar. The abyssal section-mean $\Delta\theta$ values range from 0.004° to 0.01°C. The lack of warming in the northern portion of the section along 150°W between 1984 and 1991 suggests that the abyssal warming found in all other sections may have commenced in the 1990s. However, that speculation is based on a very limited set of data.

Oceanographers often make inferences about water-mass changes from other properties such as salinity and oxygen. Examination of the potential temperature–salinity (θ–S) relationships in the abyss along these sections (not shown) reveals no clear large-scale changes in which we have confidence given the measurement error of salinity. That is to say, section average θ–S curves for the various occupations of P15 and P16 differ by less than about 0.004 in salinity, either before or after adjustment for differences among the standard seawater batches (Kawano et al. 2006a) used to standardize salinity measurements during these cruises. Nor do we find significant differences in the section-average abyssal potential temperature–oxygen (θ–O_2) curves for the various P16 occupations. Abyssal θ–O_2 curves for these sections differ by less than the accuracy of the oxygen measurements of 1–2 μmol kg^{-1}. These findings are in accord with the results of Fukasawa et al. (2004) and Kawano et al. (2006b), who also report no significant θ–S or θ–O_2 changes in their analyses of the abyssal Pacific Ocean.

It appears the rate of Pacific abyssal warming over the 1990s and 2000s decreases with distance from the source. Generally, warming rates appear to increase toward the south, being largest in the southwest Pacific Basin, and decrease toward the north, consistent with the fact that the source waters for the abyssal Pacific enter from the south. However, the statistical uncertainties make this conclusion a tentative one, as most of the section-mean differences overlap within their error bars. It has been noted previously that these increases do not need to be the direct result of changes in source water properties advected into the Pacific, but could be the result of changes in source water formation regions communicated more rapidly by planetary waves (Fukasawa et al. 2004; Kawano et al. 2006b), which would be consonant with the absence of measurable changes in the abyssal θ–S and θ–O_2 relationships discussed above. Given horizontal abyssal temperature gradients, the abyssal temperature increases reported here are consistent with a lower bound of less than 1×10^{-3} m s^{-1} for decadal variations in interior abyssal ocean horizontal advection.

With significant warming present throughout the abyssal Pacific between the decades of the 1990s and the 2000s, it is interesting to assess the potential significance of this signal in terms of the World Ocean heat

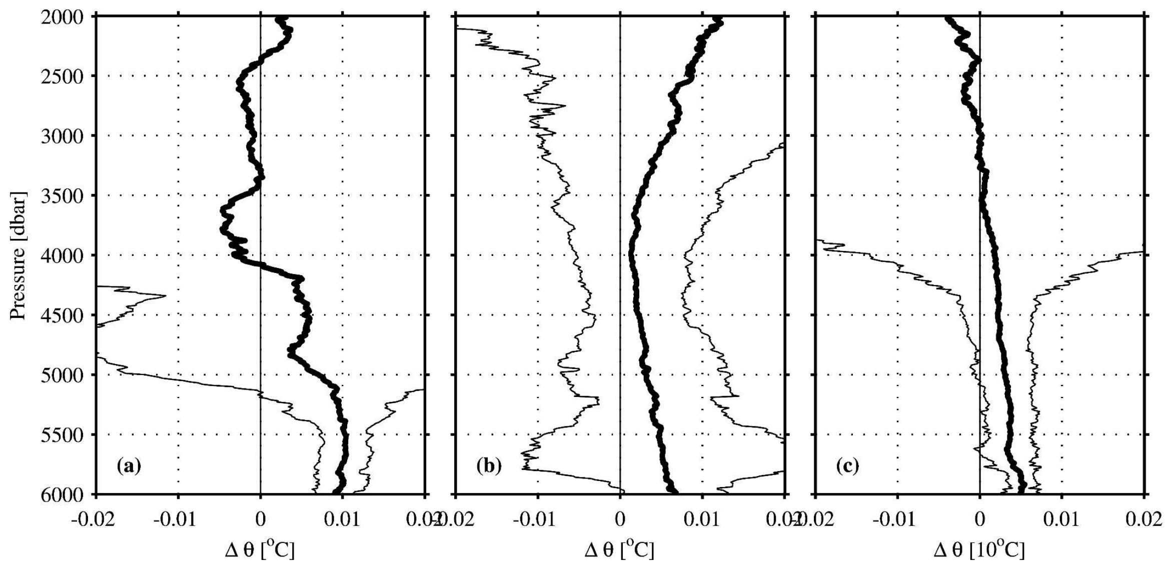

FIG. 8. Section-mean potential temperature differences ($\Delta\theta$, °C, thick lines) for (a) section P06 (nominally along 32°S) with 95% confidence limits (thin lines) using 2003–1992 data, (b) section P02 (nominally along 30°N) with 95% confidence limits (thin lines) using 2004–1993/94 data, and (c) section P01 (nominally along 47°N) with 95% confidence limits (thin lines) using 1999–85 data.

budget. The temperature differences are small, being only about an order of magnitude smaller than overall temperature increases between 2003 and 1993 in the upper 750 m of the World Ocean (Willis et al. 2004). However, they occur over a thickness of thousands of meters.

The horizontal average of heat content change ΔQ can be computed as a function of pressure p for each section:

$$\Delta Q(p) = \langle \rho c_p (T_f - T_i)/(t_f - t_i) \rangle_x, \tag{1}$$

where ρ is the time-mean in situ density, c_p is the specific heat capacity, T is the temperature, t is the time, the subscripts f and i indicate final and initial section occupations, and the $\langle\,\rangle_x$ operator indicates a lateral section average where values are present for both section occupations. If the ocean were of a uniform depth, then the vertical integral of this quantity would provide an assessment of the heat content change in terms of an ocean surface heat flux.

However, while the surface ocean occupies about 0.71 of the earth's surface area, that fraction decreases with increasing ocean depth (Fig. 9a). This hypsometry must be factored into any estimate of the heat content change from oceanographic data in terms of surface heat flux. The section estimates of ΔQ from (1) are regional, and their spatial resolution of the Pacific (Fig. 1) is too sparse to map horizontally. For a crude estimate of their significance in terms of the earth's heat budget, each regional estimate is multiplied by the fractional area of the earth covered by the World Ocean at each pressure (Fig. 9a) before vertical integration. This calculation (Table 1) gives a rough estimate of what impact the regional changes in ocean heat content would have on a uniform surface heat flux distributed over the entire earth (not just the ocean), were they representative of changes throughout the abyssal World Ocean. Between 3000 m (or 4000 m in the case of P06) and the bottom these estimates of heat flux range from 0.01 W m^{-2} along 47°N (P01) to 0.06 W m^{-2} along 170°W south of the equator (P15S). These values are between 5 and 30% of the heating trend of 0.2 W m^{-2} estimated for the 0–3000-m World Ocean heat content change between 1955 and 1998 (Levitus et al. 2005) and between 2% and 10% of the heating trend of 0.6 W m^{-2} (per unit area of the earth's surface) estimated for the 0–750-m World Ocean heat content change between 1993 and 2003 (Willis et al. 2004). Thus, abyssal Pacific Ocean heat content variations may contribute a small but significant fraction to the earth's heat budget.

The Pacific abyssal heat content changes generally decrease from south to north. Changes may be larger in the South Pacific because that region is closer to the southern source of bottom water feeding the Pacific than in the most remote reaches of the North Pacific. Interestingly, all the abyssal Pacific warming signals are smaller than those recently reported in an analysis of repeat section data in the western basins of the South Atlantic (Johnson and Doney 2006). The same calculations made above applied to these repeat section data

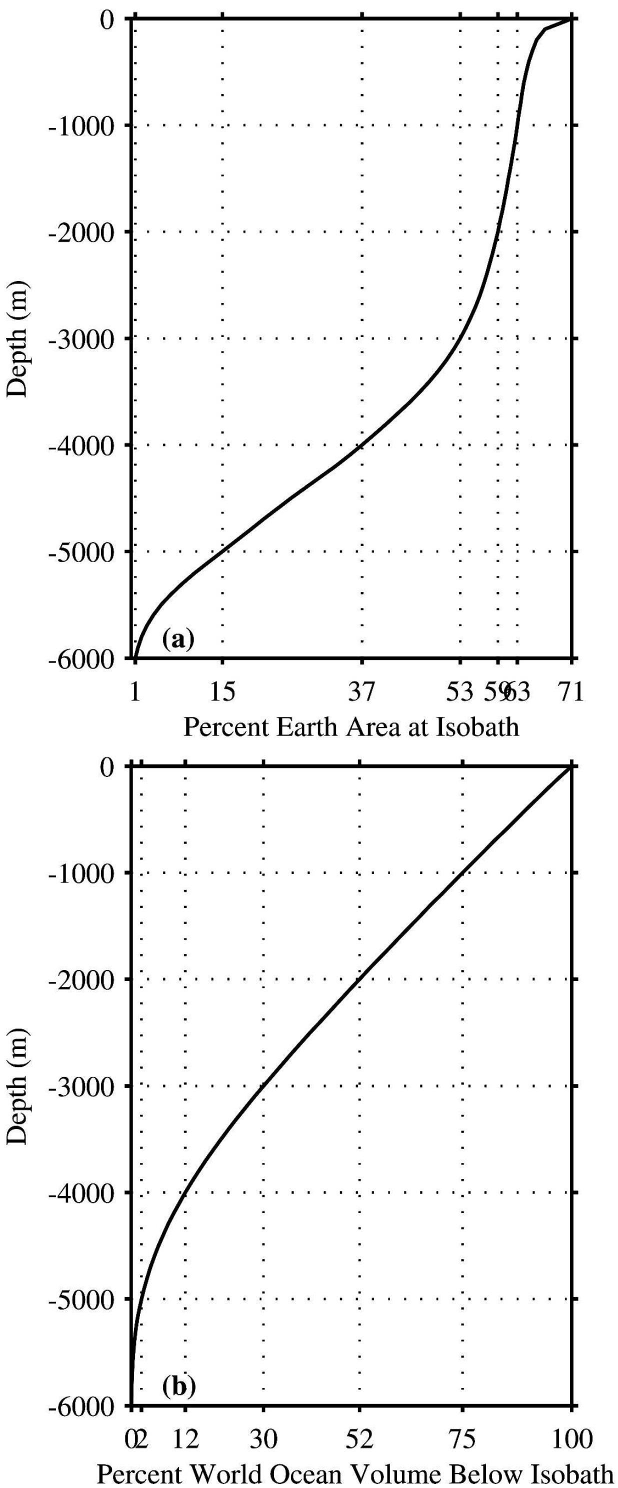

FIG. 9. (a) Percentage of the earth's surface area (0.510×10^{15} m^2) occupied by the World Ocean as a function of depth. (b) Percentage of the World Ocean volume (1.33×10^{18} m^3) below any given depth. Estimates are based on the bathymetry fields of Smith and Sandwell (1997).

result in a value of 0.2 W m^{-2} below 3000 m between 2005 and 1989–95 and from 60°S to the equator in the southwest Atlantic. Again, this number represents the impact that these regional changes in ocean heat content would have on a uniform surface heat flux distributed over the entire earth (not just the ocean) were they representative of changes throughout the abyssal World Ocean. The southwest Atlantic is adjacent to a major source of Antarctic Bottom Water in the Weddell Sea, so the large value estimated might be expected. As repeat hydrographic sections continue to be occupied in service of CLIVAR and Carbon Programs (more information is available online at http://ushydro.ucsd.edu, and http://www.clivar.org/carbon_hydro), the global distribution of these potentially important changes in heat content can be better assessed.

A simple calculation using global bathymetric data (Smith and Sandwell 1997) reveals that the upper 750 m (predominant XBT profiling depth) comprises only 19% of the World Ocean volume, the upper 2000 m (target Argo profiling depth) 48%, and the upper 3000 m (maximum published World Ocean heat budget depth) 70% (Fig. 9b). Analyses of historical data suggest there may be significant interannual variations in upper ocean heat content (Willis et al. 2004; Levitus et al. 2005). Repeat hydrographic sections are occupied sparsely in space (a few per ocean) and time (once per decade). The data from these repeat sections suggest that abyssal variations may contribute significantly to global heat, and hence sea level, budgets.

To close ocean heat, sea level, and likely freshwater budgets on interannual time scales, the ocean below 2000 m must be much better sampled in space and time than it has been, or is likely to be, relying on repeat hydrography alone. Given the extensive measurements that would be required, autonomous instruments, perhaps some combination of floats engineered to sample the abyss, gliders (e.g., Eriksen et al. 2001) similarly modified, and deep moorings may be the only viable means to achieve sampling needs.

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