Flow of abyssal water into Wake Island Passage: Properties and transports from hydrographic surveys

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[1] Water mass characteristics and volume transports of abyssal water flowing northward into Wake Island Passage in the North Pacific Ocean were examined by carrying out high-quality hydrographic surveys in May 2003, October 2004, and December 2005 along with mooring observations from May 2003 to December 2005. Close linear relationships between potential temperature (θ) and salinity, dissolved oxygen, and silicate were seen below θ ≈ 1.1°C (≈4000 m). The relationships above θ ≈ 1.1°C were scattered and were separated into relatively salty, oxygen-rich, silicate-poor water to the south, and water with the opposite properties to the north. The results suggested that there was a boundary between water masses at θ ≈ 1.1°C in the deep passage. In addition to the three hydrographic sections, two hydrographic sections previously surveyed in the deep passage in 1975 and 1999 were reexamined for transport estimates. Geostrophic calculations relative to the θ = 1.1°C surface indicated northward transports of the abyssal water from 0.5 to 2.2 Sv (1 Sv = 10⁶ m³ s⁻¹) below this surface. When 1-year mean estimated velocities at θ = 1.1°C surface were used for reference, mean transport from the five estimates increased from 1.4 to about 4 Sv. The temperature of abyssal water colder than 1.1°C was found to have increased by an average of 0.012°C between 1975 and 2005. This warming is greater than double the standard deviation from the temporal mean temperature profile obtained from mooring observations.


1. Introduction

[2] The abyssal waters of the Pacific Ocean are renewed by flow from the Southern Ocean; there is no abyssal source in the North Pacific Ocean. The northward abyssal flow plays an important role in the earth’s climate as a part of meridional overturning circulation. The northward abyssal flow for the South Pacific was quantified at two sites by moored current meter observations during the World Ocean Circulation Experiment (WOCE) in the 1990s. East of the Tonga-Kermadec Ridge (at 30.5°S), the transport was evaluated as 15.8 ± 1.4 Sv (1 Sv = 10⁶ m³ s⁻¹) [Whitworth et al., 1999; Hogg, 2001]. In the Samoa Passage and adjacent regions (10°S), the transport was evaluated as 10.6 ± 1.7 Sv [Roemmich et al., 1996]. For the North Pacific, however, no study has quantified the transport on the basis of mooring observations, before and including WOCE.

[3] Wake Island Passage (near 18°N, 169°E) connects the Central Pacific Basin with the Northwest Pacific Basin (Figure 1). Through Wake Island Passage, the coldest, saltiest, most oxygen-rich and silicate-poor bottom water is supplied to areas north of Wake Island Passage from its southern source [Mantyla and Reid, 1983]. Although the abyssal water properties in Wake Island Passage and adjacent regions were observed in 1975, no previous study has provided a volume transport of the abyssal water through Wake Island Passage, before and including WOCE. Wake Island Passage was an observational gap in the WOCE Hydrographic Programme (WHP); mooring observations of the northward abyssal flow in Wake Island Passage were proposed but did not occur in WOCE [Hogg, 2001].

[4] Transports of the Wake Island Passage abyssal flow were estimated in two recent studies. One estimate is based on conductivity-temperature-depth (CTD) with oxygen observations in 1999 across Wake Island Passage and a deep passage about 400 km south of Wake Island Passage [Kawabe et al., 2003]. The other is based on 1-year (from 1999 to 2000) moored current meter observations in Wake Island Passage [Kawabe et al., 2005]. Although Kawabe et al. [2003] provided the first estimates of volume transport of the abyssal water through Wake Island Passage, the estimates showed inconsistent transports between the two
Kawabe et al. [1997] bathymetric data set contoured at 1000-m UCHIDA ET AL.: WAKE ISLAND PASSAGE ABYSSAL WATER [2005] provided the first estimates of Station locations from WIFE (open circles and additional western passage, which was estimated from a data length to eliminate dominant 4-month variations. More-over, the mooring data did not quantify a transport in an influence of the mean value was large (1.3 Sv) due to insufficient section (0.1 Sv northward for Wake Island Passage and 0.9 Sv southward for the deep passage just south of Wake Island Passage). The inconsistency may result from the choice of a zero-velocity surface for geostrophic calculation. Kawabe et al. [2005] provided the first estimates of 1-year mean (3.6 Sv) and variations (a range from −5.3 to 14.8 Sv) of the volume transport. However, the uncertainty of the mean value was large (1.3 Sv) due to insufficient data length to eliminate dominant 4-month variations. Moreover, the mooring data did not quantify a transport in an additional western passage, which was estimated from a single observation to be about 1 Sv northward [Kawabe et al., 2003].

[5] To clarify water mass characteristics and to quantify accurately the temporal mean and variations of volume transport of the abyssal water into Wake Island Passage, we carried out the Wake Island Passage Flux Experiment (WIFE) from 2003 to 2005, which consisted of repeated shipboard hydrographic surveys and mooring array observations along a line across a deep passage just south of Wake Island Passage. Temporal mean and short-term variability of the volume transport were evaluated by means of geostrophic calculations from density measurements by moored CTDs. Velocity measurements by moored current meters were also used as reference velocities for the geostrophic calculation. These results from the WIFE mooring observations are described in a separate paper [H. Uchida et al., manuscript in preparation, 2006].

[6] The present study investigated water mass characteristics of the abyssal water in the deep passage using the WIFE shipboard hydrographic data to determine the extent and volume of the northward flowing abyssal water. Taking water mass characteristics into account, volume transports of the abyssal water were estimated for the three WIFE hydrographic sections in 2003, 2004, and 2005, and the two previously occupied hydrographic sections in 1975 and 1999, using geostrophic calculations with an assumption of a zero-velocity surface. Long-term change in the abyssal temperature was also examined using the WIFE and historical hydrographic data. Results describing short-term variability in abyssal temperature derived from the hydrographic observations from moorings were used to reinforce the results concerning the long-term change in abyssal temperature. Preliminary results from moored current meter data were also used to examine long-term mean velocities at the reference surface used for geostrophic calculations.

2. Hydrographic Observations

[7] The WIFE was designed to evaluate transport of abyssal water flowing into the Northwest Pacific Basin through Wake Island Passage (Figure 1). The WIFE observation line extended between the Marshall Seamounts and the Wake-Necker Seamounts and was chosen to cross a deep passage that connects the Central Pacific Basin to the Northwest Pacific Basin. A total of three full-depth hydrographic sections were obtained from 2003 to 2005. First, a total of 9 CTD stations (Figure 1) were occupied on the R/V Mirai cruise MR03-K02 from 27 to 30 May 2003. Second, a total of 11 CTD stations were occupied on the R/V Hakuhomaru cruise KH-04-4 leg 2 from 13 to 18 October 2004, adding a station on each sidewall of the passage to the nine stations from 2003. Finally, a total of 11 CTD stations were occupied on the R/V Mirai cruise MR05-05 leg 2 from 16 to 19 December 2005. The moored array (Figure 1) was deployed in the first cruise, replaced in the second cruise, and recovered in the final cruise. An acoustic Doppler current profiler was lowered along with the CTD at all stations to obtain current profiles. A bottom-topography map along the observation line was obtained from the multinarrow beam echo sounder on board R/V Mirai in 2003 and 2005.

[8] During the WIFE cruises, continuous profiles of conductivity, temperature, and dissolved oxygen were made with an SBE-9/11plus CTD system equipped with an SBE-43 dissolved oxygen sensor (Sea-Bird Electronics, Inc., Bellevue, Washington, USA) from the surface to within 10 m above the bottom in 2003 and 2005 and to within 20 m above the bottom in 2004. In addition, a novel optode-based oxygen sensor (Aanderaa Data Instruments A/S, Bergen, Norway) was also used in 2005. Water samples were collected using either twenty-four (2004) or thirty-six (2003 and 2005) 12-L Niskin bottles mounted on an SBE-32 Carousel water sampler (Sea-Bird Electronics, Inc.). Samples were collected at 250-dbar intervals below 2000 dbar (500-dbar intervals between 2000 and 3500 dbar in 2004). Accurate temperature measurements were made at the same time as the water samplings using an SBE-35 reference thermometer (Sea-Bird Electronics, Inc.). All water samples were analyzed for salinity, dissolved oxygen, and nutrients (nitrate, nitrite, silicate, and phosphate).
Salinity (practical salinity units) of water samples was measured with a salinometer (Autosal model 8400B; Guildline Instruments Ltd., Ontario, Canada), which was standardized with International Association for Physical Science of the Oceans (IAPSO) Standard Seawater from batches P141, P144, and P145 for the cruises in 2003, 2004, and 2005, respectively. Dissolved oxygen in water samples was measured with two sets of automatic photometric titrators (model DOT-01; Kimoto Electronic Co. Ltd., Osaka, Japan). Nutrients were measured with an autoanalyzer (TRAACS 800 system; BRAN+LUEBBE, Norderstedt, Germany). Reference material for nutrients in seawater (RMNS; The General Environmental Technos Co. Ltd., Osaka, Japan) were measured on each cruise to establish comparability of nutrient analyses between the cruises [M. Aoyama, H. Ota, Y. Arii, S. Iwano, H. Kamiya, M. Kimura, T. Kitao, S. Masuda, N. Nagai, and K. Saito, Reference material for nutrients in seawater matrix, submitted manuscript]. Analyses of CO₂-system parameters (dissolved inorganic carbon, total alkalinity, and pH), stable carbon isotope (δ¹³C), and radiocarbon (Δ¹⁴C) were performed in 2003. Analyses of chlorofluorocarbons were also performed at the three southernmost stations in 2005, although no chlorofluorocarbons were observed above the detection limits (0.02 pmol kg⁻¹ for CFC-11 and 0.01 pmol kg⁻¹ for CFC-12) below a depth of 1000 m. The variability in data from water samples is summarized in Table 1. The CTD salinity and dissolved oxygen data were corrected using the in situ water sample data. In 2005, high-quality CTD oxygen data were obtained from the optode-based oxygen sensor. The variability of the CTD salinity and oxygen data is summarized in Table 1. [11] Only two previous hydrographic surveys examined water properties or transport of abyssal water through Wake Island Passage. One involved bottle observations during the R/V Thomas Washington cruise 31WT2058 in 1975 by the Scripps Institution of Oceanography, and the other used CTD observations from the R/V Hakuho-maru cruise KH-99-1 leg 2 in 1999 by the Ocean Research Institute, The University of Tokyo [Kawabe et al., 2003]. These previous hydrographic data from across the deep passage were used for comparison to the WIFE hydrographic observations (Figure 1). [12] The bottle data from 1975 were extracted from Reid and Mantyla [1994] world data set. The data from stations 27 to 30 observed between 6 and 8 June 1975 and the data of station 13 (the northern end station) observed on 24 May 1975 were combined to create a section spanning the passage. Discrete samples for temperature, salinity, dissolved oxygen, and nutrients (nitrate, nitrite, silicate, and phosphate) were available at about 250-m intervals below 2000-m depths. At each station, these data were vertically interpolated at 1-bar intervals by the piecewise cubic Hermite spline interpolation [de Boor, 2001]. Temperature data measured on the International Practical Temperature Scale of 1968 (IPTS-68) were standardized to the International Temperature Scale of 1990 (ITS-90) by a linear approximation [Saunders, 1990]. [13] The CTD data from 1999 were the data from stations A26 to A32 in the study of Kawabe et al. [2003] observed on 6 and 7 February 1999, except that data from stations A27 and A29 were not used because maximum depths of observation (3683 dbar for A27 and 4802 dbar for A29) were fairly shallow for the estimation of abyssal flow transport by geostrophic calculation. Although Kawabe et al. estimated a transport of about 0.5 Sv between the Woden-Kopakut and Look seamounts (Figure 1) as a part of the northward flowing abyssal water, we did not use the data collected from between

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Table 1. The Quality (Reproducibility) of Water Sample and CTD Data Obtained From the WIFE Cruises, Including Standard Deviations for Standard Seawater Measurements and Replicate Samples of Salinity, Oxygen, Silicate, and ∆¹³C Measured During the Cruises

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2003 (MR03-K02)</th>
<th>2004 (KH04-1.2)</th>
<th>2005 (MR05-05.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (Standard Seawater)</td>
<td>0.0002 [12]</td>
<td>0.0005 [56]</td>
<td>0.0002 [109]</td>
</tr>
<tr>
<td>Salinity (Replicates)</td>
<td>0.0003 [48]</td>
<td>0.0004 [244]</td>
<td>0.0002 [665]</td>
</tr>
<tr>
<td>Oxygen (Replicates), μmol kg⁻¹</td>
<td>0.13 [63]</td>
<td>0.24 [400]</td>
<td>0.08 [493]</td>
</tr>
<tr>
<td>Silicate (Replicates), μmol kg⁻¹</td>
<td>0.26 [248]</td>
<td>0.13 [1373]</td>
<td>0.13 [4084]</td>
</tr>
<tr>
<td>∆¹³C (Replicates), %</td>
<td>3.3 [11]</td>
<td>Not sampled</td>
<td>Not sampled</td>
</tr>
<tr>
<td>CTD Salinity-Water Sample Salinity</td>
<td>0.0003 [132]</td>
<td>0.0008 [113]</td>
<td>0.0003 [161]</td>
</tr>
<tr>
<td>CTD Oxygen-Water Sample Oxygen, μmol kg⁻¹</td>
<td>0.41 [138]</td>
<td>0.61 [128]</td>
<td>0.08 [162]</td>
</tr>
</tbody>
</table>

*Standard deviations of the differences between the CTD and water sample data for depths below 2000 dbar from the WIFE stations are also listed. The number of samples is shown in brackets.*
these seamounts since there was only one CTD station with depths greater than 4120 m.

3. Water Properties

The properties of the abyssal water entering Wake Island Passage were examined using the extremely high-quality hydrographic data set obtained in 2005 (Table 1). Vertical sections of potential temperature ($\theta$), salinity, density, dissolved oxygen, silicate, nitrate, and phosphate were generated for the WIFE observation line for depths below 2000 m (Figure 2). Analysis of $\Delta^{14}$C data from 2003 has been completed for only two stations so far (Figure 2). Water masses in the WIFE section below 2000 m were sorted into two groups based on the definition of water mass $\theta$ classes in the Samoa Passage of Johnson et al. [1994]. The bottom water, composed of cold, salty, oxygen-rich, and silicate-poor water of Atlantic Ocean origin, is referred to as modified North Atlantic Deep Water (mNADW). The deep water, lying above the mNADW and marked by a silicate maximum at $\theta \approx 1.4^\circ$C ($\approx$3000 m) (Figure 2e), originates in the Northeast Pacific and is referred to as North Pacific Deep Water (NPDW). The radiocarbon age difference between the mNADW and the NPDW is estimated to be about 300 years, applying a decay rate of 1% every 8.3 years [Emery and Thomson, 1998] to the difference (36%) between the mean $\Delta^{14}$C data for a layer extending from 4000-m depth to the bottom and that for a layer from...
2000 to 4000 m. At depths between 4000 and 5000 m, the vertical gradients of dissolved oxygen and silicate were strong (Figures 2d and 2e) and isotherms (1.0 and 0.95°C) were descending toward the southwest (Figure 2a). These features indicate relatively strong shear in geostrophic velocity below 4000 m.

The relationships between \( q \) and the seawater properties of salinity, dissolved oxygen, and silicate along the WIFE observation line were fairly tight and linear below \( q/25 < 1.1 \) (Figure 3). Above \( q/25 > 1.1 \), however, the relationships were scattered and could be separated into two groups over the hydrographic section. For the southern stations (south of 14°N), the relationships showed a tendency toward slightly salty, oxygen-rich, and silicate-poor water compared with that of the other stations. Anomalies from the mean \( q \)-oxygen curve for the section clearly show the difference above \( q/25 > 1.1 \) (Figure 4). The difference in salinity, dissolved oxygen, and silicate between the two groups is about 0.003, 1 \( \mu \text{mol kg}^{-1} \), and 1 \( \mu \text{mol kg}^{-1} \), respectively, at \( q/25 > 1.4 \). These differences are small but significant since double the standard deviation of replicate samples for salinity, dissolved oxygen, and silicate were 0.0004, 0.16 \( \mu \text{mol kg}^{-1} \), and 0.26 \( \mu \text{mol kg}^{-1} \), respectively. The separations of the \( q \)-property relationships in the NPDW \( q \) class (1.2 < \( q \) < 2.0 for the Samoa Passage) extended to \( q/25 > 1.1 \) in the deep passage. These characteristics of the water properties suggest that the boundary between the mNADW and the NPDW in the deep passage lies at about \( q/25 > 1.1 \) (≈4000 m).

In order to examine the temporal stability of the \( q \)-property relationships in the mNADW \( q \) class, we compared the mean \( q \)-property curves calculated for each WIFE section. The Standard Seawater batch offset correction was applied to the salinity data used for the comparison. The salinity offset for batches P141 (2003), P144 (2004), and P145 (2005) from the average of recent batches (P130 to

![Figure 3. Potential temperature (°C) plotted against (a) salinity (practical salinity units), (b) dissolved oxygen (\( \mu \text{mol kg}^{-1} \)), and (c) silicate (\( \mu \text{mol kg}^{-1} \)) for the eleven stations of the WIFE section in December 2005. Contour lines in Figure 3a indicate the potential density anomaly (kg m\(^{-3}\)) referenced to 4000 dbar. Red and blue circles indicate water sample data for stations south and north of 14°N, respectively. Orange and green dots indicate downcast CTD data for stations south and north of 14°N, respectively.](image)

![Figure 4. Potential temperature (°C) plotted against dissolved oxygen anomalies (\( \mu \text{mol kg}^{-1} \)) from the mean potential temperature-oxygen curve for the same data as in Figure 3. Red and blue circles indicate water sample data for stations south and north of 14°N, respectively. Orange and green dots indicate downcast CTD data for stations south and north of 14°N, respectively.](image)
Figure 5. Potential temperature (°C) and geostrophic velocity (cm s\(^{-1}\)) relative to the 1.1°C potential temperature surface for the WIFE sections in (a and d) 2003, (b and e) 2004, and (c and f) 2005. The direction of flow into Wake Island Passage is positive; areas of negative flow are shaded. Inverted triangles denote CTD positions. Bottom topography shown was obtained from the multinarrow beam echo sounder.

P145) is \(-0.0003, -0.0005, and 0.0001\), respectively [Kawano et al., 2006a]. No notable differences between the WIFE sections were detected for the mean \(\theta\)-property curves below \(\theta = 1.1°C\). The mean differences between the 2005 and 2003 mean \(\theta\)-property curves for salinity, dissolved oxygen, and silicate were \(-0.0005, -0.06 \mu\text{mol kg}^{-1}, and -0.03 \mu\text{mol kg}^{-1}\), respectively. The mean differences between the 2005 and 2004 mean \(\theta\)-property curves for salinity, dissolved oxygen, and silicate were \(-0.0015, 0.33 \mu\text{mol kg}^{-1}, and 0.19 \mu\text{mol kg}^{-1}\), respectively.

4. Transport Estimates

[17] Computation of geostrophic velocity requires the selection of a reference surface where the velocity is thought to be zero or to have some known value. From the results of the previous hydrographic sections, we deduced that the
boundary between the mNADW and the NPDW in the WIFE section was at the surface where $\theta \approx 1.1^\circ C$. Hence we calculated the geostrophic velocity in the deep passage for 2003, 2004, and 2005 with an assumed zero-velocity surface (ZVS) at $\theta = 1.1^\circ C$ (Figure 5) and we examined the validity of this assumption.

[18] Data from the additional two stations on the side-walls of the passage in 2004 and 2005 were not used for the geostrophic calculations because their contribution to transport estimates for the mNADW across the section was small. Geostrophic velocities of the abyssal water across the section were low (a maximum of 3 cm s$^{-1}$) and alternated between positive and negative values because of the presence of mesoscale (horizontal scale of about 100 km) undulations of the isotherms. Geostrophic velocities were also calculated for the previous hydrographic sections in 1975 and 1999 using the same ZVS as for WIFE (Figure 6). Since the northern end station of the section in 1999 did not extend to the bottom (Figure 6b), temperature and salinity were estimated from 3636 dbar to the bottom (4500 dbar) by horizontal linear extrapolation. Moreover, temperature and salinity profiles at the midpoint between the northern station

**Figure 6.** Potential temperature ($^\circ C$) and geostrophic velocity (cm s$^{-1}$) relative to the 1.1$^\circ C$ potential temperature surface for previous hydrographic sections across the deep passage in (a and c) 1975 and (b and d) 1999. Bottom topography based on Smith and Sandwell [1997] bathymetric data set is shown.
showed that a boundary
Freeland
Wijffels et al.
UCHIDA ET AL.: WAKE ISLAND PASSAGE ABYSSAL WATER
than the others.
Johnson and Toole
Geostrophic transport (Sv) in potential temperature
Estimated Net Northwestward Geostrophic Transport of mNADW (in Sverdrup; 1 Sv = 10
(1993) used a ZVS of \( \theta = 1.4^\circ\text{C} \) for the same hydrographic data. For Wake Island Passage (18\(^\circ\)N) and the adjacent deep passage whose hydrographic data were reexamined in this study, Kavabe et al. [2003] selected a ZVS of \( \theta = 1.3^\circ\text{C} \). North of Wake Island Passage, in the Northwest Pacific Basin at 24\(^\circ\)N, Bryden et al. [1991] showed that a boundary between northward-flowing bottom water and the southward flow above it was at \( \theta = 1.06^\circ\text{C} \), although they assumed a ZVS of 3000 dbar (\( \theta \approx 1.4^\circ\text{C} \)). We used ZVSs of \( \theta = 1.1, 1.2, \) and \( 1.3^\circ\text{C} \) to examine the sensitivity of mNADW transport estimates for WIFE and the previous hydrographic sections (Table 2). For the transport estimates using a ZVS of \( \theta = 1.3^\circ\text{C} \), the geostrophic velocities were integrated over \( \theta \leq 1.2^\circ\text{C} \), the same as in the study of Kavabe et al. Compared with the fairly stable northward transports estimated using a ZVS of \( \theta = 1.1^\circ\text{C} \) (from 0.5 to 2.2 Sv), transports estimated using a ZVS of \( \theta = 1.3^\circ\text{C} \) or \( \theta = 1.2^\circ\text{C} \) vary greatly, especially for a ZVS of \( \theta = 1.3^\circ\text{C} \) (from \(-2.3\) to 3.8 Sv). The mean of the five transport estimates for a ZVS of \( \theta = 1.1^\circ\text{C} \) (1.4 Sv) is similar to or larger than the others (1.4 Sv for a ZVS of \( \theta = 1.3^\circ\text{C} \) and 1.1 Sv for a ZVS of \( \theta = 1.2^\circ\text{C} \)), even though the transport estimates were integrated over a smaller range of \( \theta \) than the others.

5. Bottom Water Warming

Layer transports in potential temperature classes of 0.05\(^\circ\text{C}\) width were calculated for each section by integrating the geostrophic velocities (Figure 7). In all sections, the gradient of transport against potential temperature was nearly zero at \( \theta \approx 1.1^\circ\text{C} \) and suddenly became positive (northwestward) just below this depth. This is a reflection of the fact that the depths of this isotherm were about the same at both ends of the sections and that isotherms below \( \theta \approx 1.1^\circ\text{C} \) were descending toward the southwest for each section (Figures 5 and 6). The estimated transports for the five sections ranged from 0.5 to 2.2 Sv, and the mean and root mean square of the estimates are 1.4 and 0.6 Sv, respectively. These results indicate that the choice of a ZVS of \( \theta = 1.1^\circ\text{C} \) was appropriate for the transport estimates for the mNADW in the deep passage just south of Wake Island Passage.

Transport estimates are sensitive to the choice of a ZVS. Several other studies selected a different ZVS for transport estimates of the deep western boundary current in the Pacific Ocean. Johnson et al. [1994] and Freeland [2001] assumed a ZVS of \( \theta = 1.2^\circ\text{C} \) in the Samoa Passage (10\(^\circ\)S). For the north of the Samoa Passage, Wijffels et al. [1996] also assumed a ZVS of \( \theta = 1.2^\circ\text{C} \) over the deep western boundary current in the Central Pacific Basin at 10\(^\circ\)N, although Johnson and Toole [1993] used a ZVS of \( \theta = 1.4^\circ\text{C} \) for the same hydrographic data. For Wake Island Passage (18\(^\circ\)N and the adjacent deep passage whose hydrographic data were reexamined in this study, Kavabe et al. [2003] selected a ZVS of \( \theta = 1.3^\circ\text{C} \). North of Wake Island Passage, in the Northwest Pacific Basin at 24\(^\circ\)N, Bryden et al. [1991] showed that a boundary between northward-flowing bottom water and the southward flow above it was at \( \theta = 1.06^\circ\text{C} \), although they assumed a ZVS of 3000 dbar (\( \theta \approx 1.4^\circ\text{C} \)). We used ZVSs of \( \theta = 1.1, 1.2, \) and \( 1.3^\circ\text{C} \) to examine the sensitivity of mNADW transport estimates for WIFE and the previous hydrographic sections (Table 2). For the transport estimates using a ZVS of \( \theta = 1.3^\circ\text{C} \), the geostrophic velocities were integrated over \( \theta \leq 1.2^\circ\text{C} \), the same as in the study of Kavabe et al. Compared with the fairly stable northward transports estimated using a ZVS of \( \theta = 1.1^\circ\text{C} \) (from 0.5 to 2.2 Sv), transports estimated using a ZVS of \( \theta = 1.3^\circ\text{C} \) or \( \theta = 1.2^\circ\text{C} \) vary greatly, especially for a ZVS of \( \theta = 1.3^\circ\text{C} \) (from \(-2.3\) to 3.8 Sv). The mean of the five transport estimates for a ZVS of \( \theta = 1.1^\circ\text{C} \) (1.4 Sv) is similar to or larger than the others (1.4 Sv for a ZVS of \( \theta = 1.3^\circ\text{C} \) and 1.1 Sv for a ZVS of \( \theta = 1.2^\circ\text{C} \)), even though the transport estimates were integrated over a smaller range of \( \theta \) than the others.

5. Bottom Water Warming

Long-term changes in abyssal temperatures were examined by comparing the accurate temperature data obtained from 2003 to 2005 during WIFE and the historical temperature data from 1975. Since the station locations for WIFE were different from those of the earlier hydrographic observations, a vertical profile of area-weighted mean potential temperature was calculated for each section (Figure 8). Although all of the profiles agree well for depths above about 4000 dbar (\( \theta \approx 1.1^\circ\text{C} \)), the profiles from WIFE are warmer than the 1975 profile for depths below about 4000 dbar. For temperatures colder than 1.1\(^\circ\text{C} \), the temperature difference

Table 2. Estimated Net Northwestward Geostrophic Transport of mNADW (in Sverdrup; 1 Sv = 10\(^6\) m\(^3\) s\(^{-1}\)) Through the Deep Passage South of Wake Island Passage, Obtained From WIFE and Previous Hydrographic Section Data

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>1.1(^\circ\text{C})</td>
<td>1.9</td>
<td>0.5</td>
<td>2.2</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>1.2(^\circ\text{C})</td>
<td>2.5</td>
<td>(-0.9)</td>
<td>2.5</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>1.3(^\circ\text{C})</td>
<td>3.8</td>
<td>(-2.3)</td>
<td>3.4</td>
<td>0.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>
between 1975 and 2005 had a maximum value of 0.015°C and an average of 0.012°C. The maximum difference between 2003 and 2005 was 0.008°C and the average difference was 0.0005°C.

To estimate the uncertainty of the temperature data from the bottle observations in 1975, Geochemical Ocean Sections bottle data from the 1973 R/V Melville cruise 318M8491 by the Scripps Institution of Oceanography were also used after being extracted from Reid and Mantyla's [1994] world data set. The data from station 228, except for three questionable layers below 5264 m, collected in Wake Island Passage on 15 November 1973 were compared with data from a nearby station 14 (within 45 km) obtained from cruise 31WT2058 on 24 May 1975. The vertically interpolated temperature profile from 1975 agrees well with that from 1973 for depths greater than 4500 dbar (mean temperature difference is 0.001°C). Although the accuracy of the reversing thermometers used in bottle observations is generally thought to be 0.01°C [Emery and Thomson, 1998], the result of this comparison suggests that the temperature difference (0.012°C) that we observed between 1975 and 2005 may be different enough to be significant.

Snapshots of the temperature profiles obtained from shipboard hydrographic observations were compared with a temporal mean temperature profile obtained from the WIFE mooring observations. In WIFE, five moorings were deployed across the deep passage (Figure 1). Each mooring had five attached CTDs (model SBE-37 SM, Sea-Bird Electronics, Inc.) at 500-m intervals between about 3400- and 5400-m depths. The CTDs used on moorings were attached to the shipboard water-sampling frame during hydrographic casts before mooring deployment and after mooring recovery in order to calibrate the moored CTDs. The standard deviation of the temperature differences between the corrected moored CTD data and the shipboard CTD data below 3000 dbar is less than 0.0004°C. The moored CTD data were low-pass-filtered with a half power gain at 5 days and resampled at 1-day intervals. At each mooring station, these data were vertically interpolated at 2-dbar intervals by a piecewise cubic Hermite spline interpolation. Using the time series data from the first mooring period (from May 2003 to October 2004), a temporal mean with standard deviation (a maximum of 0.007°C at about 4900 dbar) of the vertical profiles of the area-weighted mean potential temperature was calculated. The temporal mean profile thus obtained was significantly warmer (two standard deviations or more) than the profile from 1975 for depths greater than about 4000 dbar (Figure 8).

6. Discussion

6.1. Transport Estimates

Several previous studies estimated the northward abyssal water transport in the North Pacific by dynamic calculation based on two transpacific hydrographic sections, at 10°N in 1989 and at 24°N in 1985. For the section at 10°N, Johnson and Toole [1993] estimated transports of 8.1 Sv northward in the Central Pacific Basin and 4.7 Sv southward in the Northeast Pacific Basin for the abyssal water below θ = 1.2°C. Using the same data, Wijffels et al. [1996] estimated the same transports as 12 and 8 Sv, respectively, for abyssal water below θ = 1.1°C. Johnson and Toole [1993] inferred that some of the northward flowing abyssal water in the Central Pacific Basin moves eastward south of the Wake-Necker Seamounts and contributes to the southward flow in the Northeast Pacific Basin through the Clarion Fracture Zone. The eastward flow of abyssal water is also inferred from distributions of isotherm depths in the abyssal water. Temperature data from a meridional hydrographic section along 179°E [Roden, 2000] showed the 1.0°C isotherm descending about 400 m toward the north between 10°N and 15°N, although the 1.2°C isotherm depth is consistent in this area. Similarly, the 1.0°C isotherm descended substantially, by about 500 m, toward the west between 171° and 176°E along 10°N [Johnson and Toole, 1993], although the descent of the 1.0°C isotherm was less (about 120 m toward the southwest) in the WIFE section (Figure 2a). These features of the isotherm depths in abyssal waters suggest that most of the northward flow across 10°N in the Central Pacific Basin turns eastward south of the Wake-Necker Seamounts and supplies abyssal water to the Northeast Pacific Basin. Therefore by subtracting the southward transport in the Northeast Pacific Basin from northward transport in the Central Pacific Basin, the northward transport across the WIFE section is expected to be 3.4 or 4 Sv. For the section at 24°N, Bryden et al. [1991] estimated that
Differences between RMNS silicate measurements in 2003 (closed circles) and 2004 (open circles) from those in 2005 plotted against the silicate measurements from 2005. The average of the measurements for each RMNS lot is shown. The slope of the regression line shown indicates that a multiplication factor of 1.0121 will adjust 2003 silicate measurements to comparable 2005 measurements.

Figure A1. Differences between RMNS silicate measurements in 2003 (closed circles) and 2004 (open circles) from those in 2005 plotted against the silicate measurements from 2005. The average of the measurements for each RMNS lot is shown. The slope of the regression line shown indicates that a multiplication factor of 1.0121 will adjust 2003 silicate measurements to comparable 2005 measurements.

6.2. Long-Term Change in Abyssal Water Properties

The rate of the bottom water warming (0.012°C per 30 years) mentioned in section 5 is consistent with that detected in the Pacific Ocean along 47°N (about 0.005°C per 14 years) [Fukasawa et al., 2004]. These results suggest that bottom water warming might be found throughout mNADW north of Wake Island Passage in the North Pacific. In fact, similar bottom water warming was revealed along some transpacific WHP lines (P3 along 24°N, P2 along 30°N, and P10 along 149°E) through comparisons between WHP data and later reoccupation data [Kawano et al., 2006b]. Although the northward transport of abyssal water estimated for 1975 was relatively large among our five estimates, the data available are inadequate to determine whether the warming is associated with the strength of the abyssal transport.

We calculated mean θ-salinity and mean θ-dissolved oxygen curves for all 5 sections to determine long-term changes in water properties. The salinity data from 1999 and 2005 were corrected by reference to Mantyla’s [1980] standard by using values of −0.0010 for the Standard Seawater batch P133 from 1999 and −0.0013 for P145 from 2005, as proposed by Kawano et al. [2006a]. For the salinity data from 1975, the Standard Seawater batch offset correction (−0.002) was already applied in Reid and Mantyla’s [1994] world data set. The mean salinity difference below θ = 1.1°C between the θ-salinity curves was 0.001 between 2005 and 1975, and 0.0002 between 2005 and 1999. The mean dissolved oxygen difference below θ = 1.1°C between the θ-oxygen curves for 2005 and 1975 was −0.3 μmol kg⁻¹.

In the Samoa Passage, an indicator of mNADW (negative curvature in the θ-salinity relationship and a local salinity maximum in the θ classes where 0.7 < θ ≤ 1.2) fluctuated greatly with a decadal timescale [Johnson et al., 1994]. In Wake Island Passage, however, no notable changes were detected in the θ-property relationships for the abyssal water between 1975, 1999, and 2005, although the abyssal water temperature markedly increased between 1975 and 2005.

Appendix A: Nutrient Comparability

To establish comparability of nutrient analyses between the cruises, the RMNS [Aoyama et al., submitted manuscript] were measured during each cruise. The RMNS lots T, AN, AK, AM, O, and AH were measured during the cruise in 2003 and lots AS, AT, and AU were measured during the cruise in 2004. All of these lots were measured...
immediately before the cruise in 2005. Averages of nutrient (nitrate, nitrite, silicate, and phosphate) measurements for each lot from 2003 and 2004 agree well with those from 2005 except for silicate measurements in 2003. A correction factor for silicate measurements from 2003 was estimated to be 1.0121 based on a linear regression of the data (Figure A1). This systematic difference between silicate measurements in 2003 and 2005 was probably due to a lack of accuracy in the atomic absorption spectrometry silicon standard solution (1000 mg l\(^{-1}\), lot 402F9041; Kanto Chemical Co., Tokyo, Japan) used for the silicate standards in 2003.

[29] The mean profile of potential temperature against silicate for the WIFE section in 2003 before correction of silicate data is systematically lower (by about 2 μmol kg\(^{-1}\)) than that in 2004 and 2005 (Figure A2). The 2003 profile after the correction of silicate data by the factor mentioned above agrees well with profiles for 2004 and 2005, especially for potential temperatures below 1.1°C. Use of the RMNS, therefore, is considerably effective for establishing the comparability of nutrients analyses.

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References


