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Distributions of mixed layer properties in North Pacific water mass formation areas: comparison of Argo floats and World Ocean Atlas 2001

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Abstract

Winter mixed layer characteristics in the North Pacific Ocean are examined and compared between Argo floats in 2004 and 2005 and the World Ocean Atlas 2001 (WOA01) climatology for a series of named water masses, North Pacific Tropical Water (NPTW), Eastern Subtropical Mode Water (ESTMW), North Pacific Subtropical Mode Water (NPSTMW), Light Central Mode Water (LCMW) and Dense Central Mode Water (DCMW). The WOA01 is found to be in good agreement with the Argo data in terms of water mass volumes, average temperature-salinity (T-S) properties, and outcrop areas. The exception to this conclusion is for the central mode waters, especially DCMW, whose outcropping is shown to be much more intermittent than is apparent in the WOA01 and whose T-S properties vary from what is shown in the WOA01. Distributions of mixed layer T-S properties measured by floats are examined within the outcropping areas defined by the WOA01 and show some shifting of T-S characteristics within the confines of the named water masses. In 2005, all the water masses were warmer than climatology on average, with DCMW being highest at about 1°C. Similar results were found for the 2004 Argo data except ESTMW and DCMW which were slightly cooler than climatology. Differences between float data and climatology were examined for the entire North Pacific in order to put the above results into context. This analysis showed the winter North Pacific mixed layer to be warmer and fresher than climatology in both 2004 and 2005, with magnitudes of about 0.3–0.4°C and 0.06–0.07. This warming and freshening was apparent throughout a large area of the tropics and northeastern North Pacific, but in the mode water formation areas the trends were less clear.

1 Introduction

Since the time of Iselin (1939), ocean scientists have been seeking to connect the distribution of water properties at the surface of the ocean to those found in the interior. Iselin noticed that interior properties were similar in temperature-salinity (T-S) characteristics to those found at the surface. The work of Stommel (1979), Marshall et al. (1993), Huang and Qiu (1994) and Qiu and Huang (1995) and many others have laid the foundation for understanding the subduction of water from the surface ocean to where it might be observed underneath the surface sometime later. The basic result of this analysis is a subduction rate, which combines Ekman pumping and lateral induction to give a vertical mass transport into the ocean interior. While knowledge of the subduction rate can indicate how rapidly a particular water mass gets into the interior, the amount of water subducted will depend on the volume of a given water mass available, and the T-S properties of water observed in the interior depend on those at the surface when the water is subducted (Bingham et al., 2002b).

Mode waters have been observed in every world ocean except the North Indian (Hanawa and Talley, 2001). They were originally given that name because they represent a mode in a volumetric census of waters classified by temperature and salinity (Masuzawa, 1969), but more recently have come to be identified by vertical minima in potential vorticity or temperature or density gradient. Mode waters are among the most important subducted water masses because they can carry climate anomalies from the surface into the interior to resurface later (Sugimoto and Hanawa, 2005). They thus provide the ocean with a memory of wintertime conditions at the surface.

In the North Pacific, there are several varieties of mode waters (Hanawa and Talley, 2001), each with its own dynamics and formation processes. North Pacific Subtropical Mode Water (NPSTMW) is formed by strong cooling in the winter between the Kuroshio Extension front and the subtropical front (Suga and Hanawa, 1995). North Pacific Central Mode Water has two varieties, Dense Central Mode Water (DCMW) and Light Central Mode Water (LCMW) (Oka and Suga, 2005). These waters are formed between the Kuroshio and Subpolar fronts and probably in association with eddies and other mesoscale variability (Oka and Suga, 2005; Saito, personal communication). Eastern Subtropical Mode Water (ESTMW) has temperature and salinity characteristics similar to NPSTMW, but is formed in the eastern North Pacific (Hautala and Roemmich, 1998;

Ladd and Thompson, 2000).

Another important North Pacific water mass is the North Pacific Tropical Water (NPTW; Suga et al., 2000). This water mass (which partially overlaps the ESTMW) is associated with high salinity at the surface and Ekman convergence in the middle of the subtropical gyre. It is also seen in the interior as a subsurface salinity maximum (Bingham et al., 2002b).

Recently, the Argo program (Argo Science Team, 2001) has developed the ability to measure the wintertime mixed layer of the ocean to an unprecedented degree. Argo floats can profile and measure the properties at the surface at times when surface ships cannot make such measurements. Ohno et al. (2004) examined winter mixed layer depth (MLD) using Argo float data. They found that the World Ocean Atlas 2001 (WOA01; Conkright et al., 2001) MLDs generally agreed with those measured by floats, except in the northwest Pacific where the WOA01 underestimated the MLD south of the Kuroshio Extension front and overestimated the MLD north of the front.

Water mass formation is a crucial process in understanding and modeling ocean circulation (e.g. Xie et al., 2000) and a continuing challenge to ocean modelers (e.g. Tsujino and Yasuda, 2004; Qu et al., 2002). One of the most critical aspects of models is proper depiction of the surface mixed layer. Often, the mixed layer boundary condition relaxes to that given in the some version of the World Ocean Atlas, the most current version of which was released in 2001 (Conkright et al., 2002). An important issue for ocean models is to understand how well the WOA01 and other such climatologies represent the mixed layer in terms of T-S characteristics, geographic areas and water mass volumes. Only if models have proper surface boundary conditions can the water mass formation and subduction process be accurately simulated. For that reason, the main question to be addressed in this paper is: How well does the WOA01 depict the T-S properties and outcropping regions of some of the important water masses in the North Pacific? Given the heavy smoothing done in creating the WOA01, one would expect some discrepancies. Overall, the conclusion we will come to is that the mixed layer is depicted pretty well with respect to subtropical water masses, but less so with the central mode waters outcropping north of the Kuroshio extension.

2 Data and methods

Data for this study come from two sources, Argo profiles and the WOA01.

The Argo profiles we used were collected during the winter months of January-March 2005 (Fig. 1a). Data processing and quality control is described by Oka (personal communication). MLD was calculated for each profile as the depth where sigma-t exceeds that at 10 m depth by 0.125. This criterion is less strict than that recommended by de Boyer Montegut et al. (2004), but similar to that determined by Kara et al. (2000). The 0.125 criterion is standard for use with the WOA01 data (e.g. Sugimoto and Hanawa, 2005) and we wished to handle the calculation of MLD consistently between the datasets we used. Mixed layer temperature (MLT) and salinity (MLS) were given for each profile as the temperature and salinity at 10 m depth. We present results using January-March data all treated in the same way and averaged together. There is some indication (Oka, personal communication) that the MLD reaches a maximum in different areas of the ocean at different times of the winter. To make sure our results were not biased due to averaging the entire winter together, we re-ran all calculations in this paper using March-only Argo profiles and the March WOA01 average. The results were very similar, but with less certainty due to a smaller number of data.

We also examined Argo profiles from 2004 (Fig. 1b), but the data distribution is sparser. We had problems with interpolation into data-poor areas and so more limited results from this are presented here.

In order to calculate water mass volumes, Argo MLD, MLT and MLS were interpolated onto one degree squares in the North Pacific. For a given 1° latitude-longitude grid point, we searched for profiles within 2° of the grid point. If no profiles were found, the search radius was increased to 3°, and so on up to 10°. Once one or more profiles were found within a given radius, MLD, MLT and MLS values were averaged together using a Gaussian weighting function with a 1.5° e-folding scale.

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The WOA01 comes already interpolated onto a 1° grid (Stephens et al., 2002; Boyer et al., 2002). We used the winter seasonal gridded profiles from the North Pacific Basin (Conkright et al., 2002), which are averaged over January-March. MLT and MLD were given as the values at 10 m depth. MLD was calculated using the criterion mentioned above. This is the same calculation as that done by Suga et al. (2004).

Volumes were calculated by temperature-salinity (T-S) class in ranges of (0.5°C, 0.05). For each one degree square with a particular value of temperature and salinity, the volume of that water was calculated as the surface area of the one degree square times the MLD. The total volumes for each T-S class were added up with the results presented as two dimensional histograms for both Argo 2005 and WOA01 (Fig. 2).

3 Results

The distribution of mixed layer volume (Fig. 2a) reflects in part the distribution of water in the main thermocline, especially in the density range of sigma-t from 24.5 to 26.5. A mode in volume is seen between sigma-t 24.8 and 25.2, with T and S range 18-20°C and 34.75–34.85. This water is the surface expression of NPSTMW. This density is somewhat lighter than classically defined NPSTMW (Masuzawa, 1969) which has characteristics of sigma-t 25.4, 16.5–17.5°C and salinity 34.7–34.8.

There is a slight mode in volume at the density of the LCMW (25.5–26.3; Fig. 2a) and very little indication of DCMW as a maximum in volume. There is also little sign of NPTW as a maximum in volume, which one might expect in the T-S range of 20–24°C, salinity 34.9–35.5. Not shown in this figure, but clearly visible as a mode in the T-S histogram is the dichothermal water described by Miura et al. (2002) with $T<5$°C. It is formed in the Bering Sea and adjacent northwestern North Pacific and characterized by a subsurface temperature minimum.

In the pictures of Fig. 2, what is shown is the volume assuming the T-S properties of the water are constant throughout the mixed layer. This assumption is probably true for the most part in the real ocean, where the mixed layer ends at the top of the thermocline

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and sigma-t increases abruptly by more than the 0.125 criterion. However, this is a somewhat problematic assumption for this calculation using the WOA01, because the mixed layer by definition changes in density between the surface and the base. It would probably be more accurate to do this volume calculation for the entire depth of the mixed layer taking vertical T-S variation into account. This problem is resolved somewhat by the choice of bin width in Figs. 2a and b, 0.5°C and 0.05. These values give a sigma-t difference across the bin of about the same size as the mixed layer criterion of 0.125, depending on the temperature and salinity value. Thus it is unlikely that the considerably more painstaking and error-prone calculation described would yield significantly different results.

In contrast to the WOA01 volume distribution, the Argo 2005 data show clear delineations of most of the major water masses. NPSTMW is the most apparent peak, centered at 18–19°C, 34.8–34.9. There are also peaks for NPTW (22.5–24°C, 35.2–35.3) and LCMW (13–14.5°C, 34.5–34.6). There is a volume mode that may correspond to DCMW (9.5–11°C, 34.2–34.3), but this is saltier and warmer than it is normally thought of (Oka, personal communication).

The most striking contrast between the WOA01 and Argo 2005 volume distributions is the water found to the fresh side of the main thermocline in the WOA01. The signal of this water is weaker in the Argo data. It reflects a tongue of cold, fresh water close the the west coast of North America (see e.g. Suga et al., 2004, Fig. 3g). In the WOA01, this tongue is spread into the interior by the averaging process and increased in volume beyond what is apparent in the Argo data.

The North Pacific Hydrobase mixed layer climatology (Suga et al., 2004) was examined in the same way, with volume calculated. It showed a distribution similar to that of the WOA01, so results are not displayed here. This implies that the Hydrobase suffers the influence of smoothing even though the purpose was to minimize this type of problem.

We now focus on a few named water masses from the North Pacific, NPTW, NPSTMW, ESTMW, LCMW and DCMW. A summary of the T-S classifications and cal-

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culated volumes for each water mass are presented in Table 1 and water mass T-S boundaries are shown in Fig. 2c. In general the volumes of the various water masses are remarkably similar between the WOA01 and Argo. This indicates that the WOA01 does a good job of depicting the volume of each water mass, but spreads that volume out somewhat in T-S space. Some discrepancies exist. For example, the NPSTMW volume is larger for the WOA01 than for the Argo data. Argo mixed layers are deeper for NPSTMW (Ohno et al., 2004), but the surface area covered in the WOA01 is larger, making the total volume slightly larger. The DCMW volume is about 30% larger in the Argo data than in the WOA01 data. This result is probably not reliable due to the distribution of Argo profiles as shown below.

Given the randomized nature of the Argo sampling, it makes sense to compare individual profile T-S properties with those in the WOA01 for the various water masses. This is done in Fig. 3. The NPTW distribution (Fig. 3a) shows that the Argo float characteristics generally match in location with the WOA01 with the blue symbols matching the gray areas. There are some discrepancies, especially in the northwest and southeast corners of the WOA01 outcrop area.

The other water masses show similar distributions. The water mass where the WOA01 and Argo data are the most at odds is the DCMW (Fig. 3e). There appears to be no real area of pure DCMW there, with non-DCMW floats mixed up with DCMW floats both inside and outside the gray area. This is likely a result of the nature of DCMW formation (Saito, personal communication). This water mass does not have a consistent outcrop, but appears within the context of mesoscale features spun off from the Kuroshio and Oyashio extensions.

One feature apparent from examination of Fig. 3 is the change of mixed layer properties over the course of the winter. One can see individual floats where the symbol changes from green to blue during the course of the winter. A few examples can be seen, especially in Fig. 3b. This is either because the properties matched in early winter and the ML got colder as the winter progressed, or because the properties match in later winter and not early.

There are two types of discrepancies between float data and the WOA01 in Figs. 3a–e. One is where the float measured T-S characteristics of a particular water mass at 10 m, but was outside of the area given by the WOA01 (case 1; blue symbol outside of gray area in Fig. 3). The other is where a float measures water properties outside that of the given water mass, but is within the area where that water mass is shown by the WOA01 (case 2; green symbol inside gray area). Finally, there is the matching case where a float is within the characteristics of a given water mass and is also within the area shown by the WOA01 (case 3; blue symbol inside gray area). To give an idea of how well the floats measure the area of the various water masses, the ratios of numbers of float profiles is shown in Table 2. In general, the floats came up with the predicted characteristics most of the time in the subtropical water masses, doing especially well for the NPSTMW and ESTMW. The results matched less well for the central mode waters. A float measuring DCMW (LCMW) had a 58% (46%) chance of surfacing outside of the outcrop area as defined by the WOA01. 60% (56%) of the floats surfacing within the outcrop area did not have DCMW (LCMW) characteristics. These discrepancies highlight the extremely intermittent nature of CMW formation. They are in good agreement with the results of Qu et al. (2002) who found CMW formation to be strongly associated with eddies. These central mode waters could be said not to outcrop in a particular area, but to surface from time to time in a large and ill-defined region of the northwestern North Pacific.

Because surfacing floats may have properties different from the WOA01, it is worthwhile to examine the medians and standard deviations of T-S properties of floats within a given area. This will tell us if the floats are measuring characteristics very different from the WOA01. This is done in Fig. 2c, where the medians are shown for each water mass with standard deviation bars. These are the medians and standard deviations for all floats surfacing in the area defined for a particular water mass by the WOA01 (gray areas in Fig. 3, cases 2 and 3 in the previous paragraph). The distributions fall well within the range stated in Table 1 for the warmer water masses, but not for the central mode waters. The LCMW standard deviation bars extend outside the range.

For DCMW, the median is near the warm edge of the defined range with the standard deviation bars extending well outside the range. Most floats surfacing in the area defined by the WOA01 as being the DCMW outcrop had temperatures at the warm and salty side of the T-S range in Table 1.

Despite the fact that the various water masses are generally found within the outcrop areas predicted by the WOA01, there is significant T-S variability between the floats and the WOA01. To highlight this point we did the following analysis. For each float that surfaced in a water mass region (gray areas in Fig. 3), we took the difference between the float and the value taken from the WOA01 where the float surfaced. In other words, if the float surfaced and measured a mixed layer temperature of, say, 10°C, while the value of the WOA01 at the same one degree square was 9°C, we recorded the temperature difference as 1°C. A similar analysis was done for salinity. A histogram of those temperature and salinity differences is displayed in Figs. 4a–d.

The temperatures of the various water masses in 2005 are generally biased high, with the floats measuring warmer temperatures than indicated by the WOA01 (Fig. 4a). The bias is especially apparent for the DCMW region, averaging approximately 1°C. The peaks are near zero for all the other water masses, but careful inspection of the histograms shows the positive tails to be larger than the negative. The LCMW histogram appears closest to being symmetric about zero, but is still biased somewhat warm.

The 2005 salinity histograms are more mixed (Fig. 4b). Two water masses are fresher than indicated by the WOA01 (NPTW and ESTMW) and the rest are saltier. The magnitude of the increased salinity varies from 0.07 for NPSTMW, to perhaps 0.15 for DCMW, and generally increases towards increased density.

The same analysis was done for the 2004 Argo data (Fig. 4c and d). Some water masses are warmer than the climatology (NPTW, NPSTMW, LCMW) and others are colder (ESTMW and DCMW). NPTW appears to have the greatest difference, peaking around +0.8°C. In the salinity, NPTW, NPSTMW and LCMW are saltier than the WOA01 and ESTMW fresher. The DCMW is a special case. It seems to be bimodal, with one group of floats being significantly fresher than climatology, but another group being saltier. Which group a particular float belongs to probably depends on which side of the subpolar front it surfaced on.

To put the Fig. 4 results into context we did a similar analysis for the entire North Pacific (Fig. 5). For the temperature, this shows that Argo floats were warmer than climatology over a broad swath of the tropical and northeastern North Pacific for both 2004 and 2005 (Figs. 5a, c). The magnitude of the difference is generally higher in 2005 than 2004, with large differences in the Alaskan Gyre and the central tropical Pacific in 2005. There are also some areas of cooler float temperatures, especially centered east of the dateline at 30° N in 2005. The mode water formation areas of the northwestern North Pacific are a special case. There we see a mixture of cold and warm floats, blue and red symbols in close proximity, especially in 2005. In this view, it is difficult to see the same trend in temperature in the mode water formation areas that we saw in Figs. 4a and c.

For salinity, the North Pacific is fresher than climatology for a large swath of the tropical latitudes, between 0 and 15° N, wrapping around into the northeastern and northwestern basins. This is true for both 2004 and 2005 (Figs. 5b, d). An area of the central North Pacific, centered around 30° N is saltier than the WOA01 as well as some parts of the tropical eastern North Pacific. The peak of the saltier region is where the NPSTMW is formed, consistent with the histograms of Figs. 4b and d.

This analysis is summarized in histograms of North Pacific temperature and salinity (Fig. 6a–d). In 2005 (2004), the surface waters of the North Pacific are warmer than climatology by a mean of 0.42 (0.31)°C and fresher by 0.069 (0.056). These values are well above the accepted level of accuracy for the Argo instruments (Wong, personal communication) and significantly different from zero at the 95% confidence level using a standard t-test (Emery and Thomson, 2001). The temperature histograms are nearly symmetric about the mean in both years. The salinity histograms both have peaks at or near zero, but are skewed towards low salinity values (Bingham et al., 2002a). The distributions indicate clearly that the Argo floats are, on average, warmer and fresher than the corresponding WOA01 values.

We have made histograms similar to those of Fig. 6 for a number of different depths (not shown). The result of this is that the temperature and salinity differences disappear below about 100 m depth, and the climatology and float data over the North Pacific agree within statistical uncertainties.

4 Discussion

Overall, the WOA01 and 2005 and 2004 Argo floats show the outcrop areas of some major North Pacific water masses to be very similar, except for the Central Mode waters (Fig. 3). The volumes of the water masses agree well between the two data sets (Table 1) as do the T-S characteristics (Fig. 2c), again with the exception of the Central Mode waters.

Suga et al. (2005)[1] computed a subduction transport as a function of temperature and salinity class, similar to Fig. 2a for the WOA01. That is, they calculated the subduction rate at each one degree square, multiplied it by the surface area, and summed the transport up for each T-S class. The result is a calculation of water mass volume subducted in a year. The amount of water subducted in a year in a one degree square should be equal to a fraction of the depth of the late winter mixed layer, multiplied by the surface area. That is, once the winter is over, one would expect some fraction (1/2?, 2/3?) of the water in the mixed layer at the end of winter to be inducted into the interior circulation depending on the subduction rate, meridional slope of the mixed layer base, the depth of the spring seasonal thermocline, etc. Comparison of Suga et al.'s (2005)[1] results and what is presented here is consistent with this expectation. Our water mass volumes are generally larger than their subduction volumes but by less than an order of magnitude. This gives confidence in both the present study and in

[1] Suga, T., Aoki, Y., Saito, H., and Hanawa, K.: Ventilation of the North Pacific subtropical pycnocline and mode water formation, Prog. Oceanogr., submitted, 2005.

their more complicated calculation.

The formation of NPSTMW, ESTMW and NPTW is well-represented in most general circulation models (e.g. Tsujino and Yasuda, 2004) but simulating the formation of central mode waters has been more difficult (Qu et al., 2002). The present study can give a clue as to why this might be. The reliance on relaxation back to the WOA01 or other climatology could introduce problems into a model due to the difference between climatological mixed layer and what is actually present. The formation process of central mode waters is fundamentally different from the other water masses discussed here in that it occurs intermittently in space and time (Saito, personal communication). The isopycnals on which these water masses circulate are not open to the atmosphere on a regular basis over a well-defined region like the other water masses studied.

Figures 5 and 6 indicate that as a whole, in 2004 and 2005, the North Pacific mixed layer was fresher and warmer than average. These changes encompassed the vast majority of the tropics and eastern and northeastern basins. On the other hand, the mode water formation areas were much less clear as shown in Figs. 4 and 5. This illustrates the fundamentally different nature of surface processes in these areas in winter. Surface properties in the mixed layer are controlled by wintertime heat loss and subsequent convection. The mode water formation areas have a number of fronts within them, which makes the determination of the float sampling a matter of geography. Whether a float measures warmer or cooler (or fresher or saltier) than climatology depends mostly on which side of a local front the float happens to surface on. This makes determination of interannual variability of the T-S properties of mode water formation areas trickier than other regions. Interannual variations may be much more in the nature of shifts in the positions of fronts than changes in T-S properties.

We can only speculate here on the reasons for the T-S differences between WOA01 and Argo shown in Figs. 4–6. Most likely, they are due to interannual variability. That is, surface waters in 2004 and 2005 happened to be particularly fresh and warm over much of the North Pacific, except in the western mode water formation areas, where the water happened to be generally salty and warm in 2005 but more mixed in 2004.

Though this is the obvious explanation, there are others possible. Differences could be a result of spatial or temporal sampling biases in the way the floats surfaced. This is most likely a problem for the DCMW formation area, much of which was not sampled by floats in 2005 (Fig. 3e). Another potential issue is biases introduced into the WOA01 in the smoothing and averaging process. Whatever the reasons for the observed differences, the WOA01 will be used in the future as a benchmark against which changes can be measured.

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References

Argo Science Team, Argo: The global array of profiling floats, in: Observing the oceans in the 21st Century, edited by: Koblinsky, C. J. and Smith, N. R., pp. 248–258, GODAE Proj. Off., Melbourne, Australia, 2001.

Bingham, F. M., Howden, S. D., and Koblinsky, C. J.: Sea surface salinity measurements in the historical database, J. Geophys. Res.-C Oceans, 107(C12), doi:10.1029/2000JC000767, 2002a.

Bingham, F. M., Suga, T., and Hanawa, K.: Origin of waters observed along 137 degree E, J. Geophys. Res.-C Oceans, 107(C7), doi:10.1029/2000JC000722, 2002b.

Boyer, T. P., Stephens, C., Antonov, J. I., Conkright, M. E., Locarnini, R. A., O'Brien, T. D., and Garcia, H. E.: World Ocean Atlas 2001: Volume 1: Salinity, 165 pp., National Oceanographic Data Center, Silver Spring, MD, 2002.

Conkright, M. E., Locarnini, R. A., Garcia, H. E., O'Brien, T. D., Boyer, T. P., Stephens, C., and Antonov, J. I.: World Ocean Atlas 2001: Objective Analysis, Data Stastics and Figures

CD-ROM Documentation, 17 pp., National Oceanographic Data Center, Silver Spring, MD, 2002.

de Boyer Montegut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, J. Geophys. Res., 109, C12003, doi:10.1029/2004JC002378, 2004.

Emery, W. J. and Thomson, R. E.: Data Analysis Methods in Physical Oceanography, Second and Revised Edition, Elsevier Science B. V., Amsterdam, 638 pp, 2001

Hanawa, K. and Talley, L. D.: Mode waters, in: Ocean circulation and climate, edited by: Seidler, G., Church, J., and Gould, J., pp. 373–386, ACADEMIC PRESS, San Diego, CA, 2001.

Hautala, S. L. and Roemmich, D. H.: Subtropical mode water in the Northeast Pacific Basin, J. Geophys. Res.-C Oceans, 103(C6), 13 055–13 066, 1998.

Huang, R. X. and Qiu, B.: Three-dimensional structure of the wind-driven circulation in the Subtropical North Pacific, J. Phys. Oceanogr., 24(7), 1608–1622, 1994.

Iselin, C. O'D.: The influence of vertical and lateral turbulence on the characteristics of the waters at mid-depths, Trans. Am. Geophys. Union, 20, 414–417, 1939.

Kara, A. B., Rochford, P. A., and Hurlburt, H. E.: An optimal definition for ocean mixed layer depth, J. Geophys. Res., 105, 16 783–16 801, 2000.

Ladd, C. and Thompson, L.: Formation Mechanisms for North Pacific Central and Eastern Subtropical Mode Waters, J. Phys. Oceanogr., 30(5), 868–887, 2000.

Marshall, J. C., Nurser, A. J. G., and Williams, R. G.: Inferring the subduction rate and period over the North Atlantic, J.Phys.Oceanogr., 23(7), 1315–1329, 1993.

Masuzawa, J.: Subtropical Mode Water, Deep-Sea Res., 16, 463–472, 1969.

Miura, T., Suga, T., and Hanawa, K.: Winter Mixed Layer and Formation of Dichothermal Water in the Bering Sea, J.Oceanogr., 58(6), 815–823, 2002.

Ohno, Y., Kabayashi, T., Iwasaka, N., and Suga, T.: The Mixed Layer Depth in the North Pacific as Detected by the Argo Floats, Geophys. Res. Lett., 31(L11306), doi:10.1029/2004GL019576, 2004.

Oka, E. and Suga, T.: Differential Formation and Circulation of North Pacific Central Mode Water, J. Phys. Oceanogr., 35, 1997–2011, 2005.

Qiu, B. and Huang, R. X.: Ventilation of the North Atlantic and North Pacific: Subduction versus obduction, J. Phys. Oceanogr., 25(10), 2374–2390, 1995.

Qu, T., Xie, X. P., Mitsudera, H., and Ishida, A.: Subduction of the North Pacific Mode Waters in a Global High-Resolution GCM, J. Phys. Oceanogr., 32, 746–763, 2002.

Stephens, C., Antonov, J. I., Boyer, T. P., Conkright, M. E., Locarnini, R. A., O'Brien, T. D., and Garcia, H. E.: World Ocean Atlas 2001: Volume 1: Temperature, 165 pp., National Oceanographic Data Center, Silver Spring, MD, 2002.

Stommel, H.: Determination of water mass properties of water pumped down from the Ekman layer to the geostrophic flow below, Proc. Natl. Acad. Sci. USA, 76(7), 3051–3055, 1979.

Suga, T. and Hanawa, K.: The subtropical mode water circulation in the North Pacific, J. Phys. Oceanogr., 25(5), 958–970, 1995.

Suga, T., Motoki, K., Aoki, Y., and Macdonald, A. M.: The North Pacific Climatology of Winter Mixed Layer and Mode Waters, J. Phys. Oceanogr., 34(1), 3–22, 2004.

Suga, T., Kato, A., and Hanawa, K.: North Pacific Tropical Water: its climatology and temporal changes associated with the climate regime shift in the 1970s, Prog. Oceanogr., 47(2–4), 223–256, 2000.

Sugimoto, S. and Hanawa, K.: Remote reemergence areas of winter sea surface temperature anomalies in the North Pacific, Geophys. Res. Lett., 32(L01606), doi:10.1029/2004GL021410, 2005.

Tsujino, H. and Yasuda, T.: Formation and Circulation of Mode Waters of the North Pacific in a High-Resolution GCM, J. Phys. Oceanogr., 34(2), 399–415, 2004.

Xie, S. P., Kunitani, T., Kubokawa, A., Nonaka, M., and Hosoda, S.: Interdecadal Thermocline Variability in the North Pacific for 1958–97: A GCM Simulation, J. Phys. Oceanogr., 30(11), 2798–2813, 2000.

Table 1. Temperature-salinity characteristics and volumes of given water masses.

Name	Reference	Sigma-t Range	Temperature Range (°C)	Salinity Range	WOA01 Volume ($\times 10^{14}$ m^3)	Argo 2005 Volume ($\times 10^{14}$ m^3)
NPTW	Suga et al. (2000)	23.6–25.1	20.0–24.0	34.9–35.5	4.8	3.9
NPSTMW*	Oka (pers. comm.)	24.5–25.9	15.4–19.7	34.6–35.0	4.6	3.5
ESTMW*	Suga et al. (2004)	23.9–26.1	16.0–22.0	34.6–35.4	4.0	3.9
LCMW	Oka (pers. comm.)	25.5–26.3	12.0–14.5	34.3–34.6	2.5	2.0
DCMW	Oka (pers. comm.)	25.9–26.9	6.0–10.0	33.7–34.2	1.1	1.5

* ESTMW and NPSTMW overlap in characteristics, but are distinguished by geographic location. NPSTMW is taken to be west of the dateline, while ESTMW is east of it.

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Table 2. Columns 2 and 3 represent discrepancies between numbers of floats and water properties given by the WOA01, as described in the text.

Name	Column 2. case1/ (case1+case3) (%)	Column 3. case2/ (case2+case3) (%)
NPTW	34	28
NPSTMW	12	28
ESTMW	10	21
LCMW	46	56
DCMW	58	60

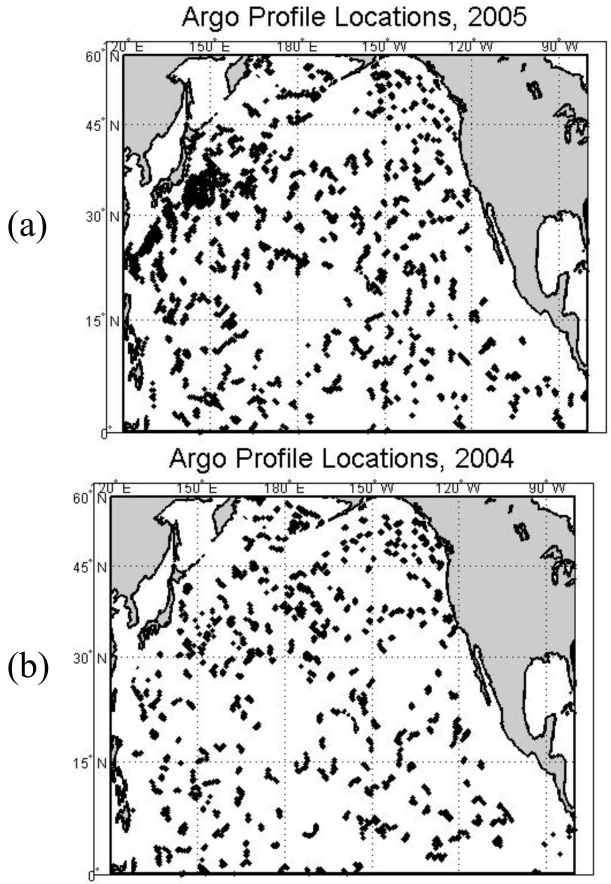

Fig. 1. Locations of Argo profiles in the indicated area in winter (January–March) **(a)** 2005 and **(b)** 2004. There were 3405 profiles in 2005 and 2359 in 2004.

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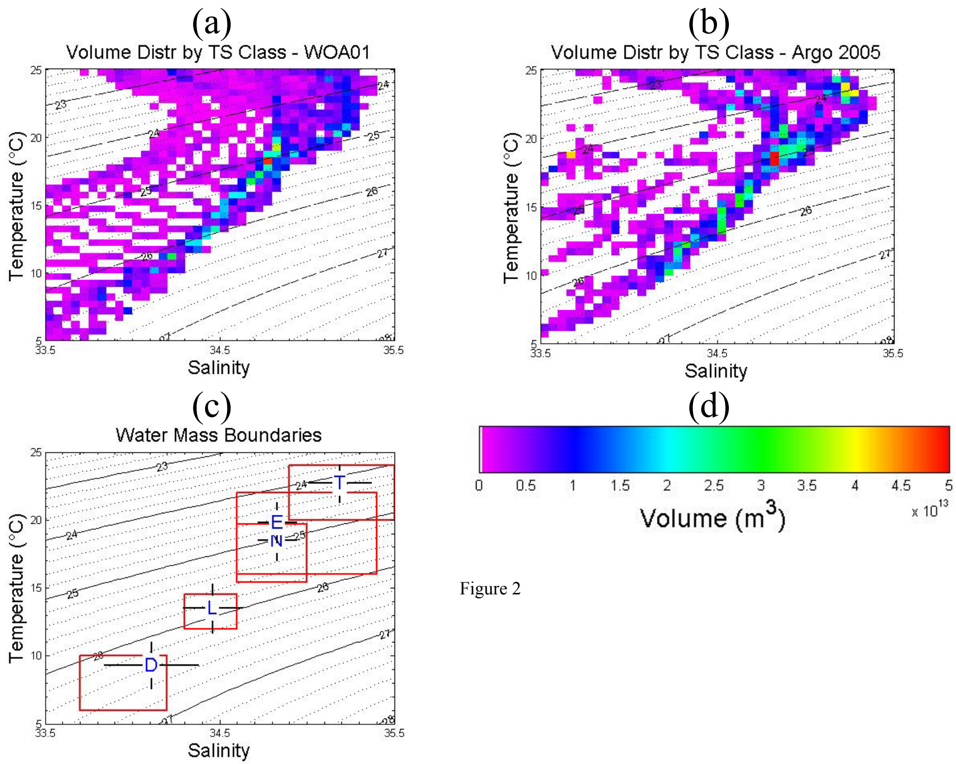

Figure 2

Fig. 2. (a) and **(b)** Distribution of water volume in the mixed layer by temperature and salinity class. Temperature and salinity are summed over ranges of 0.5°C and 0.05 respectively. (a) WOA01. (b) Argo 2005. **(c)** T-S diagram showing the boundaries of the water masses discussed in the text and shown in Table 1. Also show in are medians and standard deviations of T-S properties for Argo 2005, cases 2 and 3 in the text. The median is indicated by letters: T – NPTW; E – ESTMW; N – NPSTMW; L – LCMW; D – DCMW. Standard deviations are indicated by bars. Potential density countours are shown in panels (a)–(c). **(d)** Color scale for panels (a) and (b).

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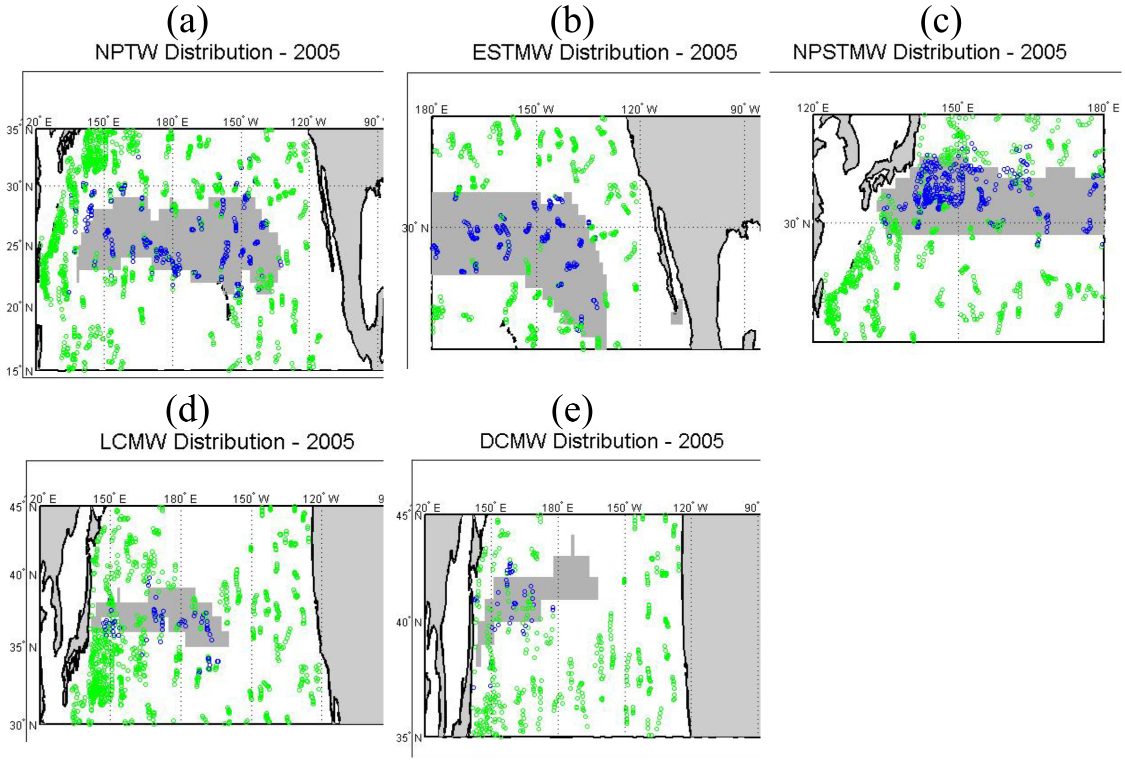

Fig. 3. Distribution of floats and various water masses in 2005. Blue (green) symbols are where floats measured properties at 10 m within (outside of) the range of the water mass as indicated in Table 1. Gray shaded areas are the where the T-S properties given in the WOA01 match the criteria for the given water mass in Table 1. **(a)** NPTW. **(b)** ESTMW. **(c)** NPSTMW. **(d)** LCMW. **(e)** DCMW. Note panels have different axis scaling to emphasize each water mass separately.

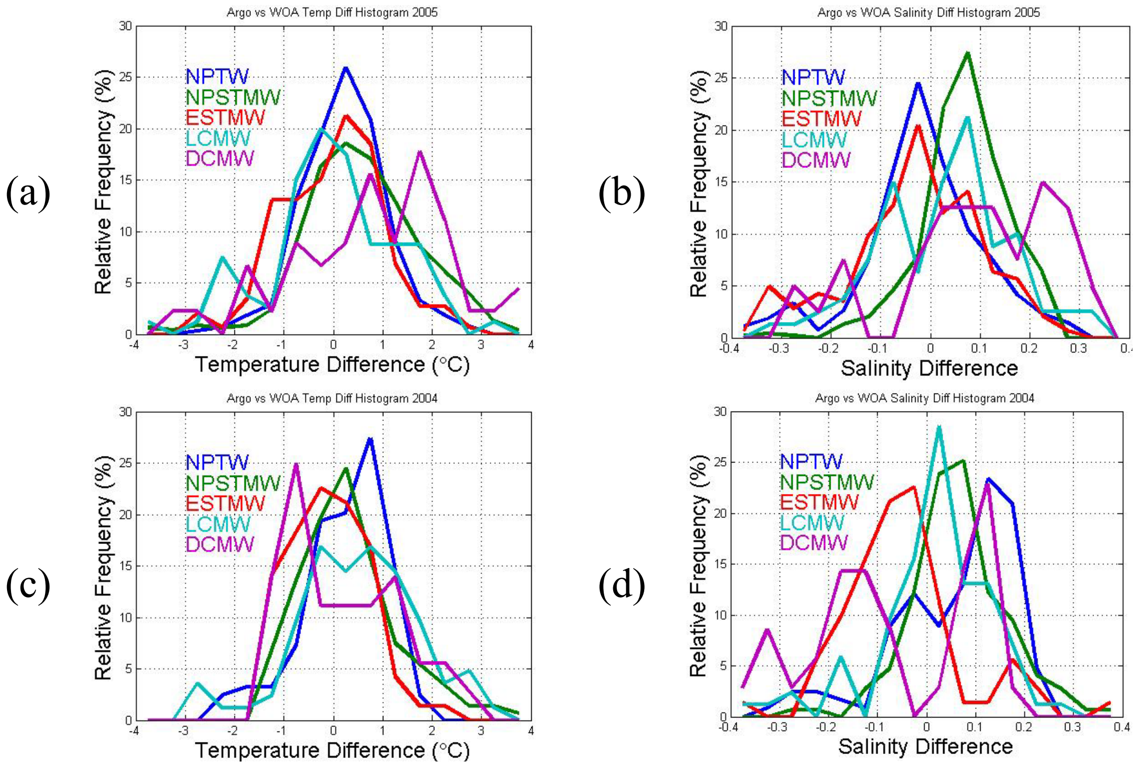

Fig. 4. Histograms of the difference between float measurements and the WOA01 for various named water masses (Table 1). Water masses are indicated by different colored lines, with keys in the figures. Results are presented as relative frequencies summed up within a temperature (salinity) range of 0.5°C (0.05). **(a)** Temperature 2005. **(b)** Salinity 2005. **(c)** Temperature 2004. **(d)** Salinity 2004.

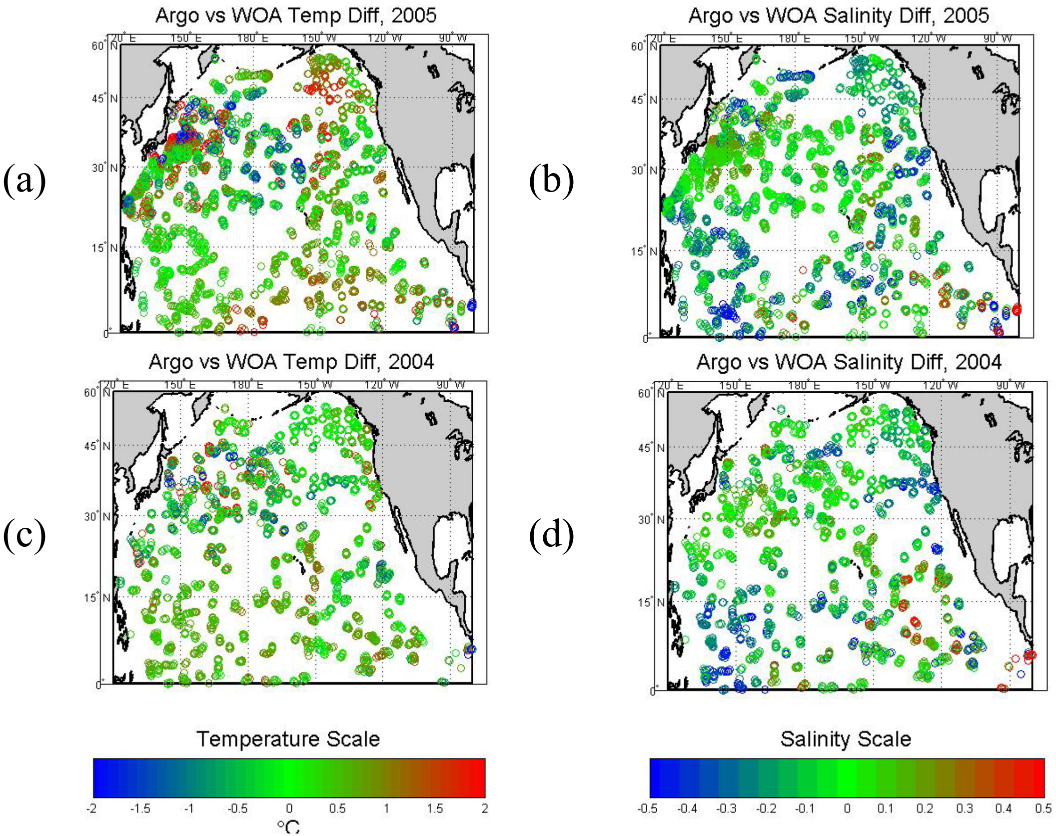

Fig. 5. Difference between Argo float and local WOA01 values at 10 m depth. **(a)** 2005 Temperature. **(b)** 2005 Salinity. **(c)** 2004 Temperature. **(d)** 2005 Salinity. At bottom are color scales for (a)–(d).

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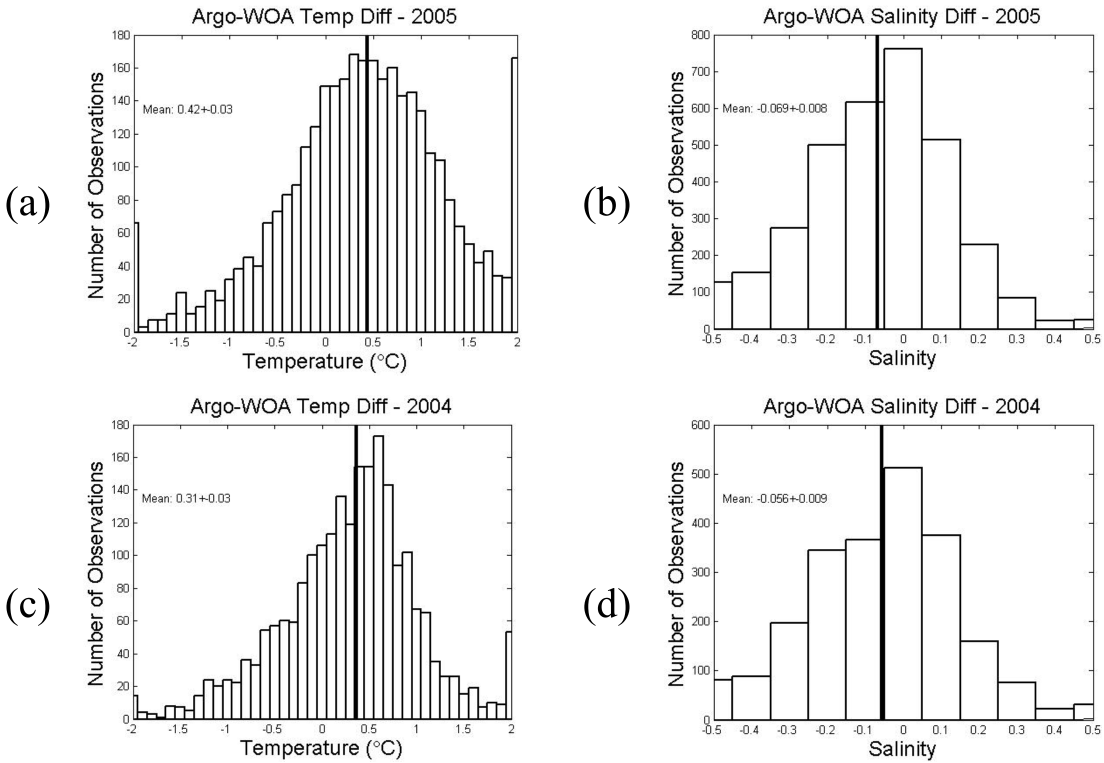

Fig. 6. Argo – WOA01 difference histograms as explained in the text. Mean values are displayed in each panel along with 95% confidence interval and indicated by solid vertical lines. Bars at the end of each distribution give numbers of observations outside the axes shown. **(a)** 2005 temperature. **(b)** 2005 salinity. **(c)** 2004 temperature. **(d)** 2004 salinity.