Formation region of North Pacific subtropical mode water in the late winter of 2003

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[1] The mixed layer structure and properties in the formation region of the North Pacific Subtropical Mode Water (STMW) east of Japan in the late winter of 2003 were examined using temperature and salinity data primarily from Argo profiling floats. The formation region extends south of the Kuroshio Extension, between 30°N and 35°N and as far east as 175°E. It is characterized by a mixed layer with depths greater than 200db and meridionally uniform temperature between 16.5°C and 18.2°C, associated with a mixed layer front at its southern edge. The mixed layer in the formation region becomes colder, fresher, and denser toward the east, leading to the formation of warmer, saltier, and lighter STMW in the western part of the region. The spatial variation of the mixed layer depth in the formation region corresponds well with the underlying permanent thermocline depth. *INDEX TERMS:* 4223 Oceanography: General: Descriptive and regional oceanography; 4283 Oceanography: General: Water masses; 4572 Oceanography: Physical: Upper ocean processes. **Citation:** Oka, E., and T. Suga, Formation region of North Pacific subtropical mode water in the late winter of 2003, *Geophys. Res. Lett.*, *30*(23), 2205, doi:10.1029/2003GL018581, 2003.

1. Introduction

[2] North Pacific Subtropical Mode Water (STMW) is identified by a thermostad of 16°–19°C lying just above and within the permanent thermocline in the western North Pacific subtropical gyre [*Masuzawa*, 1969, 1972]. It is formed in late winter in the deep mixed layer immediately south of the Kuroshio and the Kuroshio Extension (KE) [*Hanawa*, 1987; *Suga and Hanawa*, 1990; *Bingham*, 1992] and spreads through advection over the Kuroshio recirculation region [*Bingham*, 1992; *Suga and Hanawa*, 1995a].

[3] As temporal and spatial coverage of hydrographic data in the region has been sparse, previous studies concerning the formation and spreading of STMW relied on climatologies, and those concerning its year-to-year property variations depended on time-series data at selected sections or locations [e.g., *Suga and Hanawa*, 1995b]. This situation, however, has been changing due to the Argo project, initiated in 2000 [*Argo Science Team*, 2001]. Argo aims to deploy roughly 3000 profiling floats over the global oceans at three-degree intervals, to obtain vertical profiles of temperature and salinity from 2000db to the sea surface over a ten-day cycle.

[4] In the western North Pacific, Argo floats have been deployed intensively by Japan. The addition of more than 40 floats in January and February 2003 resulted in good float coverage over much of the STMW distribution region. It is now possible to monitor the distribution and properties of STMW continuously, which should dramatically improve our understanding of the water. In this paper, the mixed layer structure and properties in the STMW formation region east of Japan in the late winter of 2003 are presented, using the data from the floats and an expendable conductivity-temperature-depth profiler (XCTD) section. Almost the entire part of the STMW formation region is described for a specific winter, an accomplishment which would hardly be possible without the Argo array.

[5] The STMW formation region is located immediately south of the Kuroshio/KE and north of about 30°N with a meridional extent of several degrees [*Hanawa*, 1987; *Suga and Hanawa*, 1990; *Bingham*, 1992]. At its southern end, the mixed layer shallows sharply southward, forming a so-called mixed layer front [*Kubokawa and Inui*, 1999]. The formation region extends from 132°E to at least 160°E, although the location of its eastern end has not been clarified due to insufficient data. The deep mixed layer in the formation region becomes colder and denser toward the east because the surface water in the Kuroshio/KE, which is the source of the deep mixed layer water, is cooled through the air-sea heat exchange as it flows downstream.

[6] Recently, *Uehara et al.* [2003] demonstrated using Argo float data from the southeast of Japan during 2001 that the formation of STMW is affected by mesoscale eddies; specifically, the deeper mixed layers are formed preferentially in anticyclonic eddies where the thermocline is deep. Their results will be tested in this study, using the float data over a much larger area.

2. Data

[7] Two hundred and fifteen temperature and salinity profiles obtained by 39 profiling floats in the region of 25°–40°N, 140°E–170°W during February and March 2003 were used. Thirty-seven floats were deployed as part of Argo, while the other two were part of the Subarctic Gyre Experiment (SAGE). After the salinities of five profiles from three floats were corrected using the method established by *Wong et al.* [2003] and the climatological dataset of the JAMSTEC/FORSGC Selected Hydrographic Dataset (*Kobayashi and Minato*, Performance of Argo automatic delayed-mode salinity calibrations and suggestions for historical database improvements, submitted to the *Journal of Atmospheric and Oceanic Technology*, 2003), the salinities

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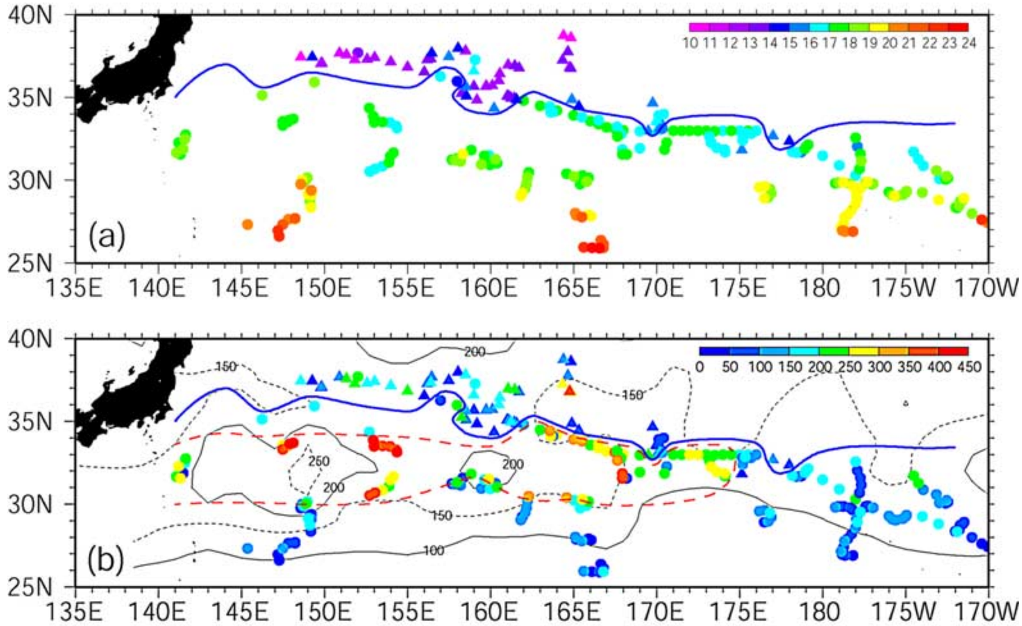

Figure 1. Distributions of (a) SST (°C) and (b) MLD (db) in February and March 2003. Circles (triangles) denote observation points located south (north) of the KE. The blue-solid curve indicates the approximate path of the KE. The red-dashed curve in (b) roughly encloses a region of MLD greater than 200db. The background contours in (b) show the MLD distribution in the climatology of *Suga et al.* [2003].

of all profiles are believed to be accurate to 0.01 on the 1978 practical salinity scale, except for those of one profile at 31.7°N, 154.2°E, which still have an error of about −0.05 (resulting in a density error of −0.04 kg m^{-3}). The temperature and salinity data at 60–70 sampling depths between the sea surface and 2000db were interpolated to every 1db resolution using the Akima spline [*Akima*, 1970]. Forty-six temperature and salinity profiles, obtained by XCTD in the same region on 4–11 February during the *R/V Mirai* MR02-K06 cruise, were also used. Potential temperature and density (called temperature and density henceforth) referred to the surface were calculated from these temperature and salinity data. It should be mentioned that during the period under investigation no Argo float was operating south of Japan (130°–140°E), so the westernmost part of the STMW formation region is not examined in this study.

[8] Values of temperature, salinity, and density at or nearest to 10db are chosen as characteristic of the sea surface, except that 40-db values are used for an observation point at 30.5°N, 162.3°E on 26 March because we are interested in the winter deep mixed layer properties. At this point, the winter mixed layer, deeper than 300db, was capped by a warm surface water shallower than 30db.

[9] The mixed layer depth (MLD) is defined as the depth at which temperature decreases by 0.5°C from the surface values, as in many previous studies. An alternative definition using a density increase of 0.125 kg m^{-3} from the surface values yields similar MLD values with a constant salinity of about 35.0 [*Levitus*, 1982]. Our data, however, showed that each MLD value defined by density tends to be slightly larger than that defined by temperature. This occurs because the downward decrease in salinity from the bottom of the mixed layer partially compensates the increase in density due to the decrease in temperature. We therefore adopted the temperature definition that detects the mixed layer bottom more accurately.

[10] Observations at which temperature at 300db is higher (lower) than 12°C are considered to be located south (north) of the KE because the KE is represented by the 12°C isotherm at 300-m depth [*Mizuno and White*, 1983]. The observation at 36.8°N, 164.8°E on 1 March has a temperature slightly higher than 12°C at 300db, but is judged to be north of the KE, because the mixed layer temperature (12.8°C) and salinity (34.47) are more similar to those at other points north of the KE than those south.

3. Results

[11] During the late winter of 2003, the KE shifts gradually southward as it meanders eastward (Figure 1). Sea surface temperature (SST) depends primarily on latitude and increases southward (Figure 1a), particularly across the KE located around 36°–37°N at 145°–155°E, 34°–35°N at 160°–170°E, and 32°–33°N at 175°E–175°W (Figures 2a–2c). Immediately south of the KE, however, SST is nearly uniform for several degrees in latitude, with values of 16°–18°C. The southern end of this uniform-SST region is at 30°N in every longitudinal range. These features were seen as meridional widening of the SST 16°–19°C zone south of the KE in late winter in *Hanawa* [1987] but are captured more clearly here.

[12] The MLD south of the KE exceeds 200db in a region extending eastward between 30°N and 35°N up to 175°E (Figure 1b; red-dashed curve). A maximum MLD of 430db is observed at 33.6°N, 147.9°E and 33.9°N, 152.9°E in the northwestern part of the region. The MLD south of the KE at 30°–35°N tends to decrease toward the east; it mostly exceeds 250db at 145°–155°E and 200db at 160°–170°E in the region, while it is mostly less than 200db at 175°E–

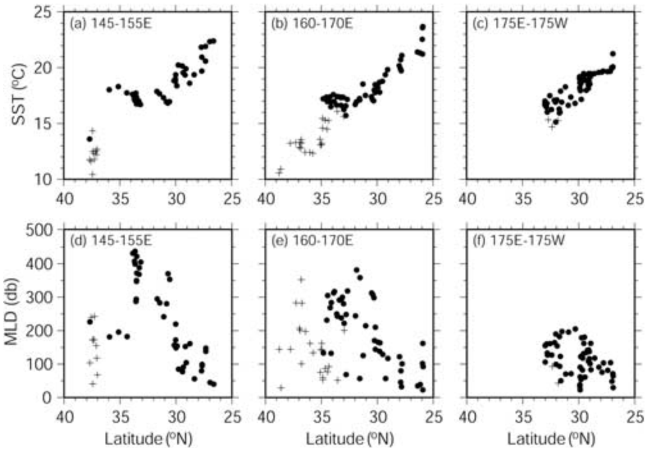

Figure 2. Plots of SST (a–c) and MLD (d–f) against latitude at 145°–155°E (a,d), 160°–170°E (b,e), and 175°E–175°W (c,f). Dots (crosses) denote observations located south (north) of the KE.

175°W east of the region (Figures 2d–2f). In contrast, the MLD south of 30°N exhibits a small zonal variation with values less than 200db in every longitudinal range. As a result, a sharp meridional gradient of MLD exists around 30°N west of 170°E at the southern end of the region.

[13] The large-MLD region is part of the uniform-SST region south of the KE, and the southern ends of the two regions coincide at 30°N (Figures 1 and 2). Thus, the large-MLD region has meridionally uniform SST of 16°–18°C and mixed layers deeper than 200db accompanied by a mixed layer front at its southern edge. This region is regarded as the STMW formation region east of Japan in the late winter of 2003. The formation region extends easterly much farther than suggested by previous studies [*Suga and Hanawa*, 1990; *Suga et al.*, 1997; *Suga et al.*, 2003] and approaches the date line, as inferred by *Hanawa* [1987].

[14] Compared with the STMW formation region in the present study, that in *Suga et al.*'s [2003] climatology, represented roughly by the 150-db contour south of the KE in Figure 1b, not only extends less eastward, but also has smaller MLD and a much less sharp mixed layer front at the southern edge. The mixed layer front for each winter is believed to be smoothed out considerably in the climatology through the averaging process.

[15] MLDs greater than 200db are also found at several observation points north of the KE around 37°N, between 151°E and 165°E. Judging from the SST (11.6°–13.3°C) and sea surface density (25.90–26.19 kg m^{-3}), these points are presumably the formation sites of North Pacific Central Mode Water [*Nakamura*, 1996; *Suga et al.*, 1997]. This supports the likely formation region of the water presented by *Suga et al.* [2003], which extends as far west as 143°E in contrast with that previously described as located east of 175°E.

[16] In the STMW formation region, the mixed layer properties exhibit significant zonal variations (Figure 3). The SST (from 16.5° to 18.2°C) and sea surface salinity (34.65 to 34.80) decrease eastward across the region by 1°C and 0.1, respectively. As a result, the sea surface density (25.05 to 25.45 kg m^{-3}) increases across the

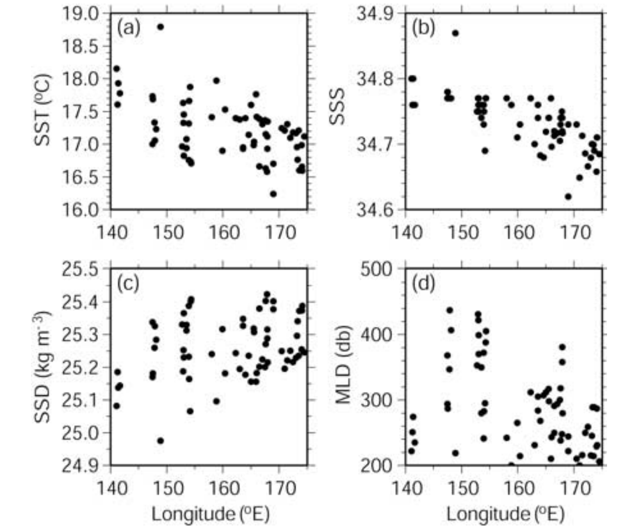

Figure 3. Plots of (a) SST, (b) sea surface salinity (SSS), (c) sea surface density (SSD), and (d) MLD against longitude in the STMW formation region. The formation region is defined as the group of observations south of the KE with MLD greater than 200db, excluding several points apart from the region shown by the red-dashed curve in Figure 1b.

region by 0.2 kg m^{-3}. These variations imply the formation of warmer, saltier, and lighter (colder, fresher, and denser) STMW in the western (eastern) part of the region. The zonal change of both temperature and density is steep west of 148°E and much less east of it. This result is consistent with *Bingham* [1992], who showed that the eastward decrease of climatological SST in the STMW formation region is abrupt in the west (130°–145°E) and gradual in the east (145°–175°E), although the SST drop from 145°E to 175°E in the present study (about 0.5°C) is much smaller than in Bingham's study (>1°C). MLD is primarily between 200db and 300db, but is particularly large around 148°E and 153°E with the maximum of 430db and 168°E with 380db.

[17] The eastward decrease of SST in the formation region is due to the cooling of the KE surface water, which is the source of the deep mixed layer water [*Bingham*, 1992]. The eastward decrease of the sea surface salinity is possibly due to the southward Ekman transport, which

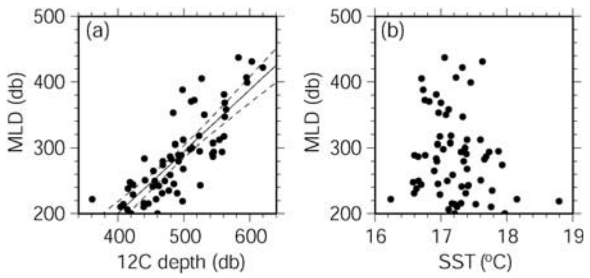

Figure 4. MLD plotted against (a) 12°C-isotherm depth and (b) SST, otherwise following Figure 3. The regression line (solid line) and its 95% confidence interval band (dashed curve) determined by the least square method are shown in (a).

brings fresher surface water north of the KE to this region [*Hanawa and Talley*, 2001]. How, then, is the MLD distribution in the formation region determined? The relation of the permanent thermocline depth, represented by the 12°C-isotherm depth as in *Uehara et al.* [2003], and SST to MLD in the formation region is examined (Figure 4). MLD is highly correlated with the 12°C-isotherm depth (coefficient 0.82) but is little correlated with SST (−0.18). The slope of the regression line between the 12°C-isotherm depth and MLD is near unity, and MLD is approximately equivalent to the 12°C-isotherm depth, minus 200db. Thus, the distribution of MLD corresponds well with the underlying thermocline depth.

[18] The 12°C-isotherm depth in the formation region (not shown) significantly changes on a scale of a few degrees, as MLD in the region changes. Therefore, the thermocline depth in the region is most likely governed by mesoscale eddies, which show high variability in the Kuroshio recirculation region [*Qiu*, 2002]. It is thus suggested that the particularly deep mixed layer, around 148°, 153°, and 168°E, is associated with anticyclonic eddies, supporting the results of *Uehara et al.* [2003].

4. Summary and Discussion

[19] Almost the entire STMW formation region was sampled for a specific winter. The STMW formation region east of Japan in the late winter of 2003 extends south of the KE between 30°N and 35°N and as far east as 175°E, much farther than recognized by previous studies based on climatology. It is characterized by a mixed layer with depths greater than 200db and meridionally uniform temperature between 16.5°C and 18.2°C, associated with a mixed layer front at its southern edge. The mixed layer front is effective in the subduction of a vertically homogeneous structure by lateral induction, according to subduction theory [e.g., *Marshall et al.*, 1993]. The meridional uniformity of the mixed layer temperature helps to form a large amount of such structure, specifically mode water.

[20] The eastern end of the formation region is also marked by a mixed layer front at 175°E (Figure 1b), west (east) of which MLD is greater (less) than 200db. This feature has appeared only in the numerical models [e.g., Figures 7 and 8 in *Xie et al.*, 2000] and has not been captured by observation to date. This result demonstrates the potential usefulness of the Argo float array, even for detecting relatively small-scale structures. Although the floats are to be distributed at an average spacing of three degrees, they drift, sometimes making it possible to examine the detailed spatial variation of properties.

[21] The mixed layer in the STMW formation region becomes colder, fresher, and denser toward the east, leading to the formation of warmer, saltier, and lighter (colder, fresher, and denser) STMW in the western (eastern) part of the region. The spatial variation of MLD in the region corresponds well with the underlying permanent thermocline depth. The particularly deep mixed layer, formed locally in the region, is probably associated with anticyclonic eddies, supporting the results of *Uehara et al.* [2003]. As the distribution of mesoscale eddies changes from year to year [e.g., *Qiu*, 2002], it may significantly affect the MLD distribution in the formation region of each winter and, therefore, the volume of STMW formed each year.

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