A role of eddies in formation and transport of North Pacific Subtropical Mode Water

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Abstract

Hydrographic data acquired during 2001 by Argo profiling floats deployed in the Kuroshio recirculation region are used to verify the inference that mesoscale eddies prevailing in the recirculation region play an important role in the formation and transport of North Pacific Subtropical Mode Water (NPSTMW). That is, the deeper winter mixed layer is formed preferentially where the thermocline is deeper in association with anticyclonic eddies. In the succeeding seasons, mesoscale eddies retain NPSTMW during their southwestward movement from the NPSTMW formation region, so that anticyclonic eddies contribute substantially to the NPSTMW transportation. The spatial distributions of the mixed layer depth in winter and the NPSTMW thickness in the succeeding seasons, based on the float data, suggest that they are affected by mesoscale eddies. The float data also provide the statistical relations of these quantities against the thermocline depth, which are consistent with our inference.
1. Introduction

North Pacific Subtropical Mode Water (NPSTMW) is characterized as a pycnostad between the seasonal and main thermoclines in the western part of the North Pacific subtropical gyre [Masuzawa, 1969]. Previous studies revealed that NPSTMW is formed south of the Kuroshio Extension (KE) by the wintertime deep convective mixing [e.g. Hanawa, 1987], capped by the seasonal thermocline through the succeeding surface warming, and widely distributed in the Kuroshio recirculation (KR) region by the southwestward advection [e.g. Suga and Hanawa, 1995]. Since these descriptions were mainly based on climatologies smoothed spatially and temporally, they were in “laminar” fashion and did not resolve mesoscale features of the NPSTMW distribution.

There have been, however, several analyses suggesting that formation and distribution of NPSTMW are in more “turbulent” fashion and affected by mesoscale eddies. Suga and Hanawa [1990] analyzed a number of historically-archived individual profiles to identify the NPSTMW formation area and showed that the particularly deep winter mixed layer was accompanied by deep thermocline. Their analysis also suggests that fluctuations of the thermocline depth related to those of the mixed layer depth are much larger than the gyre-scale spatial variation of the thermocline depth. Since the eddy activity is remarkably high in the KR region [Qiu, 1999], the particularly deep mixed layer is likely accompanied by deep thermocline caused by anticyclonic eddies.
NPSTMW in the succeeding seasons is also observed to have mesoscale variations. For example, Figure 1 shows that particularly thick NPSTMW is associated with deep thermocline. The similar relations between the NPSTMW thickness and thermocline depth were found in many hydrographic sections across the KR region in various years and locations (e.g. see figures of Hanawa and Yoritaka [2001]). Ebuchi and Hanawa [2000, 2001] analyzed the satellite altimetry to show that a number of anticyclonic and cyclonic eddies are generated in the vicinity of the KE, typically 2 to 3 each per year, and that these eddies migrate southwestward in the KR region as depicted by the schematic in Figure 2a. The ratios of their gyratory speeds to their phase speeds are estimated to be 2 to 3 for typical eddies and about 7 for the strongest ones, when the values computed by Ebuch and Hanawa are used. Following the theoretical study of Fliel [1981], such eddies with a strongly nonlinear nature can trap a substantial amount of water parcels within them (greater than 30-40% of volume) during their southwestward movement. Suga [1995] provided direct evidence for the transportation of thick NPSTMW by an anticyclonic eddy; mooring data taken in the KR region demonstrated that an anticyclonic eddy retained fairly thick NPSTMW during its westward movement.

The mesoscale features of the thickness of the 18° Water [Worthington, 1959], formed in the North Atlantic subtropical gyre under similar dynamic conditions as NPSTMW, also have been reported. Brundage and Dugan [1986] found in the Sargasso Sea that a lens of thick 18° Water was retained by an anticyclonic eddy which had moved south-southwestward from the
formation region. The station data southeast of the island of Bermuda showed that anomalously thick 18° Water was frequently found where the surface dynamic height was high in association with anticyclonic eddies [Siegel et al., 1999].

From the previous findings described above, the effect of mesoscale eddies on formation and transport of NPSTMW is inferred as follows: the extremely deep mixed layer is formed in winter where the thermocline is deep in association with anticyclonic eddies in the NPSTMW formation area south of the KE and that anticyclonic eddies retain the thick NPSTMW during their southwestward movement from the formation region in the succeeding seasons. If a typical anticyclonic eddy retains 150 m-thick NPSTMW, three eddies per year result in the NPSTMW transportation of about 2.8 Sv. This value is equivalent to the subduction rate for the density range of 25.0-25.4σθ computed by Huang and Qiu [1994], implying that anticyclonic eddies can transport a substantial volume of NPSTMW. However, it has not been directly confirmed yet that the spatial distribution of NPSTMW is largely controlled by mesoscale eddies over the KR region. The aim of this study is to test statistically this inference from the aspect of whether the particularly thick NPSTMW is accompanied by anticyclonic eddies. The present study uses the data taken during the single year of 2001 by the Argo profiling floats. The hydrographic profiles taken by the floats covered a fairly large portion of the KR region (Figure 2a). Similar tests would be possible using a larger number of historical data. Those analyses, however, would be affected by interannual variations of NPSTMW. The present analysis for the single year has
merit in this context, which has become possible owing to the large number of Argo floats deployed in the KR region.

2. Argo profiling floats

A dozen Argo profiling floats were deployed intensively in the KR region in February 2001. Most of the floats perform the conductivity-temperature-depth (CTD) measurements every 10 days as they rise from the parking depth of about 2000 dbar to the surface [Argo Science Team, 2001]. 10 to 14 floats have been in operation throughout the year. Since the 15°C isotherm at 200 m depth is a good indicator of the Kuroshio axis [Kawai, 1972], the profiles with temperature lower than 15°C at 200 m are regarded to be outside of the KR region and are excluded from the analysis. The distribution of the remaining 305 profiles is shown in Figure 2a. Each profile of temperature and salinity is interpolated vertically onto 10 dbar grids using the Akima spline [Akima, 1970], and then further interpolated linearly at every 0.025\(\sigma_\theta\) level.

The 12°C isotherm depth is used as a measure to determine whether the individual profiles were sampled inside anticyclonic or cyclonic eddies. The 12°C isotherm is located at the middle part of the thermocline in the western part of the North Pacific subtropical gyre (Figure 1). Figure 2b shows the meridional distribution of the isotherm depth based on the float data. For comparison, it is superimposed on the zonal-average depth of the isotherm given by the 1° ×1° hydrographic climatology of Macdonald et al. [2001]. The isotherm depth based on the float data is also compared with the sea surface height anomalies (SSHAs) based on the AVISO
Maps of Sea Level Anomalies obtained from a reprocessing of the TOPEX/Poseidon and ERS-2 data. The SSHA fields are available every week with a 1/3°×1/3° (longitude × latitude) spatial resolution, exhibiting that many mesoscale eddies moved southwestward in the KR region. The fluctuations of the isotherm depth are positively correlated with the SSHAs. Their correlation coefficients calculated in each 1°-zonal bands range from 0.53 to 0.89 in all latitudinal bands, except for the bands of 31°-33°N where a few extreme samples make the coefficients as low as 0.3. It is thus reasonable to regard deep (shallow) 12°C isotherm as an indicator of anticyclonic (cyclonic) eddies.

In the present study, winter is regarded as the three months from January through March and so on. Mixed layer depth is defined as the depth at which potential density increases by 0.125σθ from the surface. After capped by the seasonal thermocline, NPSTMW is detected as a minimum of potential vorticity (Q) in the temperature range of 15°-19°C. Following the definition used by Suga et al. [1989], potential vorticity is calculated by $Q = \left(\frac{f}{\rho}\right) \cdot \left(\frac{\Delta \sigma_\theta}{\Delta z}\right)$, where $f$ is the Coriolis parameter, $\rho$ in situ density, $\Delta z$ a depth difference between adjacent density levels, and $\Delta \sigma_\theta$ the potential density increment of 0.05σθ. NPSTMW thickness is defined as that of continuous layers including $Q$ minimum with $Q \leq 1.5 \times 10^{-10} \text{ m}^{-1} \text{sec}^{-1}$. In order to detect NPSTMW more strictly, the smaller threshold is adopted in this study rather than the value of $2.0 \times 10^{-10} \text{ m}^{-1} \text{sec}^{-1}$ used by Suga et al. [1989], since the vertical resolution of the float data is much better than the bottle data they used.
Float samplings are indeed too scarce to resolve individual eddies but the statistical relations of the mixed layer depth in winter and NPSTMW thickness with the 12°C isotherm depth can be derived from a fair amount of the profiles sampled in the KR region throughout the single year of 2001. As will be shown below, these relations suggest that formation and transport of NPSTMW are affected by mesoscale eddies.

3. Results

Figure 3a shows the distribution of the mixed layer depth in winter given by the float data. While the mixed layer generally deepens poleward on a large scale, its depth also has variations on smaller spatial scales indicated by 50-100 dbar differences between many adjacent pairs of profiles. At the same time, a superimposed map of the SSHAs in Figure 3a exemplifies that the KR region is filled with mesoscale eddies at every moment. In order to show the relation between the smaller-scale variations of the mixed layer depth and mesoscale eddies, the mixed layer depth is plotted against the 12°C isotherm depth in Figure 4a. Green plots in the figure denote the mixed layer with a temperature of 17.0°-17.5°C, which is confined north of 33°N and thus represents the layer immediately south of the KE. These plots suggest that the extremely deep (> 300 dbar) mixed layer is found only at the location with the 12°C isotherm deeper than 480 dbar and with positive SSHA, which is likely associated with an anticyclonic eddy. Supporting this interpretation, the temperature section (not shown here) taken in February by the research vessel Mirai along the line (the blue line in Figure 2a), together with the concurrent
SSHA map (not shown), shows that the deeper mixed layer is actually located in an anticyclonic eddy centered at about 35.5°N and the shallower mixed layer is found in a cyclonic eddy south of it. SSHA maps subsequent to the Mirai observation suggest that the float samplings indicated by the green plots were taken in these two eddies. These results are consistent with the inference that the deeper (shallower) mixed layer is formed preferentially where the thermocline is depressed (uplifted) in association with anticyclonic (cyclonic) eddies.

In contrast to the mixed layer in winter, which is deeper near the KE north of 33°N, NPSTMW thickness in summer and autumn is generally thicker in the region south of 33°N than north of it (Figure 3b). The thickness also has the smaller-scale fluctuations which suggest the effect of mesoscale eddies. The scatter diagram of the thickness south of 33°N (denoted by circles in Figure 4b) against the 12°C isotherm depth shows that NPSTMW thicker than 100 dbar is found almost exclusively where the 12°C isotherm is deeper than 500 dbar. Figure 2b indicates that the climatological 12°C isotherm depth is about 490 dbar on average in the latitudes of 27°-33°N and has little meridional variation. Therefore the isotherm deeper than 500 dbar is presumably located in anticyclonic eddies, which suggests that substantially thick NPSTMW is found mainly in anticyclonic eddies.

Figure 4b also shows that NPSTMW with a temperature of 17.0°-17.5°C was dominant in summer and autumn over the KR region. On the other hand, mixed layer temperature in winter, based on the Argo float data (Figure 4a) and the available map of sea surface temperature in
March 2001 [Japan Meteorological Agency, 2001], shows that the mixed layer of these temperatures was confined north of 33°N. Therefore, it is implied that the prevailing NPSTMW was exported south- or southwestward from its formation area near the KE, which is consonant with the migration of mesoscale eddies reported by Ebuchi and Hanawa [2000, 2001].

The above results are consistent with our inference that a substantial portion of NPSTMW is formed in and carried by anticyclonic eddies. Intensive observations, being repeated across certain anticyclonic eddies, are needed to demonstrate direct verification of the inference. It is possible that interannual variations of the eddy activity [Qiu, 1999] can affect the volume and distribution of NPSTMW, which can cause, for example, variations of the upper heat storage in the subtropical gyre [Hanawa and Kamada, 2001]. We believe that quantitative estimation of the eddy contribution to NPSTMW formation and distribution, and their variations, is an important subject of future study.
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References


Figure captions

Figure 1. Temperature cross section along the line from 26°09’N, 180°00’ to 34°45’N, 140°00’E acquired by the training vessel *Miyagi Maru* in June 2001. Thin and thick contours are drawn every 1°C and 5°C intervals, respectively. Red dots denote vertical temperature gradients less than 1.5°C/100 m with temperature of 15°-19°C.

Figure 2. (a) Distribution of locations (solid circles) at which the Argo profiling floats performed the CTD measurements during 2001, superimposed on the schematic diagram showing the inference about the effect of mesoscale eddies on formation and transport of NPSTMW. Dot-dashed line and dotted circles denote the path of the Kuroshio and mesoscale eddies, respectively. Eddies are generated in the KE region and migrate across the KR region southwestward as shown by arrows. Blue crosses and the blue line denote the positions of the expendable CTD samplings taken by the research vessel *Mirai* in February 2001. (b) Scatter plot of the 12°C isotherm depth against latitude based on the float data (circles and crosses), superimposed on the average depths of the 12°C isotherm in 1° latitudes between 140°-150°E given by hydrographic climatology of *Macdonald et al.* [2001]. The float data taken at positive (negative) sea surface height anomalies are denoted by circles (crosses).

Figure 3. Distributions of (a) the mixed layer depth in winter and (b) NPSTMW thickness in summer and autumn (shown by colors of plots), based on the data of the Argo profiling floats. For reference, the contour maps of the sea surface height anomalies on 7th March and 19th
September 2001 are also shown in (a) and (b), respectively. The contour interval is 10 cm. Solid (dashed) contours denote positive (negative) anomalies.

Figure 4. Scatter plots of (a) the winter mixed layer depth (WMLD) and (b) NPSTMW thickness in summer and autumn (H) against the 12°C isotherm depth (12CD) based on the float data. Temperatures of the mixed layer and NPSTMW are denoted by colors of plots, and shapes of plots denote the locations; solid circle shows that the profile was taken north of 33°N and the profile south of 33°N is denoted by cross in (a). In (b), the profile south of 33°N is denoted by circles, and vice versa.
figure 1
figure 3
figure 4