Interannual Variations of North Pacific Subtropical Mode Water in the 137°E Section

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ABSTRACT

Examination of interannual variations of North Pacific subtropical mode water (STMW) in the 137°E repeat hydrographic section by Suga et al. is extended to seek a relation between changes in STMW renewal and the wintertime cooling. Time series of isopycnal potential vorticity (PV) and apparent oxygen utilization (AOU) demonstrate substantial interannual variations of STMW. It is suggested that the interannual variations are closely related to the changes both in the Kuroshio recirculation system and in the formation rate. For the non-large-meander period of the Kuroshio, during which renewed STMW is advected vigorously from east of the section, the monsoon index as an indicator of cooling in a given winter, and PV and AOU at an STMW isopycnal surface in the following summer show significant correlation, indicating a strong relation between the wintertime cooling and the STMW formation.

1. Introduction

Subtropical mode waters (STMW) have been documented as pycnoclines between the seasonal and main pycnoclines in the subtropical gyre of the North Pacific (e.g., Masuzawa 1969), the South Pacific (Roemmich and Cornuelle 1992), and the North Atlantic (e.g., Worthington 1959). The STMW pycnoclines are formed rather locally within the gyre by wintertime convective mixing on the warmer side of separated western boundary currents (Fieux and Stommel 1975; Talley and Raymer 1982; Hanawa 1987; Suga and Hanawa 1990; Bingham 1992) and are distributed widely in the gyre through lateral advection associated with the recirculation systems (McCarty 1982; Suga and Hanawa 1995a). Since the evolution of the convection essentially depends on sea surface cooling, STMW is thought to contain the memory of the wintertime ocean–atmosphere interaction. The advection of STMW then transmits the memory to a wide area of the gyre.

The formation rate and properties of STMW will vary, at least partly, with variations in wintertime cooling. In this context, Jenkins (1982) and Talley and Raymer (1982) examined the time series of hydrographic data taken at Panulirus station near Bermuda, which is located downstream from the STMW formation region, to look into the interannual variations of the North Atlantic STMW, that is, the 18° Water. They showed significant variations in STMW but were unable to find a strong correlation between the heat flux south of the Gulf Stream and the STMW properties. Talley and Raymer mentioned a possibility that the time changes in the STMW at the Panulirus station could be caused by changes in the Gulf Stream recirculation system. While they concluded that this was not the case for their results, the changes in the advection path could be major noise in searching for a relation between STMW properties and ocean–atmosphere interaction.

In fact, the changes in the recirculation system have been revealed to largely influence STMW distribution and properties south of Japan. When the Kuroshio takes the large-meander path, the recirculation gyre is separated into two parts (see Fig. 1) and the substantial westward advection of STMW across 140°E is cut off (Suga and Hanawa 1995a,b). Thus, interannual changes in STMW south of Japan and its relation to ocean–atmosphere interaction should be examined taking account of this effect.

Suga et al. (1989) examined the hydrographic data of the 137°E repeat section, which is located downstream of the main part of the STMW formation area, and found considerable interannual variations in the amount and properties of STMW appearing in the section. Although they concluded that less STMW is advected during the large-meander period of the Kuroshio, they did not attempt to look for a relation between the STMW properties and the wintertime cooling. The present note is an extension of their examination of the interannual variations of STMW in the 137°E section; the main purpose is to show correlation between the changes in STMW and the wintertime cooling by excluding the effect of the advection changes.

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2. Data

The hydrographic observations along the 137°E meridian have been performed every winter (January) since 1967 and every summer (June/July) since 1972 by the Japan Meteorological Agency R/V Ryofu Maru (e.g., Masuzawa 1967; Andow 1987; Qiu and Joyce 1992). Each section consists of 40–50 serial stations sampled at standard depths from Japan to New Guinea, which are spaced 60 miles apart for the latitude range of 8° to 32°N and 40 miles for the remainder with no significant exception. The data north of 10°N and up to 1991 were used in the present study. Figure 1 displays the station positions on the acceleration potential maps at a STMW isopycnal for the non-large-meander period and the large-meander period of the Kuroshio adopted from Suga and Hanawa (1995a).

Each of the vertical profiles of various properties was interpolated to 10-m intervals using a cubic spline followed by linear interpolation to standard potential density (σθ) levels by 0.05 kg m⁻³. Since STMW is characterized by a pycnocline, a minimum in the vertical potential density gradient, a potential vorticity (PV) minimum is a useful tracer for STMW if relative vorticity and mixing can be neglected, according to quasigeostrophic theory (McCartney 1982; Talley and Raymer 1982; Suga et al. 1989). A finite-difference form of the PV,

\[ \text{PV} = \left( \frac{f}{\rho} \right) \Delta \sigma_{\theta} / \Delta z, \]

was calculated for each standard density level, where \( f \) is the Coriolis parameter, \( \rho \) in situ density, \( \Delta z \) a depth difference between two levels immediately below and above a given standard level, and \( \Delta \sigma_{\theta} \) the potential density increment between them, 0.1 kg m⁻³. Apparent oxygen utilization (AOU), which is the difference in oxygen concentration of a water parcel from its saturated value, was also calculated. AOU has a tendency to increase due to the consumption of oxygen by organic processes after isolation from the atmosphere. Ebbesmeyer and Lindstrom (1986) computed the age of a parcel of 18° Water using the apparent oxygen utilization rate given by Jenkins (1980). Suga et al. (1989) showed that AOU indicates the age of STMW in the North Pacific. Finally, each property on an isopycnal in a given section was smoothed over three stations using a hanning filter.

3. Results

Figure 2 shows wintertime and summertime vertical sections of \( \sigma_{\theta} \) and PV averaged over 1972–1991 separately for the non-large-meander period and the large-meander period of the Kuroshio (see Table 1). During the non-large-meander period, the Kuroshio flows across the section at 33°20′–32°N. In winter, the mixed layer develops to reach 150 m in depth and 24.8σθ immediately south of the Kuroshio but does not penetrate into the STMW pycnoclad at 25.3–25.6σθ lying

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**Table 1. Large-meander periods of the Kuroshio (Japan Meteorological Agency 1989, 1991).**

<table>
<thead>
<tr>
<th>Month</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr</td>
<td>1906–Sep 1912</td>
</tr>
<tr>
<td>Feb</td>
<td>1917–Mar 1922</td>
</tr>
<tr>
<td>Mar</td>
<td>1934–First half of 1944</td>
</tr>
<tr>
<td>Jul</td>
<td>1953–Dec 1955</td>
</tr>
<tr>
<td>May</td>
<td>1959–May 1963</td>
</tr>
<tr>
<td>Nov</td>
<td>1981–Aug 1984</td>
</tr>
<tr>
<td>Dec</td>
<td>1986–Sep 1988</td>
</tr>
<tr>
<td>Dec</td>
<td>1989–May 1991</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Station positions plotted on climatological maps of acceleration potential (AP) at 25.4σθ relative to 1000 db for (a) the non-large-meander period and (b) the large-meander period of the Kuroshio adopted from Suga and Hanawa (1995a). Crosses indicate grid points where the 95% confidence interval of the mean AP are beyond a typical contour interval, 0.5 m s⁻².
Fig. 2. Vertical sections of $\sigma_z$ (left panels) and PV (right panels) averaged over 1972–1991 separately for non-large-meander winter (a) and summer (b), and large-meander winter (c) and summer (d). Units are kg m$^{-3}$ and 10$^{-10}$ m$^{-1}$ s$^{-1}$ for $\sigma_z$ and PV, respectively; PV lower than 2.0 $\times$ 10$^{-10}$ m$^{-1}$ s$^{-1}$ is hatched.
mainly at 32°–26°N as indicated by the PV contour of $2.0 \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$ (Fig. 2a). The summertime pycnostad is more intense centered at 25.3–25.4$\sigma_{θ}$ between 32° and 26°N (Fig. 2b), indicating the STMW advection from east of the section as shown by Suga and Hanawa (1995a). During the large-meander period, the southward deepening of isopycnals associated with the Kuroshio occurs at 33°20’–30°N (Figs. 2c and 2d). These figures show the Kuroshio widens compared with that for the non-large-meander period. However, this is due to both that the Kuroshio path is temporally unstable and that the Kuroshio flows across the section rather slantingly than at right angle in this period. The wintertime mixed layer south of the Kuroshio is shallower and lighter than that in the non-large-meander period, while the STMW pycnostad is found at 25.3–25.6$\sigma_{θ}$ between 29° and 22°N with much the same intensity as in the non-large-meander period. On the other hand, the summertime pycnostad is located at the same density range but slightly weaker comparing with the wintertime one in contrast to the case in the non-large-meander period, implying the considerable reduction of the westward advection of STMW centered at 25.3–25.4$\sigma_{θ}$ (Suga and Hanawa 1995a).

Figure 3 shows a latitude–time diagram of PV and AOU on the 25.3$\sigma_{θ}$ surface. Note that contours before 1972 are based on only wintertime observations. Lower values of PV tend to be accompanied by lower values of AOU, which is clearly shown by good positive correlations between PV and AOU at 26°–32°N for summer and 29°–32°40’N for winter (Fig. 4). This observation supports our basic view that low PV corresponds to water formed by vertical convection, which also lowers its AOU.
Fig. 4. Correlation coefficients at each station between PV and AOU on the 25.3σθ surface in winter and summer. Dot line and broken line show the 95% and 90% confidence levels, respectively. Correlation coefficient beyond the 95% significance level is hatched.

The disappearance of the pycnostad during the large-meander period of the Kuroshio is also shown, especially in the end of the stable large-meander period

Fig. 6. Correlation coefficients at each station between wintertime MOI and both (a) PV and (b) AOU on the 25.3σθ surface in the same winter and the following summer. Dot line and broken line show the 95% and 90% confidence levels, respectively. Correlation coefficient beyond the 95% significance level is hatched.

from 1975 to 1980 as shown by Suga et al. (1989). Although the three large-meander periods in the 1980s and 1990s were not typical, the increase of PV is still recognizable in those periods. The variation of isopycnal PV confirms the variation of the STMW circulation in the Kuroshio recirculation system, which is associated with the large meander of the Kuroshio discussed in terms of climatological mean fields by Suga and Hanawa (1995a).

In order to examine the relation between the STMW variation and changes in the ocean–atmosphere interaction, we use the wintertime mean monsoon index (MOI: the sea level pressure difference between Nemuro, Japan, and Irkutsk, Russia, in hPa) as a measure of the intensity of cooling because the wintertime cooling in the western North Pacific is thought to be dominantly controlled by the East Asian wintertime monsoon, that is, the cold outbreak from the Asian continent (Hanawa et al. 1988; Hanawa et al. 1989;
Bingham et al. 1992). The MOI is also convenient because it represents the overall character of cooling in a wide area in a given winter and because it is available for the whole period of our dataset. Figure 5 shows the time series of the wintertime MOI, and the correlation between wintertime sea surface temperature (SST) in the western North Pacific and MOI (adopted from Bingham et al. 1992), clearly demonstrating that low SSTs are associated with high MOIs.

Although some of the wintertime MOI maxima are followed by intense pycnostad south of the Kuroshio, such as those in the summer of 1981, 1984, and 1986, correlations between the wintertime MOI and the isolynal PV and AOU in the same winter and the following summer were not significant except for a slight negative correlation for the following summer at 27°N (not shown). This weak correlation comes from ignoring the variation of STMW advection described above. Thus, correlations were recalculated for only the data during the non-large-meander period (Fig. 6). While no significant correlation is shown in the same winter, a significant correlation occurs at 27°–28°N and 26°–30°N in the following summer for PV and AOU, respectively. It should be noted that PV could be influenced by mesoscale eddies but AOU would not, which possibly results in stronger correlation between MOI and AOU. The negative correlation between the wintertime MOI and the PV and AOU of STMW suggests a strong relationship between the wintertime cooling and STMW renewal. This also supports some of the earlier results; that is, the lagged correlation implies that STMW found at 137°E was advected in rather than locally formed (Suga et al. 1989). Moreover, the good correlation only for the non-large-meander period of the Kuroshio is consistent with the disappearance of substantial westward advection of STMW from east of 140°E shown by Suga and Hanawa (1995a).

In conclusion, the wintertime MOI and the PV and AOU of STMW in the following summer during the non-large-meander period showed significant correlations at 27°–28°N and 26°–30°N, respectively, implying STMW can contain the memory of the wintertime cooling which, at least partly, controls the STMW formation.

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