Subduction of North Pacific central mode water associated with subsurface mesoscale eddy

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[1] During a shipboard high-density hydrographic survey carried out in the western North Pacific in fall 2008, we observed an anticyclonic eddy with a thickness of 150 dbar and a diameter of 40 km near 500 dbar depth at 27.5°N, 145°E. This subsurface mesoscale eddy contains the North Pacific central mode water (CMW), which has anomalously low potential vorticity and high dissolved oxygen compared to the climatological CMW properties in the same region. Profiling float measurements detect similar CMW patches near and south of the Kuroshio Extension as well as southward CMW migration within the CMW formation region north of the Kuroshio Extension. These observed facts suggest that CMW is subducted into the permanent pycnocline not only through large-scale eastward advection near the northern edge of the subtropical gyre but also through southward cross-frontal advection associated with the formation and migration of subsurface mesoscale eddies. **Citation:** Oka, E., K. Toyama, and T. Suga (2009), Subduction of North Pacific central mode water associated with subsurface mesoscale eddy, *Geophys. Res. Lett.*, *36*, L08607, doi:10.1029/2009GL037540.

1. Introduction

[2] In October–November 2008, a high-density hydrographic survey was carried out in the western North Pacific southeast of Japan during the KH-08-3 cruise leg 2 of R/V *Hakuho-maru*. Two meridional lines at 143° and 146°E and two shorter zonal lines at 27.5° and 34°N were occupied (thick black lines in Figures 3 and 4) using a conductivity-temperature-depth-oxygen profiler ($CTDO_2$) at intervals of 30′ or 1° in latitude/longitude and an expendable conductivity-temperature-depth profiler (XCTD) at 10′ intervals, along with other physical/biogeochemical instruments. These observations primarily aim to clarify mesoscale structure of the North Pacific subtropical mode water (STMW) [*Masuzawa*, 1969], which is comparable to that presented recently by high-resolution numerical models [e.g., *Rainville et al.*, 2007], and physical/biogeochemical processes associated with STMW; these aspects will be presented in separate papers.

[3] In the 27.5°N section of the cruise, we observed a water parcel with a thickness of 150 dbar and a horizontal width of a few tens of kilometers near 500 dbar depth, which is characterized by anomalously low potential vorticity (Q) and high dissolved oxygen (DO). The water parcel is classified as the North Pacific central mode water (CMW) [*Nakamura*, 1996; *Suga et al.*, 1997], but its location and properties differ significantly from those expected from the large-scale CMW circulation that has been assumed. Using data from the cruise, the World Ocean Atlas 2001 climatology (WOA01) [*Conkright et al.*, 2002], and Argo profiling floats [*Argo Science Team*, 2001], we here discuss the significance of this CMW parcel, and present another possible CMW formation mechanism. Specifically, CMW is subducted into the permanent pycnocline not only through large-scale eastward advection near the northern edge of the subtropical gyre but likely also through southward cross-frontal advection associated with the formation and migration of subsurface mesoscale eddies, which has hardly been observed due to its small spatial scale.

2. Observed CMW Pycnostad

[4] The 27.5°N sections of potential temperature (θ), salinity (S), potential density (σ_θ), and Q exhibit the seasonal pycnocline with θ of 20°–26°C at depths of 50–100 dbar and the permanent pycnocline with θ of 6°–20°C at 100–750 dbar (Figure 1). The seasonal pycnocline has high Q exceeding 5×10^{-10} m^{-1} s^{-1}, while the permanent pycnocline, characterized by moderately high Q of 2–4 $\times$ 10^{-10} m^{-1} s^{-1}, contains two significant low-Q areas (pycnostads) with $Q < 1.5 \times 10^{-10}$ m^{-1} s^{-1}; one is located at 150–400 dbar west of 144°40′E and east of 145°10′E, and the other exists at 450–600 dbar at 144°50′–145°E. The former pycnostad having θ of 16°–18°C is considered to be STMW, formed in the recirculation gyre south of the Kuroshio Extension and subsequently transported southward to this latitude [*Suga and Hanawa*, 1990, 1995; *Oka and Suga*, 2003; *Oka*, 2009]. The latter pycnostad having a distinct Q minimum of 0.35×10^{-10} m^{-1} s^{-1} at 516 dbar at 145°E is classified as CMW because it has θ of 10.2°C, S of 34.30, and σ_θ of 26.37 kg m^{-3} at the Q minimum (called core henceforth), at which the water properties at the time of pycnostad formation is expected to be best preserved.

[5] The biconvex shape of isopycnals implies that the CMW pycnostad is trapped in a subsurface anticyclonic eddy. Actually, if we assume gradient wind balance with a curvature radius of 16 km (the $CTDO_2$/XCTD station spacing at 27.5°N), we obtain anticyclonic circulation flowing to the north (south) at 144°40′–144°50′E (145°–145°10′E) at depths of 400–650 dbar, with a maximum speed of 17 cm s^{-1} (not shown). Current velocity data obtained by a shipboard acoustic Doppler current profiler also clearly detect the eddy structure with a diameter of 40 km and a somewhat larger maximum speed of 31 cm s^{-1} at almost the same location and depths (not shown).

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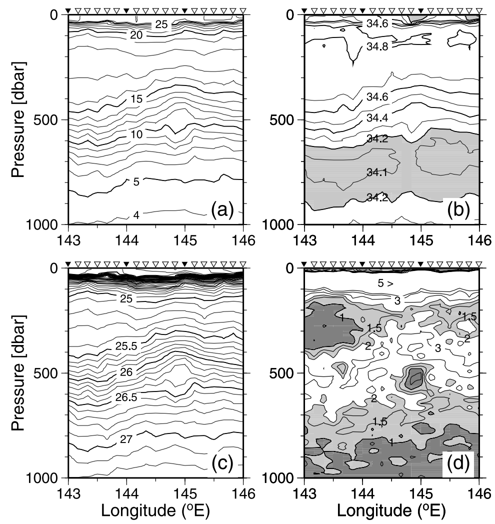

Figure 1. Zonal sections along 27.5°N of (a) θ (°C), (b) S, (c) σ_θ (kg m^{-3}), and (d) Q (10^{-10} m^{-1} s^{-1}) obtained by $CTDO_2$ and XCTD on 27–28 October 2008 in the KH-08-3 cruise leg 2. Black (white) inverted triangles on the top of each plot indicate the locations of $CTDO_2$ (XCTD) stations. Values less than 34.2 is shaded in Figure 1b. Contours are drawn at 0.5, 1, 1.5, 2, 3, 4, and 5 × 10^{-10} m^{-1} s^{-1}, and values less than 1 × 10^{-10} m^{-1} s^{-1} (of 1–2 × 10^{-10} m^{-1} s^{-1}) are heavily (lightly) shaded in Figure 1d.

[6] The CMW pycnostad is characterized not only by low Q but also by high DO with a value of 5.74 ml l^{-1} at the core at σ_θ = 26.37 kg m^{-3}, which is higher than the whole overlying layers at the same location (Figure 2). On the other hand, apparent oxygen utilization (AOU), which is the difference between the saturated and observed DO concentrations, is quite low in the pycnostad, being 0.59 ml l^{-1} at the core. Such an intense AOU minimum is not observed at the other stations in the KH-08-3 cruise. The anomalous existence of the CMW pycnostad is further explained in the next section, by comparing its properties with the climatological CMW properties.

3. Relation to Large-Scale CMW Circulation

[7] CMW originates in the deep winter mixed layer formed between the Kuroshio Extension and the subarctic front, located approximately at 35° and 42°N, respectively [*Nakamura*, 1996; *Suga et al.*, 1997]. The formation region is further divided by the northern bifurcation of the Kuroshio Extension at ~38°N into two regions, in the northern (southern) one of which a lighter (denser) type of CMW with the core σ_θ = 25.8–26.2 (26.3–26.4) kg m^{-3} is formed [*Oka and Suga*, 2005]. According to this classification, the CMW pycnostad observed in the KH-08-3 cruise (CMWP08) having the core σ_θ of 26.37 kg m^{-3} is the denser type formed north of the Kuroshio bifurcation. Both types of CMW have been believed to be subducted into the permanent pycnocline in the central North Pacific, and then advected by the anticyclonic subsurface circulation to spread in the subtropical gyre.

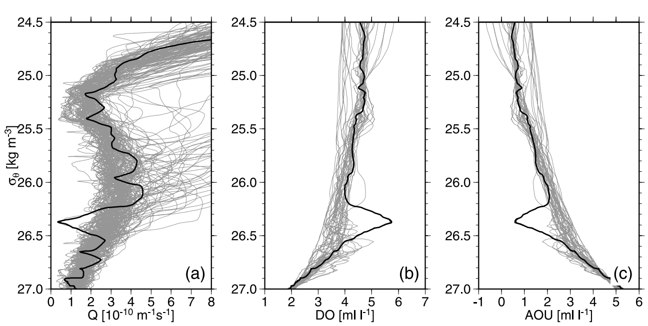

Figure 2. Vertical profiles of (a) Q, (b) DO, and (c) AOU with respect to σ_θ, obtained by $CTDO_2$ and XCTD on 22 October–4 November 2008 in the KH-08-3 cruise leg 2. Black curve (grey curves) indicates the properties at 27.5°N, 145°E (the other stations).

[8] In a climatological Q map on the σ_θ = 26.37 kg m^{-3} isopycnal constructed from WOA01, the thickest CMW with Q < 1.5 × 10^{-10} m^{-1} s^{-1} is found at 32°–42°N, 175°E–145°W (Figure 3a). Its northwestern end at 40°N, 175°E reasonably corresponds to the late winter outcrop of the isopycnal, at which subduction presumably occurs. From this subduction point, a tongue of low Q extends southeastward, and then southwestward to 27°N, 171°E, and to 21°N, 125°E. This anticyclonic CMW advection all the way to the western boundary takes roughly 15 years, according to geostrophic calculation. During the journey, the AOU of CMW increases from 0.5–1 ml l^{-1} to ~3 ml l^{-1} due to the oxygen consumption through remineralization of organic matter and to mixing (Figure 3b).

[9] The hydrographic sections of the KH-08-3 cruise lie in the region of relatively high Q exceeding 2.25 × 10^{-10} m^{-1} s^{-1}, located northwest of the low-Q tongue of CMW (Figure 3a). The observed Q at σ_θ = 26.37 kg m^{-3} in our 27.5°N section (2.06–3.57 × 10^{-10} m^{-1} s^{-1}; Figures 1c and 1d) is comparable to the climatological Q, except that there are a few extremely low values near 145°E, repre-

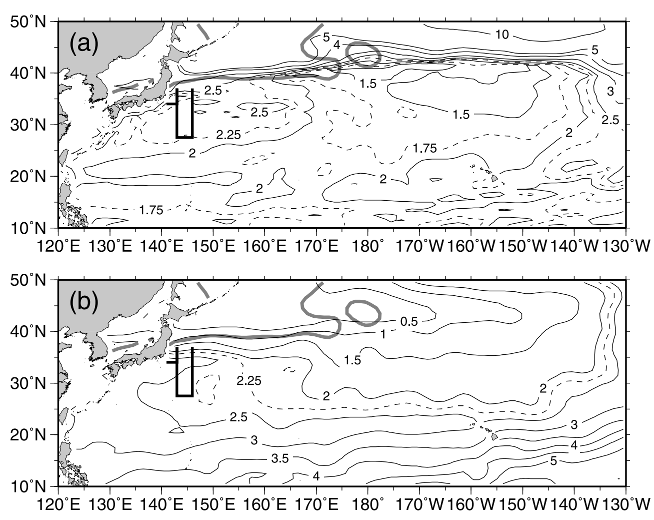

Figure 3. Annual-mean distributions of (a) Q (10^{-10} m^{-1} s^{-1}) and (b) AOU (ml l^{-1}) on the isopycnal of σ_θ = 26.37 kg m^{-3} in the North Pacific from WOA01. Thick grey curves indicate the outcrop of the isopycnal in March from WOA01. Thick black lines denote $CTDO_2$/XCTD sections of the KH-08-3 cruise leg 2.

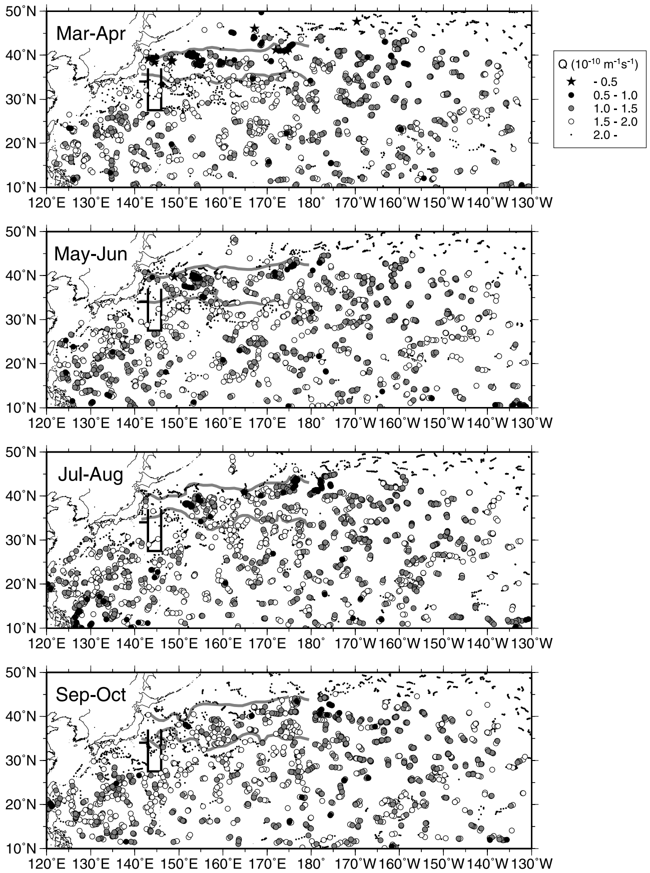

Figure 4. Distributions of Q on the isopycnal of σ_θ = 26.37 kg m^{-3} in the North Pacific from March–April through September–October 2008 from Argo float data. Thick grey curves indicate the positions of the Kuroshio Extension and the subarctic front between 140°E and 180°. Thick black lines denote the $CTDO_2$/XCTD sections of the KH-08-3 cruise leg 2.

sented by the core Q of CMWP08 (0.35×10^{-10} m^{-1} s^{-1}). The core AOU of CMWP08 (0.59 ml l^{-1}; Figure 2c) is also much lower than the AOU at σ_θ = 26.37 kg m^{-3} at the nearby $CTDO_2$ stations (~2.5 ml l^{-1}), which is comparable to the climatological AOU at the same location (~2.25 ml l^{-1}; Figure 3b). Rather, the core AOU is comparable to the climatological AOU at 40°–42°N, east of 175°E just downstream of the subduction point.

[10] The core AOU of CMWP08 is comparable to the lowest core AOUs of the STMW pycnostads observed in the KH-08-3 cruise, which occur in the σ_θ range of 25.1–25.4 kg m^{-3} (Figures 2a and 2c). These STMW pycnocstads are believed to be formed in late winter 2008, based on a comparison of STMW properties between 2007 and 2008 using Argo profiling float data (not shown). It is therefore highly possible that CMWP08 is also formed in late winter 2008, being about a half year old when it is observed in the 27.5°N section. It is thus unlikely that CMWP08 is advected from the central North Pacific to 27.5°N, 145°E by the large-scale anticyclonic circulation, which would take ~10 years or longer. There should be a shortcut from the CMW formation region to 27.5°N, 145°E that does not appear on climatological maps.

4. CMW Circulation in 2008 From Argo Float Data

[11] In climatological Q maps similar to Figure 3a, mesoscale and smaller-scale features such as CMWP08 are smoothed out and do not appear. To trace CMWP08 and investigate the existence of similar CMW pycnostads, we now examine temperature and salinity data from Argo profiling floats in the North Pacific [*Oka et al.*, 2007]. In Figure 4, Q distributions on the σ_θ = 26.37 kg m^{-3} isopycnal from late winter to fall 2008 constructed from the float data are presented, along with the positions of the Kuroshio Extension and the subarctic front (the northern and southern boundaries of the CMW formation region) determined using optimally interpolated θ and S and the definitions of $\theta_{300\ dbar}$ = 12°C [*Mizuno and White*, 1983] and $S_{100\ dbar}$ = 33.8 [*Yuan and Talley*, 1996], respectively.

[12] In March–April, two groups of the thickest CMW with $Q < 0.5 \times 10^{-10}$ m^{-1} s^{-1}, probably just after the formation, are seen at 143°–154°E and 171°–175°E in a northern part of the CMW formation region, presumably north of the Kuroshio bifurcation. As the season progresses, the eastern group is advected eastward while gradually increasing its Q values, passing through the subduction point indicated by WOA01 (Figure 3a). Therefore, this group is thought to be subducted into the permanent pycnocline through large-scale eastward advection, as inferred by previous observational and numerical studies [*Kubokawa and Inui*, 1999; *Xie et al.*, 2000; *Suga et al.*, 2004; *Tsujino and Yasuda*, 2004]. On the other hand, the western group migrates southeastward, and is located at 35°–40°N, 155°–162°E in fall. Part of this group is expected to cross the Kuroshio bifurcation to enter the southern formation region, as seen in the repeat hydrographic section across 165°E [*Oka and Suga*, 2005], while the remaining part in the northern formation region is likely to be re-entrained into the mixed layer developed in the following winter.

[13] The low-Q signature of CMW extends anticyclonically from the formation region to the eastern North Pacific, then to the lower-latitude western North Pacific centered at about 20°–25°N, although the boundary between the southern part of CMW and the low Q in the tropical region is much less evident compared to the climatological Q map (Figure 3a). Inside this anticyclonic CMW pathway, there is a region where Q mostly exceeds 1.5×10^{-10} m^{-1} s^{-1} west of 170°E, between the Kuroshio Extension and ~27°N, as seen in the climatological map.

[14] In this high-Q pool we find several CMW patches with $Q < 1.5 \times 10^{-10}$ m^{-1} s^{-1}, such as one at 33°N, 146°E in April (with the core Q of 0.91×10^{-10} m^{-1} s^{-1}) and one at 29°N, 142°E in July (1.32×10^{-10} m^{-1} s^{-1}). Their isolated distributions suggest that they have relatively small horizontal scales, possibly comparable to that of CMWP08. Although some of them are observed near the hydrographic sections of the KH-08-3 cruise, none of them are considered to be identical to CMWP08 because they have higher core Q and slightly different core θ or S. It is reasonable that CMWP08 is not detected by the Argo float observations,

because the spatial resolution of Argo array (~300 km) is one order larger than the horizontal scale of CMWP08.

[15] In addition to the CMW patches in the high-*Q* pool, we find several of them in the vicinity of the Kuroshio Extension, such as one at 34°N, 150°E in March and one at 33°N, 146°E in September. The existence of these CMW patches near and south of the Kuroshio Extension, as well as the southward migration of the western group in the CMW formation region, suggests that a certain amount of CMW is transported southward from the northern formation region across the Kuroshio bifurcation and Extension in the form of subsurface mesoscale eddies, thereby subducting into the permanent pycnocline.

[16] Such an idea of CMW subduction in the form of mesoscale eddies seems to be well supported by a theoretical study of *Spall* [1995]. He used analytic and numerical models to demonstrate that baroclinic instability and the resulting frontogenesis occurring at upper ocean fronts produce downward velocity and deep ageostrophic cross-frontal flow, which carry water in the mixed layer on one side of the front below and across the front. If this subduction occurs from a deep mixed layer, the subducted water parcels have thickness larger than the surrounding water of the same density, and quickly develop anticyclonic circulation with a typical diameter of 25 km through geostrophic adjustment [*Spall*, 1995]. Thus, the modeled cross-frontal subduction occurs in the form of mesoscale anticyclonic eddies, which corresponds well to the observed structure of CMWP08. The remaining question is by what mechanism CMWP08 reaches as far south as 27.5°N so quickly after crossing the Kuroshio Extension. If we assume that CMWP08 crosses it at 35°N at the end of April 2008, the mean southward propagation speed will be as high as 5.4 cm s^{-1}.

[17] The CMW patches near and south of the Kuroshio Extension are also seen in the float data-based PV maps on the isopycnals between 25.8 and 26.4 kg m^{-3} in the CMW σ_θ range (not shown). Therefore, the cross-frontal CMW subduction due to subsurface mesoscale eddies might be a considerable component of the total CMW subduction, and could be important for the *Q* redistribution within the subtropical gyre as well as the meridional transport of biogeochemical substances such as carbon and nutrients. However, it seems not easy to clarify the rate, mechanism, and effects of this cross-frontal subduction based on observations, due to difficulty in repeating high-density hydrographic surveys comparable to ours and to the relatively sparse distribution of Argo profiling floats. For such purposes, recent super-high resolution ocean general circulation models having a grid spacing of a few kilometers are expected to be useful.

5. Conclusion

[18] In the KH-08-3 cruise conducted in October–November 2008, we observed a subsurface mesoscale eddy containing anomalously oxygen-rich CMW at 27.5°N, 145°E. The existence of this eddy and other isolated CMW patches observed by the profiling floats suggests that CMW is subducted into the permanent pycnocline not only through the classical eastward advection near the northern edge of the subtropical gyre but also through the southward cross-frontal advection associated with the formation and migration of subsurface mesoscale eddies.

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