Subthermocline Eddies in the Western Equatorial Pacific as Shown by an Eddy-Resolving OGCM*

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ABSTRACT

Sporadic in situ observations have shown evidence that subthermocline eddies exist off the Mindanao coast. These subthermocline eddies are believed to play an important role in the heat, freshwater, and other ocean property transports of the region, but their characteristics and in particular their pathway and source of energy are poorly explored because of the lack of long-term observations. Analysis of results from an eddy-resolving general ocean circulation model has revealed that most subthermocline eddies off the Mindanao coast originate from the equatorial South Pacific Ocean to the west of the Ninigo Group. These eddies propagate northward along the New Guinea coast, cross the equator in the far western Pacific, and reach the Mindanao coast at a typical propagation speed of $-0.12 \text{ m s}^{-1}$. The dominant time scales of these eddies range between 50 and 60 days.

1. Introduction

Subthermocline eddies have been observed in many parts of the global ocean, including those in the Mediterranean outflow (e.g., Richardson et al. 2000), in the Red Sea outflow (e.g., Shapiro and Meschanov 1991), in the California Undercurrent (e.g., Simpson and Lynn 1990), and in the Peru–Chile Undercurrent (e.g., Johnson and McTaggart 2010). These subthermocline eddies are largely invisible at the sea surface, but they may significantly affect the heat, freshwater, and other property transports in the ocean. Great interest in subthermocline eddies has been aroused because of their potentially important role in climate variability.

Sporadic in situ observations have shown evidence that subthermocline eddies also exist off east Mindanao in the Philippine Sea (e.g., Wijffels et al. 1995; Kashino et al. 1999; Firing et al. 2005; Kashino et al. 2005). Based on direct measurements from a single mooring implemented from October 1999 to July 2002, Kashino et al. (2005) showed that the circulation below and offshore of the Mindanao Current (MC) was dominated by eddy activities on time scales of 50–100 days, consistent with earlier speculation by Wijffels et al. (1995). The mooring data at 2.5°S, 142°E, around 760 m between September 1998 and October 2002, also revealed large power spectral density at periods between 20 and 60 days (Kawabe et al. 2008). By analyzing Lowered Acoustic Doppler Current Profiler (LADCP) measurements from two individual cruises, Firing et al. (2005) suggested that the northward subsurface flow near the east coast of Mindanao was actually part of a set of subthermocline eddies within about 300 km off the coast.

A question that may arise immediately from these earlier studies is how the observed low-salinity, high-oxygen subthermocline water off the Philippine coast is conveyed (Reid 1965; Qu and Lindstrom 2004), given that the mean current below and offshore the MC only
reaches about 12\°–13\°N. Using results from an eddy-resolving ocean general circulation model (OGCM), Qu et al. (2012) recently reported that the northward intrusion of South Pacific water below and offshore the MC is largely due to subthermocline eddies. An ensemble of these subthermocline eddies can significantly enhance the northward property flux, explaining why water of South Pacific origin appears to extend farther northward than the mean current there.

Yet, because of the lack of long-term observations, these subthermocline eddies have not been carefully examined. Based on results from an eddy-resolving OGCM for the Earth Simulator (OFES), this study investigates the characteristics and in particular the pathway and energy source of subthermocline eddies in the western equatorial Pacific. Section 2 describes the configuration of OFES and provides a brief comparison with existing observations. Section 3 shows an example subthermocline eddy and its related property fields in the far western equatorial Pacific. The statistics of subthermocline eddies is shown in section 4, and the energy source of these eddies is discussed in section 5. Results are summarized in section 6.

2. Model description and validation

The OFES is based on the Modular Ocean Model, version 3.0 (MOM 3.0). Its domain covers a near-global region extending from 75\°S to 75\°N, with a horizontal resolution of 0.1° × 0.1°. The vertical resolution varies with a total of 54 levels from 5 m near the surface to 330 m near the bottom. The model topography was constructed from a 1/36° bathymetry dataset created by the Ocean Circulation and Climate Advanced Modelling
Fig. 2. Comparison of (a),(b) zonal velocity at different depths and (c),(d) velocity vector at ~760 m at 2.5°S, 142°E from September 1998 to November 1999 between mooring observations (a),(c) and model results (b),(d). Here, (a),(c) are after Zenk et al. (2005) and Kawabe et al. (2008), respectively.
FIG. 3. OFES-modeled profiles of (a),(c) salinity and (b),(d) potential temperature. Time–depth profiles at 0.05°S, 139.1°E during the period from 13 Mar to 12 May 1985 (top); longitude–depth profiles along 0.05°S in 15 Apr 1985 (bottom). White contours represent isopycnal surfaces of 27, 27.05, and 27.1 kg m⁻³.
A 50-yr climatological spinup was first executed from annual-mean temperature and salinity fields of the *World Ocean Atlas 1998* (WOA98). Then, the model was forced from 1950 to 2009 with daily surface wind stress, heat flux, and salinity flux based on the National Centers for Environmental Prediction (NCEP) reanalysis products. The surface fluxes were specified with bulk formula from the reanalyzed atmospheric variables of NCEP, in addition to a surface salinity restoring to the
The climatological monthly values of WOA98. The 3-day snapshot model outputs including velocity, temperature, and salinity for the period of 1980–2009 (30 years) were recently released and are used for the present study. For details about the model configuration, readers are referred to Masumoto et al. (2004) and Sasaki et al. (2008).

The OFES outputs have been analyzed by a number of earlier studies (Aoki et al. 2007; Qu et al. 2008; Dutrieux 2009; Kashino et al. 2009; Chen et al. 2010; Qu et al. 2012). These studies showed that the model reproduces nearly all of the observed features over the global ocean. In the far western tropical Pacific, Dutrieux (2009) compared the model results with available shipboard ADCP measurements, and suggested that the model represents reasonably well the regional circulation and its variability. Here, we provide additional examples of model–data comparison for the region. Figure 1 shows a comparison of the upper 220-m current between the model and mooring observations at 2.5°S, 142°E from July 1995 to July 1996. As one can see from this figure, the simulated velocities (Figs. 1d and 1e) are in good agreement with observations (Figs. 1a and 1b). The model reproduced nearly all the observed structures, including the seasonal cycle and the enhanced westward flow associated with the 1995/96 La Niña event. The correlations of upper 150-m zonal and meridional velocities between the model and the mooring data reach 0.78 and 0.70 with no time lag, respectively. The spectrum of model velocity (Fig. 1c) averaged for 150–220 m shows significant 20–30-day fluctuations, which are also marked evident in observations [Fig. 1f and Kuroda (2000)].

Figure 2 shows the comparison of the subsurface for the period from September 1998 to November 1999. Here, the eddy-like, intraseasonal fluctuations are obvious in both the simulated and observed velocity fields.
At \( \sim 760 \)-m depth (Figs. 2c and 2d), for example, the two time series are well in phase despite significant differences in magnitude of the variability. The spectrum of \( \sim 760 \)-m model velocity reveals 20–60-day fluctuations, which is consistent with the result of Kawabe et al. (2008). From these comparisons and those provided by previous studies (e.g., Masumoto et al. 2004; Sasaki et al. 2008; Dutrieux 2009), we feel that for the region studied the circulation from OFES is one of the best available in a model and the results presented in this study are mostly reliable.

3. An example subthermocline eddy

The western equatorial Pacific is populated with eddies of various time scales not only in surface layer (e.g., Kashino et al. 1999, 2007, 2009) but also in the subthermocline (e.g., Firing et al. 2005; Kashino et al. 2005; Kawabe et al. 2008). As one can see from section 2 (Figs. 1 and 2), the subthermocline eddies in the western equatorial Pacific are also simulated by the OFES. As an example, Fig. 3 shows the temporal evolution from 13 March to 12 May 1985, and the vertical structure on 12 April 1985, of an individual subthermocline eddy located at 0.05°S, 139.15°E. The time–depth and longitude–depth profiles of salinity show a low-salinity lens in mid-April, when salinity is lowered by up to 0.08 psu (Figs. 3a and 3c). This low-salinity lens extends between the depths of about 500 and 650 m, with a core lying at about 550 m around 12 April, consistent with its South Pacific origin (e.g., Qu and Lindstrom 2004). This depth range roughly corresponds to a density range of \( \sigma = 27.0–27.1 \) kg m\(^{-3}\). As shown in Figs. 3b and 3d, similar patterns are seen for potential temperature, in which a thermostad around the 5.9°–6.9°C isotherms lies between about 500 and 675 m, roughly coinciding with the maximum-salinity anomaly. Both isotherms and isohalines bow up to about 500 m above the core of the eddy but become relatively flat below it. These characteristics resemble those reported by earlier studies in other parts of the global ocean (e.g., Johnson and McTaggart 2010). According to Fig. 3 and the temperature/salinity structure in the other parts of the region studied, the main depth range of subthermocline eddies is around 600 m, and the low-salinity signature can extend upward to 500-m depth. Although the temperature/salinity measurements of the Triangle Trans-Ocean Buoy Network (TRITON; http://www.jamstec.go.jp/jamstec/TRITON/real_time/php/top.php) in the region studied only exist at the depths of 300, 500, and 750 m in the subthermocline, the data at 0°, 138°E can still reveal the existence of low-salinity events (Fig. 4), suggesting that subthermocline eddies are a prominent phenomenon of the region.
FIG. 7. Hovmöller diagrams of (left) $U_{CS}$ and (right) salinity at 605 m from 2004 to 2009 (6 years as an example) along the black line in Fig. 5f.
4. Statistics

Eddy kinetic energy (EKE) calculated from the model outputs can be used as a measure of variability. Here, the EKE (per unit mass) is defined as $EKE = \langle U_Z^2 + U_M^2 \rangle$, where $U_Z$ and $U_M$ are the zonal and meridional velocity anomalies, and angle brackets denote the temporal average over the 30 years. At 605 m, a high EKE value is shown along the Mindanao and New Guinea coasts (Figs. 5a and 5d), which confirms the earlier speculation on strong eddy activities of the region (Wijffels et al. 1995; Kashino et al. 2005). Firing et al. (2005) suspected that the subthermocline eddies represent energy that has propagated westward from the central Pacific and/or northward along the western boundary. When the subthermocline eddies propagate northward along the western boundary, they may induce high variability of zonal velocity (perpendicular to the moving direction) along their trajectories and high variability of meridional velocity (parallel to the moving direction) on their inshore and offshore edges (Fig. 6). To clarify this, the zonal and meridional EKE components ($EKE_Z$ and $EKE_M$, defined by $\langle U_Z^2 \rangle$ and $\langle U_M^2 \rangle$) are presented in Fig. 5. One high $EKE_Z (>0.02 \text{ m}^2 \text{ s}^{-2})$ band (Fig. 5b) and two high $EKE_M$ bands (Fig. 5c) appear along the Mindanao coast (5°–8°N, 127°–130°E), indicative of a north–south dominant pathway of subthermocline eddies there.

The subthermocline eddies off the Mindanao coast can be traced southward to the New Guinea coast. To better illustrate the eddy activities along the New Guinea coast, the EKE associated with alongshore and crossshore velocity deviations from the 30-yr-mean values, $\langle U_{AS}^2 \rangle$ and $\langle U_{CS}^2 \rangle$, are also presented in Fig. 5, where AS and CS stand for along- and cross-shore components, respectively. Now the northwestward propagation of subthermocline eddies along the New Guinea coast is clearly demonstrated in Fig. 5f. Similar to the EKE off the Mindanao coast (Figs. 5b and 5c), the two high $EKE_{AS}$ (>0.010 m² s⁻²) bands lie on the in- and offshore sides of northwestward-propagating eddies (Fig. 5e), while the high $EKE_{CS}$ (>0.008 m² s⁻²) band coincides with the center of the eddies (Fig. 5f). The average diameter of eddies, measured by the distance between the two high $EKE_{AS}$ bands, is about 3°, in a reasonable agreement with the estimate by Firing et al. (2005) of 200–300 km. Although there is a high $EKE_Z$ band along 1°N around 144°–147°E (Fig. 5b), no high $EKE_M$ bands are visible at these longitudes (Fig. 5c). As westward-propagating eddies may cause high $EKE_Z$ and $EKE_M$ bands simultaneously, we suspect that the high $EKE_Z$ band along 1°N cannot be forced by westward-propagating eddies. In fact, close inspection of the result indicates that the variability of zonal velocity at ~1°N, 144°–147°E is dominated by the annual cycle (45.1%), and the contribution from intraseasonal fluctuations is relatively minor (16.4%).

Following the eddies’ pathway parallel to the New Guinea coast at 605 m (marked by the black line in Fig. 5f), more than 80% of the total variance in $U_{CS}$ can be explained by fluctuations shorter than 150 days.
The Hovmöller diagrams of $U_{CS}$ and salinity along the pathway also display intraseasonal northwestward propagations (Fig. 7). The power spectral density of $U_{CS}$ suggests a dominant time scale of 50–60 days along the New Guinea coast (Fig. 8a). Similar results are found in the spectra of vorticity, salinity, and temperature (figures not shown). This dominant time scale of variability is consistent with previous observations (Kashino et al. 1999, 2005, 2007). As shown in Fig. 8b, the 50–60-day signal initially appears near 142°E around 600 m. When the signal moves northwestward along the coast, it becomes stronger (Fig. 5b) and appears to be affected by other perturbations that are possibly related to the topographic features north of New Guinea. Based on the spatial pattern of phase angle derived from the Fast Fourier Transform (Fig. 8c), the typical propagation speed of subthermocline eddies in the region studied is about 0.12 m s$^{-1}$.

![Fig. 9. Lag correlation maps of 50-60-day-bandpassed vorticity relative to the vorticity at (a) 0.675°S, 141°E and (b) 0.025°S, 139°E. Triangles, red lines, and green lines indicate the relative location, pathway of eddies, and 605-m isobath, respectively.](image)
5. Energy source

In addition to the station at 0°, 138°E discussed above, there are two other TRITON stations (0°, 147°E and 0°, 156°E) in the western equatorial Pacific. The mean salinities at 500 m of these three stations are very close (34.604, 34.607, and 34.609 psu), but their corresponding standard deviations are very different (0.0208, 0.0173, and 0.0177 psu), with the value at 0°, 138°E being significantly larger than those at the other two stations. This difference could be related to the fact that the station at 0°, 138°E is geographically much closer to the pathway of subthermocline eddies along the western boundary than the other two stations. As shown in the lag correlation maps of 50–60-day-bandpassed vorticity at 605 m relative to 0.675°S, 141°E (Fig. 9a) or roughly the middle of New Guinea Coast (the black line of Fig. 5f), most subthermocline eddies in the western tropical Pacific originate from the equatorial South Pacific. In most cases, they propagate northwestward along the New Guinea coast and cross the equator in the far western Pacific. Both Figs. 9a and 9b show that the subthermocline eddies originate from the region to the west of the Ninigo Group near ~1.25°S, 143°E but not from the east (e.g., central or eastern Pacific). These eddies propagate predominantly along the pathway marked by the red line in Fig. 9.

Firing et al. (2005) suggested that local wind forcing or instability of local upper-ocean currents cannot be the energy source of subthermocline eddies in the region studied. Kashino et al. (2005) reported that the MC intraseasonal variability was not well correlated with the atmospheric intraseasonal variability. The typical propagation speed of these subthermocline eddies (~0.12 m s⁻¹) is significantly smaller than the propagation speed (larger than 1.2 m s⁻¹) of the first baroclinic Rossby waves in the tropical ocean, suggesting that the formation of these subthermocline eddies is not associated with the β effect. The mean subthermocline current along the Mindanao coast is rather weak (Qu et al. 2012) and is unlikely the energy source of subthermocline eddies. The formation of subthermocline eddies may be related to intrinsic ocean variability (Kashino et al. 2007) and/or interaction of ocean currents with complex bathymetry. According to the time-mean energy budget (Masina et al. 1999), the barotropic conversion term can be written as $-\rho_o (U'_x U'_y) (\partial U'_x / \partial x) + \langle U'_x U'_y \rangle (\partial U'_x / \partial x) + \langle U'_y U'_y \rangle (\partial U'_y / \partial y) + \langle U'_x U'_M \rangle (\partial U'_x / \partial y)$, representing the transfer between the mean kinetic energy and eddy kinetic energy, and baroclinic conversion term can be written as $-g (\rho' W')$, representing the energy conversion between the eddy available potential energy and eddy kinetic energy, where $\rho'$ and $W'$ are the density and vertical velocity anomalies, subscript $o$ stands for mean, and $g$ denotes the acceleration of gravity. Positive values of these terms represent the conversion of mean kinetic energy or eddy available potential energy into eddy kinetic energy, and vice versa. Careful examination of model results (Fig. 10) suggests that the formation region of subthermocline eddies near ~1.25°S, 143°E is stable barotropically but not baroclinically, suggesting that barotropic instability is a major energy source of the subthermocline eddies there.

The distributions of mean currents and 50–60-day-bandpassed EKECS at 507, 605, and 694 m are shown in Figs. 11a–c. Except for a stronger signal extending farther eastward at 605 m, the EKECS distributions at these three depths show essentially the same pattern, with a high EKECS band lying northwestward along the New Guinea coast, consistent with the distribution of along-pathway power spectral density shown in Fig. 8b. The high EKECS band is located just north of the northwestward-flowing New Guinea Coastal Undercurrent (NGCUC) (Lindstrom et al. 1987). Aside from the NGCUC, the formation of
high EKE\textsubscript{CS} band could also be related to the westward-flowing Lower Equatorial Intermediate Current (LEIC). The NGCUC gets weaker with depth, and the LEIC starts to appear at depths around 694 m. Possible interaction between the two currents was previously suggested by Kawabe et al. (2008).

On the other hand, the bottom topography in the vicinity of these two currents, being composed of the Manus Island (the largest island of the Admiralty Islands) and the Ninigo Group [a group of atolls, islands, and reefs including Awin Atoll, Suynamasa Island, Sama Group, Ninigo Islands (a very large atoll), Pelleluhu Group, Heina Group, Pupol Reef (a low lying reef), and Liot Island], is very complicated and likely provides a favorable condition for the generation of subthermocline eddies there. Figures 10 and 11a–c show the NGCUC and LEIC hit the seamounts near 142°E, cause barotropic instability, and generate high EKE\textsubscript{CS} signals that propagate farther westward (Fig. 11d). We therefore suggest that interactions among the NGCUC, LEIC, and complex bottom topography associated with the Ninigo Group are primarily responsible for the generation of subthermocline eddies in the western equatorial Pacific.

6. Summary

In this study, we have provided the first quantitative evidence for the existence of subthermocline eddies in the western equatorial Pacific by examining the results from an eddy-resolving OGCM. Most subthermocline eddies in the region appear to originate from the equatorial South Pacific to the west of the Ninigo Group. These eddies convey relatively fresh South Pacific water westward to the western boundary. From there, they move northwestward along the New Guinea coast, cross the equator in the far western Pacific, and reach the coast of the Philippines, exerting notable impacts on the property distribution in the western equatorial Pacific. The dominant time scale of these eddies is about 55 days, with their strongest signature occurring near 600 m. Some of these eddies may be related to the instability of currents as is the case in many other parts of the ocean. Here, we emphasize the importance of bottom topography. We suspect that the generation of subthermocline eddies in the western equatorial Pacific is due in large part to the interactions among the NGCUC, LEIC, and complex topography associated with the Ninigo Group. The details need to be further investigated as more long-term observations become available.

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