Quasi-stationary North Equatorial Undercurrent jets across the tropical North Pacific Ocean

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1 Subthermocline circulation in the tropical North Pacific Ocean (2°N–30°N) is investigated using profiling float temperature-salinity data from the International Argo and the Origins of the Kuroshio and Mindanao Current (OKMC) projects. Three well-defined eastward jets are detected beneath the wind-driven, westward flowing North Equatorial Current. Dubbed the North Equatorial Undercurrent (NEUC) jets, these subthermocline jets have a typical core velocity of 2–5 cm s–1 and are spatially coherent from the western boundary to about 120°W across the North Pacific basin. Centered around 9°N, 13°N, and 18°N in the western basin, the NEUC jet cores tend to migrate northward by ~4° in the eastern basin. Vertically, the cores of the southern, central, and northern NEUC jets reside on the 26.9, 27.2, and 27.3 σθ surfaces, respectively, and they tend to shoal to lighter density surfaces, by about 0.2 σθ, as the jets progress eastward. Citation: Qiu, B., D. L. Rudnick, S. Chen, and Y. Kashino (2013), Quasi-stationary North Equatorial Undercurrent jets across the tropical North Pacific Ocean, Geophys. Res. Lett., 40, 2183–2187, doi:10.1002/grl.50394.

1. Introduction

[2] With the advancement of satellite altimetry in conjunction with in situ observations, our knowledge of the upper ocean circulation has increased significantly over the past two decades. In comparison, information about the subthermocline circulation features remains fragmentary. For the subthermocline Pacific basin, much of the research focus of the past decades has been directed to the equatorial band within the ±10° latitudes. In addition to the alternating equatorial deep jets centered on the equator with a vertical wavelength of several hundred meters [e.g., Firing, 1997; Johnson et al., 2002], alternating zonal jets have also been observed laterally below the permanent thermocline. These laterally aligned jets include the westward Lower Equatorial Intermediate Current on the equator, the eastward Northern and Southern Intermediate Countercurrents at ±2° latitudes, the westward North and South Equatorial Intermediate Current at ±3° latitudes, and the eastward northern and southern secondary Subsurface Countercurrents at ±5° latitudes [e.g., Firing et al., 1998; Rowe et al., 2000; Gouriou et al., 2006].

2. Profiling Float Data

[3] While all of the above studies focusing on the subthermocline equatorial zonal flows were based on shipboard Acoustic Doppler Current Profiler (ADCP) measurements, the establishment of the International Argo Program in the early 2000s [Roemmich et al., 2009] provides us now with a novel in situ data set to explore the mid-depth circulation signals. Utilizing the drifting information of consecutive float profiles, Cravatte et al. [2012] have constructed maps of the mean zonal flows in the 12°S–12°N band of the equatorial Pacific at the float parking depths of 1000 m and 1500 m. They found alternating westward and eastward jets with a meridional scale of ~1.5° and speeds of ~5 cm s–1. The jets are generally stronger in the western and central basins and tend to weaken, or disappear, in the eastern basin.

[4] In comparison to the equatorial flow system, basin-scale subthermocline circulation features in the tropical North Pacific Ocean of 10°N–30°N are yet to be explored observationally. As part of the ongoing Origins of the Kuroshio and Mindanao Current (OKMC) project, 10 SOLO-II profiling floats were deployed in the Philippine Sea in August 2011. With a repeat cycle of 5 days, a significant amount of high vertical resolution temperature-salinity (T-S) profiles in the 2000 m upper ocean has been collected in the northwestern Pacific Ocean. By combining the available float T-S data from both the OKMC and Argo projects, we seek in this study to quantify the mid-depth mean flow structures across the entire tropical North Pacific basin.

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3. The NEUC Jets

Figure 2 shows the latitude-depth sections of the mean zonal geostrophic velocities along 130°E–135°E, 175°E–180°E, and 150°W–145°W, respectively. These three sections represent the flow structures typical in the western, central, and eastern North Pacific Ocean. In the wind-driven North Pacific tropical and subtropical gyres, the base of the permanent thermocline is shallow, typically ≤500 m, and has a density of ~26.5 σθ. Along 130°E–135°E in the western basin (Figure 2a), upper ocean flows above the permanent thermocline consist of the eastward flowing North Equatorial Countercurrent (NECC) in 2.5°N–7.5°N and the broad-scale, westward flowing North Equatorial Current (NEC) in 7.5°N–25°N. In between 17°N and 25°N, one can detect multiple, surface-trapped Subtropical Countercurrent (STCC) branches that flow eastward and override the NEC [e.g., Kobashi et al., 2006]. The eastward flow north of 27.5°N in Figure 2a signifies a portion of the northeastward flowing Kuroshio south of Japan. Similar upper ocean flow patterns to Figure 2a can be seen in the central and eastern basins; the exceptions are that the Kuroshio is located north of 30°N (hence absent in Figures 2b and 2c) and that the surface-trapped STCC along 150°W–145°W in the eastern basin appears in the higher latitude of 25°N–28°N.

Figure 1. (a) Number of T/S profiles in 3° longitude × 1° latitude boxes of the North Pacific Ocean for the period of January 2001 to October 2012. (b) Histogram of the T/S profiles as a function of years/seasons.
Beneath the permanent thermocline of the westward flowing NEC, Figure 2a shows that there exist three, well-defined, eastward-flowing jets with cores centered around 9°N, 13°N, and 18°N, respectively. The cores of these subthermocline jets reside on the 26.9–27.3 $\sigma_t$ density surfaces and their velocities are on the order of 4–5 cm s$^{-1}$. Though inconspicuous in Figure 2a, there exists a tendency for the jet cores to progressively shift from a lighter to denser density surface from south to north. The three subthermocline jets can be similarly identified beneath the westward flowing NEC along the 175°E–180°E and 150°W–145°W sections (Figures 2b and 2c). Compared to Figure 2a, the cores of the three jets tend to shift northward and onto a lighter density surface, and their speed tends to drop down to 1–2 cm s$^{-1}$, when moving toward the east.

Beneath the eastward flowing NECC, Figures 2b and 2c reveal the presence of two additional, eastward-flowing subthermocline jets at 2°N–3°N and 5°N. These two jets correspond to the eastward off-equatorial jets along 2°N and 5°N identified by Cravatte et al. [2012] based on the analyses of Argo float trajectories at 1000 m. Following the nomenclature adopted by Gouriou et al. [2006] for the Southern Hemisphere current system, we can refer to the subthermocline equatorial jets at 2°N and 5°N as the Northern Intermediate Countercurrent (NICC) and the northern secondary Subsurface Countercurrent, respectively. Although the subthermocline jet at 9°N was detected by Cravatte et al. [2012], the two northern jets at 13°N and 18°N shown in Figure 2 have not been captured before. Given their presence beneath the westward flowing NEC and their common dynamic properties (to be discussed below), we propose in this study to name these three subthermocline jets collectively as the North Equatorial Undercurrent (NEUC) jets.

To explore the longitudinal continuity of the NEUC jets, we plot in Figure 3 the distribution of zonal geostrophic velocity averaged between the 26.8–27.4 $\sigma_t$ density surfaces. To aid the jet identification, we have superimposed on Figure 3 by grey marks the locations of the NEUC jet cores that are derived from the $U_y(y,z)$ profiles in each 5° longitude segment, similar to those presented in Figure 2. A roughly zonally persistent $U_y > 0$ band can be seen along 17°N–20°N from the western boundary to east of the Hawaiian Islands. This band corresponds to the northern NEUC jet depicted in Figure 2. The central NEUC jet is discernible in Figure 3 as the positive $U_y$ band slanting southwest-northeastward along 13°N–17°N. For the southern NEUC jet, it runs roughly along 9°N–10°N west of the dateline and veers northeastward further to the east. From Figure 3, it is possible to identify a fourth SW-NE tilting zonal jet in the eastern North Pacific basin along ~10°N. When compared with the three NEUC jets described above, its extension into the western basin appears less persistent.

Due to the uneven data availability in space (recall Figure 1a), the NEUC jets in Figure 3 can appear zonally disconnected in various locations. This may raise concern about the robustness of the poleward shift of the three NEUC jets. To address this concern, we plot in Figure 4a the salinity distribution on the 27.0 $\sigma_t$ surface from the float measurements. Although distorted laterally, the paths of the three NEUC jets follow roughly in parallel with the SW-NE tilting isohaline contours. Given that salinity...
is largely a passive tracer below the permanent thermocline, this parallel distribution provides independent evidence for the poleward tilt of the NEUC jets from west to east.

[12] In Figures 4b and 4c, we plot the depth and density of the NEUC jet cores as a function of longitude. As the NEUC jets migrate poleward toward east, its core shifts simultaneously to a shallower depth and a lighter density surface. These characteristics of the NEUC jets mirror very well the flow properties of the overlying NEC across the North Pacific basin. Specifically, the wind-driven NEC above the permanent thermocline has a similar NE-SW tilt in the region of 9°N–20°N and, as can be verified in Figure 2, the depth of the NEC becomes shallower and its lower boundary shoals to a lighter density surface from west to east.

4. Discussion

[13] Based on the available profiling float T-S data, our analysis of the three-dimensional circulation in the tropical North Pacific Ocean has detected the presence of three eastward flowing jets immediately beneath the permanent thermocline of the NEC. These three subthermocline jets are zonally coherent from the western boundary to about 120°W and are centered approximately along 9°N, 13°N, and 18°N in the western North Pacific basin. The spatial characteristics of these jets, i.e., veering poleward and shoaling to lighter density surfaces from the western to eastern basin, are similar to those of the overlying NEC. Given these similarities, it is proposed in this study to name these newly detected subthermocline jets the North Equatorial Undercurrent (NEUC) jets.

[14] Eastward flows below the NEC within the western North Pacific basin have been observed sporadically in the past. For example, Toole et al. [1988] presented evidence for subthermocline eastward flows at 10°N and 12°N from two hydrographic surveys along 130°E. Based on a hydrographic cruise along the same longitude, Hu and Cui [1991] observed subthermocline eastward flows at 12°N and 18°N. A subthermocline eastward jet was identified to be a time-mean feature at ~10°N by Qiu and Joyce [1992] based on long-term hydrographic surveys along 137°E. Using the multiple hydrographic surveys along 130°E, Wang et al. [1998] adopted the name of NEUC to describe the eastward flow beneath the NEC. In addition to these studies using the hydrographic data, existence of the subthermocline eastward flows is also evident in recent shipboard acoustic Doppler current profiler (ADCP) measurements [Kashino et al., 2009; Dutrieux, 2009]. Because the ADCP measurements only extend to 600 m, they capture often the top portions of the NEUC jets. In short, while their presence is hinted in the existing literature, it is the global profiling float data that provided us a means to comprehensively examine the three NEUC jets across the entire North Pacific basin.

[15] It is worth emphasizing that the three NEUC jets shown in Figure 3 remain largely unchanged, or quasi-stationary, when the \( U_w \) fields are constructed using the T-S data from 2001–2008 and 2009–2012 separately (figure not shown). Dynamically, it is also interesting to note that the SW-NE veering by the NEUC jets is opposite to the NW-SE veering by the eastward subthermocline jets identified by Cravatte et al. [2012] at 2°N and 5°N in the equatorial Pacific Ocean. This opposite tilting may reflect the different background mean circulation structures the NEUC jets versus the off-equatorial jets are embedded in. It could also imply that the equatorial and tropical subthermocline jets have different forcing mechanisms.

[16] Several studies based on high-resolution ocean general circulation model simulations have indicated the possibility that alternating zonal jets in the tropical and midlatitude Pacific Ocean are generated spontaneously by geostrophic turbulence on a \( \beta \)-plane [e.g., Nakano and Hasumi, 2005; Maximenko et al., 2005; Richards et al., 2006]. It is worth emphasizing the NEC along 9°N–18°N across the North Pacific basin is a band with relatively low mesoscale eddy activity [see, e.g., Ducet et al., 2000, Plate 8]. Dynamically, this is due to the resistance of the NEC system against baroclinic instability [Qiu, 1999]. With this low level of mesoscale eddy variability, it will be important for future studies to quantify whether the nonlinear rectification by \( \beta \)-plane geostrophic turbulence [Rhines, 1975] is a viable mechanism for generating the NEUC jets.

[17] Using a coupled atmosphere-ocean general circulation model, Taguchi et al. [2012] have recently found subthermocline zonal jets existing in the tropical central South Pacific Ocean. In accordance with the analysis by Kessler and Gourdeau [2006], Taguchi et al. [2012] demonstrated that these zonal jets are in approximate sverdrup balance with the collocated, small-scale surface wind stress curl forcing (the sverdrup prediction explains about half the amplitude of the jets). By examining the impact of sea surface temperature anomalies upon the overlying atmosphere, they further showed that the small-scale wind stress curl signals could be enhanced through feedback by the sverdrup zonal jets. Following these South Pacific Ocean studies, we have calculated the sverdrup zonal flows in the North Pacific basin based on the satellite-derived QuikSCAT wind data. No small-scale wind stress curl forcing was found to be collocated with the NEUC jets. Though lacking small-scale features, the wind stress curl forcing has large amplitudes, especially in the annual frequency band, along the 9°N–20°N band in the North Pacific basin. It will be important for future studies to quantify how this time-varying surface wind forcing can result in rectified subthermocline circulations.

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