Semiannual Variability of Middepth Zonal Currents along 5°N in the Eastern Indian Ocean: Characteristics and Causes

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ABSTRACT

Four-year (2014–17) zonal current data observed by a mooring at (5°N, 90.5°E) in the eastern Indian Ocean show a strong semiannual cycle in the middepth (~1200 m) with distinct vertical structure. This pronounced middepth semiannual variability, however, is inconsistent with the local wind forcing, which shows a predominant annual cycle. The underlying causes for this unique middepth variability along 5°N were elucidated with the addition of a reanalysis product and a continuously stratified linear ocean model. The results suggest that the observed seasonal variability in the middepth zonal flow at 5°N is primarily caused by boundary-reflected Rossby waves forced by the remote semiannual winds along the equator. Contribution from the locally wind-forced Rossby waves is much less. The theoretical Wentzel–Kramers–Brillouin ray paths further verify that the strong semiannual variability of the middepth signals over a moored region in the eastern Indian Ocean is largely a manifestation of the steep angles of propagating energy of the long Rossby waves at semiannual time scale. The annual signals are only significant in the upper and western sections (75°–80°E) as a result of the smooth trajectories of Rossby waves forced by local annual winds. Further analysis reveals that the middepth zonal currents along 5°N are expected to be associated with equatorial symmetric Rossby waves at semiannual period. Consequently, similar zonal flows should also exist in the middepth near 5°S.

1. Introduction

In the tropical Indian Ocean (IO), the dynamically important features of wind forcing are the pronounced Asian monsoonal winds that prevail the IO with strong annual cycle north of 10°S, and semiannual cycle of zonal wind along the equatorial basin (Schott and McCreary 2001; Wang 2006; Schott et al. 2009). Near the equatorial regions (2°–10°N/S), the zonal wind features a strong annual variability (365-day period), driving annual changes of circulation as well as mass and heat transports (Schott et al. 1994; Han et al. 1999; Reppin et al. 1999; Le Blanc and Boulanger 2001; Schott and McCreary 2001; Schott et al. 2009; Nyadjro and McPhaden 2014; McPhaden et al. 2015; Nagura 2018). In contrast, the zonal wind in the equatorial IO shows strong semiannual variation (180-day period), with westerly (easterly) winds in boreal spring and autumn (summer and winter) (e.g., Schott and McCreary 2001; Ogata and Xie 2011). Subsequently, the oceanic response to such semiannual winds and its dynamical influence has been extensively discussed in both observational and modeling studies (Wyrtki 1973; Knox 1974; Luyten and Roemmich 1982; McPhaden 1982; Jensen 1993; Reppin et al. 1999; Yuan and Han 2006; Nagura and McPhaden 2008; Iskandar et al. 2009; Chen et al. 2015; Duan et al. 2016; Nagura and McPhaden 2016; Rao et al. 2017; Wang et al. 2018).

In the equatorial IO, previous studies investigated the characteristics of the semiannual variability of zonal flows within the upper (0–200 m) and middepth (200–1200 m)
layers, and proposed that such strong semiannual cycle can be explained by the equatorial basin-scale resonance at semiannual time scale (e.g., Luyten and Roemmich 1982; Jensen 1993; Han et al. 1999, 2011; Ogata and Xie 2011). The theories on basin resonance in equatorial oceans have been discussed in earlier studies (Cane and Moore 1981; Cane and Sarachik 1981). Further analysis of the upper IO suggested that the part of the signals generated in the equatorial basin can propagate into the Bay of Bengal and Indonesian Seas along the eastern boundary via coastally trapped waves, affecting the circulation in these regions (Potemra et al. 1991; Yu et al. 1991; Clarke and Liu 1993; Yamagata et al. 1996; Hacker et al. 1998; Le Blanc and Boulanger 2001; Yu 2003; Cheng et al. 2017) and the southeastern IO (Chen et al. 2016, 2017).

In theory, after the eastward-propagating Kelvin waves—which are symmetric about the equator—impinge on the eastern boundary, their energy is reflected back into the ocean interior via westward-propagating equatorial symmetric Rossby waves (RWs) equatorward of the RWs’ critical latitudes, if the ocean is inviscid and neglecting bottom topography (e.g., Matsuno 1966; Clarke and Van Gorder 1994; Soares et al. 1999). Yet the effects of the strong shear of mean zonal current and slanted coastlines of the eastern Indian Ocean (EIO) can result in asymmetric meridional structures of the equatorial waves at semiannual time scale, causing the asymmetric current variability on the north and south sides of the equator (e.g., Chelton et al. 2003; Chen et al. 2017). Additionally, the local off-equatorial wind forcing also plays an important role in shaping the meridional structures of currents in regions north and south of the equator (McCreary et al. 1993, 1996; Shankar et al. 1996). The available oceanic data are helpful and contribute significantly to our understanding of the rich structures of upper-ocean processes in and around the equatorial regions and their dynamics associated with remote and local forcing. However, due to the lack of direct observations, our knowledge of the structure of middepth ocean current variability and their causes is quite limited for the semiannual time scale.

In the Pacific Ocean, several studies revealed that the middepth flows over the off-equatorial regions presented an annual cycle with downward propagating energy, and concluded the response mechanisms of the middepth penetration to the combined contribution of the equatorial remote and local wind-forced RWs (Dewitte and Reverdin 2000; Dewitte et al. 2008; Ramos et al. 2008; Vergara et al. 2017). In the IO, the fact that the remote wind forcing from the equator shows strong semiannual variation, while the local wind forcing presents a predominant annual cycle in the off-equatorial region. How the oceanic waves in the IO respond to the local and remote wind forcing and contribute to the middepth current near 5°N has still remained elusive.

An enhanced tropical middepth observing array, consisting of four Acoustic Doppler Current Profiler (ADCP) moorings, has to date been maintained for more than three years in the EIO. Here, we used these moored measurements, especially for the mooring at (5°N, 90.5°E), combined with oceanic reanalysis and modeling experiments, to reveal the seasonal variability of off-equatorial middepth zonal currents (MZCs) in the EIO and explain its forcing dynamics. The rest of the paper is organized as follows: section 2 describes the data, method, and numerical model that we used. Section 3 presents the characteristics of observed and model simulated MZCs along 5°N and their causes. Section 4 presents a discussion on the contributions of middepth RWs at annual and semiannual time scales along 5°N and examines the symmetrical/asymmetrical features of MZCs by comparing them along 5°N and in the southern tropical IO. Section 5 provides a summary of major results.

2. Data, model, and method

a. Observations and reanalysis data

Four moorings (named Q2, Q3, Q4, and Q5), each containing upward-looking and/or downward-looking 75-kHz ADCP(s), were deployed by the South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences, to observe the equatorial and off-equatorial MZCs in the EIO (Fig. 1a) (Huang et al. 2018c). Mooring Q3, observing middepth zonal currents at 5°N, was deployed at 5°N, 90.5°E in April 2014. Moorings Q2 (0°, 93°E), Q4 (0°, 85°E), and Q5 (0°, 80°E) located at the equator are used to validate the simulated and reanalysis results. The ADCPs recorded the velocity profiles over a depth range of 50–1200 m with a vertical bin size of 8 m. The velocity data were interpolated vertically to a standard 10-m depth interval and then averaged to derive the daily mean. To remove the tidal effect, a 3-day running mean was applied to the daily data. All data were averaged to obtain monthly zonal (u) and meridional (v) currents. The time ranges and the maximum observed depth spanned by these moored datasets are presented in Fig. 1b.

The Ocean Reanalysis System 4 (ORAS4; Mogensen et al. 2012; Balmaseda et al. 2013) dataset from 1993 to 2017 is analyzed to reveal the spatial and temporal variabilities of the middepth current system in the EIO. The ORAS4 product is generated by assimilating different observations into version 3.0 of the Nucleus for European Modeling of the Ocean (NEMO) oceanic model (Madec 2008), which includes temperature and
salinity profiles obtained from XBT, conductivity–temperature–depth sensors, mooring buoys, and autonomous pinniped bathythermograph and satellite altimetry data. The ORAS4 has a horizontal resolution of $1^\circ \times 1^\circ$ and a vertical resolution of 42 levels with 24 levels below 200 m. The timeline of ORAS4 forcing and assimilation datasets has been summarized in Nyadjro and McPhaden (2014) and at https://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis. The cross-calibrated multiplatform (CCMP; Atlas et al. 2011) wind stress data from 1988 to 2011 are used to diagnose the characteristics of off-equatorial wind-forced waves.

b. Linear ocean model and experiments

A continuously stratified linear ocean model (LOM) was used to analyze the causes for the seasonal variations of off-equatorial MZCs in the EIO. This model has been applied to explain the dynamics of the East Indian Coastal Current, the Equatorial Undercurrent, and western boundary reflection (McCreary et al. 1996; Shankar et al. 1996; Yuan and Han 2006). Details of model are described in appendix A. The LOM covering a realistic IO basin (Fig. 1a) was first spun up for 20 years, forced by climatological CCMP winds averaged over 1988–2011. Restarting from the spinup run, the LOM was integrated forward in time using monthly CCMP winds from 1988 to 2011. This solution is referred to as the LOM main run (LOM-MR) and the total solution of LOM-MR is the sum of the first 25 baroclinic modes. A second run was performed with a damper in the eastern basin to isolate the effects of eastern boundary-reflected waves. This damper was nonzero only in the eastern ocean [damping term with coefficient $\delta$ in Eq. (A2)] which efficiently absorbed the energy of incoming boundary waves. We refer to this run as LOM-DAMP. The difference between these two experiments (LOM-MR minus LOM-DAMP, defined as LOM-REFLECT) isolated the boundary-reflected RW effects.

3. Results

a. Characteristics of MZCs along $5^\circ$N

1) Seasonal variations of the MZCs

The seasonal and interannual evolutions of zonal currents along $5^\circ$N from mooring observations and ORAS4 reanalysis are shown in Fig. 2. The ORAS4 and mooring observations show similar features (Figs. 2a,d), with evident annual variations within the upper 150 m (Figs. 2c,f). Another outstanding feature in the zonal current profiles is the strong semiannual variability, which dominates the total current in the middepth range of 200–1200 m with direction switching four times a year (Figs. 2b,e). The power spectra (indirect estimation; appendix B) of both mooring and ORAS4 data support the dominance of the semiannual cycle in the middepth (Figs. 2c,f), even though the power density of mooring observed zonal flow not statistically significant below 700 m because of the sparse observations. As seen from the moored and reanalysis data, the maximum intensity of zonal currents is located at the near-surface layer, weakening with the increase of depth. Vertical phase propagations can be visually identified from both mooring observation and ORAS4 reanalysis. In addition, the magnitudes of zonal currents are overall weaker in ORAS4 compared to the moored data.
The reasons for this underestimation in ORAS4 are unclear. Possible explanations include the sensitivity of currents to the parameterization of vertical mixing in the ORAS4 model, the coarser $1^\circ \times 1^\circ$ resolution and discrepancies in the wind forcing (e.g., Nagura and McPhaden 2016).

Figure 3 shows the time series of zonal current at $5^\circ$N, $90.5^\circ$E averaged for different depth ranges from 1993 and 2017. Again, the mooring/ORAS4 data generally show good agreements, with semiannual cycle dominating zonal currents throughout the middepth of 200–1200 m (Figs. 3b,d,f,h), even though ORAS4 data underestimate the current magnitudes (Figs. 3a,c,e,g). The mooring/ORAS4 correlation coefficients are 0.76 and 0.65 at 200–400 and 400–600 m, respectively, exceeding 99% confidence level. Note that the moored data are only available for 1 year (2014–15) below 800 m and thereby ORAS4 is analyzed to put the moored data into longer contact (1993–2017), both of their results indicated that the semiannual cycle is the dominant signal below 800 m. Additionally, the LOM-MR outputs at the same location agree well with the ORAS4 reanalysis, with correlation coefficients exceeding 0.75 (at the 99% significant level) and standard deviation ratios being 1.23, 1.59, 1.62, 1.94, and 1.88 at 200–400, 400–600, 600–800, 800–1000, and 1000–1200 m, respectively. This linear model can reproduce the strong semiannual variability of zonal currents within the middepth range of 200–1200 m, demonstrating the skill of the LOM in simulating the key dynamics of the off-equatorial middepth zonal flows.

2) SPATIAL STRUCTURE OF THE MZCS

Similar to the spatial features found on the equator, the MZCs along $5^\circ$N show some coherent structure with clearly phase propagation (Fig. 4) but of fairly spatial discrepancies to those on the equator. For horizontal variations, the first peak of the semiannual cycle of eastward current is located in the interior between $80^\circ$ and $85^\circ$E in ORAS4 ($85^\circ$–$90^\circ$E in LOM-MR) with an amplitude of $\sim$3 cm$^{-1}$, and the second peak is weaker, with maximum located between $85^\circ$ and $90^\circ$E (Figs. 4a,b). However, these middepth semiannual signals along $5^\circ$N are primarily confined to the eastern basin east of Sri Lanka. West of Sri Lanka (east of the Maldives, $75^\circ$–$80^\circ$E), the MZCs possess an annual cycle with one maximum and one minimum per year (Figs. 4e,f). The reasons for this discrepancy have been further discussed in section 4a. Despite the strong semiannual variations with clear upward phase propagation below 200 m along $5^\circ$N, the annual cycle is comparable to (larger than) semiannual cycle in ORAS4 (LOM-MR) from $\sim$50 to 200 m, and dominating the zonal currents near the surface (Figs. 4c,d). These results demonstrate the
robustness and uniqueness of the detected patterns at semiannual and annual periods associated with the westward and upward phase propagation. Given the success of LOM-MR simulations, results of LOM experiments can be analyzed to understand the underlying dynamics associated with the propagating RWs that govern these MZCs.

b. Dynamics: Forcing by remote equatorial winds

The distinctive processes that controlling the MZCs’ variability at 5°N include the radiations of RWs that forced by local wind stress curl and reflected from the eastern boundary after the eastward propagating equatorial Kelvin waves impinge on the coast. The sensitivity experiment (LOM-REFLECT) efficiently isolates the boundary-reflected RWs and represents the signatures of equatorial remote forced Kelvin waves. Clearly, it indicates that the boundary-reflected RWs interfere constructively with the local-forced RWs’ response in the depth range of 200–1200 m from January to October (Figs. 5b,d), producing an intensified semiannual response for the spatial variations of MZCs (Figs. 5f,h). By contrast, the LOM-DAMP only includes the locally wind-forced RWs at 5°N, and wind-forced Kelvin and
Rossby waves on the equator. The results show that the local wind forcing mainly induces a strong annual response of MZCs along 5°N (Figs. 5e,g). These results confirm that the boundary-reflected RWs are the primary cause for the strong semiannual variability of the MZCs at 5°N. To further support this argument, we analyzed the time series averaged between 80° and 95°E and 200–1200 m from LOM-MR, LOM-DAMP, and LOM-REFLECT (Fig. 5i). Again, boundary-reflected RWs (blue curve) and directly wind-forced RWs (black curve) are in phase from January to October, producing intensified total MZCs (red curve). Boundary-reflected RWs, however, have apparently larger magnitudes than directly forced response. The STD of the zonal velocity of the MZCs is 1.11 cm s⁻¹ for LOM-MR, 0.37 cm s⁻¹ for LOM-DAMP, and 0.94 cm s⁻¹ for LOM-REFLECT, indicating a large percentage of LOM-REFLECT going to LOM-MR.

To further quantify the linkage of 5°N variability to the equator, we investigated the basinwide adjustment of the middepth velocity to the dynamic pressure in the EIO (Fig. 6). The results of moorings, ORAS4 and LOM-MR show that the structures of middepth dynamic pressure and zonal currents agree well with the symmetric equatorial RWs at semiannual time scale, even though there are asymmetric components in magnitudes. Reflected from the eastern boundary, two dynamic pressure lows/highs occur on both sides of equator through the year. Associated with the off-equatorial maximum dynamic pressure patterns, eastward (westward) flowing equatorial zonal currents accompany opposite direction zonal flows on both sides of the equator in the eastern basin (e.g., March and June panels of Fig. 6). The meridionally symmetric structures of dynamical pressure and currents demonstrate the importance of equatorially symmetric RWs. The coherent structures of middepth dynamic pressure and zonal velocity across the equator are summarized by Hilbert transform complex empirical orthogonal function (C-EOF) analysis (Fig. 7). For the semiannual cycle, the MZCs obtain the maximum amplitude in the central basin both in LOM-MR and ORAS4 (Figs. 7b,c), whereas the dynamic pressure structure is more complex, with relative maximum amplitude occurring north and south of the equator in the central and eastern basin and relative minima occurring near the equator where u is strong (Fig. 7a). The equatorial currents and dynamic pressure structure are approximately linked by $u = -(1/\beta) p_{yy}$, where $\beta = f_x$ and $p$ is the dynamic pressure, the equatorial expression of the geostrophic relation.
The dominant C-EOF structures clearly identify the equatorial RWs at semiannual time scale. Furthermore, the slanted eastern boundary in the EIO causes asymmetries of dynamic pressure about the equator near the eastern boundary, with relative strong magnitude over the north side of the equator. The results for this structure may be the summed contributions from both the equatorial symmetric and antisymmetric components (e.g., Han et al. 2011; Chen et al. 2017).

To better describe the meridional structures of the equatorial waves in the middepth, we extracted the empirical orthogonal functions (EOFs) of middepth dynamic pressure and zonal velocity for each longitude, separately (80°, 85°, 90°, and 93°E) (Fig. 8). Along each of the four longitudes, the southern maximum of the dominant EOF of dynamic pressure is centered at about 3°S, and the northern maximum is somewhat less localized than the southern maximum. The precise locations of the northern maxima lie between 3° and 5°N at 80°, 85°, and 90°E, but not at 93°E (Figs. 8a,d,g,j). Another notable feature is that a local minimum is centered on the equator at all of the longitudes. At all but the easternmost longitude of 93°E, the amplitude of the secondary maximum south of the equator is about half that of the northern maximum. For latitudinal structure of zonal velocity, the maxima of the EOFs at 80°, 85°, and 90°E are located at the range of 1°S–1°N. The broad central maxima are flanked by
secondary maximum values of opposite signs centered near 5°S and 4°–6°N (Figs. 8b,e,h,k). For comparison with the theoretical eigenfunctions determined locally along each of these four longitudes, the EOFs of zonal velocity are roughly similar to the symmetric structure of zonal flow of the first-meridional-mode equatorial Rossby wave of the classical theory, especially at 80°E. The latitudinal asymmetries near eastern boundary, as in Chelton et al. (2003) and Chen et al. (2017), cannot be reconciled with any of the individual meridional modes of the classical theory but with a superposition of several low-order meridional modes. The amplitude time series of the EOFs along each of the four longitudes (right panels of Fig. 8) are dominated by semiannual variability with a phase that increases westward except 93°E where there is most susceptible to potential edge effects in the eastern boundary (as in Han et al. 2011).

4. Discussion

a. The contributions of RWs at annual and semiannual time scales along 5°N

The directly wind-forced RWs propagating energy downward below the pycnocline at 5°N is a significant and robust phenomenon that associated with the local strong wind stress curl at annual time scale (e.g., Nagura 2018). However, our results also indicated that the strong boundary-reflected RWs are found to form a semiannual cycle of middepth zonal current over the moored area. Of particular interest is to understand the roles of directly wind-forced annual RWs and boundary-reflected...
Consistent with early studies in tropical IO (Han 2005; Huang et al. 2018b; Nagura 2018), the results of harmonics analysis illustrate that most energy in relation to the long RWs is trapped in the near-surface layer, but some energy is transmitted through the thermocline into the middepth. The Wentzel–Kramers–Brillouin (WKB) ray paths (Moore 1968; McCreary 1984) are traced to interpret waves’ energy penetration derived from the harmonic analysis. Theoretically, energy associated with the long low-frequency RWs penetrates downward and westward into the middepth ocean at an angle $\theta$ with the surface, where $\tan \theta = \omega$ (Kessler and McCreary 1993; Huang et al. 2018b; Nagura 2018); $\omega$ is the frequency of the RWs. This solution confirms that the angle $\theta$ with the choice of $T = 180$ days ($\omega = 2\pi/T$, semiannual period) would be larger than that with the choice of $T = 365$ days (annual period). Consequently, for the semiannual period, the ray paths display steep slopes down to the middepth interior and maximum amplitude is also found near the theoretical WKB trajectory. For the annual period, by contrast, the slopes of the ray paths are shallower because of the lower frequency. When theoretical ray paths originate at the eastern coast propagating westward, these annual RWs rarely penetrate deep enough to the middepth interior in the EIO. These results indicate that the strong semiannual (weak annual) variability of the MZCs along 5°N in the EIO are largely manifestations of the steep (shallow) angles of vertical propagating energy of the long RWs at semiannual (annual) time scale.

b. Comparison of MZCs along 5°N and in the southern tropical IO

Besides the strong MZCs along 5°N, similar seasonal signals also situate south of the equator, which to a large degree mirror those north of the equator and propagate westward (Figs. 6, 7, and 8). Note that the local wind forcing along 5°S also illustrates a strong annual cycle but the Ekman pumping is out of phase with that along 5°N (negative Coriolis parameter in the Southern Hemisphere; Fig. 9). Accordingly, the results of reanalysis and linear model illustrate that the wind-forced response of MZCs along 5°S shows a strong annual cycle with westward and upward phase propagation (Figs. 10a,c,e,g). However, this annual cycle tends to be out of phase with that at 5°N because of the opposite effects of local...
forcing between $5^\circ$S and $5^\circ$N (Figs. 5i and 10i). On the other hand, the eastern boundary effects can also be seen near $5^\circ$S, inducing strong boundary-reflected RWs at semiannual time scale with westward and upward phase propagation (Figs. 10b,d,f,h). These semiannual signals interfere constructively with the local wind-forced RWs’ response at the 200–1200-m depth from July to December (Fig. 10i), producing an intensified semiannual response of MZCs during the second half of the year. The eastern boundary-reflected semiannual signals are in phase with those at $5^\circ$N, suggesting the signals propagate away from the same equatorial origin. The baroclinic structure of the MZCs along $5^\circ$N/S both display a strong energy for the second-baroclinic-mode RWs (as on the equator; Huang et al. 2018a), but this is not “resonance.”

The inclined eastern boundary indeed plays important role in modulating the spatial structures of middepth annual and semiannual signals along $5^\circ$N/S. The features of semiannual and annual harmonics obtained from the $5^\circ$S section (not shown) are very similar to the results from the $5^\circ$N, with the theoretical WKB trajectories also matching well with the harmonic patterns. However, the significant propagating semiannual and annual signals along $5^\circ$S occur more east than that along $5^\circ$N, primarily due to the inclined coastline of the eastern boundary (e.g., Chen et al. 2017).

Unlike at $5^\circ$S, near $10^\circ$S the eastern boundary reflection effects can rarely been seen. Accordingly, the observed strong annual cycle along $10^\circ$S primarily results from long nondispersive forced RWs in response to the local wind forcing at annual time scale (Woodberry et al. 1989; Masumoto and Meyers 1998; Wang et al. 2001; Johnson 2011; Nagura 2018). Although most energy was surface trapped, there was a significant amount of energy that propagated along the WKB trajectories through the thermocline into the deep ocean (not shown). Such baroclinic structures of MZCs along $10^\circ$S are consistent with the mechanism that the longer wavelength of low-order-baroclinic-mode RWs can couple more efficiently.
to the large-scale wind forcing than the intermediate- and high-order modes (as in Shankar et al. 1996).

5. Summary

Characteristics of the MZCs along 5°N in the EIO were investigated using the ADCP moorings, ORAS4 reanalysis and a continuously stratified LOM. Although the off-equatorial middepth currents were only observed at a single point of 5°N, 90.5°E by mooring, it revealed the rich features of the off-equatorial middepth variability from the seasonal variability to the phase propagation.

The observed MZCs reveal a robust semiannual variability with upward phase propagation. The ORAS4 and LOM is capable of realistically simulating the main features of these off-equatorial variability in the EIO. An issue was then raised of the relative contributions of local forcing near 5°N and remote forcing from the equator in causing the middepth zonal flows’ variability on semiannual to annual periods along 5°N, since the local wind forcing displays a dominant annual cycle but very weak semiannual variability.

The results of a suite of LOM experiments show that the RWs reflected from the eastern boundary, rather than the local wind forcing, result in such strong semiannual variability of the MZCs along 5°N in the EIO. The strong semiannual variations of off-equatorial MZCs, essentially, are a portion of symmetric equatorial RWs. Overall, the combination of local and remote forcing gives rise to different MZCs responses on the two sides of the equator (particularly along 5°N/S). The remote forcing from the equator at the semiannual time scale generates equatorial Kelvin/Rossby waves; after the equatorial Kelvin waves impinge onto the eastern boundary, part of their energy propagates poleward and most of the energy is reflected back into the oceanic interior as RWs. The energy of the semiannual reflected RWs propagates westward and downward, intensifying the semiannual component of directly forced RWs and causing strong semiannual variability of MZCs along 5°N/S in the EIO. The results of WKB approximation ray trajectory suggested that the strong semiannual (weak annual) variability of the MZCs along 5°N in the EIO are largely manifestations of the steep (shallow) angles of vertical propagating energy of the long RWs at semiannual (annual) time scale.
The present study has provided further evidence that the energetic propagation of boundary-reflected RWs at semiannual period is the dominant forcing mechanism for the seasonal variability of zonal flows in the off-equatorial regions for the EIO. Earlier studies suggested that the second- and third-meridional-mode RWs, combining with the first meridional mode, contributed greatly to the asymmetric component about the equator in the eastern boundary (e.g., Kessler and McCreary 1993; Chen et al. 2017). Our simulated results suggest that the discrepancies between 5°N and 5°S are related to the equatorial symmetric/antisymmetric waves. Further observations and numerical simulations are necessary to quantify the roles of other-meridional-mode RWs in forming the structure characteristics of MZCs in the EIO.

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APPENDIX A

Continuously Stratified Linear Ocean Model

In the continuously stratified LOM, the equations of motion are linearized about a background state of rest with a realistic stratification represented by a spatially averaged Brünt–Väisälä frequency profile to produce the vertical modes \( n \) of the system, and the ocean bottom is assumed to be flat at 4000 m. The solutions \( X \) can be represented as expansions in the vertical normal modes of the system with eigenfunctions \( \psi_n(z) \):

\[
X(x, y, z, t) = \sum_{n=0}^{N} X_n(x, y, t) \psi_n(z), \tag{A1}
\]

where \( X \) represents the zonal velocity \( u \), meridional velocity \( v \), or pressure \( p \) and the expansion coefficients \( u_n, v_n, \) and \( p_n \) are functions of \( x, y, \) and \( t \) only. In strict terms, the total mode number should extend to infinity, but the solutions converge rapidly enough with \( n \) (McCreary et al. 1996; Shankar et al. 1996). Here, \( n = 25 \) was selected to represent the total baroclinic mode number [as in Han et al. (2011)]. The terms \( u_n, v_n, \) and \( p_n \) are governed by the following equations:

\[
\left( \frac{\partial}{\partial t} + \frac{A}{c_n^2} \right) u_n - f v_n + \frac{1}{\rho} p_{nx} = F_n + v_h \nabla^2 u_n - \delta u_n, \tag{A2}
\]

\[
\left( \frac{\partial}{\partial t} + \frac{A}{c_n^2} \right) v_n + f u_n + \frac{1}{\rho} p_{ny} = G_n + v_h \nabla^2 v_n, \quad \text{and} \tag{A3}
\]

\[
\left( \frac{\partial}{\partial t} + \frac{A}{c_n^2} \right) p_n + u_{nx} + v_{ny} = 0, \tag{A4}
\]

where \( F_n = \tau' \nabla^2 (\bar{\rho} H_n) \) and \( G_n = \tau' \nabla^2 (\bar{\rho} H_n) \), \( c_n \) is the characteristic speed for each mode number \( n \). The value of \( n = 0 \) is the barotropic mode of the system. Following earlier works (e.g., Shankar et al. 1996), although the barotropic contributions are included in the solutions, they can be neglected due to their weak coupling to the wind. The \( c_n \) values for the first 10 baroclinic modes are 264.2, 166.9, 104.5, 74.7, 59.7, 49.3, 41.5, 36.8, 32.8, and 29.7 cm s\(^{-1}\). The Coriolis parameter is \( f = \beta y \) under \( \beta \)-plane approximation, and \( v_h \) is the coefficient of the horizontal eddy viscosity. The coupling intensity of each mode to the wind field is determined by \( Z_n = \int_0^h D(z) \psi_n \, dz \) and \( H_n = \int_0^h \psi_n^2 \, dz \), and \( Z(z) \) is the vertical profile of wind that is introduced as a body force, where \( Z(z) \) is constant in the upper 50 m and linearly decreases to 0 from 50- to 100-m depth. The terms associated with \( A/c_n^2 \) represent vertical friction, with \( A = 0.00013 \, \text{cm}^2 \, \text{s}^{-3} \), and they provide damping for the extratropical RWs. The features of various baroclinic modes in the LOM experiments can be categorized into three groups: the low-order modes (1 \( \leq n \leq 2 \)), the intermediate-order modes (3 \( \leq n \leq 8 \)), and the high-order modes (9 \( \leq n \leq 25 \)) (Han 2005).

APPENDIX B

Indirect Method of Power Spectrum Estimation

Power spectrum estimation is a frequency-domain calculation method of periodic signal. In this study, an indirect method is used (Vaseghi 2000). We first get the autocorrelation function estimation of sample data, and then perform Fourier transform to obtain the power spectrum. From the spectral estimation effect, the resolution of the indirect method is significantly better than the direct method, since for the indirect method presences advantages that the spectral curves undulation is stable and the spectral resolution is high (e.g., Chao 2014).

REFERENCES


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