Semiannual variation of zonal current along the equatorial Indian Ocean

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Abstract. Semiannual current variation in the equatorial Indian Ocean is examined using currents velocity records from Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) Program. Spectral analysis shows that semiannual variation is the strongest variation in equatorial Indian Ocean. Further analysis exhibits that this variation is associated with Wyrtki Jet phenomenon and forced by wind along the equator. Upward phase propagation (downward energy propagation) is clearly shown as indication of the propagation of equatorial Kelvin wave. Cross correlation of two mooring data captures westward propagation of reflected Rossby wave that interferes the propagation of Kelvin wave. During IOD positive event, stronger reflected Rossby wave occurs and causes weakening of upward phase propagation. This result reveals that interferences of equatorial wave have important role on forming vertical structure of currents along equatorial Indian Ocean.

1. Introduction
Semiannual current variation of tropical Indian Ocean was discovered early by an observation of the equatorial Wyrtki Jet in 1973 [1]. The jet is observed during the monsoonal transition, particularly in March-May and September-November [1, 8]. It is forced by westerly wind burst occurred due to the weakening of monsoon wind in the western Indian Ocean [1]. This jet is a narrow westward strong current in equator Indian Ocean which has an average velocity of 64 cm/s. The velocity decreased exponentially until ± 100 m in depth [1, 2].

The equatorial Wyrtki Jet is associated with the eastward propagation of the equatorial Kelvin wave [3]. Upon reaching the west coast of Sumatra, the Kelvin wave propagates to south and north of equator as coastal Kelvin wave [4]. Some of the Kelvin wave energy is reflected as the westward reflected Rossby wave [3, 4]. The westward propagation of reflected Rossby wave interferes the eastward propagation of forced Kelvin wave, causing a phase difference between wind and forced currents in the equator Indian Ocean [3, 4, 7].

On interannual scale, the Indian Ocean Dipole (IOD) along with the El Nino and Southern Oscillation (ENSO) play role in the dynamics of the equatorial Indian Ocean currents. IOD and ENSO led to the weakening of Wyrtki Jet in 1994, 1999, 2000 and 2006-2011 as well as the counter flow of Wyrtki Jet in 2008 [5]. The IOD and ENSO more affected the fall Wyrtki Jet than the spring Wyrtki Jet [6].

Vertical structure of the Indian Ocean water column is affected by the dynamics of downwelling Kelvin wave as a part of Wyrtki jet [1]. The propagation of downwelling Kelvin wave affects the
shallowing of the thermocline in the west region of equator Indian Ocean, while in the east region, the thermocline is deeper [1]. On an intraseasonal scale, the Kelvin wave affects the vertical structure of equatorial zonal currents. The upward phase propagation of the vertical structure of the currents is an indication of Kelvin wave propagation’s effect [4].

The aim of the study is to evaluate the variation of semiannual zonal currents in the equator Indian Ocean. In this paper we present the variation of currents using moorings observation data. The outline of the paper is present as follow: Section 2 describes data and method used in this study, Section 3 presents the variation of currents and the forcing dynamics and the summary is presented in last section.

2. Methodology

2.1. Data

The main data in this study are ocean currents velocity obtained from Acoustic Doppler Current Profiler (ADCP) moorings as a part of Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) program. The ADCP moorings are deployed in the equator at 80.5°E and 90°E (Figure 1). Ocean currents data at 80.5°E have a 5 m-interval vertical resolution with daily resolution from the near surface down to 175 m depth. ADCP moorings at 90°E provide ocean currents data velocity, which have a 10 m-interval vertical resolution with daily resolution from the near surface down to 400m depth. In order to get comparable result, only ocean currents data between 20 and 175 meters depth from both moorings, which were taken from November 2004 to September 2008 were used.

Daily surface wind data were used to evaluate dynamics and forcing of ocean currents. The surface wind data were derived from Quick Scatterometer (QSCAT), which has 0.25° x 0.25° in spatial resolution. Wind surface data along the equator between 50°E and 95°E from November 2004 to September 2008 (Figure 1) were used in this study.

![Figure 1. Locations of ADCP moorings used in this study are marked by number 1 (80.5°E) and 2 (90°E). The location of wind surface data are marked by the line.](image)

2.2. Methods

In this study, various spectral analysis and statistical analysis were used. Fourier Transform analysis [10] was applied to evaluate the dominant frequency in both currents time series data and to describe the fluctuation of the data. Simple statistical analysis such as mean and standard deviation were applied to describe the data variation. We also applied bandpass filter using window from periods 150–200 days to separate semiannual variation from the raw data. To evaluate the dynamics of currents, cross correlation between currents data in 80.5°E and 90°E were calculated. To explore the forcing mechanism, calculation of cross correlation between currents data and wind were carried out.
3. Result and discussion

The depth-time diagrams of the observed currents (Figure 2) show that semiannual variations are clearly observed at 80.5°E and 90°E. Semiannual variations associated with the spring and fall equatorial jets. The equatorial jet occurred during strong westerly wind along the equator at monsoon transition [1]. Spectral peak in semiannual period is clearly shown in both spectral diagrams (Figure 3a, b). The spectral energy of semiannual period at 80.5°E is higher compared to that at 90°E. Beside the semiannual period, intraseasonal period also has significant energy although it is not as high as semiannual period.

The change of standard deviation along the depth (Figure 3c) suggests currents variation along the depth. The variation of the equator zonal current before bandpass filtered at 80.5°E in the near surface is the highest, measured up to 0.5 m/s and decreases gradually to 0.3 m/s at 100 m depth. From 100-120 m depth, the variation is constant at 3 m/s and gradually declines after 120 m depth. At 90°E, the variation of zonal current measured at 40–120 m depth is 0.3 m/s. The gradual decreasing of standard deviation occurred beyond 120 m depth suggests that the variation of the currents is getting smaller by the depth.

After the bandpass filter applied on the currents data, the standard deviation along the depth is then changed (Figure 3d). The semiannual zonal currents at 80.5°E have high variation on near surface and weaken gradually until 100 m depth. The variation increases after 100 depth and has its peak at 120 m depth and subsequently decreases from then. Semiannual zonal currents at 90°E, on the other hands, slightly increase from near surface to at about 80 m depth. The increasing turns sharper up to 120 m depth and decreases gradually after 120 m depth.
Figure 3. (a) Spectrum of zonal velocity averaged over 40-100 m depth in 0°S 80.5°E and (b) 0°S 90°E. Standard deviation of (c) the zonal currents in 0°S 80.5E and 0S 90°E and (d) semiannual zonal currents in 0S 80.5°E and 0S 90°E

Depth-time diagram of semiannual zonal currents velocity at 80.5°E and 90°E are presented in Figure 4. At both moorings, the eastward currents occur on the transition monsoon, which associated with the equatorial Wyrtki Jet. Depth-time diagrams show an upward phase propagation, where a gradual phase shift in depth with the deeper level leads the near surface level. Those upward phase propagations indicate the propagation of the equatorial Kelvin wave. At 80.5°E, near surface level has strongest current amplitude, while at 90°E, the strongest amplitude variability measured at 120 m depth. In relation with Indian Ocean Dipole (IOD), in normal IOD event November 2004–May 2006, semiannual zonal currents at 80.5°E had strong amplitudes at near surface. During the same interval, semiannual zonal currents at 90°E have maximum amplitude at 120 m depth. During IOD positive phase, in July 2006–February 2007, strong currents at 80.5°E were weakening and near surface currents at 90°E were strengthening.

To explain the dynamical process of the evidence, we calculated the cross correlation between semiannual currents in 80.5°E and 90°E (Figure 5). At the upper level (40-80 m depth), the signal of semiannual zonal currents in 90°E leads the 80.5°E signal. This result reveals the westward propagation of the signal and presumably indicates the propagation of reflected Rossby wave. In the deeper layer, the eastward propagation of the signal is clearly captured and it reveals the propagation of forced Kelvin wave. It can be explained that when the Kelvin Wave reaches the west coast of Sumatra, it propagates poleward both north and south of the equator and some energy is reflected and propagate as the reflected
Rossby wave. The reflected Rossby Wave then interferes the propagation of Kelvin wave [3]. This result shows that interferences of the reflected Rossby Waves on the propagation of forced Kelvin wave occurred in the near surface level. Interferences of the waves affect the vertical profile of semiannual currents. During the IOD positive events (2006-2011), as the westerly wind weakened and the forced Kelvin wave also became weaker, the strong currents at 80.5°E did not appear. On the contrary, during the same IOD positive event, the interference of reflected Rossby waves appeared clearer and the strong currents in the upper layer at 90°E was observed.

![Figure 4](image)

**Figure 4.** Time-depth diagrams of semiannual zonal currents at 0°S, 80.5°E (a) and at 0°S, 90°E (b). Positive (negative) value is eastward (westward). Black contour is mark of zero value. (c) Dipole Mode Index

In order to understand the forcing of the semiannual zonal currents, the relationship between semiannual zonal currents and wind in both data were examined. Correlation between semiannual zonal currents averaged 40–100 m depth and the semiannual wind along the equator in both data (Figure 6) indicate the forcing of currents. Currents at 80.5°E have significant correlation with wind at 70°E and have 0 days lag. This result indicates that semiannual currents at 80.5°E are forced directly by wind at 70°E. Currents at 90°E also have significant correlation with winds in 70°E but have 10 days lags, in which the wind led to the currents. This result illustrates that the semiannual currents are forced in the western Indian Ocean and propagated to the east.
Figure 5. Correlation coefficient for semiannual currents between 80.5°E and 90°E.

Figure 6. Correlation coefficients between wind along the equator and semiannual current (a) at 80.5°E, (b) at 90°E. Correlation above 95% confidence limit are shaded

4. Summary
Semiannual variation is the strongest variation in the equatorial zonal currents. The semiannual currents variability associated with the equatorial Wyrtki Jet and the propagation of Kelvin wave. The vertical structure of semiannual zonal currents is affected by the interferences of forced Kelvin wave and reflected Rossby wave. In addition, our preliminary result presents that during the IOD positive event, stronger reflected Rossby wave occurs and causes weakening of upward phase propagation. This study confirms that interferences of equatorial wave play important role on forming vertical structure of zonal currents along equatorial Indian Ocean.

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