Strong Intraseasonal Variability of Meridional Currents near 5°N in the Eastern Indian Ocean: Characteristics and Causes

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(Manuscript received 9 November 2016, in final form 27 February 2017)

ABSTRACT

This paper reports on strong, intraseasonal, upper-ocean meridional currents observed in the Indian Ocean between the Bay of Bengal (BOB) and the equator and elucidates the underlying physical processes responsible for them. In situ measurements from a subsurface mooring at 5°N, 90.5°E reveal strong intraseasonal variability of the meridional current with an amplitude of ~0.4 m s⁻¹ and a typical period of 30–50 days in the upper 150 m, which by far exceeds the magnitudes of the mean flow and seasonal cycle. Such prominent intraseasonal variability is, however, not seen in zonal current at the same location. Further analysis suggests that the observed intraseasonal flows are closely associated with westward-propagating eddylike sea surface height anomalies (SSHAs) along 5°N. The eddylike SSHAs are largely manifestations of symmetric Rossby waves, which result primarily from intraseasonal wind stress forcing in the equatorial waveguide and reflection of the equatorial Kelvin waves at the eastern boundary. Since the wave signals are generally symmetric about the equator, similar variability is also seen at 5°S but with weaker intensity because of the inclined coastline at the eastern boundary. The Rossby waves propagate westward, causing pronounced intraseasonal SSHA and meridional current in the upper ocean across the entire southern BOB between 84° and 94°E. They greatly weaken in the western Indian Basin, but zonal currents near the equator remain relatively strong.

1. Introduction

Sea surface winds over the tropical Indian Ocean exhibit strong intraseasonal variability (ISV), which is associated with atmospheric intraseasonal oscillations (ISOs), with the Madden–Julian oscillation (MJO) as the dominated mode (e.g., Madden and Julian 1971; Hendon and Glick 1997; Webster et al. 2002; Shinoda et al. 2013). In response to the surface wind forcing, the upper-ocean circulation of the tropical Indian Ocean shows strong intraseasonal variations (e.g., Masumoto et al. 2005). Based on in situ observations and numerical models, several studies have reported prominent ISV of the meridional currents in the equatorial Indian Ocean (McPhaden 1982; Reppin et al. 1999; Sengupta et al. 2001; Masumoto et al. 2005; Ogata et al. 2008; Iskandar...
and McPhaden 2011), which contributes to seasonal-to-interannual cross-equatorial heat and salt transports (e.g., Halkides et al. 2007). Farther north, there are two large marginal seas in the north Indian Ocean, namely, the Arabian Sea and Bay of Bengal (BOB), with distinct water mass properties (e.g., Mamayev 1975; You and Tomczak 1993; Vinayachandran and Kurian 2007; Vinayachandran et al. 2013). The meridional ocean currents between the equatorial Indian Ocean and the two marginal seas are essential for heat, freshwater, and nutrient distributions over the tropical Indian Ocean and thereby affect the large-scale air–sea interaction (e.g., Izumo et al. 2010). However, because of the shortage of direct observations, our knowledge of the meridional ocean current variability in this region is quite limited, especially at the intraseasonal time scale.

A subsurface mooring system was deployed at 5°N, 90.5°E by the South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences, to monitor the upper-ocean water exchanges between the BOB and the equatorial Indian Ocean (red star in Fig. 1). During the observation period of April 2013–April 2014, a striking phenomenon is captured by the current measurements of the mooring. Strong intraseasonal variability of meridional current is detected in the acoustic Doppler current profiler (ADCP) records (Fig. 2b), which is, however, not evident in the zonal current (Fig. 2a). The meridional current anomalies have a typical amplitude of \( \sim 0.4 \text{ m s}^{-1} \), by far exceeding the mean flow and is comparable to the major western boundary
currents of the tropical Indian Ocean (e.g., Lutjeharms et al. 1981; Schott and Quadfasel 1982; Shetye et al. 1993).

The ISV of the equatorial winds over the Indian Ocean has been shown to significantly affect the adjacent areas. Intrasessional equatorial Kelvin waves driven by winds associated with the MJO can propagate to the eastern Indian Ocean (EIO) boundary and the Indonesian Seas, affecting the ISV of sea level along the coasts of Sumatra and Java (Iskandar et al. 2005) and the Indonesian Throughflow (Qiu et al. 1999; Schiller et al. 2010; Pujiana et al. 2013). Consequently, the observed ISV by the mooring at 5°N, 90°E may be affected by equatorial winds through symmetric/asymmetric Rossby waves. Careful and comprehensive analysis is required to achieve an in-depth understanding of the observed variability.

The goal of this research is to characterize and explain the observed strong ISV of meridional current near 5°N. Satellite and in situ observations are analyzed to document the characteristics of intrasessional currents, and ocean general circulation model (OGCM) experiments are performed to provide insight into the underlying mechanisms. The rest of the paper is organized as follows: Section 2 describes observational data utilized in this study and OGCM experiments performed for our analysis. Section 3 presents the results of our analysis, with section 3a describing the observed characteristics of intrasessional meridional currents, section 3b exploring local and remote forcing effects of ISO winds, and section 3c discussing essence and components of the observed current anomalies. Section 4 provides a summary and discussion for this research.

2. Data and methods

a. Data

The mooring was deployed in the southern BOB at approximately 5°N, 90.5°E (star in Fig. 1) from April 2013 to April 2014, equipped with an upward-looking 75-kHz and a downward-looking 150-kHz Workhorse ADCP in the main float. Vertical resolution of the ADCP measurements is 8 m. The sampling time frequency of the ADCP is 1 h. The effective measurement range covers 20–145 and 180–570 m. In this study, the ADCP current velocities are linearly interpolated onto uniform 5-m intervals, and hourly measurements are averaged into daily data.

The Ocean Surface Current Analysis–Real Time (OSCAR) product is available beginning December 1992 with a horizontal resolution of $\frac{1}{3}^\circ \times \frac{1}{3}^\circ$ and 5-day intervals (Bonjean and Lagerloef 2002; Johnson et al. 2007) and represents the total ocean current (both geostrophic and Ekman components) of the upper 30 m. In this study, the OSCAR surface current estimate from 2001 through 2014 are used as observed surface current data. The daily $\frac{1}{4}^\circ \times \frac{1}{4}^\circ$ sea surface height (SSH) and surface geostrophic current products distributed by the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO; Le Traon et al. 1998; Ducet et al. 2000) for 2011–14 are analyzed to understand ISV of SSH and meridional current. The daily $\frac{1}{4}^\circ \times \frac{1}{4}^\circ$ gridded Advanced Scatterometer (ASCAT) satellite ocean surface wind vectors (Bentamy and Croize-Fillon 2012) during 2011–14 are used to understand the relationship between intrasessional SSH anomalies (SSHA) and wind forcing of ISOs. The monthly subsurface ocean state estimate, with a horizontal resolution of $1^\circ \times 1^\circ$ and 42 vertical levels, of the European Centre for Medium-Range Weather Forecasting (ECMWF) Ocean Reanalysis System, version 4 (ORAS4; Balmaseda et al. 2013), is available beginning 1958 and is used to compute the mean thermocline depth (represented by the depth of 20°C isotherm) and calculate the first and second baroclinic modes speeds. Current measurements from two equatorial moorings of the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA; see McPhaden et al. 2009) are used to verify the model performance on ISV of equatorial currents. One mooring is deployed at 0°, 90°E and provides data from 14 November 2000 to 7 June 2012 at depths ranging from 40 to 410 m. The other is deployed at 0°, 80.5°E and provides data from 27 October 2004 to 17 August 2012 at depths from 25 to 350 m. Data are often missing at deeper layers.

b. OGCM and experiments

The OGCM used in this study is the Hybrid Coordinate Ocean Model (HYCOM; e.g., Wallcraft et al. 2009), version 2.2.18, which is configured to the Indian Ocean Basin (50°S–30°N, 30°E–122.5°E) with a horizontal
resolution of $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ and 26 vertical layers (Li et al. 2014, 2015). The surface atmospheric forcing fields include 10-m winds from the cross-calibrated multiplatform (CCMP), version 1.1, product (Atlas et al. 2008); the $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ ASCAT satellite ocean surface vector winds; $1^\circ \times 1^\circ$ surface net shortwave radiation (SWR) and longwave radiation (LWR) from the Clouds and the Earth’s Radiant Energy System (CERES; Wielicki et al. 1996); $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ precipitation from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) level 3B42 V7 product (Kummerow et al. 1998); and the $2^\circ \times 2^\circ$ 2-m air temperature and humidity from ERA-Interim (Dee et al. 2011). Detailed information about the model configuration and forcing fields can be found in Li et al. (2014).

The model is spun up from a state of rest for 30 yr using monthly climatological forcing. Then HYCOM was integrated forward from 1 March 2000 to 31 December 2014 with the daily forcing fields described above. Note that the model was forced by CCMP winds from 1 March 2000 to 31 December 2010 and by ASCAT winds from 1 January 2011 to 31 December 2014. Earlier studies have shown that HYCOM is successful in representing the upper-ocean processes in the tropical Indian Ocean, including ISV of sea surface temperature (e.g., Li et al. 2013, 2014), sea surface salinity (Li et al. 2015), and SSH (Chen et al. 2015a). HYCOM is also able to well simulate the annual cycle and interannual variability of equatorial currents (Chen et al. 2015b) and eastern equatorial Indian Ocean upwelling (Chen et al. 2015a, 2016). As we shall see below, the wind-driven equatorial wave dynamics play an important role in generation of strong intraseasonal meridional currents in the southern BOB. Thus, we will further verify the HYCOM performance in simulating the ISV of equatorial currents by comparing with RAMA observations.

The high correlation coefficients of 0.86 and 0.84 between intraseasonal zonal flow from RAMA moorings and from the HYCOM solution averaged in the upper ocean at $0^\circ$, $90^\circ$E and $0^\circ$, $80.5^\circ$E, together with their similar standard deviations (STDs) of 0.10 versus 0.12 m s$^{-1}$ and 0.11 versus 0.13 m s$^{-1}$ (Fig. 3), suggest that HYCOM reasonably captures both amplitude and phase of intraseasonal variability of equatorial zonal current. HYCOM also reproduces the observed feature that ISV of the $v$ component is larger than ISV of $u$ component at $5^\circ$N, $90^\circ$E. The simulated intraseasonal $v$ by HYCOM generally agrees with the observed $v$, especially for the larger $v$ events. The simulated $v$ at 20–145 m has a comparable magnitude (0.12 m s$^{-1}$) with the observed $v$ (0.13 m s$^{-1}$), and their correlation coefficient reaches 0.65 (figure not shown). The STDs of observed and simulated intraseasonal $u$ are 0.08 and 0.07 m s$^{-1}$, respectively, and the correlation coefficient of $u$ at 20–145 m is 0.46. In section 3, we will also see that HYCOM successfully simulates the fundamental processes governing the eddylike SSHAs and thus is suitable for our investigation.

In this study, the ASCAT-forced run between 2011 and 2014 is used for our analysis and referred to as the
HYCOM Main Run (MR). Besides MR, three additional experiments were performed for the 2011–14 period with ASCAT wind forcing. To entirely exclude the forcing by atmospheric ISOs, in the NoISO experiment all of the atmospheric forcing fields are low-pass filtered with a 105-day Lanczos digital filter. The difference, MR $\rightarrow$ NoISO, hence measures the overall impact of ISO-related intraseasonal atmospheric forcing on the ocean. The third experiment, NoSTRESS, is performed with only the wind stress 105-day low-pass filtered. Hence, the difference between MR and NoSTRESS quantifies the effect of intraseasonal wind stress associated with the ISOs through ocean dynamics.

To assess the relative importance of local wind forcing within the area of interest versus remote wind forcing outside the region, an additional experiment, named NoLOCAL, is performed, in which the wind stress in the area of $2^\circ$–$8^\circ$N, $84^\circ$–$100^\circ$E (blue rectangle in Fig. 1) is 105-day low-pass filtered. Outside this rectangle area, there is a 1° the transition zone (red dashed rectangle in Fig. 1), where the daily wind stress gradually changes to 105-day low-passed winds. The difference, MR $\rightarrow$ NoLOCAL, thus isolates the ISO-related local wind stress forcing effect, and NoLOCAL measures the remote forcing effect outside the box area. This experiment can help assess the relative importance of the local and coastal processes within the box and remote forcing from the equator. Output of the four experiments is all stored as 3-day mean data for the analysis period of 2011–14.

### 3. Results

#### a. Observed intraseasonal meridional currents

Figure 2 shows the daily time series of zonal current $u$ and meridional current $v$ observed by the SCsio mooring from April 2013 to April 2014 over $20$–$145$- and $180$–$400$-m depths (section 1; Fig. 1). Evidently, $u$ and $v$ exhibit distinct characters in their variability. While $u$ exhibits strong seasonal and semiannual variations, $v$ is dominated by intraseasonal variability, with northward/southward flows alternating on intraseasonal time scales throughout the observation period and amplitude of $\lesssim 0.4$ m s$^{-1}$ above the main thermocline ($\sim 115$ m for the climatological $20^\circ$C isotherm from ORAS4). The power spectra of the $20$–$145$-m-averaged $v$ show strong spectral power at intraseasonal periods, with two distinct peaks at 38- and 47-day periods (red line in Fig. 4a). The ISV is much stronger than the variability at lower frequencies (0–0.01 day$^{-1}$; $>100$ days in period). The spectra of the $180$–$400$-m-averaged $v$ also show significant power at intraseasonal periods, with peaks at 47 and 38 days but with much weaker magnitudes (Fig. 4b). These results indicate that the observed $v$ is associated with oceanic intraseasonal waves, with energy propagating downward from the surface, as is clearly shown by the upward phase propagation of $v$ (Fig. 2b). In comparison, the spectra of $u$ have considerably weaker power at the intraseasonal time scale of 30–50 days but stronger power at semiannual and annual frequencies ($< 0.01$ day$^{-1}$) in the upper layer and semiannual frequency in the deeper
layer (Fig. 4, black curves). This means that the strong intraseasonal flow is a unique feature for $\nu$ at the mooring site of $\sim 5^\circ$N and worthy of in-depth investigation.

To better understand the current variability at the mooring site, we compare the OSCAR surface $v$, surface geostrophic current $v_g$ from AVISO, and ADCP-measured $\nu$ at 20 m and averaged between 20 and 145 m in Fig. 5. During the observation period of the mooring, the three datasets are highly consistent. Interestingly, amplitudes and phases of the intraseasonal $\nu$ (30–105-day bandpass filtered; Fig. 5b) are quite similar to those of the original daily $\nu$ (Fig. 5a), confirming the dominance of ISV in the total meridional flow. The STDs of intraseasonal $\nu$ from OSCAR, AVISO, and mooring at 20 m are 0.18, 0.22, and 0.15 m s$^{-1}$ during the mooring observed period, which are 81%, 76%, and 79% of the total daily $\nu$ standard deviation, respectively. Besides, the correlation coefficient between the daily $\nu$ and intraseasonal $\nu$ reaches 0.87, 0.81, and 0.88 for the three datasets. Note that the intraseasonal OSCAR $\nu$ agrees well with the AVSIO $v_g$ (Fig. 5b; $r = 0.80$). Therefore, the ISV is primarily contributed from the geostrophic component, and contribution from the Ekman flow is much less. The conclusion stands for $3^\circ$–$9^\circ$N in the eastern Indian Ocean (figure not shown).

Consequently, we use AVISO SSH data to explore the spatial structure and temporal evolution of the observed current and sea level variability during the mooring observational period.

Time–longitude plot of intraseasonal SSHA along section $5^\circ$N suggests that the significant intraseasonal SSHA at the mooring site is mainly attributed to the westward propagation of Rossby waves with a phase speed of 0.20–0.71 m s$^{-1}$ (Fig. 6a). Note that equatorial Yanai waves with westward phase propagation also exist at the 30–105-day periods and may still have appreciable magnitude near $5^\circ$N (e.g., Chatterjee et al. 2013). They, however, are antisymmetric about the equator and have eastward group velocity (Yanai and Maruyama 1966). As we shall see below (e.g., Fig. 10), it is primarily the westward-propagating symmetric Rossby wave that contributes to the SSHAs here. Larger phase speeds tend to occur in boreal winter–spring due to the stronger oceanic stratification (Fousiya et al. 2016). For our composite analysis below, we use one STD of SSHA as the criterion for the selection of positive/negative SSHA events at the mooring site, and the peaks of these events are labeled by white squares and green circles in Fig. 6a. During the peaks of the high (low) SSHA events, the composite AVISO SSHA and OSCAR currents suggest that the mooring site is located roughly at the center of an anticyclonic (cyclonic) eddylike structure (Figs. 6b,c). As these eddylike structures propagate westward and pass...
the mooring, strong intraseasonal $\nu$ is observed at the mooring site. In contrast, since the mooring site is roughly at the latitude of the eddy centers, the large zonal currents on the eddy edge is missed, and this is why we did not observe strong corresponding $u$ at the mooring site (Figs. 2a, 4). We further examine the time–latitude plot of intraseasonal SSHA along section 90.5°E (Fig. 6d), which confirms our discussion above, since the strong zonal gradients of positive/negative SSHA at $\sim$5°N are associated with strong geostrophic meridional currents, with strong zonal currents occurring around 4° and 6°N where strong meridional gradients of SSHA exist. Superimposed on the SSHA are meridional velocity vectors observed by the mooring at 5°N, 90.5°E from a depth of 20 m.

To understand whether or not the strong intraseasonal $\nu$ is a unique situation of the mooring observational period, longer data records of OSCAR and AVISO at the mooring site are examined from 2011 to 2014. Figure 5 suggests that the geostrophic current remains the dominant component during 2011–14. Besides, the mooring site is always passed by centers of eddylike anomalies, as revealed by composite analysis using data.

The figure shows time–longitude plots (a) and time–latitude plots (c) of intraseasonal SSHA along the mooring site (5°N, 90.5°E) and section 90.5°E, respectively. The plots display the positive and negative SSHA events as well as the geostrophic currents observed by the mooring.
from 2011 to 2014 (figure not shown). In fact, the mooring site is even affected by eddylike currents in the annual climatology of 2001–14 (Fig. 1). These results verify that the strong intraseasonal $v$ at the mooring site near 5°N is a common feature. Because of the westward propagation of the eddylike structures, we expect that strong intraseasonal $v$ also exists west of the mooring. Power spectra of $u$ and $v$ verify our speculation (Fig. 7).

Based on the daily AVISO geostrophic currents for 2011–14, power spectra of zonal and meridional velocities at each grid point along 5°N are computed. Intraseasonal variation with a spectral peak of ~36 days dominates the meridional velocity, and the power peak extends westward from 94°E to 84°E (Fig. 7b). The wavelength is 1555 km, corresponding to the phase speed of 0.5 m s$^{-1}$ (Fig. 6a) and period of 36 days, which is consistent with the wavelength of the intraseasonal Rossby wave in the Pacific Ocean (Farrar 2008). In comparison, the dominant zonal currents are at lower frequency with periods of longer than 100 days (Fig. 7a).

b. Wind forcing effects by the ISOs

To understand the causes for intraseasonal SSHA and thus intraseasonal meridional velocity, we choose a boxed area (3°–7°N, 84°–94°E as shown in Fig. 6b), which is centered at the mooring latitude of 5°N in the southern BOB, to form a reference time series. The STD of AVISO intraseasonal SSHA is 1.77 cm, which is approximately 50% of the STD of its climatological-mean seasonal cycles of 3.78 cm. The simulated intraseasonal SSHA by HYCOM MR generally agrees with the observed SSHA (Fig. 8a), with a correlation coefficient of 0.86 and a STD value of 1.80 cm during 2011–14.

Given the success of HYCOM MR, results of other HYCOM experiments can be analyzed to understand the underlying physical processes. For example, in NoISO the forcing effects of atmospheric ISOs are removed, and therefore MR − NoISO measures the total forcing effect of ISOs. The intraseasonal SSHA from MR − NoISO agrees quite well with that in MR, showing a linear correlation coefficient of 0.93 (above 95% significance; Fig. 8a). The STD of intraseasonal SSHA in MR − NoISO is 1.65 cm, which is also close to that in MR (1.80 cm). The good agreement between MR and MR − NoISO suggests that the observed SSHA and current ISV is predominantly forced by atmospheric ISOs rather than induced by oceanic internal instabilities. By excluding intraseasonal wind stress forcing in the NoSTRESS experiment, we further find that the effect of atmospheric ISOs on SSHA is mainly through intraseasonal wind stress forcing (Fig. 8b), which affects SSHA through ocean dynamical processes rather than through surface buoyancy fluxes (heat and freshwater fluxes). The SSHA induced by surface wind stress (MR − NoSTRESS) has a comparable magnitude (1.58 cm) with that induced by total ISO forcing, and their correlation coefficient reaches 0.90.

Variability of SSH and upper-ocean circulation in the study region is affected by both local wind forcing and remote forcing of the equatorial zonal winds. To explore the effects of local versus remote wind stress forcing within and outside the southern BOB region (Fig. 1), we perform lagged correlation analyses between ASCAT intraseasonal zonal wind stress anomaly at each grid and AVISO intraseasonal SSHA averaged in the box shown in Fig. 6b. The results demonstrate that intraseasonal SSHA in the southern BOB is significantly affected by zonal wind stress in the equatorial region (left column of Fig. 9). While positive correlation exceeds 0.6 from 80° to 90°E along the equator when wind stress leads by
25 days (black contour in Fig. 9a, top panel), negative correlation exceeds $-0.4$ in a similar region when wind stress leads by 0 or 5 days (Fig. 9a, two bottom panels). This result suggests that both eastern boundary reflected and directly forced Rossby waves are important in causing the observed SSHA at the mooring location, as further elaborated below.

Given that equatorial waves induce convergence and divergence along the Sumatran coast (Chen et al. 2016), we perform composite analyses with respect to SSHA along the Sumatran coast, labeled by the red box in Fig. 10 with a width of 1° longitude off the coast between 5°S and 5°N. The plus or minus one STDs of SSHA averaged in the red box from AVISO for the 2011–14 period are ±3.16 cm, which are used to identify positive/negative SSHA events (figure not shown). Based on this criterion, we identify 18 positive and 19 negative SSHA events. Because of their similar evolution, we only show the composite results of positive SSHA events below. The days with SSHA maxima are taken as 0 days. Then, SSHA composites from AVISO and currents from OSCAR for 15 days before ($-15$ days) and 25 days after ($+25$ days) day 0 are obtained (Fig. 10). To examine the sensitivity of results to the selection of the box, we also obtain the composite based on SSHA on the equator, similar to the analysis of Iskandar and McPhaden (2011), who used moored time series as an index, and obtain similar results. The composites of intraseasonal OLR and wind stress anomalies in the tropical Indian Ocean corresponding to the positive SSHA events are presented in Fig. 11.

Intraseasonal westerly wind anomalies in the equatorial Indian Ocean (arrows of Fig. 11; $-15$ days), which
are associated with strong intraseasonal atmospheric convection (active phase of the ISOs; blue shading in Fig. 11) cause equatorial Ekman convergence, increasing SSHA and eastward flows along the equator (Fig. 10). The positive SSHA signals first propagate eastward along the equator as equatorial Kelvin waves. Upon arriving at the eastern boundary, part of the energy propagates northward along the coast of Sumatra.
as coastal Kelvin waves and subsequently radiates westward as long Rossby waves with eddylike structures centered at 5°N, increasing SSHA at the mooring location after 20–25 days (+5 days and +10 days in Fig. 10). Meanwhile, intraseasonal easterly wind anomalies occupy the equatorial Indian Ocean (+5 days in Fig. 11), inducing cyclonic eddylike structures around the mooring location after another 20–25 days (Fig. 10; see also Fig. 16 below). These explain the lagged correlation shown in Fig. 9a and the alternating meridional currents observed by the mooring. Note that in the equatorial Indian Ocean, the propagating first meridional mode Rossby waves associated with the first baroclinic mode exist when the period is longer than ~30 days, and those associated with the second baroclinic mode exist when the period is longer than ~40 days (see Fig. 12 of Han 2005). Consequently, the observed 38-day spectral peak of \( v \) (Fig. 4a) is largely contributed from the Rossby waves associated with the first baroclinic mode and the 47-day peak, from both the first and second baroclinic modes.

Accompanying the equatorial Ekman convergence and positive SSHA, there is off-equatorial Ekman divergence and therefore negative SSHA on both sides of the equator (Fig. 10). This is the typical structure of the first meridional mode Rossby wave that is directly driven by zonal wind stress over the eastern equatorial basin [see also Nagura and McPhaden (2014) for directly forced Rossby waves]. These directly forced Rossby waves explain the negative correlation with 0–~5-day lead of zonal wind stress in the eastern equatorial basin (Fig. 9a, two bottom panels).

In addition to zonal wind stress in the equatorial basin, Ekman pumping associated with local wind stress curl over the southern BOB can also affect SSHA there, which is also mentioned by previous studies.
Indeed, SSHA in the southern BOB is negatively correlated with the local Ekman pumping velocity anomaly with correlation coefficients exceeding $2^{0.4}$ with $0$--$5$-day lead by Ekman pumping velocity (Fig. 9b). This is because positive (negative) Ekman pumping velocity associated with positive (negative) wind stress curl anomaly shoals (deepens) the thermocline and reduces (increases) SSHA. The SSHA signals can propagate westward as Rossby waves, affecting the SSHA in the western bay. Note that propagating Rossby waves exist at $5^8N$ in intraseasonal periods because the critical latitudes (McCreary et al. 1986) of intraseasonal Rossby waves associated with the first baroclinic mode are higher than $5^8N$. The critical latitude $\theta_c$ is defined as $\tan \theta_c = c/(2\omega R)$, where $c$ is baroclinic mode speed, $R$ is Earth’s radius, $\omega$ is the frequency with $\omega = 2\pi/T$, and $T$ is the period. Based on the density profile from ORAS4 data, we estimate the theoretical Kelvin wave phase speed of the first baroclinic mode speed being $3.05$ $m$ $s^{-1}$ in our region of interest. For $T = 36$ days, which is close to the lower bound of intraseasonal periods (Fig. 4a), $\theta_c = 6.8^8N$. In comparison, the second baroclinic mode with phase speed of $1.52$ $m$ $s^{-1}$ can affect $47$-day variability on the equator but not at $5^8N$ since its $\theta_c$ is less than $5^8N$.

To provide quantitative estimates for the effects of remote versus local wind forcing, we trace the SSHA signals along the route composed by the eastward route along the equator, the northwestward route along the Sumatran coast and the westward route at $5^8N$ meridian (the route A–B–C–D with longitudes of $80^8E$, $98.5^8E$, $95^8E$, and $80^8E$ shown by the red line in the bottom panel of Fig. 9a). Figure 13 (below) shows the time–distance plots of intraseasonal SSHA from AVISO, HYCOM MR, HYCOM NoLOCAL (assessing the remote forcing effect outside the Fig. 1 boxed region), and MR – NoLOCAL (assessing local wind forcing effect within the box). Both AVISO and HYCOM MR show clear propagation from A–B–C with faster speed and from C–D with slower speed (Figs. 13a,b). It takes $10.4$ ($20.7$) days for the first (second) baroclinic mode Kelvin waves to propagate from A to C and another $5.4$ days for the first baroclinic mode Rossby wave from C to the mooring site. Indeed, the travel time of the observed and simulated SSHA signals from A to C indicates a mixed behavior of first and second baroclinic modes. Wind forcing may also obscure pure free Rossby wave phase speeds, leading to slower speeds than expected for free wave propagation. In NoLOCAL, the SSHAs present similar features and magnitudes to those in HYCOM MR and AVISO observation, suggesting that remote winds outside the boxed region play an important role in affecting the intraseasonal SSHA in the southern BOB (Fig. 13c). Composite intraseasonal SSHA and surface currents from NoLOCAL further verify the dominant role of remote, equatorial forcing (Fig. 12). In comparison, in MR – NoLOCAL, the SSHAs are visibly weaker (Fig. 13d). Interestingly, the intensity of locally
generated SSHA shows obvious interannual variation. As a result, local wind forcing also makes significant contributions to strong SSahas in some years, which also propagate westward (Fig. 13d).

To better quantify the remote versus local wind forcing effects, in Fig. 8c we compare the box-averaged intraseasonal SSHA time series from MR, NoLOCAL, and MR – NoLOCAL. Overall, remote wind forcing dominates the total SSHA. The correlation coefficient between MR and NoLOCAL is 0.82, while that between MR and MR – NoLOCAL is 0.46. The STDs of intraseasonal SSHA are 1.61 and 1.03 cm in NoLOCAL and MR – NoLOCAL, respectively, accounting for 89% and 57% of the total SSHA in MR. Albeit with smaller amplitude and correlation, local wind forcing effects are also considerable, particularly for some strong SSHA events. Specifically, both remote and local forcing effects contribute to the SSHA in July 2011, May 2013, and December 2014 (red arrows in Fig. 8c), whereas they have opposite effects on SSahas of January 2011, August 2011, and July–August 2014 (blue arrows). We therefore conclude that the observed ISV in SSH and meridional current is primarily induced by remote forcing of the equatorial winds through both reflected and directly forced Rossby waves and secondarily through local forcing of wind stress curl anomalies near 5°N.

c. Symmetric equatorial Rossby waves

Besides the eddylike SSahas near 5°N, eddylike SSahas can also be seen south of the equator from 1° to 25° days (Fig. 10), propagating westward along 5°S but with smaller amplitudes. The rough symmetric signals about the equator, with in-phase SSahas on both sides of the equator, resemble the structure of the equatorially symmetric waves. The equatorially symmetric structure, with positive SSahas off the equator and weakly negative SSHA on the equator, is the typical structure of the first meridional mode Rossby waves. Because of the slanted eastern boundary in the EIO,
However, Rossby waves are not purely symmetric (Han et al. 2011), and there are contributions from antisymmetric components.

To understand the components of the observed ISVs, we perform a meridional decomposition to the intraseasonal, observed SSHA to Kelvin wave mode $D_0$ and Rossby wave modes $D_n$ in the form of

$$h_5 h_0 D_0 + \sum_{n=1}^\infty h_n D_n + (n+1)D_n \text{ in the form of }$$

$$h_n [D_n + (n+1)D_n]$$

$$\text{where parabolic cylinder functions } D_n(y') \text{ can be represented in terms of the Hermite polynomial } H_n(y') \text{, as } D_n(y') = \left( e^{-y'^2/2} / \sqrt{\sqrt{2\pi}} \right) H_n(y') \text{ (Zheng et al. 1995). Herein, }$$

$$y' = y' / \sqrt{g'H} \text{ is a nondimensional meridional coordinate, where } c = \sqrt{g'H} \text{ is the phase speed of baroclinic mode inertial wave in a 1.5-layer ocean model, } g' \text{ is the reduced gravity parameter, and } H \text{ is the mean upper-layer thickness of the 1.5-layer model. The quantity } \beta \text{ is defined by } \beta = 2 \Omega \cos \theta / r_0, \text{ where } \Omega \text{ is the rotation rate of earth, } \theta \text{ is the latitude, and } r_0 \text{ is Earth’s radius. The } H_n(y') \text{ are derived from } e^{-y'^2/2} H_n(y') = (-d/dy') e^{-y'^2/2}. \text{ More details can be found in White and Tai (1992) and Zheng et al. (1995).}$$

Three profiles, at 85°E, 90.5°E, and 93°E, are chosen to represent the different areas of the EIO. Based on the AVISO SSHA composites shown in Fig. 10, we expand SSHAs along the three profiles on 25, 110, and 125 days to understand their features in different stages. Overall, the AVISO SSHAs (gray dots in Fig. 14) can be well represented by the sum of the Kelvin wave mode and the first two meridional modes’ Rossby wave (red lines in Fig. 14). On -5 days, when Kelvin waves dominate the equatorial area, the Kelvin wave mode and the first meridional mode symmetric Rossby wave (red dashed line in Fig. 14) control the meridional distribution of SSHA. In comparison, the second meridional mode antisymmetric Rossby wave (blue lines in Fig. 14) contributes less to SSHA. On +10 days, when the reflected Rossby waves start to appear, the first meridional mode symmetric wave induces equatorial symmetric SSHA along 93°E, with peaks around 5°N and 5°S. At the same time, the second meridional mode antisymmetric Rossby wave leads to high SSHA around 5°N but low SSHA around 5°S. As a result, SSHA along 93°E presents significantly asymmetrical features around the equator with high SSHA in the northern part. The asymmetrical Rossby waves propagate westward and arrive at 85°E on +25 days (Fig. 10, where SSHA are still contributed from the first three modes (Fig. 14). In comparison, because the high SSHA event has passed by and no new one arrives, the SSHA along 90°E on +25 days tends to be symmetric and dominated by symmetric wave modes (Fig. 14). Because of the generation of another low SSHA event (Fig. 10), the SSHA along 93°E on +25 days becomes asymmetric again, and the antisymmetric modes contribute substantially to the SSHA meridional distribution (Fig. 14).

The decomposition of SSHA into meridional modes supports the observations and model results, showing...
that the sum of the Kelvin wave mode and first two meridional mode Rossby waves reproduce the observed SSHA well in the equatorial Indian Ocean. The first meridional mode Rossby wave dominates the solution near 5°N, and the second meridional mode contributes to the asymmetric component about the equator. Strong ISV of meridional velocity at 5°N is part of the eddylike structures associated with the Rossby waves, whose natural modes ensure peaks around this latitude (Fig. 14). The Kelvin wave mode is indispensable to the solution within an equatorial Rossby radius of the equator, but it tends to weaken the effects of Rossby waves and contributes less to the eddylike SSHAs.

4. Summary and discussion

In response to the strong wind forcing of atmosphere ISOs, zonal currents in the eastern equatorial Indian Ocean exhibit pronounced intraseasonal variability, which has been intensively investigated by many studies (e.g., Han et al. 2001; Iskandar and McPhaden 2011; Nagura and McPhaden 2012). In comparison, there are far fewer studies for the intraseasonal variability in meridional currents. The SCSIO deployed a subsurface mooring at 5°N, 90.5°E (Fig. 1). The 1-yr records of the ADCPs reveal pronounced ISV in the meridional current, which is characterized and explained in this study.

In the ADCP measurements of the mooring there are strong intraseasonal meridional currents with an amplitude of 0.4 m s\(^{-1}\) and a typical period of 30–50 days in the upper 150 m (Fig. 2). They are by far larger in magnitude than the mean flow and seasonal cycle of meridional velocity. Such prominent ISV is, however, not seen in zonal current \(u\). Further analysis shows that those anomalous meridional currents are primarily geostrophic and closely associated with frequently occurring eddylike SSHAs centered near 5°N (Fig. 6). These eddylike SSHAs propagate westward, causing pronounced ISV of upper-ocean \(v\) not only at the mooring site but also in the entire southern BOB between 84° and 94°E (Fig. 7). Since most of the eddylike SSHAs are centered near 5°N, there is no significant ISV in zonal current observed by the mooring. To the southeast of Sri Lanka, the SSHAs are considerably weakened, while some intraseasonal SSHAs are generated locally (Fig. 6a). In addition to local wind forcing,
the strong ocean internal instabilities off Sri Lanka (Chen et al. 2012; Sengupta et al. 2001) should contribute to generating these local SSHA signals. Short Rossby waves with eastward energy propagation may occur around southeast of Sri Lanka but have no visible influence on SSHA and currents at the mooring site before they are severely damped by mixing due to their slow eastward group velocity and short wavelengths (figure not shown).

Further analysis of observational data and HYCOM experiments demonstrate that the observed eddylike SSHAs at 5°N are predominantly caused by remote equatorial wind stress forcing associated with atmospheric ISOs, through directly forced and eastern boundary-reflected Rossby waves. The equatorial westerly (easterly) wind stress anomalies directly force symmetric Rossby waves with negative (positive) SSHA around 5°N and 5°S. Meanwhile, intraseasonal equatorial zonal wind stress excites equatorial Kelvin waves, which propagate eastward to the Sumatran coast and subsequently reflect back into the ocean interior as westward-propagating Rossby waves, contributing to the eddylike SSHAs at the mooring location (Figs. 10, 13). Similar processes also have been shown at seasonal and interannual scales (McCreary and Yu 1992; Shankar et al. 2002; Vinayachandran et al. 2002). Compared to remote forcing, local wind stress

Fig. 15. Composite intraseasonal wind stress anomaly (vectors) and OLR anomaly (color) for eight phases of the RMM index.
forcing in the southern BOB is less important, but it also contributes significantly to some strong SSHA events through local Ekman pumping and the generation of westward-propagating Rossby waves, such as those that occurred in July 2011, May 2013, and December 2014 (Fig. 8c).

Based on the statistics for the intraseasonal SSHAs near the Sumatran coast, there are 19 events that occurred in November–April and 18 events that occurred in May–October. No evident seasonal preference is detected in terms of event number. It is likely that both the winter MJO and the summer monsoon ISO (e.g., Yasunari 1980; Krishnamurti and Subrahmanyam 1982) can cause the strong ISVs in SSH and meridional current at 5°N. Based on the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004), we identify significant MJO variance with the amplitude larger than 1.5 and then obtain the composite intraseasonal OLR and wind stress maps for the eight MJO phases (Fig. 15). Strong wind stress anomalies are seen in the equatorial Indian Ocean. For example, westerly winds are seen near the equator at phases 3–4, while easterly winds are seen at phases 7–8. These surface wind anomalies, together with their accompanied off-equatorial wind stress curls, are the primary drivers of the observed SSH and meridional current ISV at 5°N in November–April, as has been demonstrated in our analysis. On the other hand, the wind anomalies of the summer monsoon ISO are dramatically different in spatial–temporal characteristics from those of the MJO. Therefore, the two dominant modes of ISOs may induce varied ocean current ISVs in strength, spatial distribution, and even mechanisms, which is an interesting theme for future studies.
The eddylike structures, in essence, are part of symmetric equatorial waves. Overall, the meridional structures of SSHAs in the eastern equatorial Indian Ocean can be well represented by the sum of the Kelvin wave mode and the first two meridional mode Rossby waves (Fig. 14). While the first meridional mode Rossby wave dominates the meridional structure of SSHAs overall, the second meridional mode antisymmetric Rossby wave contributes to the SSHAs particularly in the eddylike regions near 5°N and 5°S (Figs. 10, 14). In general, the intraseasonal SSHAs and meridional currents are stronger north of the equator than in the south, which is primarily due to the inclined coastline of the eastern boundary that affects the Kelvin wave reflection (Fig. 10; Han et al. 2011).

The eddylike Rossby wave signals can have a significant impact on the upper-ocean circulation in the eastern equatorial Indian Ocean, particularly in the southern BOB. Because of the dissipation and modification by local winds, the Rossby waves are greatly attenuated in the western basin, but their associated equatorial zonal flow remains considerable in magnitude (Fig. 16). At 0°, 60°E, the related intraseasonal zonal currents averaged at the upper 30 m can reach 0.2 m s⁻¹ at +50 days of the composite, which may significantly impact intraseasonal variability of upper-current currents, such as the Wyrtki jets, over the equatorial Indian Ocean.

Acknowledgments. We thank two reviewers for their constructive comments on an earlier version of this manuscript. The AVISO data were obtained at http://www.avenio.fr/en/data/data-access.html, the OSCAR data at ftp://podac-fdp.jpl.nasa.gov/allData/oscar/preview/L4/oscar_third_deg, the ASCAT data at http://apdrc.soest.hawaii.edu:80/dods/public_data/satellite_product/ASCAT/daily, and the ORAS4 data at http://apdrc.soest.hawaii.edu:80/dods/public_data/Reanalysis_Data/ORAS4. The processed mooring data used to construct figures in this work are also available, and anyone who wants to get access to these data could contact the corresponding author, Dongxiao Wang (dxwang@scsio.ac.cn). G. Chen, D. Wang, and W. Wang are supported by NSF 41521005, NSFC 41676013, XDA1010102, and Youth Innovation Promotion Association CAS (2017397). W. Han and Y. Li are supported by NSF AGS 1446480, NSF OCE 1558736, and NMMD SSC-03-002. M. J. McPhaden is support by NOAA.

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