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The Kelvin Wave Processes in the Equatorial Indian Ocean during the 2006–2008 IOD Events

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Abstract The present study investigates the role of Kelvin wave propagations along the equatorial Indian Ocean during the 2006–2008 Indian Ocean Dipole (IOD). The 2006 IOD lasted for seven months, developing in May and reaching its peak in December, while the 2007 and 2008 IODs were short-lived events, beginning in early May and ending abruptly in September, with much weaker amplitudes. Associated with the above IODs, the impulses of the sea surface height (SSH) anomalies reflect the forcing from an intraseasonal time scale, which was important to the evolution of IODs in 2007 and 2008. At the thermocline depth, dominated by the propagation of Kelvin waves, the warming/cooling temperature signals could reach the surface at a particular time. When the force is strong and the local thermocline condition is favorable, the incoming Kelvin waves dramatically impact the sea surface temperature (SST) in the eastern equatorial Indian Ocean. In July 2007 and late July 2008, the downwelling Kelvin waves, triggered by the Madden-Julian Oscillation (MJO) in the eastern and central equatorial Indian Ocean, suppressed the thermocline in the Sumatra and the Java coast and terminated the IOD, which made those events short-lived and no longer persist into the boreal fall season as the canonical IOD does.

Keywords: Kelvin wave, IOD, equatorial Indian Ocean, MJO

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1 Introduction

The Indian Ocean Dipole/zonal mode (IOD) refers to the anomalous cooling off the Sumatra and Java coast in the tropical southeastern Indian Ocean and warming in the central and western equatorial Indian Ocean at interannual time scales (Saji et al., 1999; Webster et al., 1999). During 2006–2008, the Indian Ocean experienced three consecutive positive IODs, a strong IOD in 2006 and two weak IODs in 2007 and 2008 (Cai et al., 2009; Schott et al., 2009; Yuan and Liu, 2009). Recent studies suggest the short-lived IOD in 2007 and 2008 relates to intraseasonal variations. Rao et al. (2009) found that the convection-suppressing phase of the Madden-Julian Oscillation (MJO) in an IOD year can cause thermocline shoaling in the southeastern tropical Indian Ocean (SETIO) through anomalous upwelling Kelvin waves. Cai et al. (2009) also indicated that the equatorial upwelling Kelvin waves enhance the seasonal upwelling and thus change the sea surface temperature (SST) gradients in the SETIO. Iskandar et al. (2005) and Nagura and McPhaden (2012) investigated the intraseasonal variability in the equatorial Indian Ocean and found that it plays an important role in regional ocean dynamics.

In this paper, we focus on the Kelvin wave processes associated with the 2006–2008 IOD events. The paper is organized as follows: section 2 describes the data; in section 3, the evolution of the three IOD events is given; in section 4, we compare the ocean temperature evolutions at surface and thermocline; and the results are summarized in section 5.

2 Data

In this study, daily SST is derived from optimally interpolated sea surface temperature (OISST, Reynolds et al., 2002) analysis and weekly ocean surface winds from Quick Scatterometer (QuikSCAT), 1999–2009 (Chelton et al., 2006). The weekly multi-satellite merged altimeter data spans from 1993 to 2008. In situ data from Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) is used to identify vertical structure in the equator and verify the result from the model (McPhaden et al., 2009). RAMA provides moored buoy array measurements in the tropical Indian Ocean to enhance monsoon research and forecasts. We utilize temperature at 500 m in (93°E, EQ) from the 2000–2008 RAMA observations. In this paper, the daily Hybrid Coordinate Ocean Model (HYCOM) assimilation product from 2003–2008 is used with 1/12° resolution, which assimilates satellite altimetry, observed SST, expendable bathythermographs (XBT) temperature, Array for Real-time Geotropic Oceanography (ARGO) temperature, salinity data, and others (Chassignet et al., 2007). HYCOM is a multi-institutional effort sponsored by the National Ocean Partnership Program to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Bleck, 2002). All anomalies in the above data refer to their annual cycle in 2000–2008, except for HYCOM, which is based on 2003–2008. We remove the climatology in a daily/weekly/monthly interval for corresponding data.

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3 General feature of 2006–2008 IOD

Concurrent with a strong El Niño in the Pacific, the 2006 IOD is regarded as a strong event, indicated in the IOD index (Cai et al., 2009), developing from May and reaching its peak in December. The SST decreased remarkably in the region east of the Java coast, but remained normal near the Sumatra coast (Fig. 1a). Off the Sumatra coast, beneath the thick barrier layer, the thermocline was deep and had difficulty exchanging water mass with the mixed layer, which needed continuous impacts of easterly wind to induce upwelling and cool down in the SST (Du et al., 2008). In July-August 2006, the SST cooled off the Java coast and warmed in the central equatorial Indian Ocean (Fig. 1b). From September-October 2006, easterly wind anomalies were greatly enhanced, which spread the SST cooling to the area near the coast of Sumatra and extended the SST warming westward (Fig. 1c). In the last two months of 2006, the easterly wind anomalies dominated the equatorial Indian Ocean, and the canonical IOD pattern was fully established, with SST cooling off the Sumatra and Java coast and warming in the central and western equatorial Indian Ocean (Fig. 1d).

The 2007 IOD was established in May-June, with an easterly wind anomaly near the equator, SST cooling off Java and warming in the western equatorial Indian Ocean (Fig. 1e). The IOD decayed quickly with weakening easterly winds from September-October (Fig. 1g) and a strong westerly wind followed (Fig. 1h). The 2008 IOD was similar to the 2007 event, as it forms in early May when the easterly wind anomalies develop, with significant SST cooling near Java and Sumatra (Fig. 1i). From July-August 2008, the easterly wind anomalies along the equator weakened. West of the equator, westerly wind anomalies appeared, which induced the SST warming in the central Indian Ocean (Fig. 1j). From September–December, the westerly wind anomalies extended to the Sumatra coast, which terminated the IOD (Figs. 1k–l).

4 The equatorial Kelvin wave during IOD events

4.1 Wave, wind, and sea surface height (SSH)

Along the equator, the westerly wind usually corresponds with a downwelling Kelvin wave, which raises the SSH and propagates eastward (Fig. 2), whereas the easterly wind forces an upwelling Kelvin wave, having an opposite effect on the SSH (Luyten and Roemmich, 1982; Qiu et al., 2009; Schiller et al., 2010). The eastward propagation of the downwelling Kelvin wave from June-July 2006 is generated in response to a westerly wind anomaly

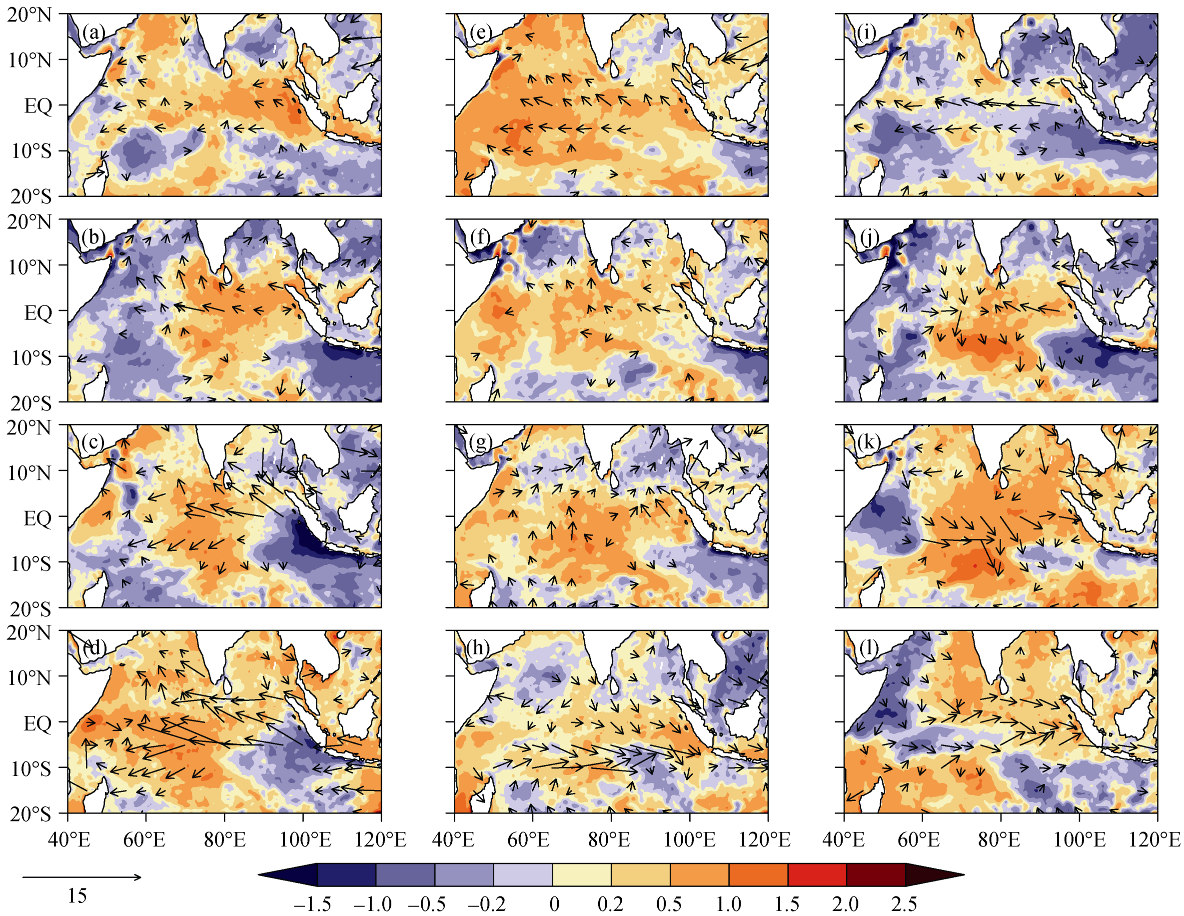

Figure 1 Bi-monthly anomalies of SST (shaded, units: °C) and wind stress (vectors, units: N m^{-2}), (a, e, i) May-June (MJ), (b, f, j) July-August (JA), (c, g, k) September-October (SO), and (d, h, l) November-December (ND) in 2006 (left column), 2007 (middle column), and 2008 (right column).

in the central equatorial Indian Ocean and raises the SSH anomaly (SSHa) near the Sumatra coast. The upwelling Kelvin wave in August 2006 is forced by an easterly wind anomaly, which propagates eastward and terminates the SST warming in the central and eastern equatorial Indian Ocean, declining the SSH near the Sumatra coast significantly. Furthermore, the local wind contributes to the SST cooling off the Sumatra coast.

There was a significant eastward propagation of Kelvin waves in 2007 (Fig. 2b). The SSHa rises with the formation of downwelling Kelvin waves during March-April, July, and October-November, which are related to the westerly wind anomalies. Occasionally, the SSHa drops due to forcing an easterly wind anomaly (e.g., May-June 2007). From May–July 2008, the IOD was established when the easterly wind anomalies dominated the eastern equatorial Indian Ocean, whereas the westerly wind anomalies occupied the western basin. However, the downwelling Kelvin waves generated in the western basin did not affect the equatorial eastern Indian Ocean until July-August 2008. At the time, the Kelvin waves played an important role in the termination of the IOD event. Afterward, local wind anomalies turned westerly and further increased the SSH in the east (Fig. 2c).

4.2 Thermocline variation in the eastern equatorial Indian Ocean

Along the equator, the Kelvin waves propagate downward and impact the subsurface temperature. Figure 3a compared the temperature from HYCOM with the observations from RAMA at 500 m in (93°E, EQ). The correlation coefficient was 0.8. Figure 3a showed that the HYCOM assimilation was in agreement with the observations, and thus, we used the HYCOM data to study the temperature variation in the thermocline. Figure 3b illustrated that the maximum temperature anomalies occur in the thermocline.

Variation in thermocline was generally consistent with the surface wind forcing. Warming in the thermocline from January–April 2006 corresponded to the westerly wind anomalies (Fig. 2a). The warming was terminated by the upwelling Kelvin waves, induced by the easterly wind anomalies in May (Fig. 2a). The easterly wind anomalies then switched to westerly at the end of June (Fig. 2a), terminating the cooling (Fig. 3b). From July 2006 to April 2007, the thermocline temperature exhibited strong cooling, primarily due to the establishment of the strong 2006 IOD. From October-November 2006, the thermocline cooling reached the surface (Fig. 3b). The IOD was terminated when strong westerly wind anomalies dominated the entire equatorial basin in April 2007 (Fig. 2b), but the thermocline showed weak cooling until the end of 2007. The thermocline temperature varies within a short time frame, shifting between warming and cooling from May to August, which is associated with westerly and easterly wind anomalies, respectively (Fig. 3b). From October 2007–April 2008, the thermocline warming was quite strong and even affected the sea surface from January-February 2008. In May 2008, an IOD pattern formed and persisted for three months (Fig. 2c), and the maximum thermocline cooling appeared in June, two to three weeks after the strongest wind in late-May (Fig. 2c).

The equatorial thermocline acts as a wave guide for Kelvin waves (Gill, 1982; McPhaden, 1982), as shown in Fig. 2. The temperature variation at the upper thermocline depth (100 m) was quite different from the SST variation (Fig. 4). From May 2006, SST in the equatorial eastern

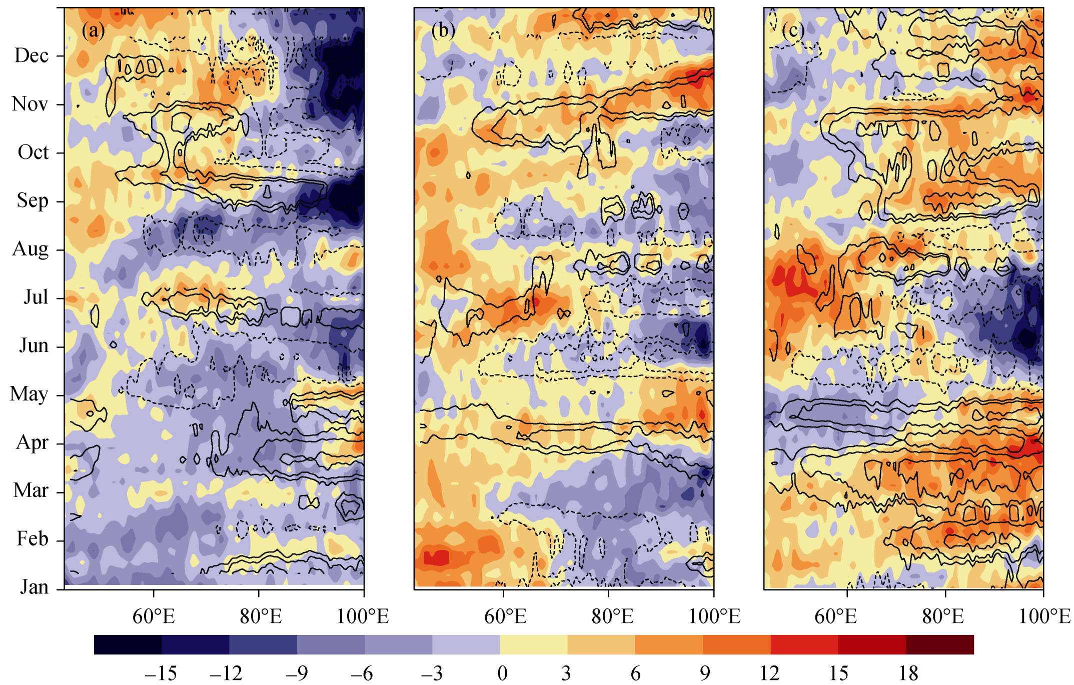

Figure 2 Weekly anomalies of SSH (shaded, units: cm) and zonal wind (contours, units: m s^{-1}) along the equator in (a) 2006 (left column), (b) 2007 (middle column), and (c) 2008 (right column).

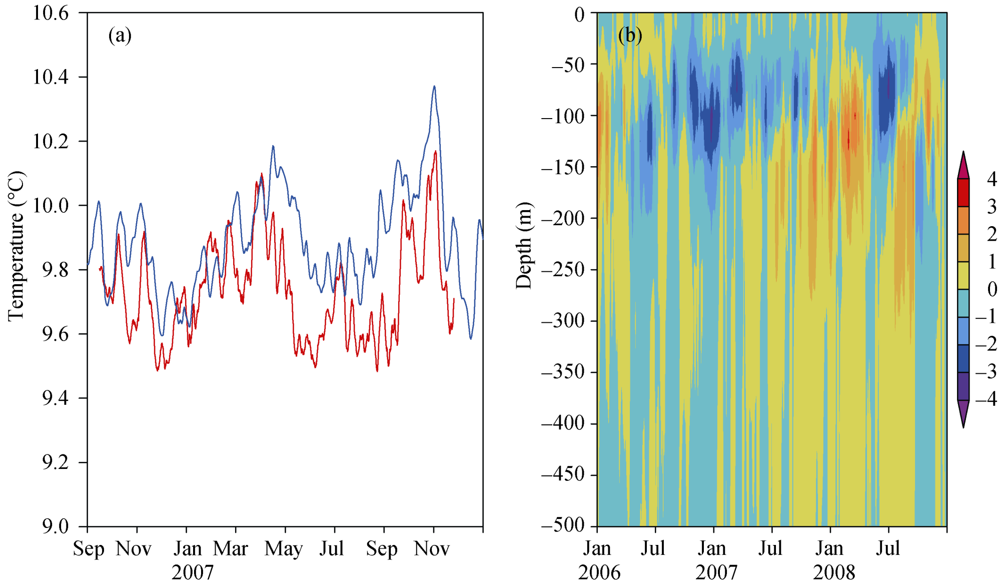

Figure 3 Temperature (units: °C) at (93°E, EQ) for (a) time serials at 500 m from HYCOM (blue line) and RAMA (red line); (b) the vertical distribution of temperature anomaly (units: °C) from HYCOM.

Indian Ocean maintained large positive anomalies until September 2006, when the IOD was established. Additionally, the temperature at the thermocline depth was generally lower than normal in May (Fig. 4a), particularly in the eastern Indian Ocean. In 2007, the thermocline temperature pattern featured warming in the west and cooling in the east, implying favorable ocean conditions for the 2007 IOD. At the same time, the SST warmed in the entire Indian Ocean basin (Fig. 4b). Figure 1 reveals that the cooling pole of the 2007 IOD was constrained in the region off the Java coast. In 2008, SST continued cooling in the west. The eastward propagation of upwelling Kelvin waves was clearly demonstrated from the surface to the thermocline from May-June 2008 (Fig. 4c). From August–November, three groups of downing Kelvin waves terminated this strong cooling and reversed the temperature from the thermocline to the surface (Fig. 4c).

5 Summary

This study investigated the Kelvin waves associated with the 2006–2008 IOD. The 2006 IOD appeared in May, developed from June–November, and peaked in December. Lasting for seven months, The 2006 IOD was classi-

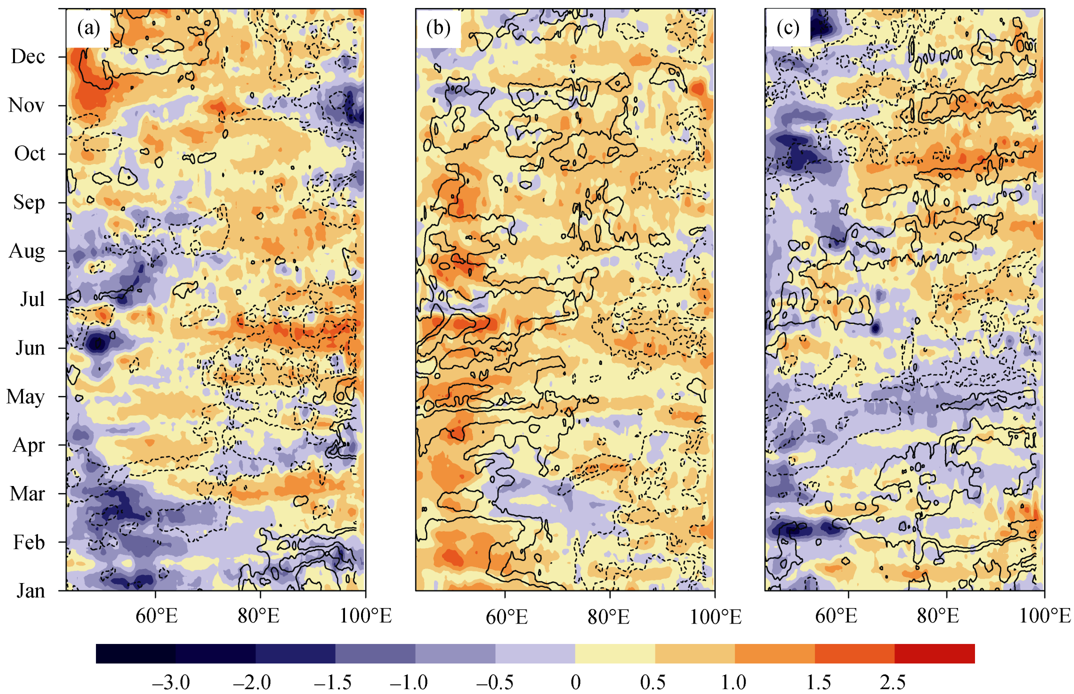

Figure 4 Weekly anomalies of SST (shaded, units: °C) and temperature at 100 m depth (contours, units: °C) along equator in (a) 2006 (left column), (b) 2007 (middle column), and (c) 2008 (right column).

fied as a strong event. The 2007 and 2008 IODs were short-lived events, beginning early in May and ending abruptly in September. The thermocline variation is consistent with the general evolution of the IOD at the surface and highlights the role of the Indian Ocean's equatorial dynamics. The eastward propagation of Kelvin waves is crucial to the development and decay of the IOD (Fig. 2). In 2007 and 2008, additional Kelvin waves formed due to more active MJO events. The downwelling Kelvin waves in the west and central equatorial Indian Ocean propagated to the east and terminated the IOD, making the 2007 and 2008 IODs short-lived events.

In the western equatorial Indian Ocean, the SST variations are consistent with the temperature variations in the thermocline. In this region, the thermocline is shallow, which makes it favorable to exchange with the mixed layer, and thus easy to have an impact on the SST. For the eastern equatorial Indian Ocean, variations in the subsurface layer may be different from the SST due to the deep thermocline and a weak exchange with the mixed layer, such as from May–July 2006, 2007, and June-July 2008. When the Kelvin waves are strong enough, as in July 2007 and late-July 2008, the thermocline variation induced by the Kelvin waves can easily affect the SST in the eastern equatorial Indian Ocean. These processes indicate that the equatorial Kelvin wave processes, forced by MJO, can modulate the evolution of an IOD, particular in a weak event.

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