Pathways of intraseasonal Kelvin waves in the Indonesian Throughflow regions derived from satellite altimeter observation

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ABSTRACT

The gridded sea level anomaly (SLA) data-set provided by AVISO is used to track the propagation of intraseasonal Kelvin waves in the Indonesian Throughflow (ITF) region. The large root mean square of intraseasonal SLA along the Sumatra and Java coast is closely related to the propagation of intraseasonal Kelvin waves that derive from the equatorial Indian Ocean. These Kelvin waves are further found to propagate following different pathways at the Lombok Strait. Pathway A propagates eastward throughout the Sumba Strait and Savu Sea to reach the Ombai Strait. Pathway B penetrates into Lombok and propagates northward to reach the Makassar Strait. Pathway C propagates southeastward along the southwest coast of the Sumba Island. The equatorial Kelvin waves take around 15 days to travel from the equatorial Indian Ocean to Lombok Strait, and around 5 days to penetrate into the Makassar and Ombai straits. The Kelvin wave-induced SLA persists in the ITF region for an additional 5 days and then diminishes subsequently. The phase speeds of these intraseasonal Kelvin waves along Pathways A, B, and C are 1.91–2.86, 1.69, and 1.96 m s\(^{-1}\), respectively—in agreement with the first two baroclinic modes of Kelvin waves.

1. Introduction

The Indonesian Throughflow (ITF), which flows from the equatorial Pacific into the Indian Ocean through the Indonesian seas, provides the only oceanic channel for inter-ocean exchange in the tropical oceans. The importance of the ITF lies in the fact that it is the key component of the so-called ‘ocean conveyor belt’, which plays an important role in the heat and salt balance of the global ocean (Gordon 1986; Broeker 1991). In addition, the ITF also serves as a unique oceanic signal channel, through which tropical Indian Ocean anomalies can propagate to the equatorial Pacific Ocean to influence ENSO (Yuan et al. 2011; Yuan, Zhou, and Zhao 2013). Previous studies have suggested significant intraseasonal oceanic variability (ISV) in the main inflow and outflow straits and passages of the ITF, i.e. the Lombok Strait, Ombai Strait, Timor Passage, and Makassar Strait, based on \textit{in situ} observations (Arieff and Murray 1996; Ffield and Gordon 1996; Molcard, Fieux, and Ilahude 1996; Chong et al. 2000; Wijffels and Meyers 2004) and satellite data (Syamsudin, Kaneko, and Haidvogel 2004; Iskandar et al. 2005). These ISVs can be traced back to the intraseasonal equatorial Kelvin waves forced by the MJO over the equatorial central Indian Ocean (Qiu, Mao, and Kashino 1999; Schiller et al. 2010).

Benefit from the International Nusantara Stratification and Transport 2004–2006 program (Sprintall et al. 2004), the ISV of the ITF in the Indonesian seas has been further revealed (Sprintall et al. 2009; Gordon et al. 2010). Pujiana et al. (2009) suggested that the dominant variability of 45–90 days in the Makassar Strait thermocline is due to the combination of intraseasonal waves propagating from the Lombok Strait and Sulawesi Sea, rather than exerte...
by the local atmospheric ISV forcing. The ISV in Makassar is attributed to the second baroclinic mode of Kelvin waves propagating from the Lombok Strait along the 100-m isobaths, which is estimated to reduce the southward transport through the Makassar Strait by up to 2 Sv (Pujiana, Gordon, and Sprintall 2013). The along-channel flows in Lombok and Ombai have also been found to be subject to ISV, which explains the flow reversal during the monsoon transition period (Sprintall et al. 2009; Gordon et al. 2010). The ISVs in the outflow straits have been identified to be associated with the first and second baroclinic Kelvin waves that derive from the equatorial Indian Ocean, which propagate along the equator and the southwest coast of the Lesser Sunda Islands (Schiller et al. 2010; Iskandar et al. 2014).

As supplements to in situ observations, satellite altimeter products provide high-resolution sea level anomaly (SLA) data, not only in the straits but over the entire ITF region, making it possible to track the propagation of intraseasonal Kelvin waves in the ITF region. Drushka et al. (2010) and Pujiana, Gordon, and Sprintall (2013) used weekly altimeter SLA data as evidence of the propagation of Kelvin waves. However, the pathways of intraseasonal Kelvin waves that derive from the equatorial Indian Ocean in the ITF region—in particular after being trapped by the eastern boundary—have not been examined using satellite altimeter observations. In this study, SLA data obtained from AVISO are used to describe the different pathways of the intraseasonal Kelvin waves in the ITF region.

2. Data and methodology

This study employs the gridded SLA products (Version 5.0) produced by Segment Sol multi-missions dALTimetrie, d’orbitographie et de localisation précise/Data Unification and Altimeter Combination System (SSALTO/DUACS) and distributed by AVISO, with support from CNES (http://www.aviso.altimetry.fr/duacs/). The data-set is daily, with a resolution of 0.25° × 0.25°, available from October 1992 to the present day. The sea surface winds from ERA-Interim, which covers the period 1979 to the present day, with a horizontal resolution of 0.75° × 0.75° and time interval of 6 h (Dee et al. 2011), are also used to show the generation and propagation of wind-forced Kelvin waves.

The SLA and sea surface wind are filtered by a 20–90-day band-pass filter, which are defined as intraseasonal anomalies in the following text. Positive intraseasonal events are defined as the peak of positive intraseasonal SLA greater than 1 standard deviation. The composite analysis is achieved by averaging each positive event in a time window of ±35 days. The lag correlations are calculated based on the band-passed anomalies, with the Student’s t-test used to represent the level of significance.

3. Results

The root mean square (RMS) of the intraseasonally band-passed SLA in the ITF region shows strong variation along the Sumatra and Java coast, with the largest RMS beyond 5 cm (Figure 1). These ISVs are attributable to the propagation of intraseasonal Kelvin waves along the coast that derive from the equatorial Indian Ocean. Therefore, we define some key areas and straits or passages to study the ISVs and their propagation in the ITF region. It should be noted that there is also a strong RMS in the southeastern Indian Ocean between 10 and 12°S, which is related to mesoscale eddies induced by the baroclinic instability of the South Equatorial Current (Feng and Wijffels 2002; Yang et al. 2015). The dynamics of these ISVs is beyond the scope of this paper because it is independent of the propagation of Kelvin waves.

Figure 2 shows the composite phase of positive intraseasonal events in each key area shown in Figure 1 using 20–90-day band-passed SLAs. The averaged period of ISVs along west coast of the Sumatra and in all straits is

![Figure 1. RMS of intraseasonal SLAs (20–90-day band-pass filtered) in the ITF region. Notes: Boxes show key areas along the pathways of the intraseasonal Kelvin waves. Black, blue, and green lines indicate Pathways A, B, and C, respectively, of intraseasonal Kelvin waves along the southwest coast of the Lesser Sunda Islands. The dashed green line indicates an uncertainty pathway.](image1)

![Figure 2. Composite phase of ISV in different straits and passages of the ITF.](image2)
around 25–30 days. The amplitude at the west coast of the Sumatra is 4 cm. The amplitudes in other areas varies from 5.5 cm south of Sunda Strait to 1.5 cm at Timor Passage, suggesting that the Kelvin waves have decayed during propagation, which may be attributable to the fact that the equatorial Kelvin waves are partly penetrating into each strait subsequently, and partly propagating along the southwest coast of the Lesser Sunda Islands during the propagation.

Figure 3 shows snapshots of the intraseasonal SLA and sea surface wind anomalies for the composite phase shown in Figure 2. Since the Kelvin waves bifurcate at Lombok Strait, we therefore define the ISVs of SLA at Lombok as the reference to show the propagation of intraseasonal Kelvin waves from the equatorial Indian Ocean to the Indonesian seas. The results using the ISVs in other straits as the reference show similar patterns and are thus omitted here. Day(0) indicates the peak of the intraseasonal SLA at Lombok Strait. On day(−20), before the Lombok peak, there are westerlies over the equatorial Indian Ocean that drive downwelling Kelvin waves to induce positive SLAs, which propagate eastward to reach western Sumatra on day(−15) (Figure 3(a) and (b)). Between day(−20) and day(+15), there are easterlies and negative SLAs in the Indonesian seas and south of Java. The equatorial Kelvin waves are trapped by the eastern boundary and then propagate along the southwest coast of Sumatra and Java, as revealed by the eastward moving positive SLAs from day(−10) to day(+5) (Figure 3(c)–(f)). It is also found that positive SLAs leap over the Sunda Strait on day(−10) and then arrive at Lombok on day(−5). The ensuing propagation is divided into three pathways: propagating eastward throughout the Sumba Strait and Savu Sea to reach the Ombai Strait (Pathway A); penetrating into Lombok and propagating northward to reach the Makassar Strait (Pathway B); and propagating southeastward along the southwest coast of the Sumba Island (Pathway C). It

Figure 3. Composite intraseasonal SLAs and sea surface wind anomalies over the equatorial Indian Ocean and Indonesian seas.
The lag correlation analysis for Pathway B shows a maximum correlation of 0.31/0.32 between the north of Lombok Strait in the Java Sea/Makassar Strait and Sumatra, with the former lagging by six and nine days, respectively (Figure 4(d)–(f)). This suggests that the phase speed for downwelling Kelvin waves propagating from Lombok to Makassar is around 1.69 m s\(^{-1}\)—in agreement with that of the second baroclinic Kelvin waves. The correlation between Sumba and Sumatra is 0.27 at the time lag of nine days, which is three days later than Lombok Strait, and suggests a phase speed of 1.96 m s\(^{-1}\) along Pathway C. The lag correlations between Timor and Sumatra are much smaller, and thus barely provide useful information for the propagation from Sumba to Timor.

The Hovmöller diagrams shown in Figure 5 indicate the eastward propagation of SLAs from the central equatorial Indian Ocean to the Ombai and Makassar straits and the Timor Passage along Pathways A, B, and C. The equatorial Kelvin waves take about 14 days to travel from the equatorial Indian Ocean (70°E) to the western coast of Sumatra, which are trapped by the eastern boundary of the Indian Ocean. The ensuing coastal Kelvin waves then propagate along the southwest coast of the Lesser Sunda Islands. After arriving at Lombok Strait, the Kelvin waves divide into three branches, with more energy intruding into the Makassar Strait than through the Sumba Strait to reach the Ombai Strait, evidenced by the fact that there are larger SLAs in the Makassar than Ombai Strait. The other branch
along Pathway C shows an eastward propagation terminating at Savu Strait, which is reminiscent of the lack of correlation in SLAs between the Timor Passage and equatorial western Sumatra.

4. Summary

Gridded SLA data provided by AVISO are used in this study to track the propagation of intraseasonal Kelvin waves in the ITF region. The large RMS of intraseasonal SLAs along the Sumatra and Java coast is closely related to the propagation of intraseasonal Kelvin waves that derive from the equatorial Indian Ocean. These Kelvin waves are further found to propagate along different pathways in the Lombok Strait (Figure 1). Through lag correlation analysis and Hovmöller diagrams of SLAs, we estimate the phase speed of the intraseasonal Kelvin waves for Pathways A, B, and C to be 1.91–2.86, 1.69, and 1.96 m s⁻¹, respectively—in agreement with the first two baroclinic modes of Kelvin waves.
Disclosure statement

No potential conflict of interest was reported by the authors.

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