Kelvin wave propagation along the southern coasts of Sumatra, Java, and Lesser Sunda Islands generated by Madden-Julian Oscillation (MJO) Phase 3

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Abstract. Kelvin wave propagation along the southern coasts of Sumatra, Java, and Lesser Sunda Islands generated by the Madden-Julian Oscillation (MJO) phase 3 (April 28 – May 6, 2004) has been studied by using sea surface height anomaly (SSHA) data simulated by a 1/8\textdegree global version of the HYbrid Coordinate Ocean Model (HYCOM), satellite-observed outgoing longwave radiation (OLR) data, and zonal wind data. In order to investigate the influences of MJO known as the intraseasonal oscillation (30 – 90 days), analysis of the data was carried out after 10–100 days band-pass filtering. The analysis results show that the intraseasonal oscillation SSHA along the coasts of Sumatra, Java, and Lesser Sunda Islands generally have a spectral peak at 91 days associated with the spectral peak of the MJO, except for Sunda Strait (61 days), southern coast of West Java (55 days), Sawu Sea (58 days), and Ombai Strait (100 days). Further analysis suggests that the MJO phase 3 generates Kelvin waves propagating eastward along the coasts of Sumatra, Java, and Lesser Sunda Islands with phase speed ranging from 2.56 to 3.85 m/s.

1. Introduction

In equatorial Indian Ocean (EIO), it has been well recognized that there are semiannual equatorial jets during the monsoon transitions (April-May and October – November), which flow eastward associated with downwelling Kelvin wave. This downwelling Kelvin wave is mainly triggered by abrupt changes in wind speed and direction along the EIO during the monsoon transitions [1]. Surface zonal velocity of the jets can reach more than 80 cm/s [2-5]. The equatorial downwelling Kelvin wave on reaching the eastern boundary of the EIO (Sumatra coast) bifurcates into two coastally trapped Kelvin waves in which one propagates northward and the other is southward. The southward Kelvin wave propagates along the western coast of Sumatra and the southern coasts of Java and Lesser Sunda Islands (LSI).

Previous studies [6-10] have reported that the downwelling Kelvin wave propagation along the coasts of Sumatra, Java and LSI influences the oceanic variabilities in Indonesian seas, such as variations of ocean temperatures and currents, sea level, thermocline depth, and the Indonesian through flow (ITF). For example, in the presence of semiannual coastal Kelvin waves originating in the EIO during the transitional monsoons, the eastward-flowing South Java Current (SJC) is enhanced and its deeper Undercurrent (SJUC) flows eastward [11-12, 8]. In addition to the semiannual time scale, Iskandar \textit{et al.} (2006)[13] have confirmed the existence of intraseasonal variations of the SJC and SJUC associated with propagation of the Kelvin waves, which are driven by strong 90-day winds over the central EIO (remote wind) and local wind. Moreover, one of the most prominent intraseasonal signals in tropical weather is the Madden-Julian Oscillation (MJO) characterized by an equatorial, eastward propagating pulse of cloud and rainfall on weekly to monthly timescales. MJO provides about 20% of total intraseasonal variability in the southeastern Indian Ocean and the maritime continent and it also reduces the annual mean ITF and the associated westward advection of
temperature [9]. It is important to obtain a better understanding of the MJO influence on the intraseasonal Kelvin wave propagation and its characteristics along the southern coasts of Sumatra, Java, and LSI both for scientific and practical reasons.

In this study, the MJO influence on the intraseasonal Kelvin wave propagation along the southern coasts of Sumatra, Java, and LSI was investigated by using sea surface height anomaly (SSHA) data simulated by the HYbrid Coordinate Ocean Model (HYCOM). This paper is arranged as follows. Material and method used in this study are described in Section 2. Next, the existence of the intraseasonal Kelvin wave propagation and its characteristics along the area of study generated by the MJO is discussed in Section 3. Furthermore, our conclusions are given in Section 4.

2. Material and Method
In this present study, the presence of downwelling Kelvin wave generated by the MJO along the southern coasts of Sumatra, Java, and LSI was investigated by using sea surface height anomaly (SSHA) data. An along-coast transect of study area and locations of the SSHA observation stations used in this study are shown in Figure 1. The SSHA data were derived from simulation results of a 1/8° global version of the HYCOM from April – June 2004. The simulated SSHA of the HYCOM version used in this study has been verified against that of the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data). Further details of numerical model description of this applied HYCOM version and its verification can be found in our earlier publications [14-15]. In addition, satellite-observed outgoing longwave radiation (OLR) and zonal wind data derived from NCEP (National Centers for Environmental Prediction) were used to support the analysis in this study. MJO index established based on the NCEP reanalysis from 2004 to 2006 and MJO phase diagram derived from http: bom.gov.au/climate/MJO were also used in this study to analyze energy spectrum of the MJO and to illustrate its progression through different phases, respectively.

Figure 1. The along-coast transect of study area and locations of the SSHA observation stations used in this study (marked by Points 1-13).

To describe the intraseasonal oscillation (30 – 90 days), a 10–100 days band-pass filter was applied to the data sets used in this study (e.g., SSHA, zonal wind, and OLR data). The intraseasonal characteristics of the datasets were then examined using spectral analysis to evaluate the dominant frequency for the MJO and SSHA. In addition, we have carried out a lagged correlation analysis on the 10–100 days band-pass filtered SSHA time series for each station pair (marked by Points 1-13 in Figure 1) to estimate the phase speed of the eastward propagating signal.
3. Results and Discussion

3.1. Intraseasonal signals

Figure 2 shows energy spectrum analyses of the MJO Index and the SSHA at the Stations 1-13 (as shown in Figure 1) within the intraseasonal timescale. It is shown that the MJO has a significant intraseasonal peak at 91 days. In general, the intraseasonal SSHA at the Stations 1-13 also have a spectral peak at 91 days corresponding to that of the MJO, except for Sunda Strait (Station 6; 61 days), southern coast of West Java (Station 7; 55 days), Sawu Sea (Station 12; 58 days), and Ombai Strait (Station 13; 100 days).

Figure 2. Energy spectrum analyses of the MJO index and the SSHA at the Stations 1-13 (Figure 1) within the intraseasonal time scale.

3.2. Propagation of intraseasonal Kelvin wave after the MJO peak passes through phase 3

The progression of the MJO through different phases during the period of 1 April 2004 to 30 June 2004 is illustrated in a MJO phase diagram as shown in Figure 3. It can be seen in the Figure 3 that the MJO peak occurred on May 5, 2004 (phase 3). In this study, we focus on the investigation of propagating Kelvin wave along the Sumatran coast and the Southern coasts of Java and LSI after the MJO peak passes through phase 3.

For further understanding of the intraseasonal Kelvin wave revealed due to the MJO influence, we have performed the time-space diagram of the OLR, zonal wind, and SSHA after 10–100 days band-pass filtering, as shown in Figure 4. The horizontal axis indicates the distance along the transect in Figure 1 from the west to the east. Figure 4a shows the eastward propagation of the MJO represented
by the OLR values and indicated by a green line before and after the MJO peak occurring in phase 3, whereas a green line in Figure 4b denotes the zonal wind speed associated with the eastward propagating MJO. The wind bursts associated with the MJO lead to downwelling coastal Kelvin waves represented by the positive SSHA values (Figure 4c), which propagate eastward along the Sumatran coast and the Southern coasts of Java and LSI as denoted by a green line in Figure 4c. This study clearly demonstrated the existence of Kelvin waves propagating eastward along the transect on the area of interest.

**Figure 3.** The MJO phase diagram for the period April–June 2004 (Source: bom.gov.au/climate/MJO). In this period, the MJO peak occurred in phase 3.

**Figure 4.** Time-distance diagrams of the 10–100 days of the band-pass filtered OLR, zonal wind, and SSHA during the period of April–June 2004. A green line in Figure 4a indicates the eastward propagation of the MJO before and after its peak occurring in phase 3 (Figure 3). Eastward propagation of the intraseasonal Kelvin wave generated by the MJO phase 3 is indicated by a green line in Figure 4c. Meanwhile, a green line in Figure 4b denotes the zonal wind speed associated with the eastward propagating MJO.
To further confirm the existence of propagating Kelvin waves, we have carried out temporal variations of the SSHA after the MJO peak passes through phase 3. As an example, we only show the temporal variations of the SSHA at Stations 4, 9, and 11 (Figure 5). It is shown in the Figure 5 that there are increases in the SSHA at the stations after the MJO peak passes through phase 3, which correspond to the propagating Kelvin waves.

![Figure 5](image_url)

**Figure 5.** The 10–100 days of the band-pass filtered SSHA after the MJO peak passes through phase 3 at Stations 4, 9, and 11 (Figure 1). The zeroth day is the day with a peak MJO index, which is marked with arrow in Figure 1.

| Stations | Time Lag (days) | Phase Speed (m/s) |
|----------|-----------------|-------------------|
| St.4-St.5 | 1               | 3.85              |
| St.4-St.8 | 4               | 3.85              |
| St.4-St.9 | 5.5             | 3.50              |
| St.4-St.11| 7               | 3.85              |
| St.4-St.12| 12              | 2.56              |

![Figure 6](image_url)

**Figure 6.** (a) Lagged correlation analysis of the 10–100 days of band-pass filtered SSHA at stations along the Sumatran coast and the Southern coasts of Java and LSI. A positive (negative) lag indicates that the SSHA variability in a previous station leads (lags) that in the latter station; (b) Estimated phase speed between station pairs and their respective time lags. The 99% significance level is approximately ±0.4.

To estimate the phase speed of the eastward propagating Kelvin waves due to the MJO influence, we have calculated a lagged correlation analysis on time series of the 10–100 days band-pass filtered SSHA for each station pair (Figure 6b). It is found that the phase speed ranges from 2.56 to 3.85 m/s. The speeds are slightly stronger than those of [16] for the intraseasonal Kelvin waves during boreal summer and winter with phase speed ranging from 1.5 to 2.86 m/s, which are attributable to remote wind over the EIO and the local alongshore wind forcing.
4. Conclusions

Influence of the MJO after its peak passing through phase 3 (May 5, 2004) on the intraseasonal Kelvin wave propagation along the southern coasts of Sumatra, Java, and LSI has been investigated by using the SSHA data simulated by the HYCOM. The present results show that the MJO has a significant intraseasonal peak at 91 days. In general, the 10–100 days of band-pass filtered SSHA at stations along the transect on the area of interest also have a spectral peak at 91 days corresponding to that of the MJO, except for Station 6 (the Sunda Strait; 61 days), Station 7 (the southern coast of West Java; 55 days), Station 12 (the Sawu Sea; 58 days), and Station 13 (the Ombai Strait; 100 days).

This study has revealed the presence of Kelvin wave propagating eastward along the area of study with the phase speed ranging from 2.56 to 3.85 m/s, which are attributable to the MJO forcing. In the current study, the MJO influence on the intraseasonal Kelvin wave has been studied only for the case of the MJO peak in phase 3 during transitional monsoon period (May 2004). To obtain a better understanding of the MJO influence on the generation of intraseasonal Kelvin wave and its propagating characteristics along the coasts of studied region, it is necessary to investigate influence of several MJO events, which occur during both southeast and northwest monsoons. For further study, this kind of study needs to be carried out as an extension of this research program.

Acknowledgments

Parts of this research were funded by P3MI ITB (Bandung Institute of Technology) Research 2018. We would like to thank the support given by the ITB.

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