The characteristics of the equatorial waves caused a record torrential rain event over western Sumatra

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Abstract. This study examined the cause of a record torrential rain event over the western coast of Sumatra Island in March 2016. The influence of atmospheric equatorial waves (EWs) and the characteristics of the EWs were investigated. Analysis of the Japanese 55-year Reanalysis data (JRA-55) and precipitation data from the Global Precipitation Measurement (GPM) satellite showed that the event was caused by the combined effects of Kelvin waves, equatorial Rossby waves, and westward inertia-gravity (WIG) waves. An examination of the characteristics of the EWs revealed that the Kelvin waves had longitudinal scales of ~6,000 km, with a period of ~6 days and phase speed of ~12 m s⁻¹, which was typical of the convectively coupled Kelvin waves in this region. The WIG waves had a scale of ~2,500 km, with a period of 2.5 days and a relatively fast phase speed of 12~13 m s⁻¹. Heavy precipitation occurred when an eastward Kelvin wave from the Indian Ocean encountered a westward inertia-gravity (WIG) over Sumatra Island. It was concluded that along with the Kelvin and equatorial Rossby waves, the WIG waves might have played a major role in the formation of the extreme precipitation event.

1. Introduction

A widespread torrential rain event occurred on the western coast of Sumatra Island (Fig. 1) in March 2016. Daily rainfall of 370.0 mm was observed at Padang Meteorological Observatory on 21 March (Fig. 2). The total amount of rain recorded at most observation points in the province of West Sumatra on the day exceeded 100 mm (not shown). The heavy rain resulted in one of the worst floods recorded in Padang City, the capital of the province.

Sumatra Island is located in the equatorial region, with the west of the island facing the Indian Ocean. Convective activity over the island is generally active throughout the year, particularly on the mountainous areas and over the sea off the west coast (e.g., Wu et al., 2003[1]; Hara et al., 2009[2]). Convection on and around the island exhibits a distinct diurnal cycle, with heavy rain frequently over the island in the afternoon and over the sea at night (e.g., Mori et al., 2004[3]; Kikuchi and Wang, 2008[4]). The afternoon convection is results from the development of the mixed layer and diurnal changes in the boundary-layer flow driven by strong solar irradiance (Wu et al., 2003[1]; 2009[5]).

The Madden-Julian Oscillation (MJO) is the most significant element of the 30- to 90-day intraseasonal variability in the tropical atmosphere (Madden and Julian, 1994[6]). The MJO significantly impacts rainfall variability over Sumatra Island and the surroundings (e.g., Kamimera et
al., 2012[7]; Peatman et al., 2014[8]; Birch et al., 2016[9]). The MJO increases (decreases) the probability of extreme precipitation events over the western and central parts of Indonesia by up to 70% (40%) (Muhamad et al., 2021[10]). Wu et al. (2017[11]) investigated the effects of an active phase of the MJO on the extreme precipitation event that occurred at Bengkulu on the western coast of Sumatra Island during the pre-Years of the Maritime Continent (YMC) field campaign. Their results showed that an active phase of the MJO combined with westward-moving diurnal convection from the mountains could cause torrential rain on the western coast of the island. However, the period during late March 2016 when the torrential rain event occurred on the western coast of the island was not in a local active phase of the MJO.

Convectively coupled equatorial waves (CCEWs), including Kelvin waves, equatorial Rossby waves, westward-moving mixed Rossby–gravity (WMRG) waves, and westward inertio-gravity waves, are an essential part of the atmospheric circulation in the tropical regions. They control a significant fraction of cloud and precipitation variability on timescales of days to intraseasonal periods in the equatorial region (Wheeler and Kiladis, 1999[12]). The interaction of Kelvin wave with equatorial Rossby wave assists the triggering and maintenance of convective activity within the MJO envelope, playing a critical role in the MJO propagation (Masunaga et al., 2006[13]; Masunaga, 2007[14]). Therefore, these waves have the potential to impact the occurrence of extreme heavy rain. Baranowski et al. (2016[15]) studied the scale interactions between atmospheric convectively coupled Kelvin waves (CCKWs) and the diurnal cycle over the Maritime Continent, showing CCKWs in phase with the diurnal cycle over Sumatra and Borneo has more significant precipitation anomaly. Kelvin waves have a significant influence on heavy rainfall over Indonesia, while westward-moving Mixed Rossby-Gravity and Kelvin waves impact Malaysia rainfall (Lubis and Respati, 2021[16]; Ferrett et al., 2020[17]). Although the impacts of CCEWs on rainfall extremes in Java, Indonesia has been investigated by Lubis and Respati (2021[16]), how different components of EWs combine to cause extreme event in different regions in the Maritime Continent and the features of CCEWs that cause extremely heavy rain in the Maritime Continent remain unclear.
The purpose of the present study was therefore to determine the factors that generated the record torrential rain that occurred over the western coast of Sumatra Island on 21 March 2016, by investigating the atmospheric EW activity and the characteristics of the EWs during the heavy rain event using a variety of data sets, including surface meteorological observations and satellite observations.

2. Data and analysis
In this study, Japanese 55-year Reanalysis (JRA-55) data were used to examine the activities of atmospheric EWs before and during the heavy rain event. The Japan Meteorological Agency (JMA) conducted the JRA-55 Reanalysis project using a sophisticated data assimilation system based on an operational system installed in December 2009 (Kobayashi et al., 2015[18]). The dataset contains global data on a 1.25° × 1.25° latitude-longitude grid and 37 pressure levels from the surface to 1 hPa every 6 hours.

A space-time spectral filtering analysis was performed to extract EW components from the JRA-55 horizontal wind fields. The procedure used in this study followed that proposed by Wheeler and Kiladis (1999[12]). Space-time spectra were calculated from the 128-day data record, in which included the 2016 February-April period. Before the space-time spectral analysis, the daily anomaly time series of wind data from the first three harmonics from the original 365-day time series was calculated to remove the seasonal cycle. In order to extract EW components, the daily anomaly time series were analyzed separately by a fast Fourier transform in both the zonal wavenumber and time domain. A time series of each CCEW component was obtained by filtering in a specific wavenumber-frequency domain. The Kelvin filtering was conducted in the wave number-frequency domain of zonal wave numbers 1–14, period of 2–25 days, and equivalent depth of 8–90 m; the Rossby wave filtering was conducted within a domain of zonal wave numbers 1–14 and period of 10–42 days (Wheeler and Kiladis, 1999[12]).

In addition to the JRA-55 Reanalysis data, precipitation data sets obtained from the Global Precipitation Measurement (GPM) satellite were also used in this study. The three-hourly combined microwave-IR estimates (with gauge adjustment), the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) data set (version 7), with a 0.1° × 0.1° latitude-longitude grid and 3-hour time resolution was used. The Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset was also used in part of this work. The MSWEP dataset optimally merges a wide range of the gauge, satellite, and reanalysis data to provide reliable precipitation estimates over the entire globe with 0.1° × 0.1° latitude-longitude and 3-hour temporal resolution (Beck et al., 2019[19]).

A spatio-temporal wavelet transform (STWT) analysis of the 3-hourly GPM data was performed. The STWT enabled us to document the convective signals in terms of CCEWs in great detail through the localization of space-time spectra at any given location and time (Kikuchi and Wang, 2010[20]), whereas the conventional two-dimensional Fourier transform approach (Wheeler and Kiladis, 1999[12]) provides averaged spectrum over space and time. The STWT analyses in this study followed the approach of Kikuchi et al. (2018[21]). First, we pre-processed the data by removing the linear trend and the first three harmonics of the annual climatological cycle. The data were then separated into symmetric and antisymmetric components about the equator. Spectra were calculated at each latitude and averaged over 15°S and 15°N. For more details about the STWT analysis please refer to Kikuchi and Wang (2010[20]).

3. Origin and horizontal structure of an equatorial Kelvin wave and an equatorial Rossby wave in March 2016
The oceanic and atmospheric features in March 2016 indicated weakening strong El Nino conditions. During late March, as the active phase of the MJO propagated over the western Pacific (Wheeler and
Hendon, 2004[22], the intraseasonal variability interfered constructively with the ENSO signal, leading to enhanced convection over the western Pacific, and suppressed convection across the equatorial Indian Ocean and the western Maritime Continent. Meanwhile, the Indian Ocean Dipole (IOD) mode index (Saji et al., 1999[23]) indicated a neutral IOD phase in March 2016. Sea surface temperatures were close to normal across the tropical Indian Ocean, sea surface temperatures to the west of Sumatra Island was relatively high, as usual.

To investigate the activities of atmospheric EWs before and during the heavy rain event on the western coast of Sumatra Island, Kelvin and Rossby wave components were obtained by filtering the JRA-55 horizontal wind fields for March 2016 in a specific wavenumber-frequency domain.

**Figure 3.** Kelvin-wave filtered potential velocity anomalies at 850 hPa, their corresponding divergent wind vectors, and total precipitation (Multi-Source Weighted-Ensemble Precipitation: MSWEP) (shaded) for 18–21 March 2016. Kelvin filtering: wavenumbers 1–14, period of 2–25 days, and equivalent depth of 8–90 m. Positive (negative) values of the velocity potential anomalies are indicated by red (blue) contours at intervals of $3 \times 10^6$ m$^2$s$^{-1}$.

**Figure 4.** Rossby wave filtered stream function anomalies at 850 hPa, their corresponding wind vector anomalies, and total precipitation (Multi-Source Weighted-Ensemble Precipitation: MSWEP) (shaded) for 18–21 March 2016. Rossby wave filtering: wavenumbers 1–14 and period of 10–42 days. Red (blue) contours indicate positive (negative) values of the stream function anomalies. The contour intervals are $5.0 \times 10^6$ m$^2$s$^{-1}$. 
The Kelvin-wave filtered potential velocity anomalies at 850 hPa and corresponding divergent/divergent wind vectors for 18–21 March 2016 are plotted in Figure 3, together with the MSWEP-based precipitation accumulation for the 24 h period on each day. Because the velocity potential is proportional to large-scale convergence/divergence, it can be used to track regions of lower-level convergence/divergence, where organized convection is enhanced/suppressed. From 18 March, westerly anomalies and high values of velocity potential over the western Indian Ocean were moving eastward, corresponding to the regions in which precipitation was enhanced. This suggests an eastward-moving convectively coupled equatorial Kelvin wave was active during this period. As the Kelvin wave propagated eastward towards Sumatra Island, it made landfall on 21 March on the western coast of the island. The propagation speed of the wave was estimated to be approximately 12 m s⁻¹.

Because the structure of equatorial Rossby (ER) waves is dominated by the rotational component of wind (Kiladis and Wheeler, 1995 [24]), the Rossby wave filtered stream function anomalies at 850 hPa, corresponding wind vector anomalies, and total precipitation (MSWEP) for the 24 h period on each of the days of 18–21 March 2016 are shown in Figure 4. An equatorial Rossby wave was identified as cyclonic vortex twins on either side of the equator in the 850 hPa wind field anomalies. The cyclonic circulation anomaly in the southern hemisphere was more robust than its northern hemisphere counterpart. The Rossby waves propagated westward from the western Pacific in early March 2016 (not shown). The propagation speed of the waves was estimated to be approximately 2–3 m s⁻¹. Westerly wind anomalies were evident in the near-equatorial region between the cyclonic vortex twins. The westerly wind anomalies associated with the Kelvin and Rossby waves superimposed near western Sumatra Island on 21 March, resulting in a persistent westerly along the coast. It is considered that the strong westerly wind should have transported a large amount of water vapor from the Indian Ocean to the Coast of Sumatra Island and created a strong lower-level wind convergence along the coast. In consequence, an extreme precipitation event occurred on 21 March 2016 over the western coast of the island when the EWs propagated over Sumatra Island.

4. Occurrence of westward inertio-gravity (WIG) waves and their effect on the torrential rain event

Figure 5 shows the longitude-time section of the GPM satellite derived precipitation averaged over the equatorial band, 5°S and 5°N, during 11 March to 1 April 2016. The eastward propagation of the equatorial Kelvin wave from the western Indian Ocean during the late half of March 2016, as described in the previous section, was also clearly seen in the satellite-derived precipitation. As mentioned above, the Kelvin wave was estimated to have moved eastward at a phase speed of 12 m s⁻¹. Previous studies have shown that convectively coupled Kelvin waves are frequently observed over the Indian Ocean, within and outside of an active MJO envelope (Roundy, 2008[25]; Kikuchi et al., 2018[21]). Kelvin waves typically propagate more slowly over the Indian Ocean (12–15 m s⁻¹) than in other regions (Yang et al., 2007[26]; Kikuchi et al., 2018[21]). Therefore, the Kelvin wave occurred in the latter half of March was typical of convectively coupled Kelvin waves in this region. In addition to the eastward propagating disturbances, higher frequency westward propagating disturbances were evident (blue broken lines). It is important to note that heavy precipitation occurred over the western coast of Sumatra Island on 21 March, when the eastward disturbances intersected with westward disturbances originated from western Kalimantan Island.

To inspect the space-time scales of these eastward and westward disturbances, the local symmetric STWT spectra are shown in Figure 6. The spectrum indicates that eastward signals appeared as a peak at 0.16 cpd (i.e., cycles per day, or period of around 6 days) centered on eastward wave number 6 (corresponding to a wavelength of around 6,000 km) (green dot). These were identified as equatorial Kelvin waves. In addition to the Kelvin waves, clear westward propagating signals were also identified in the local spectrum, as a strong peak at 0.4 cpd (or period of 2.5 days) centered on
westward wave number 14 (wavelength of around 2,500 km) (blue dot). From the STWT spectrum, the westward disturbances were identified as quasi-2-day WIG waves (Takayabu 1994[27]; Chen et al. 1996[28]; Takayabu et al. 1996[29]). However, these westward propagating signals were not evident in the JRA-55 Reanalysis wind field, due to the low spatio-temporal resolution of the reanalysis data used in this study.

Because the extreme precipitation occurred over the western coast of Sumatra Island when convection associated with the eastward Kelvin waves intersected with the WIG waves, it was considered that along with the Kelvin and equatorial Rossby waves, the WIG waves might have played a critical role in formation of the extreme rain event. During the boreal winter, westward propagating convective disturbances with periods of about two days are frequently observed in the equatorial western Pacific (Takayabu 1994[27]). This wave type appears to be most prevalent in the active phase of the MJO (Nakazawa 1988[30]; Hendon and Liebmann 1994[31]). However, it is still unclear whether the occurrence of the quasi-2 day disturbances over land in the Maritime Continent is similar to that over the Pacific Ocean.

**Figure 5.** Hovmoller diagrams of the Global Precipitation Measurement (GPM) satellite-derived precipitation averaged over 5°S to 5°N from 11 March to 1 April 2016.

**Figure 6.** Local spatio-temporal wavelet spectra along 100.375°E from 15°S to 15°N for 1800 UTC 21 March 2016. Each spectrum was normalized by its corresponding background spectrum. Only significant values at the 90% level are shaded. The e-folding space-time scales of each wave component when the local spectra were calculated are denoted by dashed circles in Fig. 5. The frequency in the ordinate is cycles per day (cpd).

Inspection of satellite infrared (IR) imagery indicated that strong convection occurred regularly during the late afternoon to nighttime over Sumatra Island and Kalimantan Island before the arrival of the eastward-moving Kelvin wave in mid-March 2016 (not shown). Widespread strong convection occurred over Kalimantan Island in the evening on 20 March. Previous studies have shown that when
the MJO main convective envelope is over the Indian Ocean, rainfall and its diurnal cycle over the land in the Maritime Continent reach their maxima due to an increase in the atmospheric instability caused by intense solar insolation in the clearer skies and moistening environment (e.g., Rauniyar and Walsh, 2011[32]; Peatman et al. 2014[8]; Birch et al. 2016[9]). In the case being studied, the diurnal convection on Kalimantan Island was probably enhanced when the Kelvin wave was propagating over the eastern Indian Ocean. Then, WIG waves might be excited by the energetic diurnal convection on the island.

Liebmann et al. (1997[33]) proposed a mechanism for the generation of two-day convective disturbances in the form of inertio-gravity waves initiated by convective activity within the envelope of a supercluster. They argued that because the eastward movement of the supercluster, which usually occurs in association with Kelvin waves (Nakazawa, 1988[30]), is about the same speed as the phase speed of the westward-moving inertial gravity wave, which is diurnally excited, enhanced convection tends to be projected onto two-day WIG waves. Because convective activity over the Maritime Continent is generally active, westward propagating convective disturbances are presumably excited by the vigorous diurnal convection over the islands. In the present study, the westward disturbances (WIG waves) had pronounced diurnal cycle peaks (Fig. 5). The phase speed of the eastward Kelvin waves and the westward inertial-gravity waves were both about 12 m s⁻¹. The WIG wave from western Kalimantan Island took about 24 h to arrive at the western coast of Sumatra Island, working together with the Kelvin waves and equatorial Rossby waves to cause the record torrential rain event.

Meanwhile, previous studies have shown that Kelvin waves tend to encompass WIG waves as their internal structure (e.g., Nakazawa, 1988[24]; Liebmann et al., 1997[33]). It is considered that the relatively larger-scale components (Kelvin waves, equatorial ER waves and sometimes the MJO) defines large-scale environment in which extreme precipitation events occur. On the other hand, extreme precipitation events are associated with more closely with synoptic-scale wave components such as WIG waves. These synoptic-scale components are, for the most part, intimately tied to mesoscale convective systems, resulting in extreme precipitation events over Sumatra Island. To clarify the role of the WIG waves in the formation of torrential rain, additional case studies of the behavior of the WIG waves and their interaction with other disturbances are needed.

5. Summary
This study examined the causes of the recorded torrential rain event over the western coast of Sumatra Island in March 2016. Because the extreme rain event occurred not in a local active phase of the MJO, the activity of atmospheric equatorial waves (EWs) was investigated, using data from the JRA-55 reanalysis data and precipitation data from various sources. A space-time spectral filtering analysis was performed to extract EW components from the JRA-55 horizontal wind fields. The results showed that the event was caused by the superimposition of equatorial Kelvin waves, equatorial Rossby waves, and westward inertio-gravity (WIG) waves on the island.

A spatio-temporal wavelet transform (STWT) analysis of the 3-hourly GPM precipitation data showed that the Kelvin waves from the Indian Ocean had longitudinal scales of ~6,000 km, with a period of ~6 days and moving speed of ~12 m s⁻¹, which were typical of the convectively coupled Kelvin waves in this region. The extreme precipitation occurred when the Kelvin wave encountered a WIG wave. The WIG waves had a zonal wavelength of 2500 km, with a relatively fast phase speed of 12–13 m s⁻¹ and a period of 2.5 days. It was concluded that, along with the Kelvin waves and the equatorial Rossby waves, the WIG waves were a critical factor in the formation of the extreme rain event on the western coast of Sumatra Island.

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