Phase locking between atmospheric convectively coupled equatorial Kelvin waves and the diurnal cycle of precipitation over the Maritime Continent

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2016GL069602

Convectively coupled Kelvin waves (CCKWs) are a major component of the tropical atmospheric circulation, propagating eastward around the equatorial belt. Here we show there are scale interactions between CCKWs and the diurnal cycle over the Maritime Continent. In particular, CCKW packets that pass a basepoint in the eastern Indian Ocean at 90°E between 0600–0900 UTC subsequently arrive over Sumatra in phase with the diurnal cycle of convection. As the distance between Sumatra and Borneo is equal to the distance travelled by a CCKW in one day, these waves are then also in phase with the diurnal cycle over Borneo. Consequently, this subset of CCKWs has a precipitation signal up to a factor of 3 larger than CCKWs that arrive at other times of the day, and a 40% greater chance of successfully traversing the Maritime Continent.

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1. Introduction

The Maritime Continent is the archipelago between the Indian and Pacific Oceans, including Indonesia, Malaysia, Phillipines and New Guinea. It lies at the heart of the Indo–Pacific warm pool, the largest area of very high sea surface temperatures (SSTs) on Earth. As a result, it is a major centre of tropical atmospheric convection and precipitation. The Maritime Continent is the central pivot of the Asian–Australian monsoon system [*Chang et al.,* 2005]. Above the Maritime Continent rises the ascending branch of the Walker circulation, fluctuations of which are major ingredients of El Niño events and the Indian Ocean Dipole [*Vinayachandran et al.,* 2007]. Atmospheric convection over the Maritime Continent provides the heat source for teleconnections that influence global climate [*Neale and Slingo,* 2001].

However, the difficulties of representing convective processes in atmospheric models, and their multi-scale interactions in the tropics, combined with the land-sea contrasts and steep, high topography over the Maritime Continent, make simulation and prediction of precipitation over this region particularly problematic [*Love et al.,* 2011; *Birch et al.,* 2015].

Precipitation over the Maritime Continent is dominated by the diurnal cycle [*Yang and Slingo,* 2001] , with deep convection developing over the islands during the afternoon and evening, associated with sea breeze circulations. During the early morning, this precipitation moves offshore [*Nesbitt and Zipser,* 2003]. Other modes of tropical variability such as the Madden–Julian Oscillation (MJO) have high amplitude over the Maritime

Continent and interact strongly with the diurnal cycle of precipitation there [*Peatman et al.,* 2014].

Convectively coupled equatorial waves [*Kiladis et al.,* 2009] are also prominent modes of tropical atmospheric variability. In particular, convectively coupled equatorial Kelvin waves (CCKWs) propagate eastwards along the equator with phase speeds in the range 10–15 m s^{-1}, and have a high amplitude over the Maritime Continent [*Roundy,* 2008]. These CCKWs are an important part of the tropical circulation. As well as their "own" precipitation, they form part of the convective envelope of MJO events [*Nakazawa,* 1988; *Gottschalck et al.,* 2013]. There are also significant ocean-atmosphere interactions with surface fluxes from CCKWs cooling the ocean, which again has an impact on MJO events [*Baranowski et al.,* 2016].

However, the nature of the direct interaction of CCKWs with the Maritime Continent and its diurnal cycle of convection is a knowledge gap. Because of their relatively high phase speed and spatially localised structure, the convectively active part of an individual CCKW passes through a particular longitude quickly, with a time scale of approximately one day [*Baranowski et al.,* 2016]. Hence, the *time of day of the arrival of a CCKW* over the Maritime Continent may be important for its subsequent interactions and development. If it arrives in phase with the convectively active part of the diurnal cycle over the Maritime Continent, the CCKW and diurnal cycle may enhance each other. If the CCKW arrives during the convectively suppressed part of the diurnal cycle, the interaction may be weak. We also note that *the longitudinal spacing between the two equatorial islands of Sumatra and Borneo is approximately the distance that a CCKW travels in one day.*

Hence, if a CCKW arrives in phase with the diurnal cycle over Sumatra, it will also be in phase with the diurnal cycle over Borneo when it arrives there one day later. This provides a potential mechanism for phase locking of CCKWs to the diurnal cycle over the Maritime Continent. In this paper, we explore these hypotheses and investigate the interactions between CCKWs and the diurnal cycle over the Maritime Continent.

2. Data and methodology

Precipitation was analysed using the Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation product [*Huffman et al.,* 2007]. The data used were 3-hourly maps on a $0.25° \times 0.25°$ grid from 1 January 1998 to 31 December 2013.

A Lagrangian database of CCKWs was constructed to analyse the interactions between the CCKWs and the diurnal cycle over the Maritime Continent. The details of the methodology are described in *Baranowski et al.* [2016] and summarised here. First, following the methodology of *Wheeler and Kiladis* [1999], the TRMM precipitation data were averaged over the 2.5°S–2.5°N equatorial band. Then a two-dimensional Fourier transform in longitude and time was performed to transform to wavenumber–frequency space. Filtering was applied to isolate the CCKW signal, and the data reverse-transformed back to longitude–time space. Finally, the Lagrangian CCKW database was then constructed by identifying coherent eastward-propagating precipitation maxima in this Kelvin wave-filtered Hovmöller data set. Each CCKW in the database consists of a trajectory: a set of time-longitude paired values, indicating the central position (longitude) of the CCKW at each time (with 3 hr resolution). In total, 1,840 CCKW trajectories were identified in the 15-year data set.

3. Diurnal cycle over the Maritime Continent

The dominance of the diurnal cycle in precipitation over the islands and seas of the Maritime Continent can be most clearly seen by comparing maps of mean precipitation at opposite phases of the diurnal cycle. At 0300 UTC, which corresponds to mid-morning (0900–1100 local solar time, LST) across the Maritime Continent, the islands of the western Maritime Continent (Java, Sumatra, Borneo, Sulawesi), and peninsular Malaysia are almost rain-free, with 3-hour average precipitation rates near 2.5 mm day^{-1} (Figure 1a). By contrast, the surrounding coastal seas have high precipitation, above 10 mm day^{-1}.

Twelve hours later, at 1500 UTC (approximately 2100-2300 LST), deep convection has developed over the islands (Figure 1b), and the 3-hour mean rainfall rate is above 15 mm day^{-1}. Simultaneously, precipitation over the surrounding coastal seas has decreased to below 5 mm day^{-1}.

The diurnal cycle of precipitation over the open Indian Ocean to the west of the Maritime Content is much weaker, with mean precipitation remaining fairly constant throughout the day.

The development of the diurnal cycle and land–sea contrast in precipitation over the Maritime Continent is shown using a "diurnal cycle Hovmöller diagram", i.e., a longitude–time diagram of the mean diurnal cycle, averaged over the equatorial band (Figure 1c). In particular, precipitation develops over the mountains of western Sumatra (100°E) during the afternoon, then propagates westward over the adjoining sea during the night. Similarly, afternoon convection builds over Borneo (110–115°E) and then moves offshore by a combination of propagation westward, and a "jump" eastward to 118°E.

4. Convectively coupled equatorial Kelvin waves

4.1. Case study during CINDY–DYNAMO

A case study of the interaction between CCKWs and the diurnal cycle of precipitation over the Maritime Continent is shown for a two-week period during November–December 2011 (Figure 2). This was during the CINDY–DYNAMO field experiment [*Yoneyama et al.,* 2013]. The two eastward-propagating precipitation signals indicated by the black lines in Figure 2 have been previously identified as two CCKWs, which themselves formed part of the active phase of an MJO event [*Gottschalck et al.,* 2013]. Precipitation associated with the first of the CCKWs stalls over Sumatra and this trajectory terminates within the Maritime Continent. The second trajectory propagates through the region.

The mean diurnal cycle is shown by the 12.5 mm day^{-1} red contour, reproduced from Figure 1c and repeated every day in Figure 2. The passage of the CCKWs over the Maritime Continent shows strong interaction with the diurnal cycle. For example, on 23 and 24 November, before the arrival of the first CCKW, there is almost no precipitation (i.e., no blue shading) and no diurnal cycle at Sumatran longitudes (96–102°E) to match the mean diurnal cycle there (red contour).

On 25 November, the envelope of precipitation associated with the first CCKW arrives over Sumatra. However, the response over the Maritime Continent is not one of continuous precipitation throughout the day. Instead, the diurnal cycle itself is strongly enhanced. On 25 November, precipitation over Sumatra develops during the day to a 3-hour average rate of over 60 mm day^{-1}, and then propagates westward overnight over the sea, in phase with the mean diurnal cycle shown by the red contour on that day (which is a precipitation rate of only 12.5 mm day^{-1}). Hence the diurnal cycle over Sumatra on 25 November is enhanced from the mean by a factor of over 5. Overnight the precipitation over Sumatra drops back to near zero, and then the next two days (26 and 27 November) also experience a very strong diurnal cycle. A similar response is seen over Bornean longitudes (110–115°E). Prior to the arrival of the CCKW envelope (up to and including 26 November) there is almost zero precipitation and no diurnal cycle. On 27 and 28 November, with the arrival of the CCKW, the diurnal cycle is strongly enhanced.

After the first CCKW has passed (28 November for Sumatra, and 29 and 30 November for Borneo), there is a suppression of precipitation and the diurnal cycle. With the arrival of the second CCKW, the mean precipitation and diurnal cycle are enhanced again, especially over Borneo.

Hence, there are strong interactions between the passage of CCKWs over the Maritime Continent and the diurnal cycle of precipitation over the land and sea. The main interaction appears to be one way, with the previously existing CCKW propagating eastward from the Indian Ocean and modulating the diurnal cycle over the Maritime Continent. However, there may also be scope for an interaction in the opposite sense. The precipitation that develops over Sumatra on 26 November, within the envelope of the first CCKW, propagates westward as usual over the neighbouring seas. But instead of petering out, it continues westward to 83°E over the next two days and influences precipitation as part of the second CCKW.

4.2. Composite mean CCKW

The case study in Section 4.1 showed intriguing interactions between the passage of CCKWs and the diurnal cycle of precipitation over the Maritime Continent. In this section, a statistical analysis of the CCKWs is presented, to allow for a systematic evaluation of these interactions.

CCKW trajectories from the Lagrangian database were selected if they passed through the region immediately "upstream" (in the sense of an eastward-propagating wave) of the Maritime Continent, beginning west of 85°E and ending east of 100°E. In total, 447 trajectories satisfied this criterion and were included in the analysis. Within this domain, a base point was chosen to be at 90° as this is close to the Maritime Continent, while being outside of the direct influence of its diurnal cycle. Lagged composite daily means of these CCKW events were constructed, such that day 0 corresponds to the time when the CCKW passes through the upstream base point over the Indian Ocean at 90°E.

On day −1 (Figure 3a), the active precipitation centre of the CCKW is over the central Indian Ocean (west of 85°E) and the precipitation over the Maritime Continent is near normal. On day 0 (Figure 3b), the CCKW has propagated eastward, and its precipitation anomaly is a maximum at 90°E, by design of the analysis. On subsequent days, the CCKW continues to propagate eastward, until by day 4 (Figure 3f), it has crossed the Maritime Continent.

The strongest precipitation signals are observed on day 0. However, this is an artifact of the composite mean procedure. The CCKWs are all in phase on day 0, by design. At higher lags, CCKWs with slightly different phase speeds will begin to destructively interfere when averaged, reducing the strength of the mean signal.

The net anomalous precipitation over the Maritime Continent associated with CCKWs was then calculated by averaging over the life time of each CCKW event (from day −1 to day 4), and then averaging over latitude (the 2.5°S–2.5°N equatorial band). There is a clear longitudinal dependence to this CCKW-associated precipitation (thick black line in Figure 4). The maximum precipitation associated with the CCKW is between 90–97°E (the sea west of Sumatra, consistent with the anomaly maps in Figure 3). There is then a relative minimum in precipitation at 104°E over eastern Sumatra, before net CCKW precipitation increases again over Borneo (110–115°E).

5. Phase locking between diurnal cycle and Kelvin waves

Given the relatively narrow time window of approximately 1 day that a CCKW is active for at any particular longitude (Figure 3), it is possible that any interaction between the CCKW and the diurnal cycle is dependent on the *time of the day at which the CCKW arrives over the Maritime Continent*. If the peak of the CCKW arrives during the convectively active phase of the diurnal cycle, it might be expected to constructively interact with the diurnal cycle. Conversely, if the CCKW peak arrives during the convectively suppressed phase of the diurnal cycle, its interaction with the diurnal cycle may be weak. Also, given that the longitudinal distance from Sumatra to Borneo is approximately equal to the distance a CCKW propagates in one day, then if a CCKW arrives at a favourable time for convection over Sumatra, it will also arrive at a favourable time over Borneo, and a phase locking may emerge.

To investigate this, the 447 selected CCKW events from Section 4.2 were further subsetted, depending on the time of day of their arrival at the base point at 90°E, to the west of the Maritime Continent. Based on their arrival time, each CCKW event was allocated to one of four 6-hour bins: 0000 or 0300 UTC; 0600 or 0900 UTC; 1200 or 1500 UTC; 1800 or 2100 UTC. The distribution of events was even, with 102, 117, 120 and 108 trajectories in each bin, respectively. Hence, there was no preferred time of day for the arrival of the CCKW events at the western edge of the Maritime Continent.

The net anomalous precipitation contribution from CCKWs arriving at 90°E in the 0600–0900 UTC window is shown by the green dotted line in Figure 4. It is up to 50% higher than the average contribution from all CCKWs (black line) over the islands of the Maritime Continent. This is consistent with CCKW dynamics. A CCKW passing 90°E at 0730 UTC (middle of the 0600–0900 UTC bin), and propagating eastward with a typical phase speed of 10–15 m s^{-1} will arrive at 97°E, just offshore of western Sumatra, at 2200–0500 UTC (green dotted line in Figure 5). This is at the time of maximum precipitation in the diurnal cycle here (shading in Figure 5). Hence, CCKWs arriving in this window are at the right time to constructively enhance the diurnal cycle, and therefore the mean precipitation offshore of Sumatra. These CCKWs then go on to enhance the diurnal cycle and precipitation over Borneo (110–115°E; green dotted lines in Figures 4 and 5), consistent with the phase locking hypothesis described above.

Conversely, the net precipitation contribution from CCKWs arriving 6 hours earlier (the 0000–0300 window; red dashed line in Figure 4) is very different. Over Sumatra, these CCKWs are not in phase with the diurnal cycle and have a precipitation signal there similar to that of the mean CCKW (black line). However, over Borneo, although these CCKWs do still have a net positive precipitation anomaly, it is much weaker than the 0600–0900 CCKWs. The mean trajectory of the 0000–0300 CCKWs (red dashed line in Figure 5) is only plotted up to 102°E. East of this point, the anomalies are very weak, and the associated spread of the trajectories in this subset becomes so large that their mean position within the diurnal cycle becomes meaningless.

The effect of the phasing of the CCKWs with the diurnal cycle on the longevity of the CCKWs was then examined, by testing what fraction of CCKWs successfully traversed the Maritime Continent (i.e., terminated east of 125°E). 47% of the 0600–0900 CCKWs (in phase with the diurnal cycle) successfully traversed the Maritime Continent, while only 33% of the 0000–0300 CCKWs (out of phase with the diurnal cycle) managed to.

The two other CCKW subsets (1200–1500 and 1800–2100 arrivals at 90°E; not shown) are intermediate in behaviour. To test the robustness of the analysis, the data set was split into two (1998–2005 and 2006–2012). Each independent data set was analysed separately. The results were qualitatively similar.

The case study examined earlier is consistent with this composite behaviour. The first CCKW in the case study (Figure 2) arrives at 90°E outside the 0600–0900 UTC window. It is not exactly in phase with the diurnal cycle and peters out between Sumatra and Borneo. However, the second CCKW arrives at 90°E inside the 0600–0900 UTC window. This wave interacts strongly with the diurnal cycle and successfully crosses the Maritime Continent.

6. Discussion

We have shown a systematic impact on CCKWs over the Maritime Continent that depends on the time of day of their arrival. CCKWs that pass a basepoint over the Indian Ocean at 90°E are in phase with the diurnal cycle over Sumatra and Borneo. Compared with CCKWs that arrive 6 hours earlier, these favoured waves have a precipitation signal that is up to three times larger, and they are 40% more likely to successfully traverse the Maritime Continent. These scale interactions between the diurnal cycle and CCKWs are an example of rectification in the climate system.

The magnitude of the phase locking effect varies throughout the year. The difference between the two groups is largest during boreal fall (SON) and winter (DJF) seasons and weaker during boreal spring (MAM) and summer (JJA) seasons, nevertheless this effect never reverses – the 0600–0900UTC group has always larger precipitation anomaly than 0000–0300 UTC group. The seasonal differences in the phase locking between CCKWs and the diurnal cycle are likely due to seasonal changes in the background circulation and CCKWs characteristics. That will be a subject of our further studies.

Our analysis focuses on CCKW events which propagate along the equator. However, there are other events which propagate northward or southward along the coast of Sumatra. For example *Ridout and Flatau* [2011] described a CCKW event, which propagated northward along a dynamic equator (a 0 planetary vorticity line). In boreal winter season some of the events propagate southward along the coast of Sumatra due to interaction with topography [*Guo et al.,* 2014]. Therefore it is possible that we underestimate number of CCKWs, which propagated across the Maritime Continent, because they detoured part or the entire region. However, sensitivity tests with respect to the meridional extend of the equatorial band used in trajectory calculations (see Supplementary Information) indicate that over Indian Ocean and Maritime Continent this potential underestimation is small. Therefore it may have only limited effect on the results.

The dynamical nature of these interactions between CCKWs and the diurnal cycle are unknown. However, the forthcoming international Years of the Maritime Continent field experiment should provide a comprehensive observational data set that can be used to tackle this problem. The ability of atmospheric models to capture these interactions, and particularly their dependence on horizontal resolution and whether convection is parameterised or explicitly resolved will also be of great interest.

Acknowledgments. DBB has been supported by Office of Naval Research Global NICOP program (award N62909-15-1-2021 to the University of Warsaw). MKF has been supported by the Chief of Naval Research through the NRL Base Program, PE 0601153N. PJF has been supported by ONR DRI (Unified Physical Parameterization for Extended-Range Prediction). Development of the Kelvin wave trajectories database has been supported by Polands National Science Centre (Narodowe Centrum Nauki; decision no. 2012/07/N/ST10/03303). Analysis of the DYNAMO field campaign data have been supported by the Office of Naval Research under Program Element 601153N.

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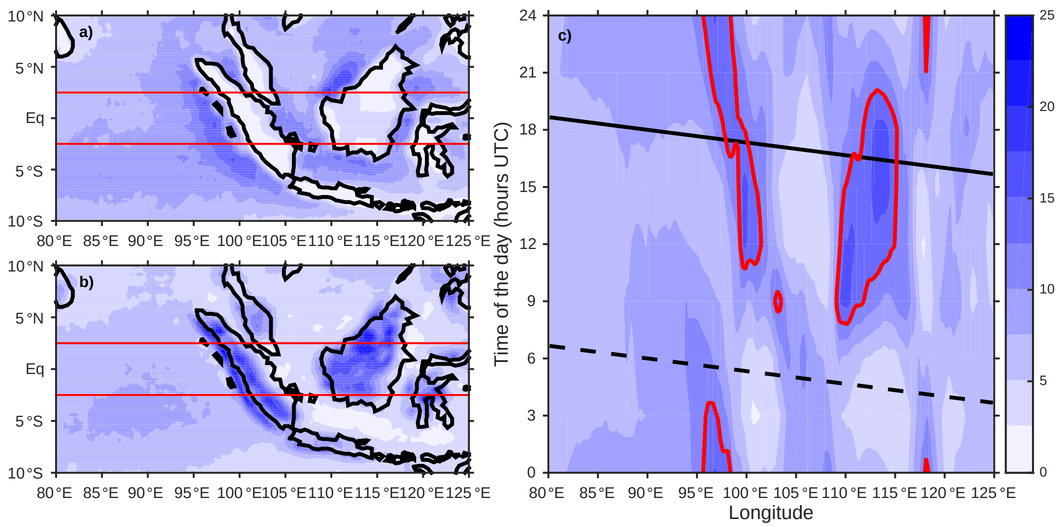

Figure 1. Diurnal cycle of precipitation over the Maritime Continent. Mean precipitation rate (mm day^{-1}; see legend for shading) at (a) 0300 UTC (approximately 0900–1100 LST), (b) 1500 UTC (approximately 2100-2300 LST). The red lines at 2.5°S and 2.5°N indicate the equatorial band used in the further analysis. (c) Mean diurnal cycle of precipitation rate averaged over the equatorial band (2.5°S–2.5°N). The 12.5 mm day^{-1} contour is highlighted in red. The black solid (dashed) line indicates local midnight (noon).

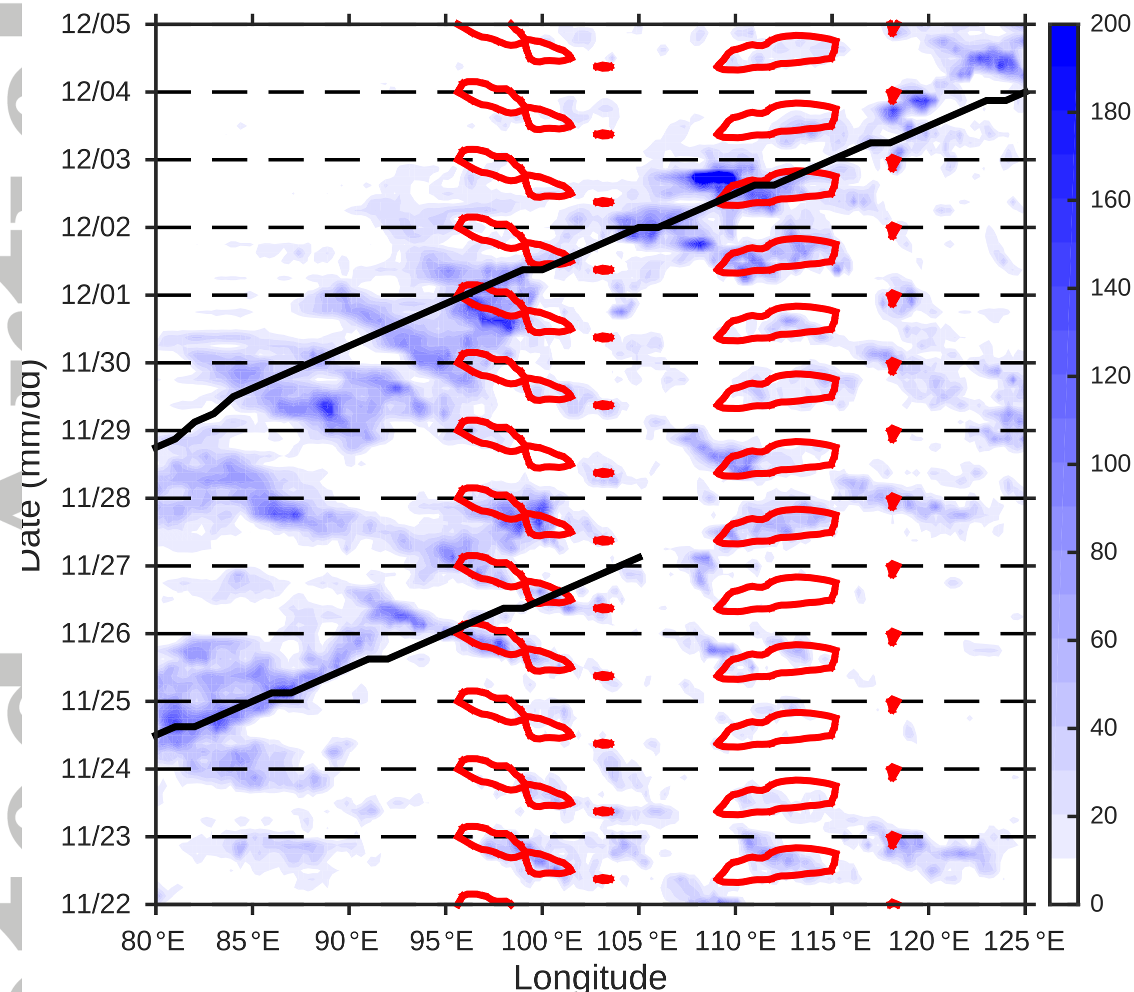

Figure 2. Hovmöller diagram of total precipitation rate (mm day^{-1}; see legend for shading) averaged over the equatorial band (2.5°S–2.5°N) for the period 22 November to 5 December 2011. The tick marks on the vertical axis are at 0000 UTC each day. The two black lines indicate the propagation of the two CCKWs during this period. The red lines show the 12.5 mm day^{-1} contour from the mean diurnal cycle in Figure 1.

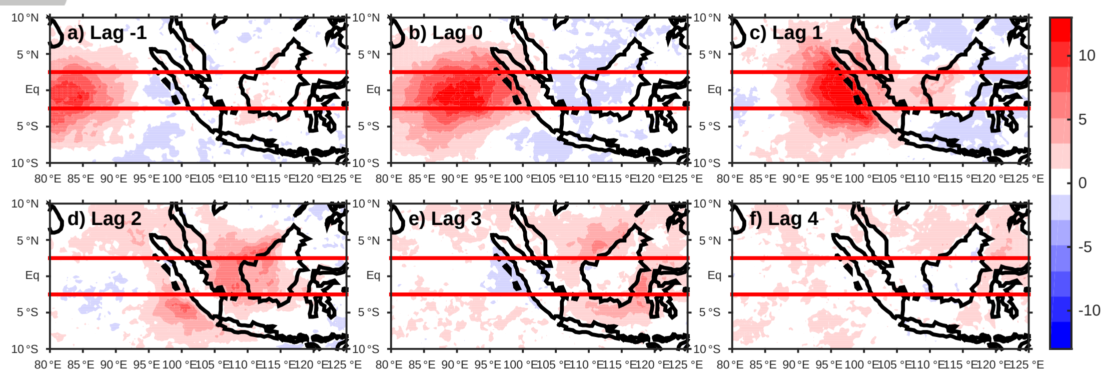

Figure 3. Lagged composite maps of daily mean total precipitation rate anomalies (mm day^{-1}; see legend for shading) for convectively coupled equatorial Kelvin waves on: day (a) −1, (b) 0, (c) 1, (d) 2, (e) 3, (f) 4. Day 0 corresponds to the time when the Kelvin wave passes through 90°E. It means that precipitation is averaged for the entire day (8 data points) at which CCKW is at 90E for lag 0 (see Supplementary Information for details of compositing and anomalies calculation).

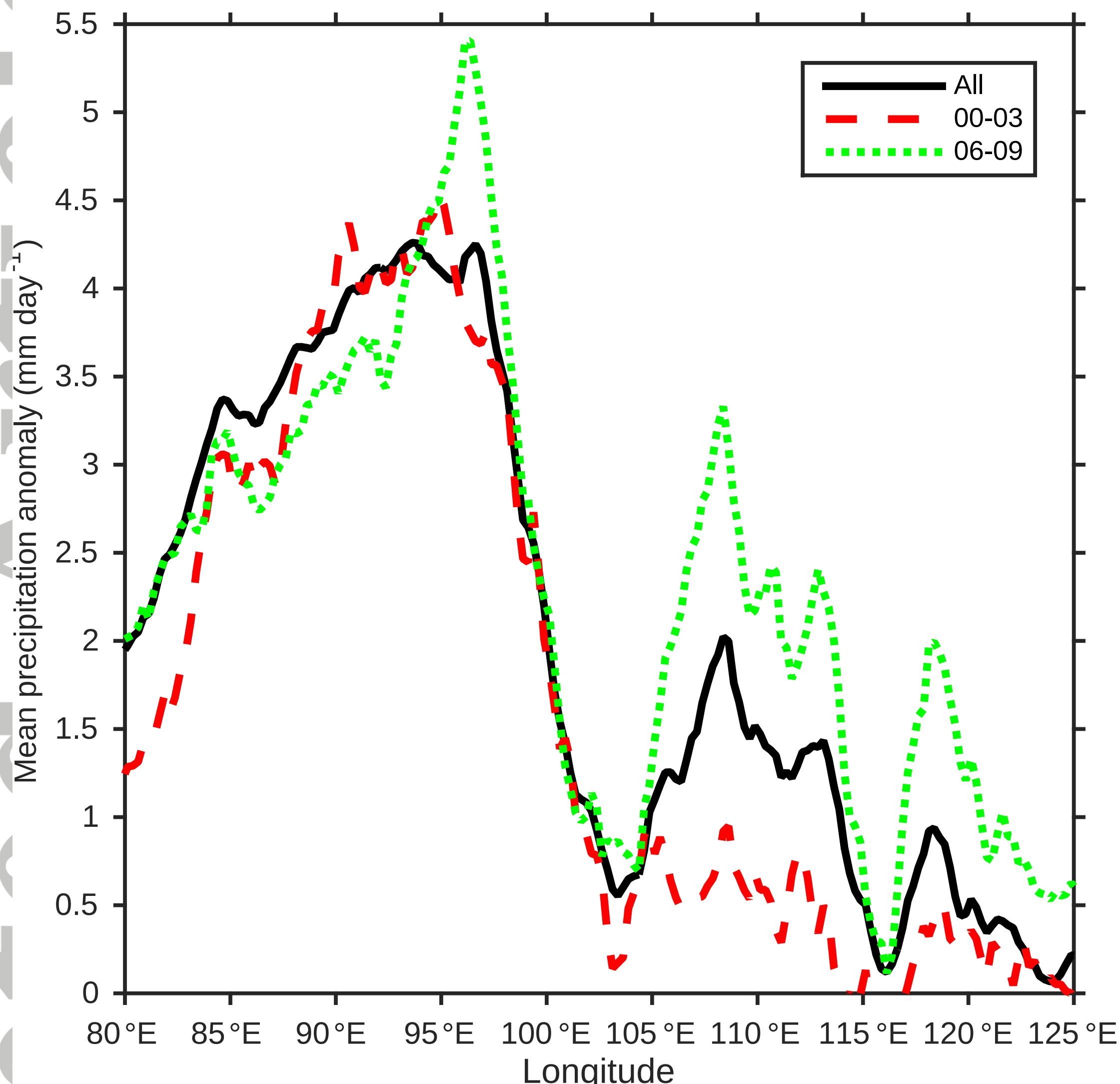

Figure 4. Mean anomalous total precipitation rate (mm day^{-1}) for CCKWs averaged over the passage of the wave (days −1 to 4), as a function of longitude. The thick black line is calculated from all CCKWs. The green dotted (red dashed) line is calculated only from CCKWs arriving at 90°E between 0600–0900 UTC (0000-0300 UTC) (see Supplementary Information for details of compositing and anomalies calculation).

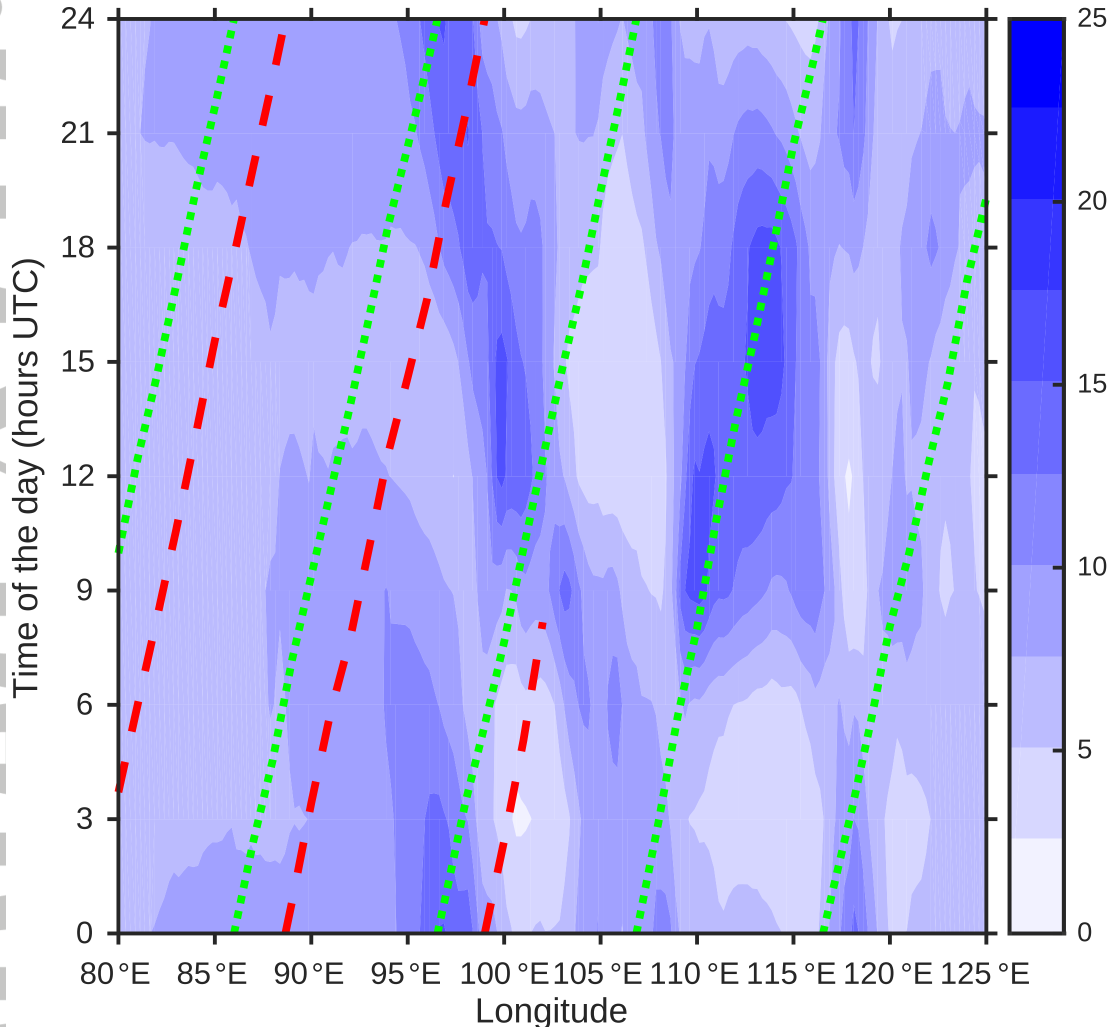

Figure 5. Mean trajectory of CCKWs [green dotted (red dashed) line for CCKWs arriving at 90°E between 0600–0900 UTC (0000-0300 UTC)] derived from observations, superimposed on mean diurnal cycle of precipitation over the Maritime Continent (same as in Figure 1c).