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Vertical structure of Convectively Coupled Equatorial Waves (CCEWs) during Boreal Summer and Winter

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AbstractAtmospheric variability in the tropics on the daily to intraseasonal timescale is often related to convectively coupled equatorial waves (CCEWs), including Kelvin, MRG, ER, and TD-type waves. This study aims toanalyze the observed vertical structures of the CCEWsduring boreal summer and winter fromthe NCEP-DOE reanalysis dataset. Consistent with a linear wave theory, the vertical structure of CCEWs is characterized by a distinctive phase tilt,indicatingadistinct direction of wave energy propagation.The vertical structure of Kelvin, MRG and ER waves is signified by westward phase tilts with height, especially in the upper troposphere when the waves become dry (i.e.there is noeffect of moisture), while in the lower troposphere, the phase tiltsdeviatesignificantly from the linear wave theory, whenthe waves become moist. On the other hand, the TD-type waves exhibit a perpendicular,baroclinic structure with height. The vertical structures of the Kelvin, MRG and TD-Type waves are more clearly observed during boreal summer, while ER waves are more observed during boreal winter. This is consistent with the increasing wave amplitudesdue to a stronger wave sourceduring those periods.Future studies are still required in order to understand how the vertical modulation of CCEWs on RH and wind fields can be used to better improve weather predictions in the tropics.

1. Introduction

Equatorial atmospheric waves are an important class of disturbances trapped in the equator and propagate throughout the tropics [1]. These disturbances are generated by diabatic heating organized by tropical convection. Waves emanated and coupled with the convection are called Convectively Coupled Equatorial Waves (CCEWs) [2-6].

Convectively Coupled Equatorial Waves (CCEWs) are waves that are coupled by large-scale convective heating in the equatorial troposphere and control most of the variability of rainfall and circulation of the tropical atmosphere [7]. CCEWs consist of Kelvin, Equatorial Rosby (ER), Mixed Rosby-gravity (MRG) and Tropical Depression-type (TD-type). CCEWs are found in the lower troposphere to the lower stratosphere in the equatorial region between 20°N - 20°S and 10°N - 10°S. This atmospheric wave propagation can cause convective storms that are interconnected even at long distances [1] and their existence are important for the projection of tropical precipitation in the global climate models[8-10].

CCEWs activities strongly influence weather in the tropics and have significant effects on Madden-Julian Oscillation (MJO), El-Nino Southern Oscillation (ENSO) and Quasi Biennial Oscillation QBO [11-12].Research on CCEWs has been widely studied, but most of them only focus on the horizontal structure and its associated impacts. Although, a research on the vertical structure of the CCEWs has been conducted by Kiladis [5] previously, here we focused on two seasons usinga longer period of OLR daily data, so the expected results should be more robust. The focus of this study is to identify and to analyze the vertical structure of the Convectively Coupled Equatorial Waves(CCEWs).

2. Data and methods

The data used in this research are daily Outgoing Longwave Radiation (OLR), multi-level zonal wind, meridional wind, temperature, and relative humidity with periods of 1981-2010. All data are obtained from NCEP / DOE Reanalysis II issued by National Oceanic and Atmospheric Administration (NOAA). We focused on the equatorial latitudinal band between at latitude 20°N - 20°S with global longitude.

STSA is used to show the zonal propagation properties of atmospheric waves. This method decomposes the space and time data fields into data fields in the wave number and frequency domains, for waves propagating eastward and westward. The STSA used is a modification of STSA WK 99 [7]. The STSA modification of this study does not part data into symmetric and anti-symmetric components, considering that tropical disturbances are asymmetric to latitude or the Inter-tropical Convergence Zone (ITCZ). Moreover, the amplitude variations of CCEWs in different seasons have been examined. Amplitude is calculated as the variance of the filtered field, where a high (low) variance value indicates that the influence of the related wave is large (small). Furthermore, cross-correlation analysis was used to examine the relationship between dynamical fields [13].

3. Results and discussion

3.1. Potential wave formation and wave activity over the tropics

Diabatic heating controlled by convective activity, such as large-scale cumulus convection in the tropics, evokes large-scale wave motion in the tropics [14]. The calculation of the daily OLR average value is done to show the region that has the potential for wave formation. Low OLR values indicate large-scale cumulus convection.

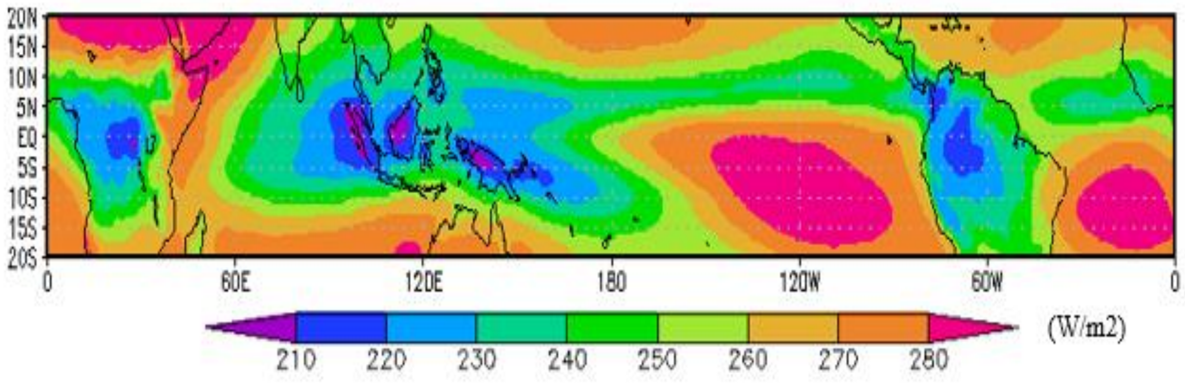

Figure 1. Spatial distribution of OLR in the tropics.

Figure 1 shows that the average annual OLR distribution in the tropics. Maritime Continent, southwestern American Contine, western to central African Continent and eastern Pacific Ocean, is lower compared to other regions. This lower daily OLR average is because of Walker Circulation [15-16]. The North Pacific Ocean and Southern Ocean has a low daily OLR average, because the North Pacific Ocean region is crossed by the ITCZ belt, while the South Pacific Ocean region is the region crossed by the Southern Pacific Convergence Zone (SPCZ) [17]. These areas become centers of convergence, where the ascends of humid air results in many convective clouds forming [18]. The use of OLR data in this study is intended as the main proxy to differentiate the region of deep convection in the tropics that associated with CCEWs activities.

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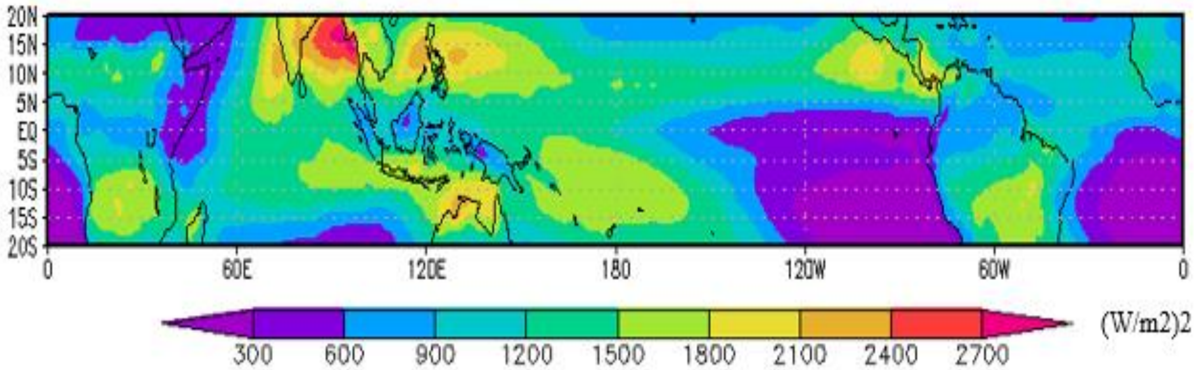


Figure 2. Spatial distribution of OLR variances in the tropics.

Figure 2 show that the Maritime Continent to the Pacific Ocean area was identified to have a higher level of daily OLR variability than other regions. Daily OLR variability is observed to be greater in the Northern Hemisphere (BBU) than in the Southern Hemisphere (BBS). CCEWs activity is dominant in the Northern Hemisphere (BBU) compared to the Southern Hemisphere (BBS).

3.2.Space Time Spectral Analysis (STSA) CCEWs

The STSA diagram is able to identify the daily disturbances of the tropical atmosphere, including Kelvin, ER, MRG and TD-type waves and MJO at an effective depth of 5-100 m [3].Figure 3a show that the Kelvin wave (red polygon) has a period of about 2.5-17 days. MRG wave (pink polygon) has a period of 3-6 days. ER wave (dark green polygon) has period of 10-48 days. Then the TD-type wave (light green polygon) has period of 2.5-5 days [5]. The results of seasonal analysis showed that Kelvin, MRG and TD-type wave activity are stronger and have longer period during boreal summer (figure 3b), while ER waves activity are stronger and have longer period during boreal winter (figure 3c).

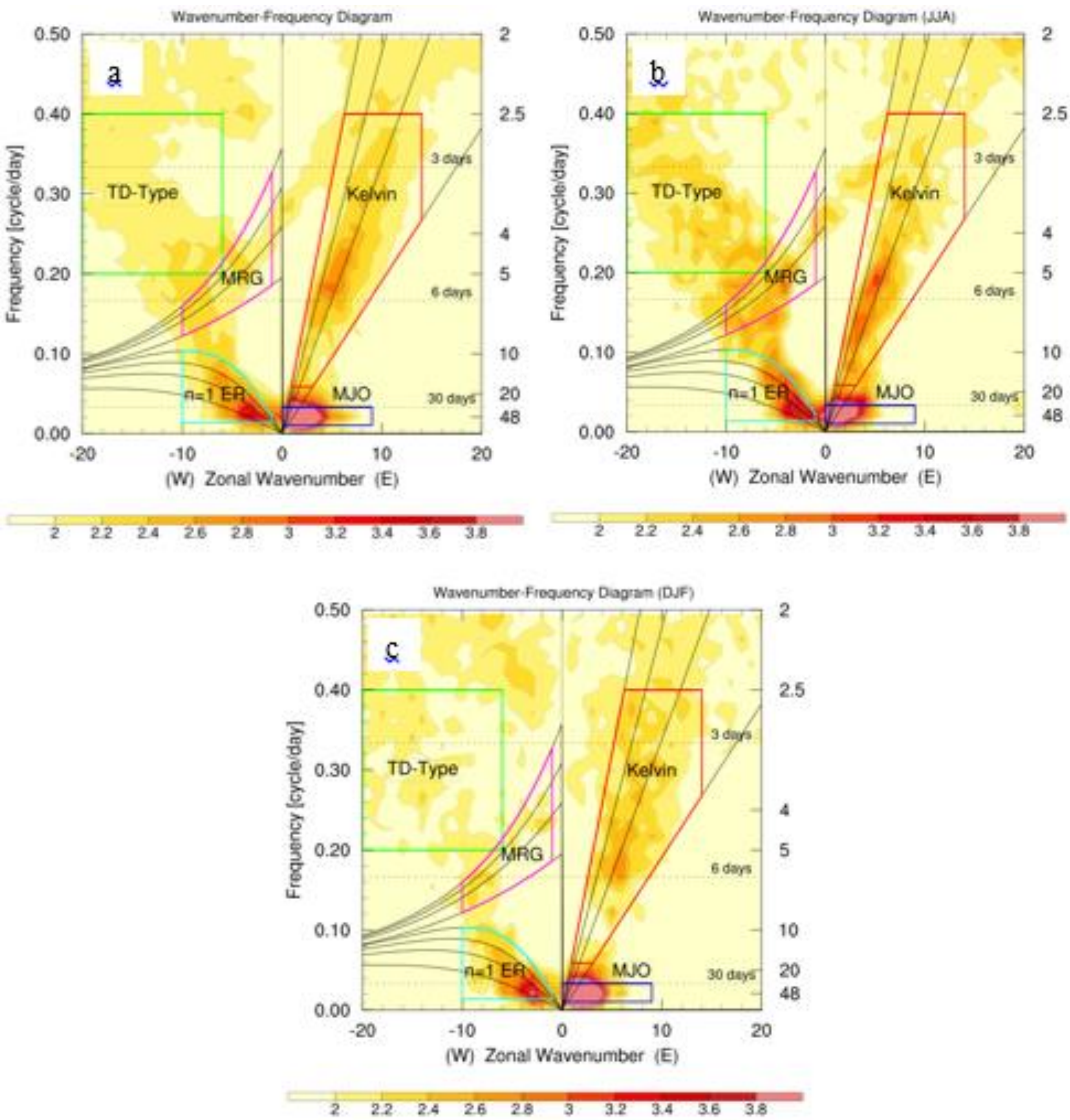


Figure 3. Space-time spectral analysis (STSA) ofOLR at 20°N - 20°S for: (a) all seasons, (b) boreal summer (JJA), and (c) borealwinter (DJF). The y-axis indicates the frequency and the x-axis indicates the zonal-wave numbers(west and east zonal direction).

3.3. Spasial Distribution of CCEWs Activity

After the CCEWs activities were identified through STSA, an analysis of the spatial distribution of CCEWs activities was carried out. The analysis is done by OLR filtering for CCEWs. Figure 4a show that Kelvin wave activity is observed at 15°N - 10°S and 0°- 125°W or at the equatorial latitude and propagates from the Indian Ocean to the northern Pacific Ocean along the ITCZ, because the Kelvin wave is a symmetric wave to the equator that propagates eastward [19-20]. The areas marked with white cross on (Figure 4a) are the base points selected for analysis of the vertical structure of the Kelvin wave. This base point is at 6°N and 170°W, where the activity is the strongest. These results indicate that Kelvin wave activity is predominantly amplified during the boreal summer, because the Kelvin wave activity is related to incoming solar radiation, so its activity is forced by the equatorial heating system. In this case, it is related to the source of the Kelvin wave generator, namely the Sea Surface Temperature (SST) in the northern Pacific Ocean along the ITCZ.

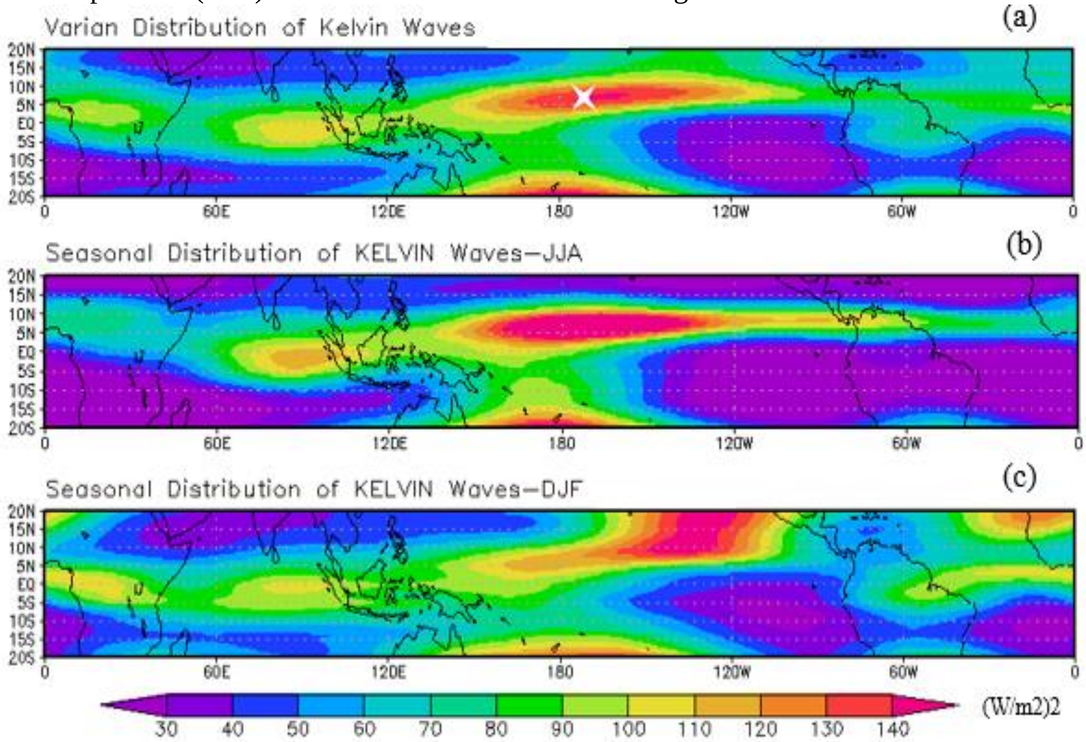


Figure 4. Distribution of Kelvin wave variances for:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

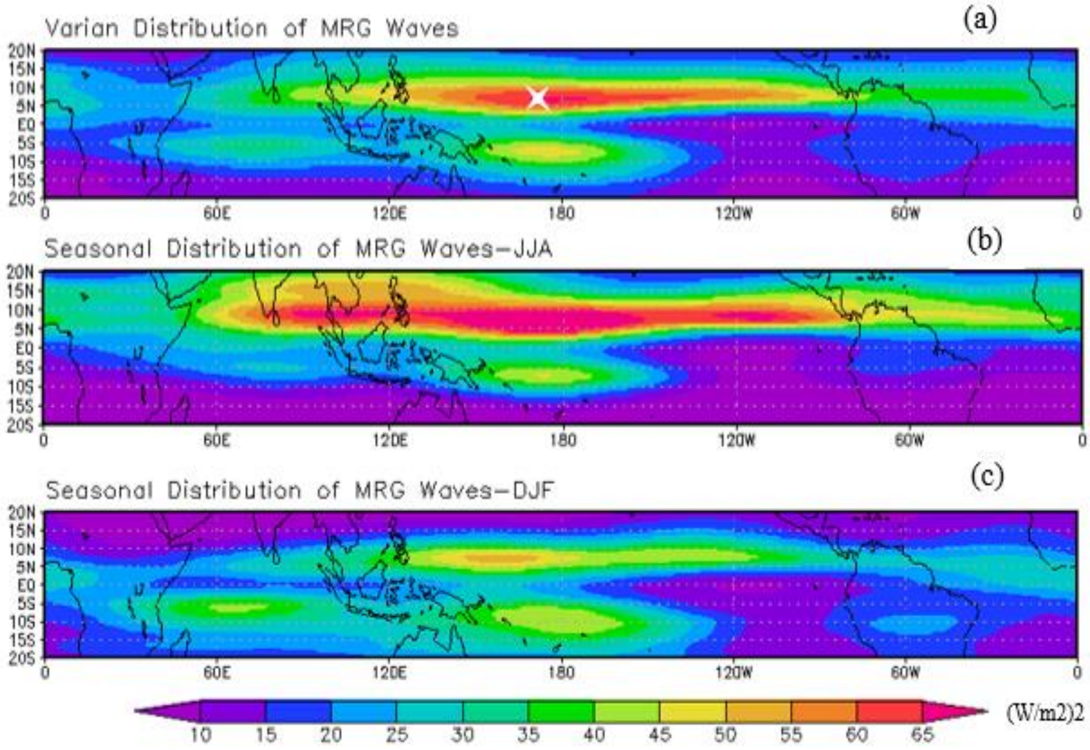


Figure 5. Distribution of MRG wave variances for:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

Figure 5 shows that the spatial distribution of MRG waves that dominate at 5°N - 15°N, 5°S - 15°S and 60°E - 60°W. The dominant MRG wave activity is stronger at BBU compared to BBS. The distribution of dominant MRG wave activity strengthens in the northern part of the Pacific Ocean and weakens in the southern part of the Pacific Ocean. This is because the Pacific Ocean region experiences high convective activity, due to the high sea-surface temperature distribution, and its coincidence with the ITCZ region [21].

The areas marked with white cross on (figure 5a) are the base points selected for the analysis of MRG wave vertical structures. This base point is at 6°N and 170°E, where the MRG wave activity (variant value) is the strongest. The distribution of MRG wave activity weakened during boreal winter (figure 5c), whereas during the boreal summer (figure 5b) MRG wave activity strengthened and propagated along the ITCZ and SPCZ [5]. This is because some MRG wave energy is triggered from Tropical Cyclone (TC) in the tropical Pacific region during boreal summer [7].

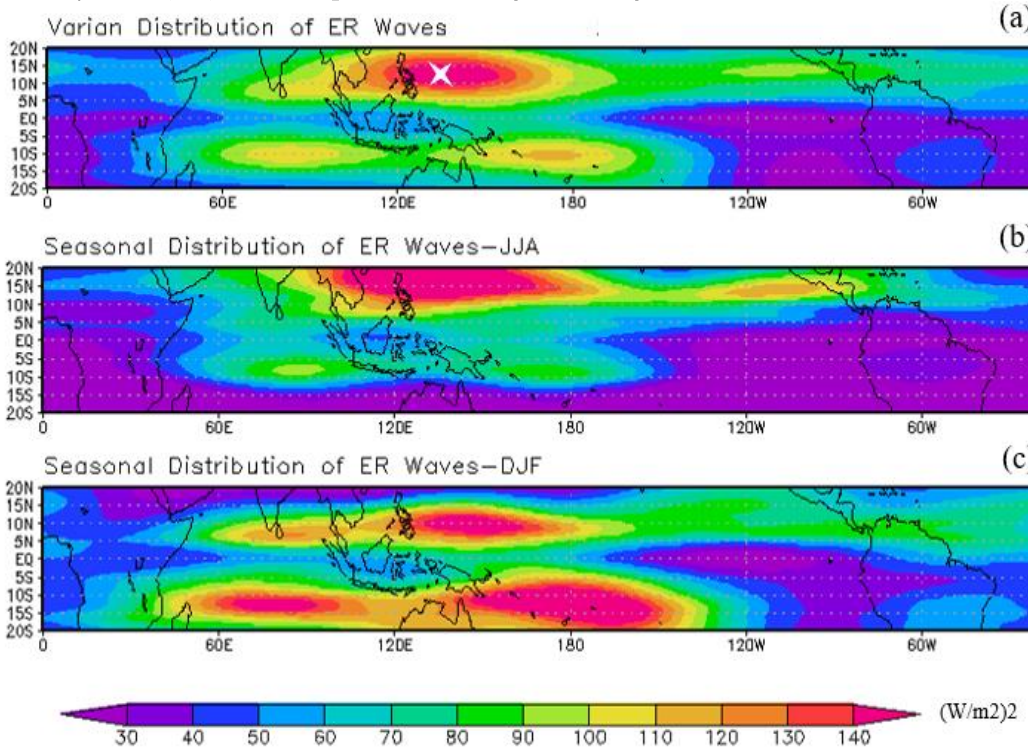


Figure 6. Distribution of ER wave variances for: (a) all seasons, (b) boreal summer (JJA), and (c) during boreal winter (DJF).

ER wave activity is observed at 20°N - 20°S or precisely in the western North Pacific Ocean (Northwest Pacific Ocean) and the western South Pacific Ocean (Southwestern Pacific Ocean) and propagated westward (figure 6). Areas marked with white cross on (figure 6a) are the base points chosen for the analysis of the ER vertical wave structure. This base point is at 11°N and 135°E, where the activity is the strongest. Observations during boreal winter (figure 6c) indicate that ER wave activity tends to resemble the overall ER wave activity pattern, when the ER wave activity is detected during the summer boreal (figure 6b) rises around the maritime continent. These results indicate that ER wave activity strenghtens during boreal winter. This is related to the ER wave base flow associated with the strengthening of the monsoon that propagates westward and Tropical Cyclone (TC) in the western North Pacific and Asia.

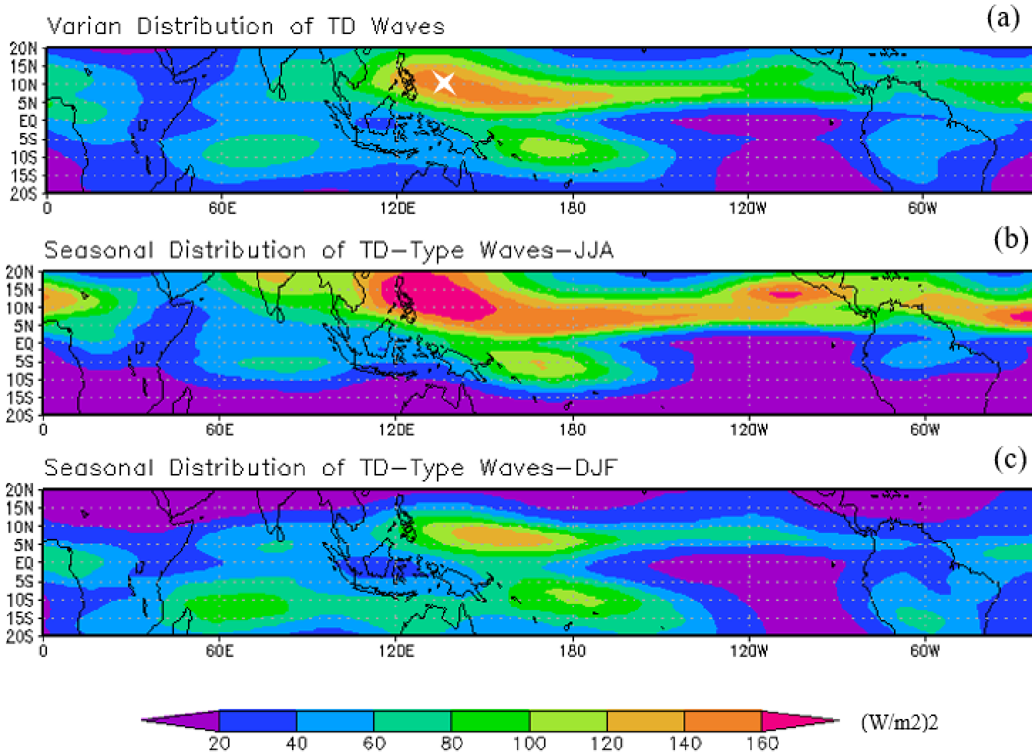


Figure 7. Distribution of TD-type wave variances for:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

TD-type wave activity in observation (figure 7a) tends to resemble MRG and ER waves, which are detected around the North Pacific Ocean and the western Pacific Ocean and propagate westward. TD-type waves are generated from the North African Continent (Sahara Desert) which can trigger the emergence of Tropical Cyclone (TC) and Hurricanes. Area marked with white cross on (figure 9a) is the base points selected for analysis of TD-type vertical wave structures. This base point is at 10°N and 130°E, where the activity of the TD-type wave is the strongest. Seasonal analysis showed that TD-type wave activity strengthens (weakens) during boreal summer (winter). This occurs because the TD-type wave tends to occur when the poleward temperature gradient is positive and low level jet bursts occur.

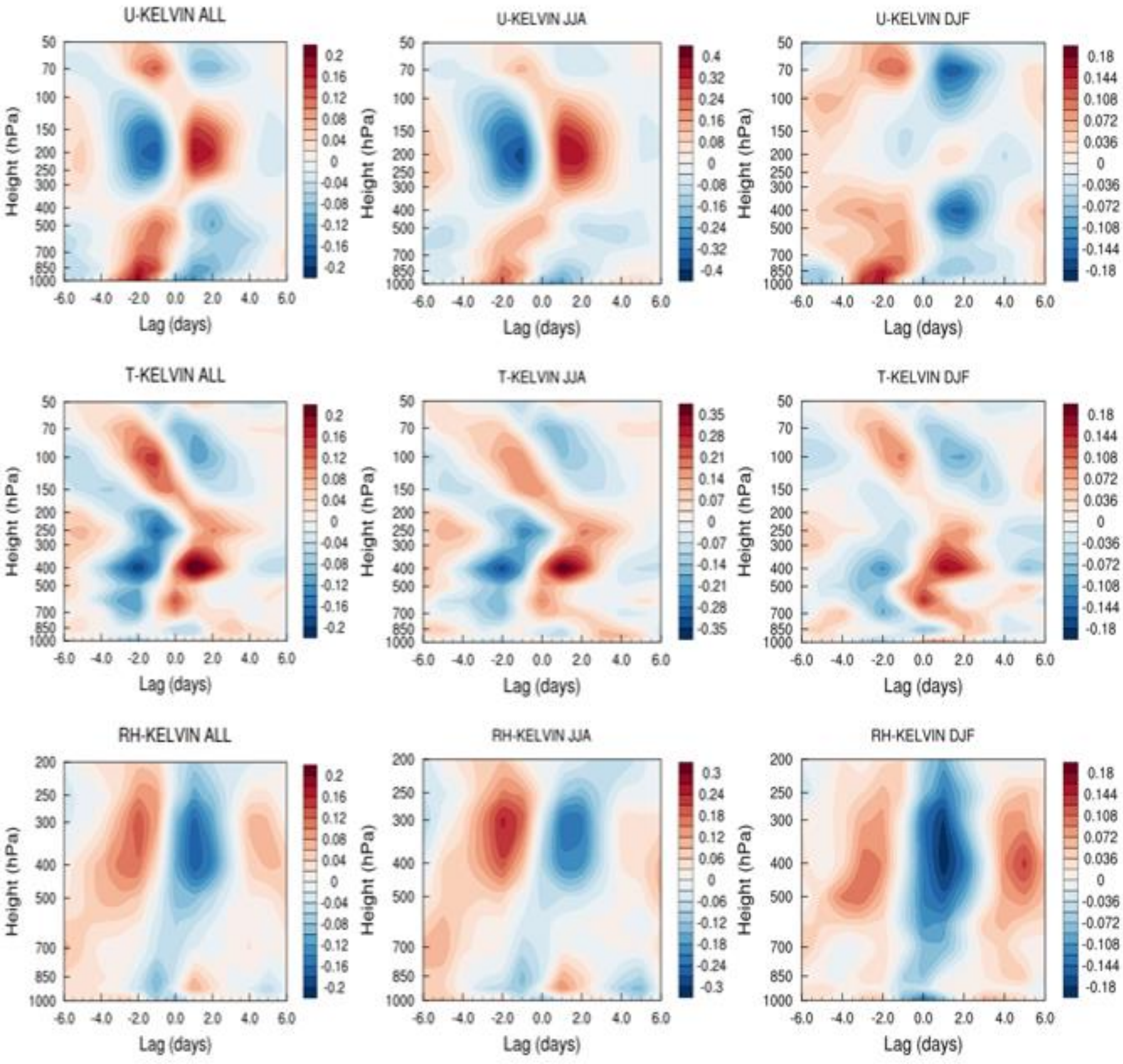
3.4.Vertical structure of CCEWs

Analysis of the vertical structure of CCEWs was identified using zonal wind components (u), meridional wind (v), temperature (T), and relative humidity (Rhum). This analysis is carried out using the cross correlation method by first determining the base point for the analysis. The chosen base point is the coordinate point where the activity of each CCEWs is the strongest as in subsection 3.3.

Based on the distribution of Kelvin wave activity in figure 4a, the base point is chosen where the activity of the Kelvin wave is strongest. The base point chosen for the analysis of the vertical structure of the Kelvin wave is in the Central Pacific (6°N and 170°W). The dark gray in the image shows a positive correlation, while the light gray shows a negative correlation for each component (u, T, Rhum). Positive or negative from lag refers to the relative period after or before the Kelvin wave activity strengthens at the base point on day 0. The vertical wind structure and temperature (figure 8a) have a tendency to tilt eastward in the lower troposphere, while in the upper troposphere it tends to tilt westward.

The vertical structure of relative humidity (figure 8a) is observed perpendicular to time and height. The temperature and moisture evolution can also belinked to the morphology of cloudiness, to begin with shallow convection,progress to deep convection by day 0, and end withupper tropospheric cloud overlying a relatively cloud-freelayer (i.e., stratiform cloudiness and precipitation) after the main convective signal has passed [21].

Latent heat is important in determining the structure of the wave temperature. Convectively coupled wave structures are influenced by interactions between heating and vertical advancement. Wave energy produced by moving tropospheric heat sources is a response to propagation into the upper troposphere. The relationship between the stratospheric zonal wind and Kelvin wave temperature has a slope that is consistent with the propagation of wave energy caused by the upper tropospheric heat source that moves eastward. CCEWs signals in the lower stratosphere or upper troposphere are dominated by dry waves, which generally have vertical wavelengths and greater wave velocities so that upward propagation is more efficient.

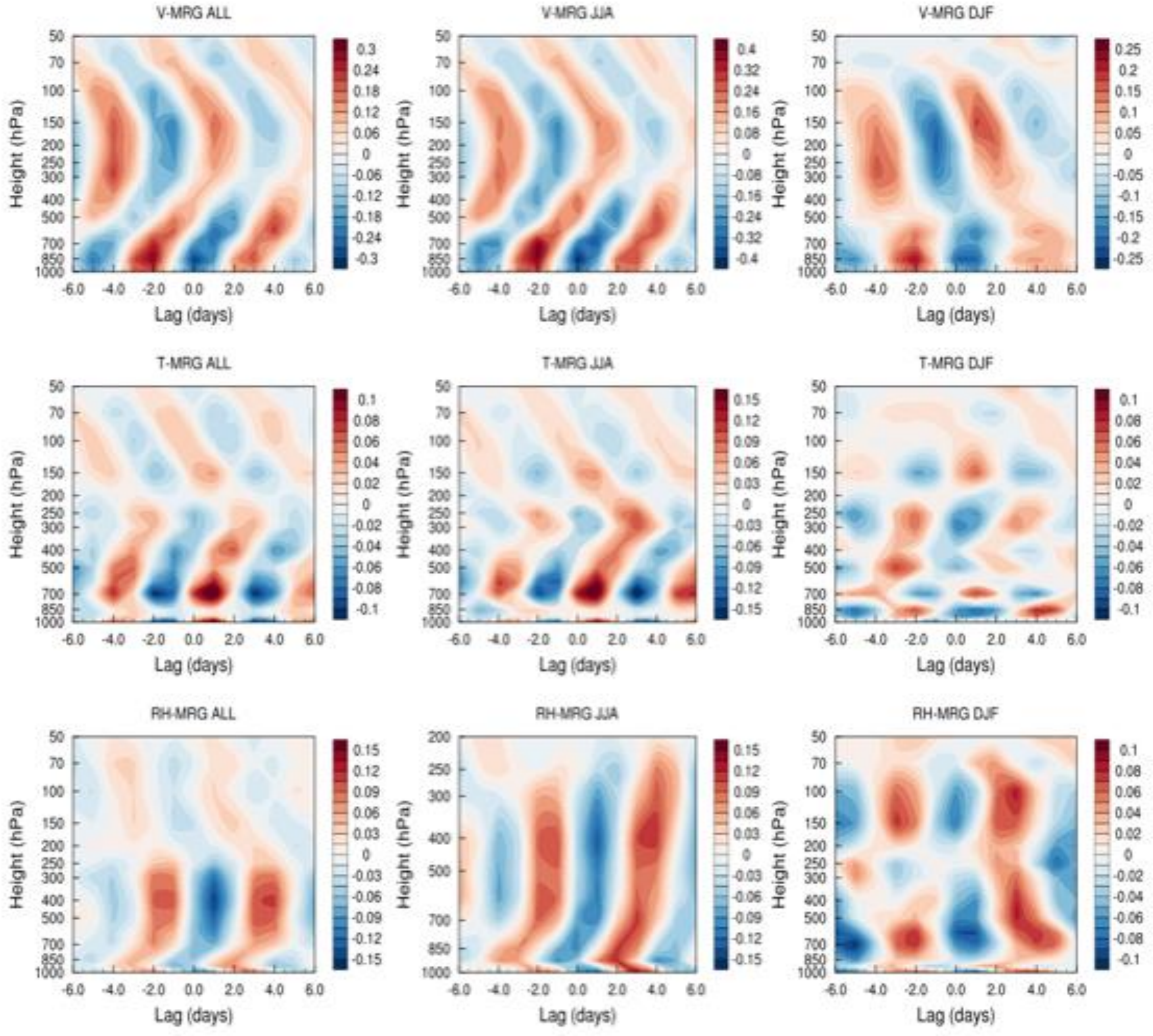


(a) (b) (c)

Figure 8. Vertical structures of Kelvin waves (calculated based on cross-correlation analysis)in (top) zonal wind, (middle) temperature, and (bottom) relative humidityfor:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

Figure 8a show that the vertical structure of the Kelvin wave is characterized by the slope of the phase angle of the zonal wind component and the temperature to the west, especially in the upper troposphere when the wave dries and the structure changes when the wave becomes moister in the lower troposphere. This is consistent with dry wave theory [19], whereas the vertical structure of relative humidity does not have a phase angle slope [5]. In a lag of approximately 6 days there are 2 phases of propagation or modulation of Kelvin waves. Wind and temperature structures are baroclinic, i.e. at different pressure levels the wind flow and temperature are also different. Meanwhile, the moisture structure is more barotropic, where the flow of moisture at all height levels is almost the same.

Seasonal analysis of vertical structures also shows that during boreal summer (figure 8b), all components of the vertical structure of the dominant Kelvin wave appear more clearly and resemble the overall vertical structure. While during boreal winter (figure 8c) the vertical structure of the Kelvin wave for the zonal wind component of the pattern is not clearly observed, because during the winter boreal the Kelvin wave activity tends to weaken. This result is consistent with the analysis of variance and STSA that the Kelvin wave strengthens during the boreal summer.



(a) (b) (c)

Figure 9. Vertical structures of MRG waves(calculated based on cross-correlation analysis) in (top) meridional wind, (middle) temperature, and (bottom) relative humidity for:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

Based on the distribution of MRG wave activity in figure 5a, the base point is in the Central Pacific (6°N and 170°E), which the MRG wave activity is the strongest. Figure 8a shows that the vertical structure of the MRG wave is characterized by the tilted slope of the phase angle of the meridional wind component and the temperature to the west, especially in the upper troposphere when the wave becomes dry and its structure changes when the wave becomes moister in the lower troposphere. This is consistent with dry wave theory [19]. Whereas the vertical structure of relative humidity does not have a phase angle slope [5].

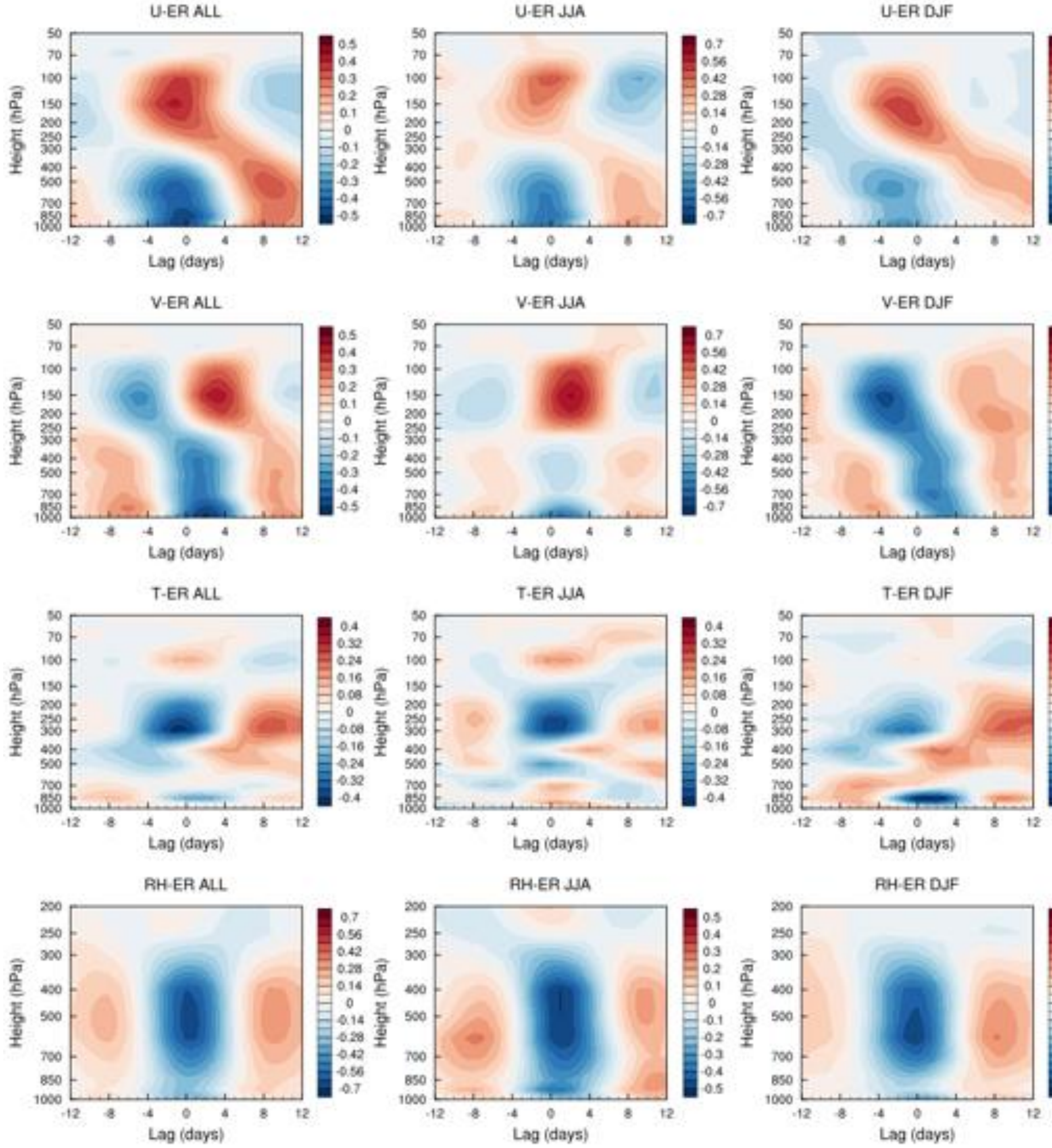
In lag approximately 6 days there are 2-6 phase propagation or MRG wave modulation. This shows that MRG wave modulation is faster than Kelvin and ER waves, but slower than TD-type waves. The observed meridional wind and temperature structures are baroclinic, which means that at different pressure levels the flow is also different. Meanwhile, the observed moisture structure is more barotropic, where the flow at all altitude levels is almost the same. Seasonal analysis of vertical structures also shows that during the boreal summer (figure 9b), all components of the dominant MRG wave vertical structure appear more clearly and resemble the overall vertical structure. While at the boreal winter (figure 9c) the MRG wave vertical structure for all components of the pattern is not clearly observed, because at the time of boreal winter, MRG wave activity tends to weaken. This result is consistent with the analysis of variance and STSA performed, that the dominant MRG wave strengthens during boreal summer.

Based on the distribution of ER wave activity in figure 6a, the base point is chosen where the ER wave activity is the strongest. The base points chosen for the analysis of the vertical structure of ER waves are in the western North Pacific Ocean (11°N and 135°E). ER wave vertical structures are identified by cross-correlation between filtered OLR (ER waves), with zonal wind anomalies, meridional winds, temperature, and relative humidity.

Vertical structure of the ER wave is characterized by the tilted phase angle slope of the zonal and meridional wind components to the west, especially in the upper troposphere when the waves become dry and the structure changes when the waves become moister in the lower troposphere. This is consistent with dry wave theory [18]. While the ER wave temperature structure is more complex with shallow cold layers in the convective region, whereas the vertical structure of relative humidity does not have a phase angle slope [5].

In lag approximately 12 days there are 2-3 phase propagation or ER wave modulation. This shows that the ER wave modulation is slower than the Kelvin, MRG and TD-type modulation. Zonal wind structures, meridional winds and observed temperatures are baroclinic, which means that at different pressure levels the flow is also different. Meanwhile, the observed moisture structure is more barotropic, where the flow at all altitude levels is almost the same.

Seasonal analysis of vertical structures also shows that during boreal winter (figure 10c), all components of the dominant vertical ER wave structure are more clearly visible and resemble the overall vertical structure. While at the boreal summer (figure 10b) the vertical wave structure pattern of ER was not clearly observed, except Rhum, because rhum is more constant. This happens because during the boreal summer the ER wave activity tends to weaken. This result is consistent with the analysis of variance and STSA that the dominant ER wave strengthens during boreal winter.

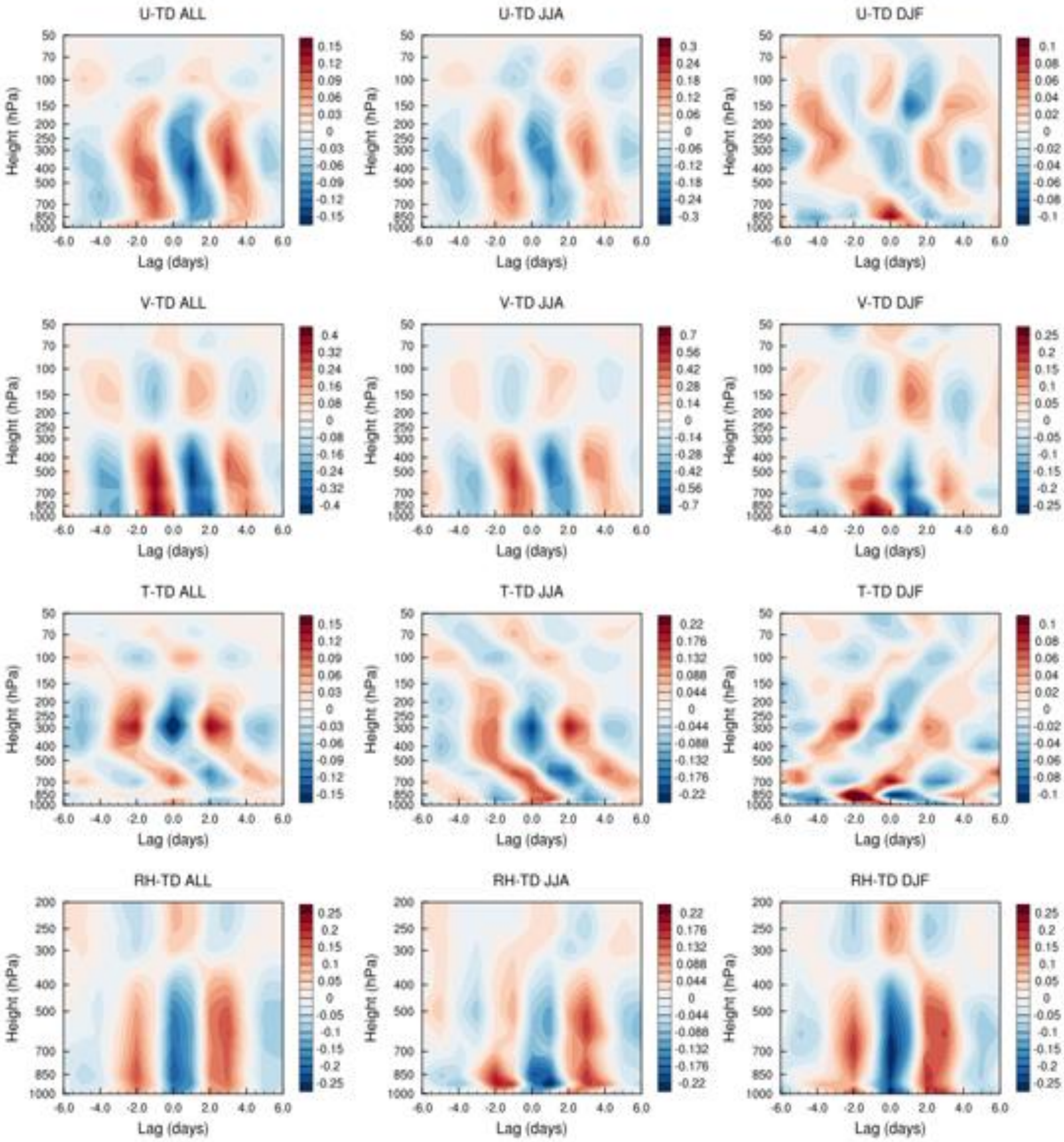


(a) (b) (c)

Figure 10. Vertical structures of ER waves(calculated based on cross-correlation analysis) in (first row) zonal wind, (second row) meridional wind, (third row) temperature, and (fourth row) relative humidity for:(a) all seasons, (b) boreal summer (JJA), and (c) boreal winter (DJF).

Based on the distribution of TD-type wave activity in figure 7a, the base point is chosen where the TD-type wave activity is the strongest. The base point chosen for the analysis of the TD-type vertical wave structure at 10°N and 130°E.Figure 13a shows that the vertical structure of TD-type waves almost resemble MRG waves. All components analysis (u, v, T, and Rhum) for the TD-type vertical wave structure do not show phase angle slope and the vertical structure is perpendicular to time and height. In lags (days) of approximately 6 days there are 4-6 propagation phase or TD-type wave modulation. This shows that the TD-type wave modulation is faster than the Kelvin, MRG, and ER wave modulation.

Overall the observed TD-type wave vertical structure is baroclinic, which means that at different pressure levels the flow is also different. Seasonal analysis of vertical structures also shows that during the boreal summer (figure 11b), all components of the dominant TD-type vertical wave structure appear more clearly and resemble the overall vertical structure. While at boreal winter (figure 11c) the TD-type wave vertical structure for the zonal wind component of the pattern is not clearly observed, because at the time of winter boreal TD-type wave activity tends to weaken. These results are consistent with the analysis of variance and STSA performed, that the dominant TD-type waves strengthen during boreal summer.



(a) (b) (c)

Figure 11. As in Figure 10, but for TD-type waves.

4. Conclusions

The vertical structures of convectively coupled equatorial waves(CCEWs) from NCEP-DOE Reanalysis II have been studied. The wave properties and the associated vertical structures were analysed using space-time spectral analysis and cross correlation technique. Our results indicated thatthe vertical structures of the Kelvin, MRG and TD-Type waves are seen more clearly during boreal summer, while the ER waves are seen clearly during boreal winter. This is in fact consistent with the amplitudeof the waves (as shown by the variance of wave-filtered OLR)being strongly during those periods.In a time-height plane,the vertical structures of Kelvin, MRG and ER waves are characterized by a westward phase tilt with height, especially in the upper troposphere when the waves become drier,consistent with the linear wave theory. In the lower troposphere, the structure changes when the waves become moister and are coupled with convection. On the other hand, the TD-type wave structures are characterized by a perpendicular,baroclinic structure with height. Future studies are still neededin order to understand how the modulating effects of CCEW on the vertical structure of RH and wind fields,can be used to understand thedistribution of the atmospheric tracers and to improve the weather predictions in the tropics.

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