

Modulation of the Convectively Coupled Kelvin Waves by the MJO over Different Domains

J. M. NEENA,^a E. SUHAS,^a AND XIANAN JIANG^b

^a *Earth and Climate Science, Indian Institute of Science Education and Research, Pune, India*

^b *UCLA Joint Institute for Regional Earth System Science and Engineering (JIFRESSE), University of California, Los Angeles, California*

(Manuscript received 21 August 2021, in final form 29 April 2022)

ABSTRACT: In this study we have examined the modulation of convectively coupled Kelvin waves (CCKWs) by different Madden–Julian oscillation (MJO) states over the Indian, Pacific, and Atlantic Ocean domains. Convectively active CCKW events associated with active MJO convection, suppressed MJO convection, and quiescent MJO states were derived using wavenumber–frequency-filtered outgoing longwave radiation (OLR) indices over the three domains. Composite analysis of CCKW events during different MJO states indicates that the amplitude and phase speed of CCKW are modulated by the MJO state. CCKW amplitude is stronger (weaker) and it propagates relatively slower (faster) and more (less) eastward when the MJO amplitude is strong (weak). The phase speed of CCKW is much slower over the Indian Ocean domain, whereas it propagates relatively faster over the Atlantic Ocean domain. It is hypothesized that the observed difference in CCKW phase speeds is related to the gross moist stability (GMS). The clear linear relationship observed between GMS and CCKW phase speeds over the different domains and during different MJO states and the observed differences in CCKW vertical structures support this hypothesis. It is found that CCKWs exhibit a baroclinic vertical structure over the Indian and Pacific Ocean domains and a barotropic vertical structure over the Atlantic Ocean. Planetary-scale convection associated with the MJO reduces the static stability allowing for baroclinic modes to prevail, which in turn reduces the GMS and the effective equivalent depth, eventually slowing down the CCKW phase propagation. The results suggest that CCKW events may be treated as a mixed-moisture mode.

KEYWORDS: Kelvin waves; Large-scale motions; Madden-Julian oscillation

1. Introduction

The Madden–Julian oscillation (MJO) and convectively coupled Kelvin waves (CCKWs) are both eastward-propagating disturbances observed in the convective and dynamical fields in the tropics (Madden and Julian 1972; Takayabu 1994; Wheeler and Kiladis 1999). Although the MJO and CCKWs exhibit similar dynamical properties, they are considered as distinct tropical modes. The MJO is a ubiquitous slowly propagating ($\sim 5 \text{ m s}^{-1}$) planetary-scale tropical mode of variability that exhibits a 30–90-day periodicity. On the other hand, the CCKW events are more equatorially confined fast-propagating ($\sim 17 \text{ m s}^{-1}$) disturbances with a shorter spatial scale (wavenumbers ~ 3 –8) and higher frequency (periodicity ~ 3 –20 days) (Takayabu and Murakami 1991; Takayabu 1994; Dunkerton and Crum 1995; Wheeler and Kiladis 1999; Roundy 2008; Hendon and Wheeler 2008). They respectively account for the first and second largest variances associated with propagating disturbances in the tropics and together represent a significant fraction of tropical convection (Wheeler and Kiladis 1999; Kiladis et al. 2009). It is well known that a large fraction of tropical convection is organized by the MJO and CCKWs (Hendon and Wheeler 2008; Takayabu et al. 2016). While both the modes are active throughout the tropics, convective activity associated with the MJO are more pronounced over the Indian Ocean and the west Pacific (Hendon and Liebmann 1994), and the CCKW activity is more prominent over the intertropical convergence zone (ITCZ) (Kiladis et al. 2009; Straub and Kiladis 2002; Dias and Pauluis

2011). A crucial dynamical factor that separates the MJO from the CCKWs is the amplitude of the meridional wind anomalies associated with these disturbances. Meridional winds associated with the CCKW events are significantly weaker than those associated with the MJO. Seasonality is another factor that differentiates the MJO and the CCKWs. While the MJO exhibits pronounced activity during boreal winter, CCKW events show dominant activity during boreal spring (Wheeler and Kiladis 1999; Wheeler et al. 2000; Roundy and Frank 2004; Masunaga 2007).

Although their dominant spectral variances in the wavenumber–frequency space clearly indicate that the MJO and CCKWs are distinct modes, studies have reported that they are dynamically interactive (Dunkerton and Crum 1995; Straub and Kiladis 2003; Roundy 2008). Several studies have also pointed out that the MJO modulates the CCKW activity over different geographical domains (Dunkerton and Crum 1995; Straub and Kiladis 2003; Roundy 2008; Wang and Fu 2007; Mekonnen et al. 2008; Roundy 2012; Guo et al. 2014, 2015). As a planetary-scale envelope, the MJO has the potential to modulate the CCKWs and thereby exert control on other high-frequency disturbances. For example, studies have reported a strong link between the passage of CCKWs and tropical cyclogenesis over different ocean basins (Bessafi and Wheeler 2006; Schreck 2015; Ventrice et al. 2012). The MJO plays an active role in this interaction by inducing significant anomalies in the CCKW meridional wind fields, which in turn can result in cyclonic rotational anomalies that can favor tropical cyclogenesis (Roundy 2008; Schreck 2015). Several studies, mostly focusing on the Western Hemisphere, have reported

Corresponding author: J. M. Neena, neena@iiserpune.ac.in

DOI: 10.1175/JCLI-D-21-0641.1

© 2022 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

Brought to you by UNIVERSITY OF CALIFORNIA Los Angeles | Unauthenticated | Downloaded 09/17/26 08:37 PM UTC

that the CCKWs influence the synoptic and mesoscale variability over the eastern Pacific, Amazonia, the tropical Atlantic, and equatorial Africa (Kiladis et al. 2009; Nguyen and Duvel 2008; Mounier et al. 2007). Ventrice et al. (2012) suggested that the residue of MJO convective activity over the east Pacific initiates CCKWs that propagate to the tropical Atlantic and Africa. Guo et al. (2014) reported an enhanced CCKW activity when the MJO is in phases 8, 1, and 2 of the Real-time Multivariate MJO (RMM) index. Roundy (2008) explored the role of MJO convective activity in modulating the dynamical properties of CCKWs over the Indian Ocean domain, and reported that the amplitude of the CCKW convective phase is higher during the convectively active phase of MJO. The same study also revealed that CCKWs propagate relatively more slowly during convectively active phase of MJO, implying a stronger convection–circulation feedback.

While these studies have helped to bring out some important aspects of the MJO–CCKW interactions, some critical concerns call for a re-examination of these interactions over different geographical domains. Synoptic and mesoscale activity within the MJO convective envelope is found to be enhanced during the active MJO convection state as compared to the convection suppressed state (Hendon and Liebmann 1994; Dunkerton and Crum 1995). Similarly, the CCKW convection state is known to modulate the Atlantic ITCZ, the West African monsoon, and the mesoscale convective activity over central and eastern Africa (Liebmann et al. 2009; Wang and Fu 2007; Mounier et al. 2007; Mekonnen et al. 2008). Hence it is important to distinguish the MJO and CCKW convection active and convection suppressed states of while examining the MJO–CCKW interactions. Studies including Ventrice et al. (2012) and Guo et al. (2014) explored the MJO–CCKW interactions by defining the MJO events based on the RMM amplitude and phase and not separating the convection active or suppressed state of MJO. Also, the RMM index is known to give a higher weightage to MJO circulation, especially over the Western Hemisphere (Ventrice et al. 2013), and hence a higher RMM amplitude may not be a sufficient criterion to define an MJO convective state.

In this study we investigate the composite structure and dynamical properties of CCKWs during different MJO states over different geographical domains by adopting an approach similar to Dunkerton and Crum (1995) and Roundy (2008). Even though Roundy (2008) provides a good analysis of the MJO–CCKW interactions over the Indian Ocean domain, the study used a rather broad spectral range for defining the MJO (wavenumbers 0–10, period of 30–100 days) and CCKW events (wavenumbers 1–14, period of 2.5–20 days), which raises a concern that the CCKW convective signal separation might have been affected by the inclusion of unrelated spatial scales. Many previous studies have shown that a major fraction of MJO convective variance falls in the scale represented by eastward wavenumbers 1–6 (Salby and Hendon 1994; Wheeler and Kiladis 1999). By using a more restrictive convective measure of MJO and CCKW, we focus our attention on how the convection active state of CCKW is modulated by active MJO convection, suppressed MJO convection, and quiescent MJO states. It is expected that a comprehensive

understanding of the role of MJO phases in modulating the convection state of CCKW might provide new insights into the scale interactions between the planetary- and synoptic-scale disturbances and in turn might be helpful in improving the extended-range prediction skill associated with the high-frequency modes.

2. Data and methodology

National Oceanic and Atmospheric Administration (NOAA) daily OLR data of 2.5° horizontal resolution from 1 January 1979 to 31 December 2019 were used for characterizing the convective MJO and CCKW fields (Liebmann and Smith 1996). ERA-Interim 2.5° horizontal resolution zonal and meridional winds, geopotential height, vertical pressure velocity, temperature, and water vapor mixing ratio data at 29 pressure levels from 1000 to 50 hPa from 1 January 1979 to 31 August 2019 were used to characterize the MJO and CCKW dynamic and thermodynamic fields (Dee et al. 2011). The daily climatological seasonal cycle was estimated by keeping the annual mean and first three harmonics of daily climatology. Daily anomalies were obtained by removing the daily climatological seasonal cycle from the raw data. The 3–20-day anomalies of dynamical and convective fields were constructed by applying the Lanczos bandpass filter on the daily anomalies (Duchon 1979). Westerly and easterly phases of the quasi-biennial oscillation (QBO) were identified using ERA-Interim zonal-mean zonal winds at 50 hPa averaged between 2.5°S and 2.5°N . Phases of El Niño–Southern Oscillation (ENSO) were identified using Niño-3.4 index data from January 1979 to December 2019 obtained from NOAA's Climate Prediction Center (CPC) (<https://psl.noaa.gov/data/climateindices/list/>).

The symmetric wavenumber–frequency power spectra (Wheeler and Kiladis 1999) of OLR normalized by the red background was used to identify and isolate the zonally propagating tropical disturbances (Fig. 1a). The clear spectral gap between the MJO (wavenumbers 1–5, period of 30–90 days) and the CCKW (wavenumbers 2–10; period of 3–20 days) indicates that the two are distinct eastward-propagating modes. However, Roundy (2012) cautioned that the observed spectral gap might be an artifact of the ad hoc red background spectra. Figure 1b shows the wavenumber–frequency symmetric coherence-squared spectra between OLR and zonal wind anomalies at 850 hPa with the phase difference between the two fields embedded on top of it as vectors. Coherence-squared spectra are a useful metric that quantifies the relationship between convection and circulation in the wavenumber–frequency space (Hendon and Wheeler 2008; King et al. 2015). The coherence-squared spectra are not normalized with the ad hoc red background and show the similar distribution of coherence-squared values as in the normalized symmetric spectra (Fig. 1), giving further confirmation that the MJO and the CCKW are distinct modes. It can be deduced from Fig. 1b that more than 40% of CCKW circulation variability is associated with convection. It is clear from Fig. 1 that majority of the CCKW variance lies between equivalent depths of 10 and 100 m. The dispersion relation corresponding to an equivalent depth of 35 m passes through the center of local maxima of CCKW variances and from this the global average CCKW

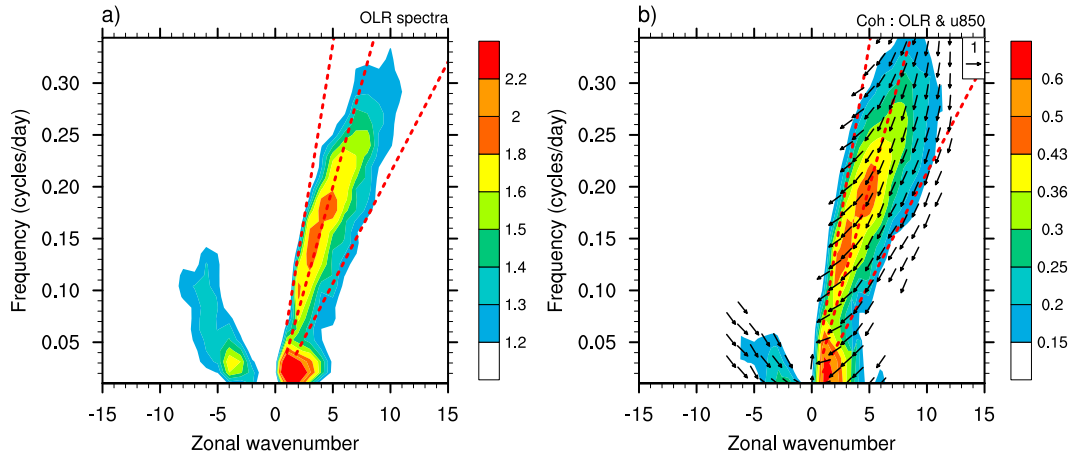


FIG. 1. (a) Symmetric/background wavenumber–frequency power spectra of OLR (b) Symmetric wavenumber–frequency coherence-squared spectra (shaded contours) and phase vectors of OLR and zonal wind at 850 hPa (u850) for the period 1979–2019. Red dashed lines represent the dispersion relation of Kelvin waves with equivalent depths of 10, 35, and 100 m. Shaded regions are statistically significant at 99% confidence level. Upward (downward)-directed vectors imply that OLR and u850 are in (out of) phase, and vectors directed toward the right (left) indicate that OLR leads (lags) u850.

phase speed is estimated as $\sim 18.5 \text{ m s}^{-1}$, which agrees well with those reported in earlier studies (Wheeler and Kiladis 1999; Straub and Kiladis 2002). The MJO signal in OLR was extracted by applying a wavenumber–frequency filter for eastward wavenumbers from 1 to 6, and frequency from $1/90$ to $1/30 \text{ cycles day}^{-1}$ (Fig. 1). Similarly, the CCKW signal in OLR is extracted by applying a wavenumber–frequency filter for eastward wavenumbers 2–10 and frequency of $1/20$ – $1/3 \text{ cycles day}^{-1}$ that lies between equivalent depths 10 and 100 m. The additional equivalent depth criterion was applied to filter out the disturbances that fall outside the CCKW category and hence enhance the signal-to-noise ratio (Fig. 1). A more restrictive OLR-based measure of MJO and CCKW activity was used since we are interested in understanding how the planetary-scale MJO convective envelope modulates the CCKWs.

To identify the geographical domains of activity of the MJO and CCKWs, the variance of these modes was calculated at each grid point for the period 1979–2019 (Fig. 2). The MJO is dominant over the Indian Ocean, western Pacific, eastern Pacific, and equatorial Atlantic, whereas CCKWs are found to be active throughout the equatorial region and, as expected from theory, are more meridionally confined (Matsumo 1966; Kiladis et al. 2009). To explore how the different states of the MJO (convection active, convection suppressed, and quiescent MJO) modulate CCKW events over different geographical domains, regional indices representing the MJO and CCKW were constructed by area averaging the MJO- and CCKW-filtered OLR anomalies over the three domains and then normalizing the resultant time series with their respective standard deviations. The MJO- and CCKW-filtered

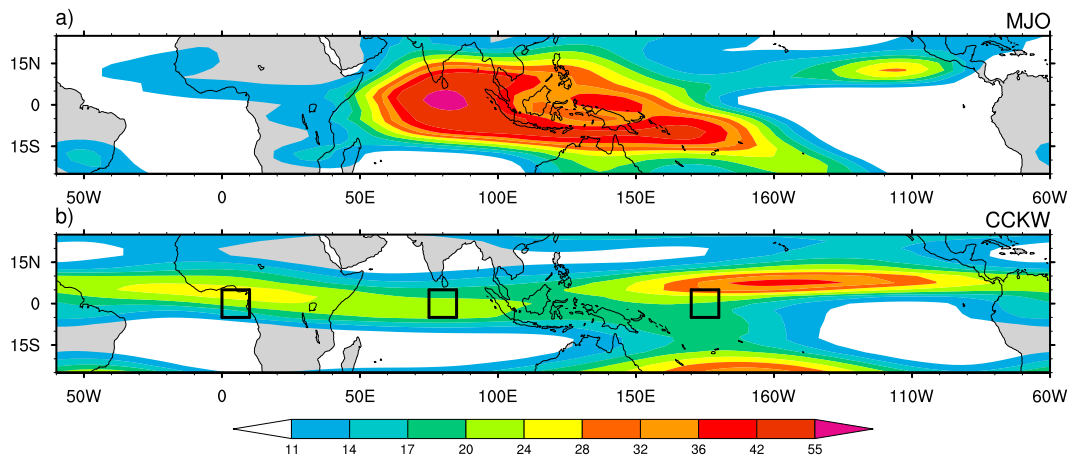


FIG. 2. (a) MJO and (b) CCKW-filtered OLR variance ($\text{W}^2 \text{ m}^{-4}$) for the period 1979–2019. Three rectangular boxes represent the locations over which the MJO and CCKW indices were derived.

TABLE 1. CCKW event statistics over different domains during the period 1979–2019. IO, PO, and AO indicate the Indian, Pacific, and Atlantic Ocean domains, respectively.

Domain	CCKW convective events co-occurring with active MJO convection state	CCKW convective events co-occurring with suppressed MJO convection state	CCKW convective events co-occurring with quiescent MJO state	Total number of CCKW events	MJO index standard deviation (W m^{-2})	CCKW index standard deviation (W m^{-2})
IO	21	24	35	125	6.8	3.4
PO	20	10	59	141	3.9	3.7
AO	27	19	37	120	2.7	3.8

OLR anomalies were area-averaged over $10^\circ \times 10^\circ$ grid boxes over the Indian Ocean (5°S – 5°N , 75° – 85°E), Pacific Ocean (5°S – 5°N , 170°E – 180°), and equatorial Africa (5°S – 5°N , 0° – 10°E). The grid boxes were identified as regions where both the modes are active. Since the CCKWs are largely trapped to the equatorial region, the latitudinal extent of the grid boxes was limited to 5°S – 5°N . But the results are not overly sensitive to the latitudinal extent of the grid boxes.

The indices are designed to capture the passage of MJO and CCKW over the three domains. CCKW convective events that pass over a given domain are identified as when the OLR-based regional CCKW index is less than -1.0 at least for three consecutive days. The peak of each event is then identified as the local minimum. To examine the dependence of the CCKW convectively active state on the different MJO states, the CCKW events are further grouped as co-occurring with MJO convection active, MJO convection suppressed, and quiescent MJO states. A CCKW event is grouped into the active MJO convection category if the MJO index is less than -1.0 throughout the length of the CCKW event. Similarly, if the MJO index is greater than 1.0 throughout the length of a CCKW event, the CCKW event is then categorized as co-occurring with suppressed MJO convection. A CCKW event is grouped into the quiescent MJO category if the MJO index lies between -0.5 and 0.5 throughout the event length. It should be noted that a quiescent MJO state can either be an inactive MJO state or a transition period between two opposite MJO convective states.

The Radon transform method (RTM) was used for objectively estimating the phase speeds of CCKW from the time-longitude distribution of OLR anomalies during the CCKW events (Challenor et al. 2001). The RTM is known to be less sensitive to the outliers than fitting a line and hence many recent studies have used this technique to estimate the phase speeds of propagating disturbances (Challenor et al. 2001; Yang et al. 2007; Dias and Pauluis 2011; Mayta et al. 2021). Refer to Yang et al. (2007) for more details on RTM.

The normalized gross moist stability (GMS) is calculated following Benedict et al. (2014) and Jiang et al. (2015) methodology. The total GMS and its vertical and horizontal components are represented as follows:

$$\Gamma = - \frac{T_R \left[(\mathbf{v} \cdot \nabla s) + \left(\omega \frac{\partial s}{\partial p} \right) \right]}{L[\nabla \cdot (r\mathbf{v})]}, \quad (1)$$

$$\Gamma_v = - \frac{T_R \left(\omega \frac{\partial s}{\partial p} \right)}{L[\nabla \cdot (r\mathbf{v})]}, \quad (2)$$

$$\Gamma_h = - \frac{T_R (\mathbf{v} \cdot \nabla s)}{L[\nabla \cdot (r\mathbf{v})]}, \quad (3)$$

where Γ is the total GMS, Γ_v and Γ_h are the vertical and horizontal components of GMS respectively, T_R is the reference temperature (273.15 K), L is the latent heat of vaporization ($2.5 \times 10^6 \text{ J kg}^{-1}$), r is the water vapor mixing ratio, ω is the vertical pressure velocity, $\mathbf{v}$ is the horizontal wind vector, and s is the moist entropy. The square brackets represent the mass-weighted vertical integral from 1000 to 100 hPa. Refer to Benedict et al. (2014) and Jiang et al. (2015) for more details about GMS computations.

3. Results and discussion

The CCKW event statistics collected over the three domains are summarized in Table 1. Among the three domains, the highest number of CCKW events are observed over the Pacific Ocean domain, and the numbers of CCKW events observed over the Indian and Atlantic Ocean domains are comparable. The observation of large numbers of CCKW events over the Pacific Ocean is consistent with the geographical distribution of CCKW variance (Fig. 2b). The relatively small number of CCKW events observed during different MJO states is possibly due to the differences in seasonality of the MJO and CCKWs. Whereas the MJO becomes more active during boreal winter, the CCKW is found to be more active during May–June (Wheeler and Kiladis 1999; Roundy and Frank 2004; Masunaga 2007). It is interesting to note that about 42% of CCKW events over the Pacific Ocean domain occurred when the MJO was quiescent. About 21% of the CCKW events occurred when the MJO amplitude was strong, of which a higher number of events were associated with active MJO convection (14%) as compared to the suppressed MJO convection state (7%). Over the other two domains, about 36%–38% of the CCKW events occurred when the MJO amplitude was strong and about 28%–30% of the CCKW events occurred when the MJO was quiescent. Similar to the Pacific, the CCKW events over the Atlantic show a greater preference for the active MJO convection state (23%) as compared to the suppressed MJO convection state (16%). Over the Indian Ocean, about 17% of CCKW events are associated

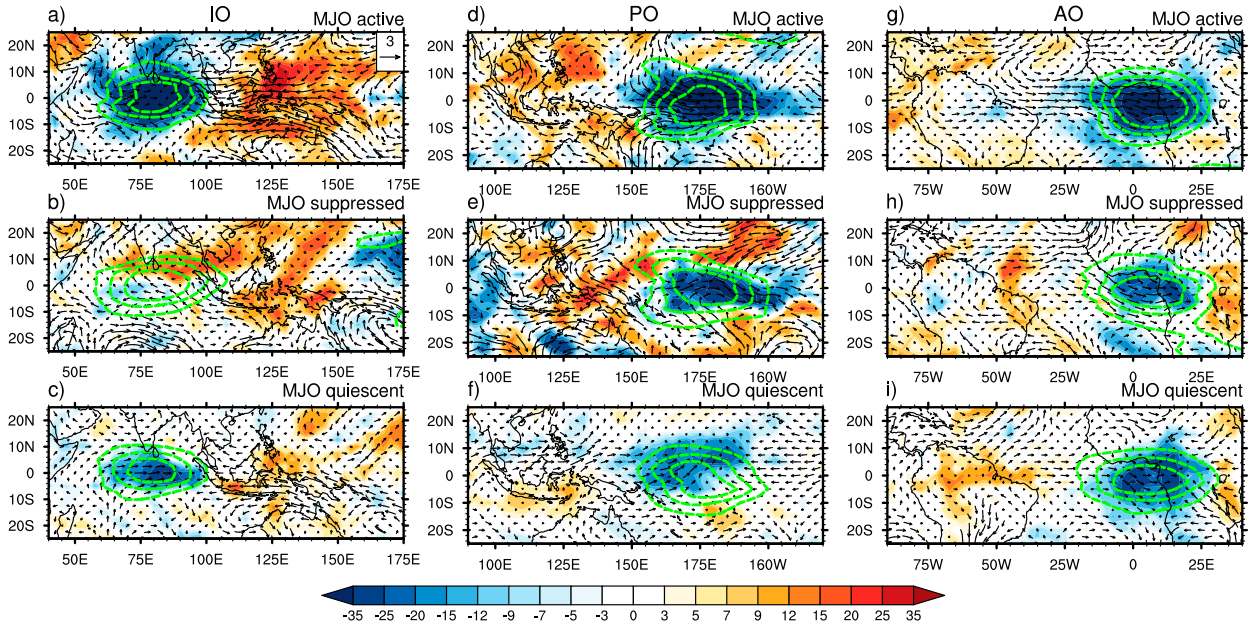


FIG. 3. OLR (W m^{-2}) and 850-hPa wind (m s^{-1}) anomalies composited for the peak days of all CCKW events over the (a)–(c) Indian, (d)–(f) Pacific, and (g)–(i) Atlantic Ocean domains, co-occurring with (a),(d),(g) MJO convection active and (b),(e),(h) MJO convection suppressed, and (c),(f),(i) during quiescent MJO states. Composites of CCKW-filtered OLR (W m^{-2}) anomalies (green contour lines representing -2.5 , -5 , and -7.5 W m^{-2}) are overlaid to highlight the location of CCKW convective region.

with active MJO convection and about 19% of CCKW events are associated with the suppressed MJO convection state.

Figure 3 shows the composites constructed using unfiltered OLR and wind anomalies for the peak days of all CCKW events associated with different MJO states over the three domains. The convection active phase of CCKW over each domain, highlighted by the overlaid contours, is constructed by compositing the CCKW filtered negative OLR anomalies over the peak days of all CCKW events during different MJO states. While the MJO structure dominates the composites for the active MJO convection state (Fig. 3a), the CCKW structure is discernible in the composites for the quiescent MJO state (Fig. 3c). Hence the methodology employed for identifying the CCKW events and MJO states seems to be robust enough to capture the CCKW structures.

The mean spatiotemporal structure and evolution of CCKW events during active MJO convection, suppressed MJO convection, and quiescent MJO states were examined by carrying out a lead-lag composite analysis over the three domains. Since the unfiltered anomalies are dominated by the MJO, 3–20-day bandpass-filtered OLR and wind anomalies were used for characterizing the evolution of the dynamic and convective fields associated with the CCKW. As the event identification is already based on wavenumber–frequency-filtered OLR anomalies, to avoid oversmoothing we have refrained from using wavenumber–frequency-filtered OLR anomalies for constructing the composites. Roundy (2015) pointed out the significance of smaller spatial scale CCKWs; by using only time-filtered anomalies in the composite analysis, we try to preserve the smaller spatial scale CCKWs. The CCKW

composite structure was extracted for different leads, 4 days before and 4 days after the peak of CCKW events.

Figure 4 shows the lead-lag composites of 3–20-day bandpass-filtered OLR and 850-hPa wind anomalies associated with the CCKW events over the Indian Ocean domain that co-occurred with different MJO states. The eastward propagation of CCKWs from eastern Indian Ocean to the Maritime Continent is evident and, as reported in many previous studies, westerly (easterly) wind anomalies are found to be associated with enhanced (suppressed) CCKW convection (Wheeler and Kiladis 1999; Wheeler et al. 2000; Roundy and Frank 2004). The amplitude and meridional extent of the CCKW convective anomalies are largest when the event occurs during the active MJO convection state. The rotational component of CCKW wind is more predominant, with a stronger meridional component when the MJO amplitude is strong (Figs. 4b,g). From the lead-lag composites, it can be inferred that the average periodicity of CCKW events over the Indian Ocean domain is about 10 days.

In the lead-lag composites of CCKW events over the Pacific Ocean domain during different MJO states, the eastward propagation of CCKWs from west to east Pacific is evident (Fig. 5). It is interesting to note that the CCKW convection shows more eastward extent when the MJO amplitude is strong. As observed over the Indian Ocean domain, CCKW winds are more zonally oriented when the MJO is quiescent. CCKWs over the Pacific Ocean domain exhibit a dominant spatial scale of wavenumber 4 and a period of 6–7 days (Fig. 5). Although the CCKW index over the Pacific Ocean domain was derived from an equatorial region, it still captures the off-equatorial

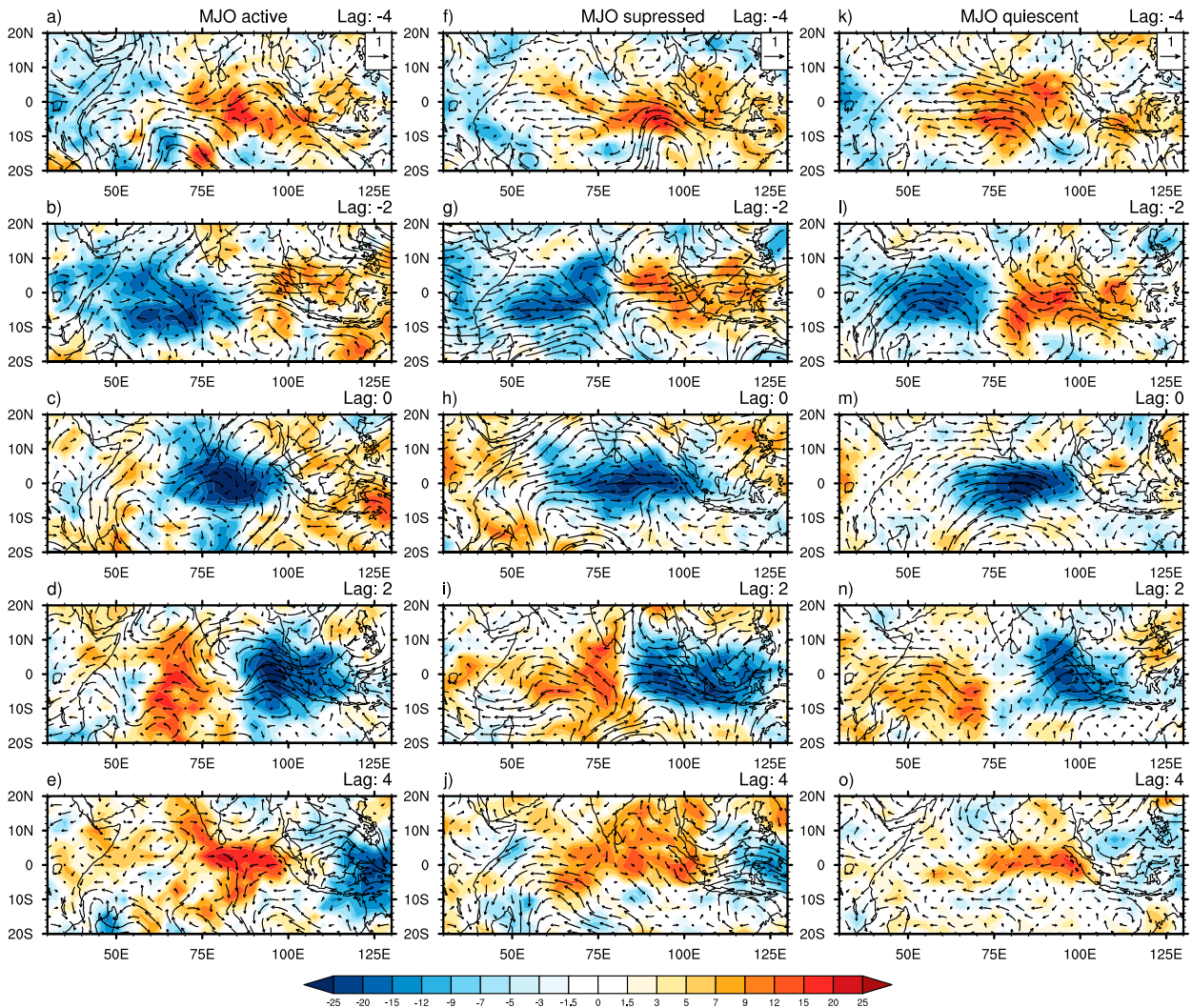


FIG. 4. Lead-lag composites of CCKW events over the Indian Ocean domain, constructed using 3–20-day-filtered OLR (W m^{-2}) and 850-hPa wind (m s^{-1}) anomalies during (a)–(e) MJO convection active, (f)–(j) MJO convection suppressed, and (k)–(o) quiescent MJO states. Positive (negative) lag days indicate the number of days after (before) the peak of CCKW convection. Lag (in days) is shown on the upper-right-hand corner of each panel.

distribution of OLR anomalies as the CCKW propagates over the eastern Pacific. Figure 6 shows the lead-lag composites of CCKW events observed over the Atlantic Ocean domain during different MJO states. It describes the propagation of CCKWs from equatorial Central America to the West African region. The amplitude of CCKWs is higher when MJO convection is active; also, irrespective of the MJO state, the CCKW events over the Atlantic Ocean domain exhibit a smaller spatial scale (wavenumbers 5–6) and a shorter periodicity (5–7 days).

The CCKWs are observed to have a baroclinic vertical structure (Kiladis et al. 2009). Roundy (2008) reported that the CCKWs over the Indian Ocean domain associated with active MJO convection exhibit more pronounced meridional wind anomalies at 200 hPa. To understand whether the vertical structure of CCKWs over the three domains is modulated

by the MJO state, composites of CCKW OLR and 200-hPa wind anomalies were examined for active MJO convection, suppressed MJO convection, and quiescent MJO states (Fig. 7). It is found that over all the three domains the CCKW events have a significant meridional wind component and the rotational component of CCKW winds are more dominant when the MJO amplitude is strong. Upper-level winds associated with the CCKWs are more zonal when the MJO is quiescent.

The phase speeds of CCKWs over the three domains during different MJO states were quantified by applying RTM on the latitudinally averaged lead-lag composites of OLR and 850-hPa zonal wind anomalies. Figure 8 shows the composite time-longitude distribution of CCKW OLR and 850-hPa zonal wind anomalies averaged over 5°S – 5°N during different MJO states over the three domains. It is evident that the CCKW amplitude is largest and it propagates beyond the

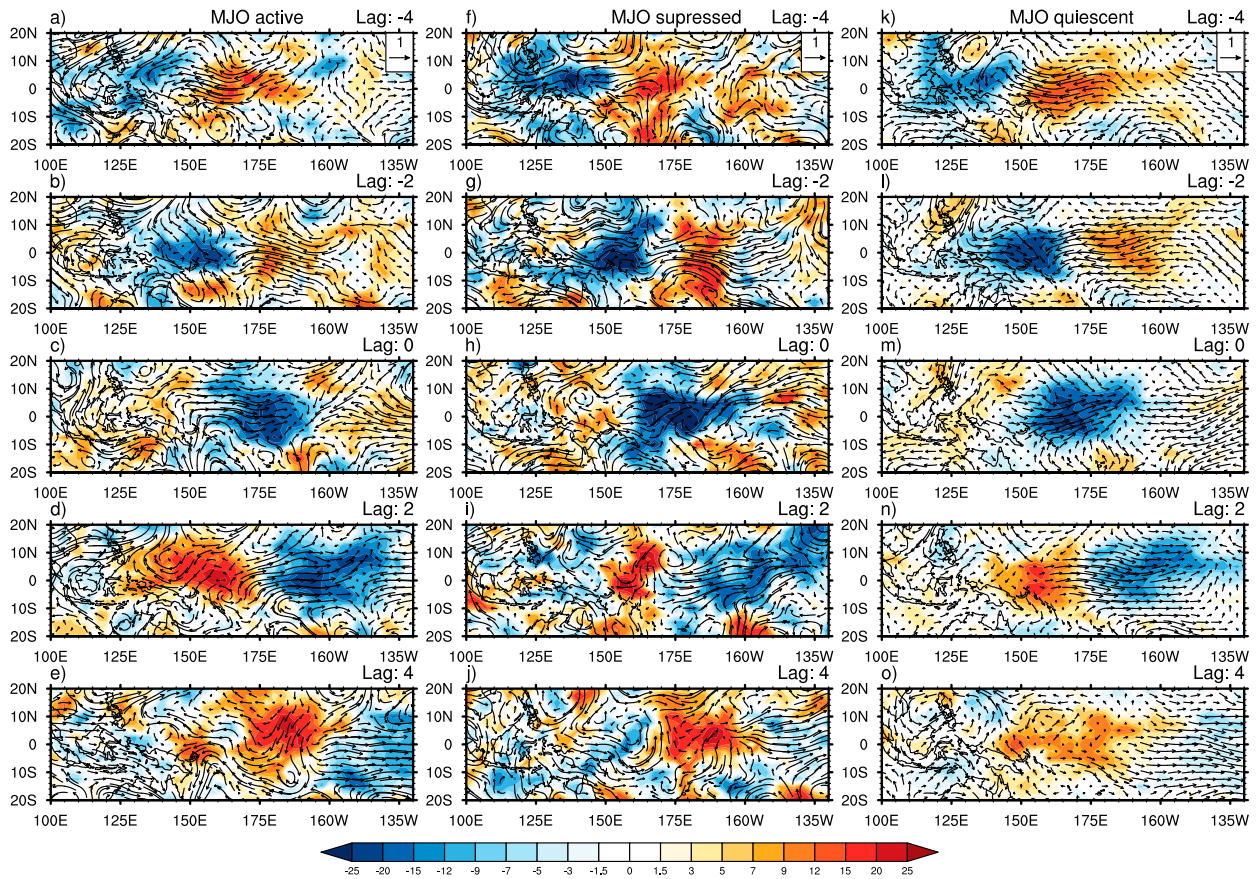


FIG. 5. As in Fig. 5, but for CCKW events over the Pacific Ocean domain.

Maritime Continent when the MJO convection is active over the Indian Ocean (Figs. 8a–c). Objective estimation of CCKW phase speed using RTM reveals that the CCKW convective phase propagates with an approximate phase speed of 13.37 m s^{-1} during the active MJO convection state, 14.48 m s^{-1} during the suppressed MJO convection state, and 15.8 m s^{-1} when the MJO is quiescent over the Indian Ocean. The observed range of CCKW phase speed over the Indian Ocean domain largely agrees with the estimates reported by earlier studies (Dunkerton and Crum 1995; Roundy 2008), even though there were some differences in the methodology employed for identifying the CCKW and MJO events. The CCKW phase speed is relatively higher when the MJO convection is suppressed and when the MJO is quiescent. Over the Pacific Ocean domain, the CCKW phase speed is faster than that over the Indian Ocean (Figs. 8d–f). The CCKW phase speed during the active MJO convection state (15.78 m s^{-1}) is comparable to the phase speed during the suppressed MJO convection state (15.11 m s^{-1}). The CCKW propagates with a higher phase speed of 16.52 m s^{-1} when the MJO is quiescent. Compared to the other two domains, CCKWs over the Atlantic domain propagate with a significantly faster speed during different MJO states (Figs. 8g–i). A phase speed of 20.27 m s^{-1} is observed when the MJO convection is active, 22.85 m s^{-1} when the MJO convection is suppressed, and 24.4 m s^{-1} when the MJO is quiescent. It is also

observed that the CCKW amplitude is significantly higher when the MJO convection is active. As expected, the average CCKW phase speed ($\sim 17.6 \text{ m s}^{-1}$) across the different domains, during different MJO states, approximately agrees with the value derived from the wavenumber–frequency spectra (18.5 m s^{-1} ; Fig. 1). The statistical significance of the observed differences in CCKW phase speeds was tested using the bootstrap method. Except for the difference in CCKW phase speeds associated with active MJO convection and suppressed MJO convection states over the Pacific Ocean domain, all other CCKW phase speed differences are statistically significant.

Convection–circulation coupling strength and gross moist stability are considered as major factors that can affect the phase speed of MJO and other convectively coupled equatorial waves (Roundy 2008; Kiladis et al. 2009; Raymond et al. 2009; Frierson et al. 2011; Benedict et al. 2014). We investigate the relative roles of these factors in explaining the observed differences in CCKW phase speeds during different MJO states over the different domains. Roundy (2008) reasoned that a stronger feedback between convection and circulation might be one of the reasons for the slower CCKW phase speed during the active MJO convection state over the Indian Ocean. Differences in convection–circulation coupling strength during different MJO states is evident from Fig. 8.

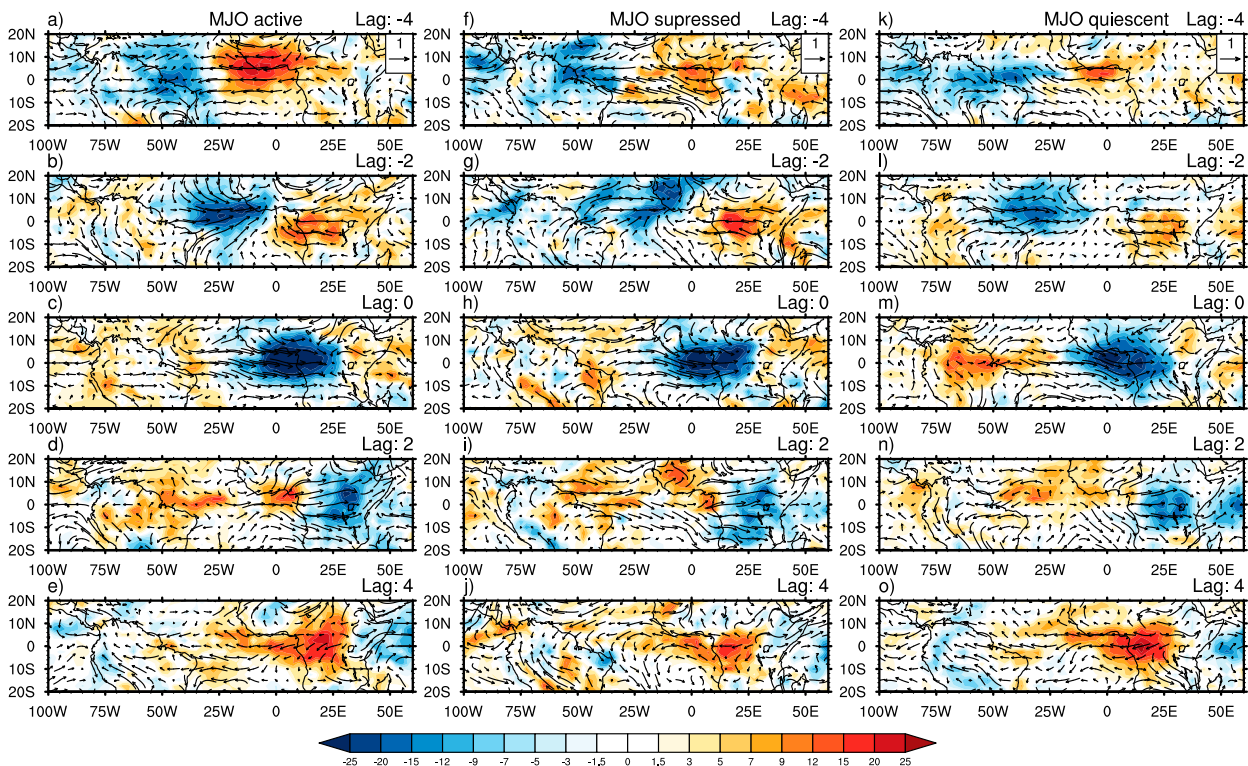


FIG. 6. As in Fig. 5, but for CCKW events over the Atlantic Ocean domain.

The coherent eastward propagation of OLR and zonal wind anomalies and the relatively slow CCKW phase speed imply a stronger convection–circulation coupling during the active MJO convection state.

To bring out more clear and direct evidence for the strength of convection–circulation coupling in the CCKW time scale, coherence-squared spectra were calculated for a 30-day window period centered around each of the CCKW

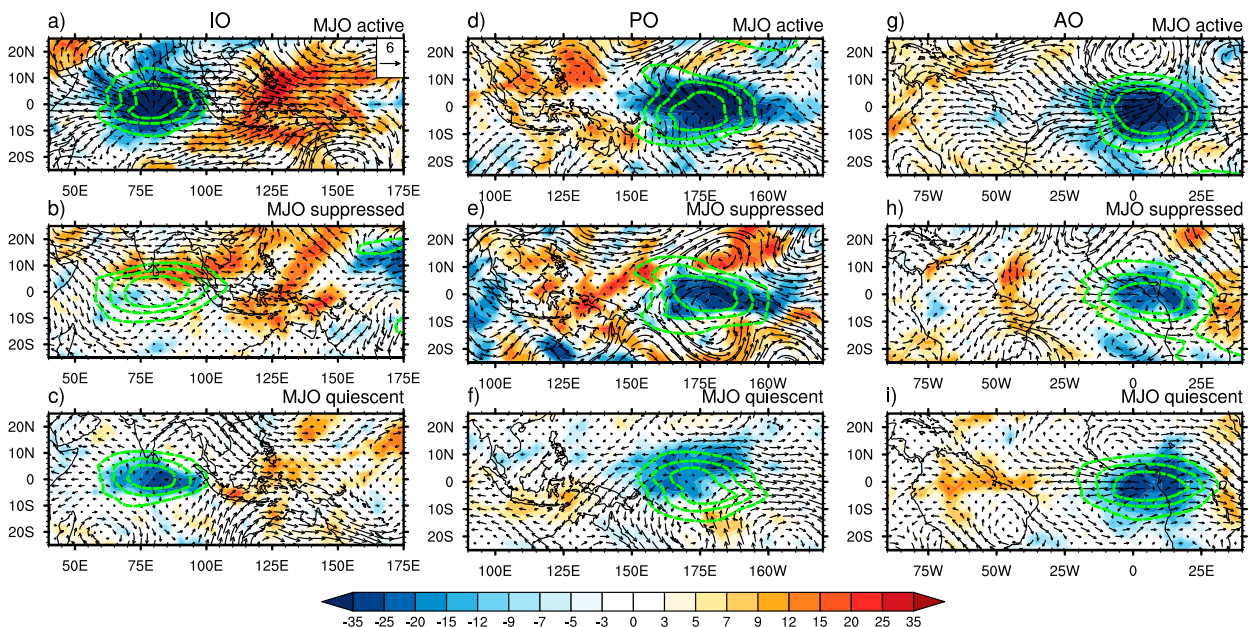


FIG. 7. As in Fig. 3, but wind anomalies at 850 hPa are replaced with those at 200 hPa.

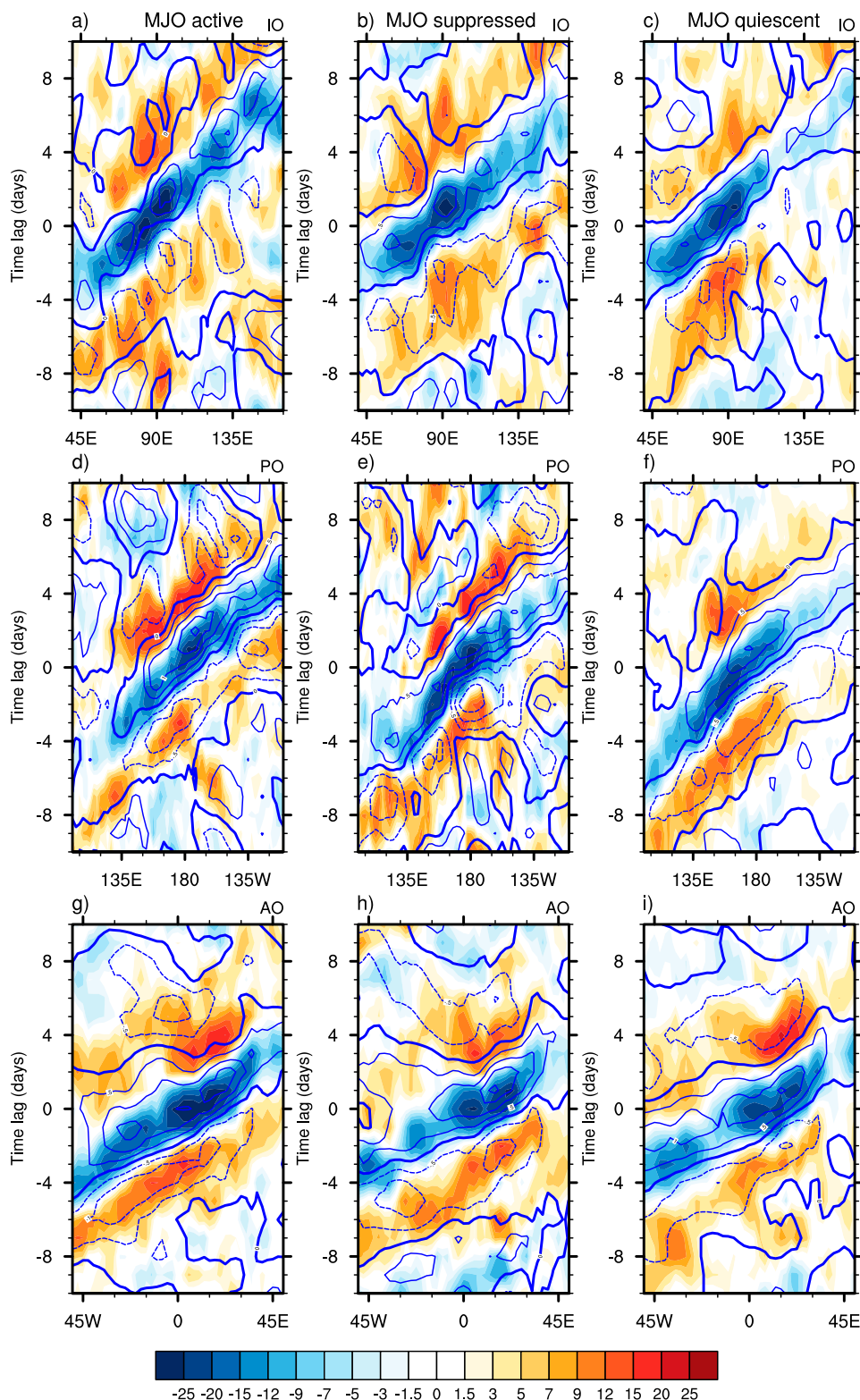


FIG. 8. Phase propagation of CCKW events in OLR (W m^{-2}) and 850-hPa zonal wind (m s^{-1}) anomalies over the (a)–(c) Indian Ocean, (d)–(f) Pacific Ocean, and (g)–(i) Atlantic Ocean domains during the (a),(d),(g) MJO convection active, (b),(e),(h) MJO convection suppressed, and (c),(f),(i) quiescent MJO states. The composite CCKW phase propagation was estimated by averaging the lead–lag composites in Figs. 5–7 over 5°S – 5°N .

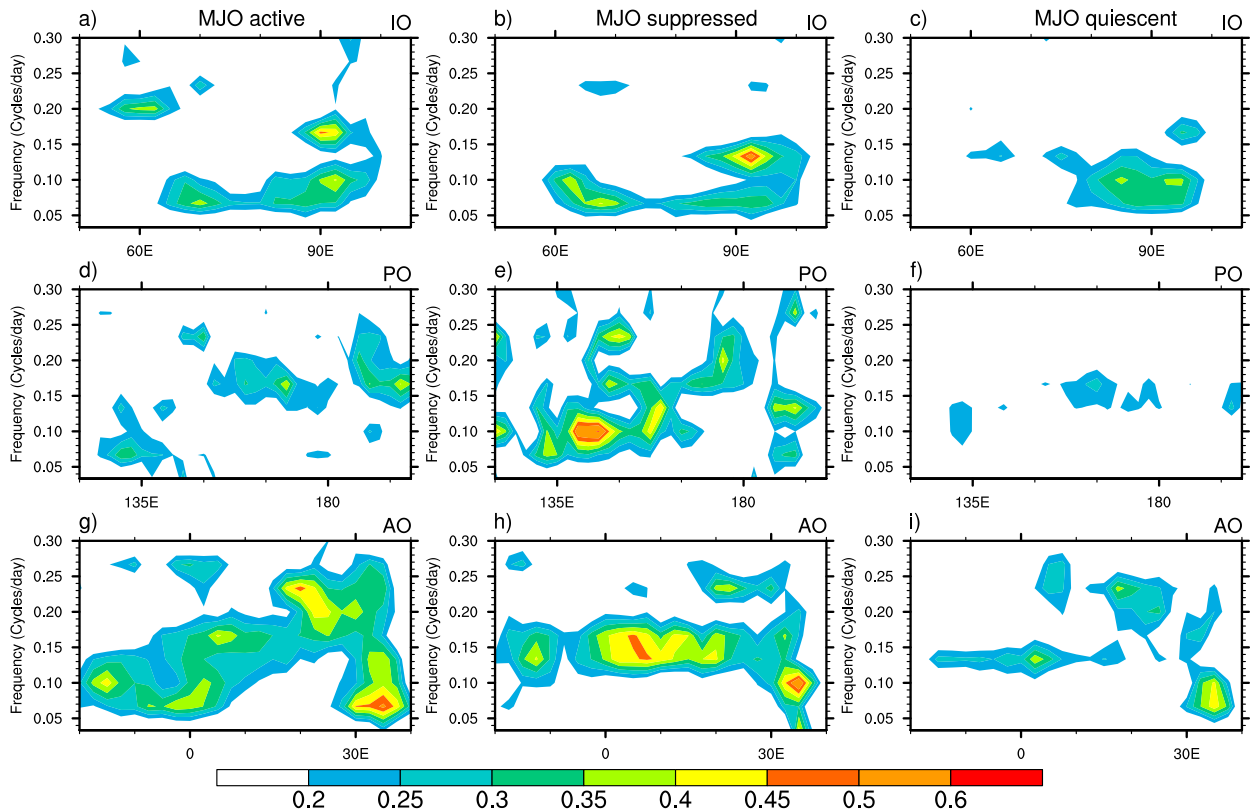


FIG. 9. Composite coherence-squared spectra between OLR and 850-hPa zonal wind anomalies estimated for CCKW events co-occurring with (a),(d),(g) MJO convection active and (b),(e),(h) MJO convection suppressed, and during (c),(f),(i) quiescent MJO states over the (a)–(c) Indian Ocean, (d)–(f) Pacific Ocean, and (g)–(i) Atlantic Ocean domains. Composite coherence-squared spectra were estimated by averaging the coherence-squared spectra over all the events in each category and averaging symmetric with respect to the equator between 5°S and 5°N. Shaded regions are statistically significant at 99% confidence level.

events and the resultant values were averaged between 5°S and 5°N. The composite coherence-squared spectra between OLR and 850-hPa zonal wind anomalies were then computed for different MJO states over the three domains (Fig. 9). Larger coherence-squared values indicate stronger convection–circulation coupling. Over all the three domains, the fastest CCKW phase speed is observed during the quiescent MJO state and consistently very low coherence-squared values are observed during the quiescent MJO state. Over the Pacific Ocean domain, compared to the active MJO convection state, stronger coherence-squared values are observed when MJO convection is suppressed. Compared to the other two domains, relatively higher coherence-squared values are observed over the Atlantic Ocean domain, implying stronger convection–circulation coupling on the CCKW time scale. However, this is inconsistent with the observed higher phase speed of CCKWs over the Atlantic Ocean, as a stronger convection–circulation coupling would result in a slower phase speed.

It has been shown that both the upper-tropospheric and lower-stratospheric zonal winds respond to the CCKWs (Hendon and Wheeler 2008). The coupling between CCKW convection and zonal wind anomalies at different pressure levels from 1000 to 50 hPa was further examined using

coherence-squared spectral analysis. The approach is similar to the one described above; over the three domains, for the different MJO states the composite coherence-squared spectra was computed at each pressure level. Figure 10 shows the longitude–pressure distribution of composite coherence-squared values averaged for the time period that captures the maximum coherence values between OLR and winds at 850 hPa (Fig. 9) over the different domains. The composite coherence-squared values were averaged over the period 7–15 days over the Indian Ocean domain, 7–10 days over the Pacific Ocean domain, and 5–10 days over the Atlantic Ocean domain. Strong convection–circulation coupling in the troposphere is observed from surface up to the 500-hPa level over the Indian Ocean domain (Figs. 10a–c). Over the other two domains, the highest coherence-squared values are mostly restricted below the 700-hPa level (Figs. 10d–i). This might be related to the fact that MJO convection is more intense and active over the Indian Ocean domain and it possibly enhances the convection–circulation coupling strength in the CCKW scale through nonlinear scale interactions. Over all the three domains, strong convection–circulation coupling is also observed near the tropopause and lower stratosphere and the coupling strength is in general weaker during quiescent MJO

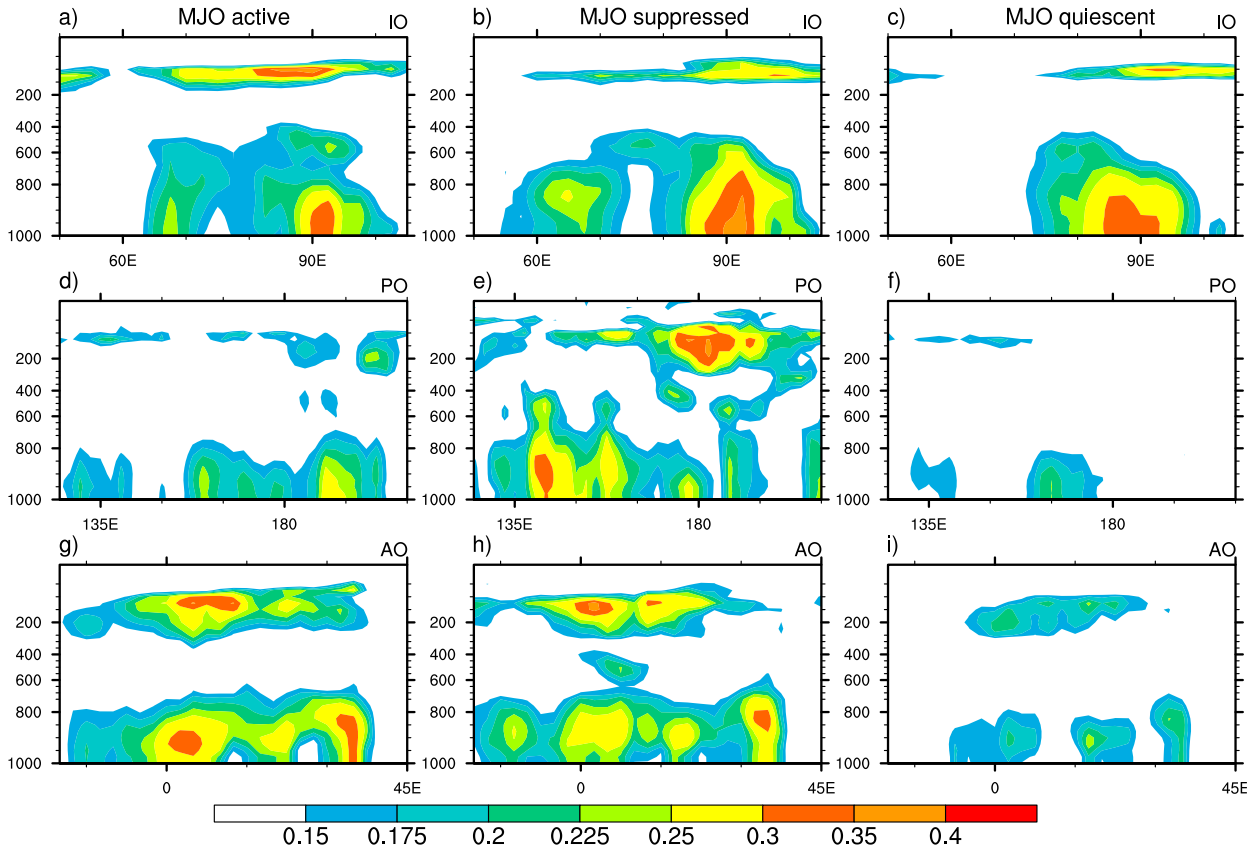


FIG. 10. Pressure–longitude coherence-squared spectra between OLR and 850-hPa zonal wind anomalies averaged over CCKW time scales estimated for all CCKW events co-occurring with (a),(d),(g) MJO convection active, (b),(e),(h) MJO convection suppressed, and (c),(f),(i) quiescent MJO states over the (a)–(c) Indian Ocean, (d)–(f) Pacific Ocean, and (g)–(i) Atlantic Ocean domains. Shaded regions are statistically significant at 99% confidence level.

states. Similar to convection–circulation coupling observed at the 850-hPa level (Fig. 9), over the Pacific Ocean domain, higher coherence-squared values are observed in the lower and upper troposphere and lower stratosphere when MJO convection is suppressed (Figs. 10d–f). Over the Atlantic Ocean domain, higher coherence-squared values are observed both in the lower and upper troposphere and lower stratosphere when the MJO amplitude is strong (Figs. 10g–i). However, the strong convection circulation coupling observed over the Atlantic Ocean domain cannot explain the high CCKW phase speed observed over the domain.

Many previous studies identify the major convectively coupled equatorial waves and the MJO as moist modes and hypothesize that the phase speed of these waves may be related to the gross moist stability (GMS) (Neelin et al. 1987; Frierson et al. 2011; Benedict et al. 2014). According to linear wave theory, the phase speed of equatorial waves is proportional to the square root of its equivalent depth. Since GMS is considered as a measure of effective equivalent depth, a linear relationship is expected between the magnitude of GMS and the phase speed of convectively coupled equatorial waves. However, such an association has not been examined so far using observations. Benedict et al. (2014) found an inverse linear

relationship between the vertical component of GMS and the ratio of eastward to westward power in the MJO spectral band in climate model simulations. Frierson et al. (2011) attributed the differences in CCKW phase speed simulated by different convective triggers to the differences in GMS. To explain the observed differences in CCKW phase speed over the different domains during different MJO states, we explore the possible relationship between CCKW phase speed and the corresponding magnitude of GMS.

Diagnostic analysis using reanalysis and multimodel data has shown that the vertical component of GMS is more dominant during active phase of convection and displays an association with the strength of convectively coupled tropical disturbances (Raymond et al. 2009; Benedict et al. 2014; Inoue and Back 2015; Jiang et al. 2015). On the other hand, the contribution of the horizontal component of GMS to the total GMS is negligible during active phase of convection and it is found to be more dominant during decay phase of convection (Inoue and Back 2015). The vertical component of GMS indicates the degree of moistening/drying of the atmosphere during convective processes and hence can be considered as a measure of stability of the atmosphere. The vertical and horizontal components of GMS during different MJO states were

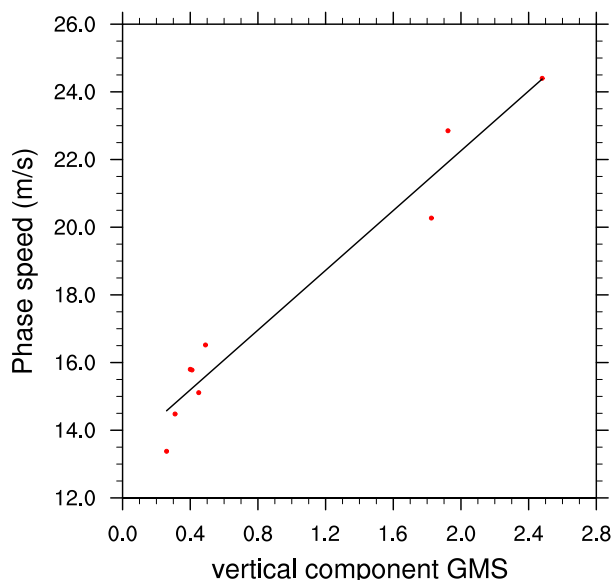


FIG. 11. The relationship between the vertical component of normalized gross moist stability and CCKW phase speeds (m s^{-1}) over the Indian, Pacific, and Atlantic Ocean domains for MJO convection active, MJO convection suppressed, and quiescent MJO states. Black line represents the least squares fit.

calculated over the different domains and their relationship with the observed CCKW phase speeds was examined. It is observed that the vertical component of GMS accounts for a major fraction of the total GMS and it exhibits a stronger correlation (correlation coefficient ~ 0.9) with the CCKW phase speeds (Fig. 11; Table 2). A strong linear relationship is also observed between the total GMS (correlation coefficient ~ 0.85) and the CCKW phase speeds. The GMS has the highest value when the MJO is quiescent over the Atlantic Ocean domain and is lowest when the MJO convection is active over the Indian Ocean domain. The observed relationship explains not only the differences in CCKW phase speed over the different domains but also the differences observed during different MJO states. The possible connection between the GMS and CCKW is hypothesized as follows. Reduced static stability in the regions of planetary-scale convection allows for baroclinic modes to exist (Charney 1963; Holton 2004). A baroclinic vertical structure permits communication between the lower and upper troposphere, resulting in a lower GMS. A lower effective equivalent depth due to the lower GMS will in turn lower the phase speed of the waves (Kiladis et al. 2009; Frierson et al. 2011).

To test this hypothesis, we examined the composite vertical structures of CCKWs during different MJO states over the different domains. Because the vertical structure of CCKWs is more evident in temperature (Kiladis et al. 2009; Frierson et al. 2011), the composite vertical structure is extracted using 3–20-day bandpass-filtered temperature anomalies (Fig. 12). CCKWs over the Indian and Pacific Ocean domains exhibit a second baroclinic vertical structure with an east–west tilt in the troposphere (more vertical tilt is found over the Indian Ocean domain) and a west–east tilt in the lower stratosphere

TABLE 2. Vertical component of normalized GMS when CCKW events occur together with active MJO convection, suppressed MJO convection, and quiescent MJO states over the different domains. The corresponding CCKW phase speeds (m s^{-1}) are indicated inside the parentheses.

Domain	Active MJO convection state	Suppressed MJO convection state	Quiescent MJO state
IO	0.26 (13.34)	0.31 (14.48)	0.4 (15.8)
PO	0.41 (15.78)	0.45 (15.11)	0.49 (16.52)
AO	1.83 (20.27)	1.92 (22.85)	2.48 (24.4)

(Wheeler et al. 2000; Kiladis et al. 2009). On the other hand, the vertical structure of CCKWs over the Atlantic Ocean domain is different from the other two domains. The vertical structure of CCKWs over the Atlantic Ocean domain is nearly barotropic in the troposphere and exhibits a west–east tilt in the lower stratosphere. It is consistent with a recent study by Yang and Hoskins (2017), who showed that synoptic-scale tropical disturbances exhibit an equivalent barotropic vertical structure over the Atlantic Ocean domain. Scale analysis for the tropical atmosphere over the Western Hemisphere indicate that the region permits equivalent barotropic vertical structure (Yang and Hoskins 2017). It can be inferred from Fig. 12 that the vertical scale of CCKWs is relatively larger over the Atlantic Ocean domain and smaller over the Indian Ocean domain.

In general, the Indo-Pacific domain supports planetary-scale convection and hence baroclinic vertical structures are favored over the region. The relative strength of MJO is different over different domains (Fig. 2, Table 1), with strongest amplitude observed over the Indian Ocean domain and weakest amplitude observed over the Atlantic Ocean domain. Stronger planetary-scale convection associated with the MJO might make the Indian and Pacific Ocean domains more baroclinic, reduce the GMS, and lower the CCKW phase speeds. On the other hand, the relative strength of the MJO being small over the Atlantic Ocean domain might result in weak baroclinic modes and favor a higher GMS, which is reflected in the overall higher CCKW phase speeds. It is clear from Fig. 12 that the observed vertical structure of CCKWs in the troposphere over the Atlantic Ocean domain is nearly barotropic. The observed differences in CCKW vertical structures over the different domains are consistent with the observed differences in GMS and phase speeds, in accordance with the hypothesis. The relationship between GMS and CCKW phase speed and the range of magnitude of CCKW phase speed indicate that the CCKW events might constitute a mixed-moisture mode (Adames et al. 2019).

4. Summary and conclusions

We have examined the modulation of convective activity associated with CCKWs by different MJO states over the Indian, Pacific, and Atlantic Ocean domains using OLR and ERA-Interim reanalysis wind anomalies for the period 1979–2019. The dominant CCKW and MJO spatial and temporal scales were identified using wavenumber–frequency

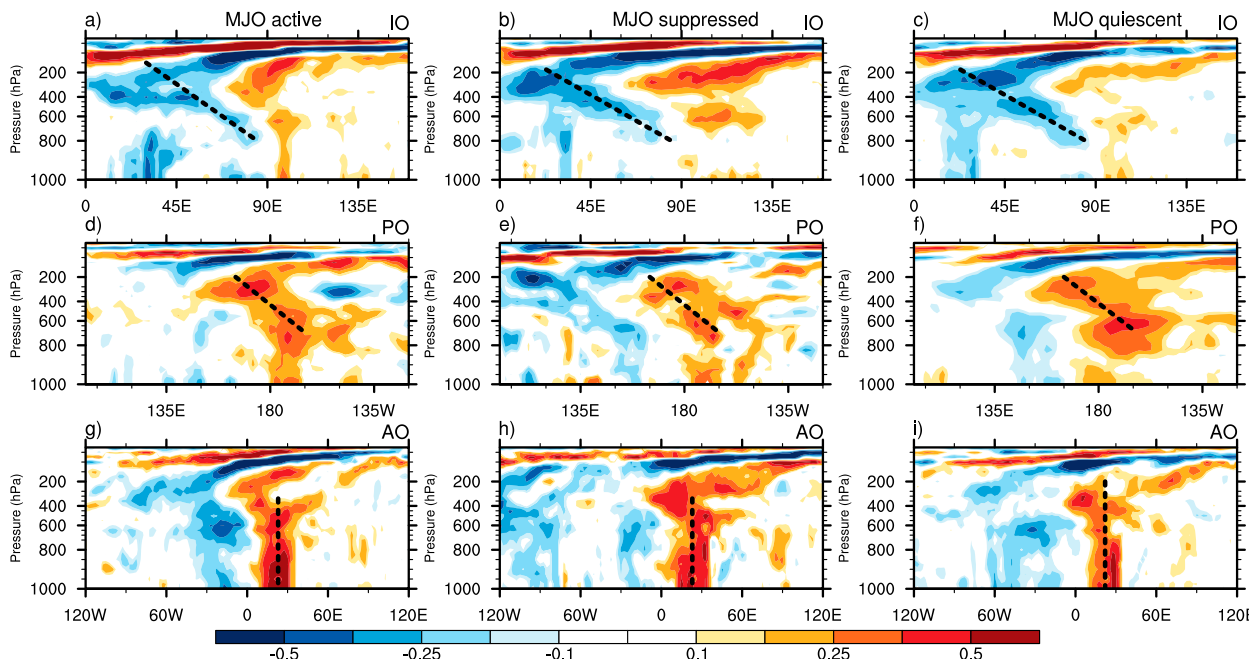


FIG. 12. Pressure–longitude distribution of 3–20-day bandpass-filtered temperature anomalies (K) averaged for all CCKW events co-occurring with (a),(d),(g) MJO convection active and (b),(e),(h) MJO convection suppressed, and (c),(f),(i) during quiescent MJO states over the (a)–(c) Indian Ocean, (d)–(f) Pacific Ocean, and (g)–(i) Atlantic Ocean domains. Dashed black lines are indicative of the tilt in the CCKW vertical structure in the troposphere.

power spectral analysis of OLR and coherence-squared spectral analysis of OLR and zonal wind anomalies. Convective anomalies with wavenumbers 1–6 and a 30–90-day period were identified as the MJO and those with wavenumbers 2–10 and a 3–20-day period, with equivalent depths between 10 and 100 m, were identified as CCKWs (Fig. 1). The MJO and CCKW convective signals were extracted by applying a wavenumber–frequency filter on the OLR data using these criteria. Based on the spatial distribution of MJO and CCKW variance (Fig. 2), three equatorial locations where both the MJO and CCKWs are active were identified over the Indian (5°S – 5°N , 75° – 85°E), Pacific (5°S – 5°N , 170°E – 180°), and Atlantic Ocean (5°S – 5°N , 0° – 10°E) domains. CCKW convection active events over the three domains were identified using CCKW-filtered OLR data averaged over the respective local domains. Further, the CCKW events that occurred together with active MJO convection, suppressed MJO convection, and quiescent MJO states were identified.

Lead–lag composite analysis reveals that the amplitude of the MJO modulates the intensity and phase speed of CCKW events (Figs. 3–5). It is also noted that over the three domains, the CCKW propagates more eastward when MJO convection is active. Analysis of the phase speed of CCKW convective events over the three domains during different MJO states reveals that the CCKWs propagate with a consistently faster phase speed when the MJO is quiescent (Fig. 8). It is observed that, in general, the CCKWs propagate relatively more slowly over the Indian Ocean domain (~ 13 – 16 m s^{-1}) and relatively faster over the Atlantic Ocean domain (~ 20 – 24 m s^{-1}). To

understand the differences in CCKW phase speeds over the different domains during different MJO states, the relationship of CCKW phase speed with the convection–circulation coupling strength and gross moist stability was explored.

Convection–circulation coupling strength during different MJO states was quantified by performing coherence-squared spectral analysis between OLR and 850-hPa zonal wind anomalies for all the CCKW events observed over the three domains (Fig. 9). The analysis reveals that convection–circulation coupling strength is indeed higher when the MJO amplitude is strong. The longitude–pressure distribution of coherence-squared values averaged over the CCKW frequency range shows that the coherence between OLR and zonal wind anomalies is significantly higher when the MJO amplitude is strong. The observation of higher coherence-squared values when the MJO amplitude is strong and lower coherence-squared values when the MJO is quiescent can be interpreted as a difference in the convection–circulation coupling strength. Strong coherence is observed in the upper troposphere and lower stratosphere when the MJO amplitude is strong, implying the possible role of the MJO in modulating the stratospheric circulation by influencing vertical easterly momentum transport via CCKWs (Fig. 10). However, convection–circulation coupling strength does not explain the differences in CCKW phase speed observed over the different domains. For example, convection–circulation coupling strength is found to be largest over the Atlantic Ocean domain where the CCKWs exhibit faster phase speeds.

On the other hand, the vertical component of GMS over the different domains during different MJO states exhibits a

strong linear relationship with the CCKW phase speeds (Fig. 11, Table 2). The vertical component of GMS can be considered as a measure of effective stability of the atmosphere and a higher GMS indicates higher stability (Inoue and Back 2015). The lowest GMS value is observed over the Indian Ocean domain when the MJO convection is active, and the highest GMS value is observed over the Atlantic Ocean domain when the MJO is quiescent. These observations are consistent with the CCKW phase speeds. It can be hypothesized that planetary-scale convection associated with the MJO and the resulting low static stability allow for baroclinic modes to prevail, which in turn reduces the GMS and effective equivalent depth and slows down the CCKW phase speed (Kiladis et al. 2009; Frierson et al. 2011). The CCKW composite vertical structures over different domains support this hypothesis (Fig. 12). While the CCKWs exhibit a baroclinic vertical structure over the Indian and Pacific Ocean domains, a nearly barotropic vertical structure is observed over the Atlantic Ocean domain. The observed range of values of CCKW phase speeds and its relationship with GMS suggest that CCKWs may be treated as a mixed-moisture mode (Adames et al. 2019).

It should be noted that the large-scale low-frequency modes of variability such as ENSO and the QBO might also modulate the characteristics of both the CCKWs and the MJO and possibly affect the MJO–CCKW interactions. Preliminary analysis of the frequency of occurrence of CCKW events over the three domains for the easterly/westerly phase of the QBO indicates that unlike the MJO, which is reported to be more frequent during QBO easterly phase (Yoo and Son 2016; Martin et al. 2021), CCKWs show a higher preference for the westerly QBO phase (figure not shown). Similarly, a slightly higher probability of CCKW events was also observed during the El Niño phase of ENSO (figure not shown). While the analysis provides some qualitative insight on how the QBO/ENSO might affect the MJO–CCKW interactions, we refrain from exploring it any further as it is beyond the scope of the present study.

While the present study explores the modulation of the convection active state of CCKWs by the co-occurring MJO state, it should be noted that the lead-lag interactions between CCKWs and the MJO has not been addressed in the study. Such lead-lag interactions are equally important. For example, CCKWs are considered as one of the precursors for MJO initiation over the Indian Ocean domain, and CCKWs over South America and the Atlantic Ocean may be excited from the residue of the MJO over the east Pacific (Masunaga 2007; Ventrice et al. 2012). These aspects are of great importance in terms of the predictability of the MJO as well as the synoptic and mesoscale systems and these interactions will be addressed in a future study.

Acknowledgments. NJM acknowledges an early career research grant from SERB-DST, Government of India. SE acknowledges SERB-DST, Government of India, for the Ramanujan Fellowship. ERA Interim data are obtained from the website <https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/>. NOAA interpolated OLR data are obtained from <https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html>.

REFERENCES

- Adames, Á. F., D. Kim, S. K. Clark, Y. Ming, and K. Inoue, 2019: Scale analysis of moist thermodynamics in a simple model and the relationship between moisture modes and gravity waves. *J. Atmos. Sci.*, **76**, 3863–3881, <https://doi.org/10.1175/JAS-D-19-0121.1>.
- Benedict, J. J., E. D. Maloney, A. H. Sobel, and D. M. W. Frierson, 2014: Gross moist stability and MJO simulation skill in three full-physics GCMs. *J. Atmos. Sci.*, **71**, 3327–3349, <https://doi.org/10.1175/JAS-D-13-0240.1>.
- Bessafi, M., and M. C. Wheeler, 2006: Modulation of south Indian Ocean tropical cyclones by the Madden–Julian oscillation and convectively coupled equatorial waves. *Mon. Wea. Rev.*, **134**, 638–656, <https://doi.org/10.1175/MWR3087.1>.
- Challenor, P. G., P. Cipollini, and D. Cromwell, 2001: Use of the 3D Radon transform to examine the properties of oceanic Rossby waves. *J. Atmos. Oceanic Technol.*, **18**, 1558–1566, [https://doi.org/10.1175/1520-0426\(2001\)018<1558:UOTRTT>2.0.CO;2](https://doi.org/10.1175/1520-0426(2001)018<1558:UOTRTT>2.0.CO;2).
- Charney, J. G., 1963: A note on large-scale motions in the tropics. *J. Atmos. Sci.*, **20**, 607–609, [https://doi.org/10.1175/1520-0469\(1963\)020<0607:ANOLSM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1963)020<0607:ANOLSM>2.0.CO;2).
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.
- Dias, J., and O. Pauluis, 2011: Modulation of the phase speed of convectively coupled Kelvin waves by the ITCZ. *J. Atmos. Sci.*, **68**, 1446–1459, <https://doi.org/10.1175/2011JAS3630.1>.
- Duchon, C. E., 1979: Lanczos filtering in one and two dimensions. *J. Appl. Meteor.*, **18**, 1016–1022, [https://doi.org/10.1175/1520-0450\(1979\)018<1016:LFIOAT>2.0.CO;2](https://doi.org/10.1175/1520-0450(1979)018<1016:LFIOAT>2.0.CO;2).
- Dunkerton, T. J., and F. X. Crum, 1995: Eastward propagating ~2- to 15-day equatorial convection and its relation to the tropical intraseasonal oscillation. *J. Geophys. Res.*, **100**, 25 781–25 790, <https://doi.org/10.1029/95JD02678>.
- Frierson, D. M. W., D. Kim, I.-S. Kang, M.-I. Lee, and J. Lin, 2011: Structure of AGCM-simulated convectively coupled Kelvin waves and sensitive to convective parameterization. *J. Atmos. Sci.*, **68**, 26–45, <https://doi.org/10.1175/2010JAS3356.1>.
- Guo, Y., X. Jiang, and D. E. Waliser, 2014: Modulation of convectively coupled Kelvin waves over South America and the tropical Atlantic Ocean with the Madden–Julian oscillation. *J. Atmos. Sci.*, **71**, 1371–1388, <https://doi.org/10.1175/JAS-D-13-0215.1>.
- , D. E. Waliser, and X. Jiang, 2015: A systematic relationship between the representations of convectively coupled equatorial wave activity and the Madden–Julian oscillation in climate model simulations. *J. Climate*, **28**, 1881–1904, <https://doi.org/10.1175/JCLI-D-14-00485.1>.
- Hendon, H. H., and B. Liebmann, 1994: Organization of convection within the Madden–Julian oscillation. *J. Geophys. Res.*, **99**, 8073–8083, <https://doi.org/10.1029/94JD00045>.
- , and M. C. Wheeler, 2008: Some space–time spectral analysis of tropical convection and planetary-scale waves. *J. Atmos. Sci.*, **65**, 2936–2948, <https://doi.org/10.1175/2008JAS2675.1>.
- Holton, J. R., 2004: *Introduction to Dynamic Meteorology*. 4th ed. Elsevier Academic Press, 535 pp.
- Inoue, K., and L. E. Back, 2015: Gross moist stability assessment during TOGA COARE: Various interpretations of gross moist stability. *J. Atmos. Sci.*, **72**, 4148–4166, <https://doi.org/10.1175/JAS-D-15-0092.1>.
- Jiang, X., and Coauthors, 2015: Vertical structure and physical processes of the Madden–Julian oscillation: Exploring key

- model physics in climate simulations. *J. Geophys. Res. Atmos.*, **120**, 4718–4748, <https://doi.org/10.1002/2014JD022375>.
- Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy, 2009: Convectively coupled equatorial waves. *Rev. Geophys.*, **47**, RG2003, <https://doi.org/10.1029/2008RG000266>.
- King, M. J., M. C. Wheeler, and T. P. Lane, 2015: Association of convection with the 5-day Rossby–Haurwitz wave. *J. Atmos. Sci.*, **72**, 3309–3321, <https://doi.org/10.1175/JAS-D-14-0316.1>.
- Liebmann, B., and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc.*, **77**, 1275–1277, <https://doi.org/10.1175/1520-0477-77.6.1274>.
- , G. N. Kiladis, L. M. V. Carvalho, C. Jones, C. S. Vera, I. Bladé, and D. Allured, 2009: Origin of convectively coupled Kelvin waves over South America. *J. Climate*, **22**, 300–315, <https://doi.org/10.1175/2008JCLI2340.1>.
- Madden, R. A., and P. R. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.*, **29**, 1109–1123, [https://doi.org/10.1175/1520-0469\(1972\)029<1109:DOGCC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<1109:DOGCC>2.0.CO;2).
- Martin, Z., S.-W. Son, A. Butler, H. Hendon, H. Kim, A. Sobel, S. Yoden, and C. Zhang, 2021: The influence of the quasi-biennial oscillation on the Madden–Julian oscillation. *Nat. Rev. Earth Environ.*, **2**, 477–489, <https://doi.org/10.1038/s43017-021-00173-9>.
- Masunaga, H., 2007: Seasonality and regionality of the Madden–Julian oscillation, Kelvin wave, and equatorial Rossby wave. *J. Atmos. Sci.*, **64**, 4400–4416, <https://doi.org/10.1175/2007JAS2179.1>.
- Matsumoto, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43, https://doi.org/10.2151/jmsj1965.44.1_25.
- Mayta, V. C., G. N. Kiladis, J. Dias, P. L. Silva Dias, and M. Gehne, 2021: Convectively coupled Kelvin waves over tropical South America. *J. Climate*, **34**, 6531–6547, <https://doi.org/10.1175/JCLI-D-20-0662.1>.
- Mekonnen, A., C. D. Thorncroft, A. R. Aiyer, and G. N. Kiladis, 2008: Convectively coupled Kelvin waves over tropical Africa during the boreal summer: Structure and variability. *J. Climate*, **21**, 6649–6667, <https://doi.org/10.1175/2008JCLI2008.1>.
- Mounier, F., G. N. Kiladis, and S. Janicot, 2007: Analysis of the dominant mode of convectively coupled Kelvin waves in the West African monsoon. *J. Climate*, **20**, 1487–1503, <https://doi.org/10.1175/JCLI4059.1>.
- Neelin, J. D., I. M. Held, and K. H. Cook, 1987: Evaporation–wind feedback and low-frequency variability in the tropical atmosphere. *J. Atmos. Sci.*, **44**, 2341–2348, [https://doi.org/10.1175/1520-0469\(1987\)044<2341:EWFAF>2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044<2341:EWFAF>2.0.CO;2).
- Nguyen, H., and J. -P. Duvel, 2008: Synoptic wave perturbations and convective systems over equatorial Africa. *J. Climate*, **21**, 6372–6388, <https://doi.org/10.1175/2008JCLI2409.1>.
- Raymond, D. J., S. L. Sessions, A. H. Sobel, and Ž. Fuchs, 2009: The mechanics of gross moist stability. *J. Adv. Model. Earth Syst.*, **1**, 9, <https://doi.org/10.3894/JAMES.2009.1.9>.
- Roundy, P. E., 2008: Analysis of convectively coupled Kelvin waves in the Indian Ocean MJO. *J. Atmos. Sci.*, **65**, 1342–1359, <https://doi.org/10.1175/2007JAS2345.1>.
- , 2012: Observed structure of convectively coupled waves as a function of equivalent depth: Kelvin waves and the Madden–Julian oscillation. *J. Atmos. Sci.*, **69**, 2097–2106, <https://doi.org/10.1175/JAS-D-12-03.1>.
- , 2015: On the interpretation of EOF analysis of ENSO, atmospheric Kelvin waves, and the MJO. *J. Climate*, **28**, 1148–1165, <https://doi.org/10.1175/JCLI-D-14-00398.1>.
- , and W. M. Frank, 2004: A climatology of waves in the equatorial region. *J. Atmos. Sci.*, **61**, 2105–2132, [https://doi.org/10.1175/1520-0469\(2004\)061<2105:ACOWIT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<2105:ACOWIT>2.0.CO;2).
- Salby, M. L., and H. H. Hendon, 1994: Intraseasonal behavior of clouds, winds, and temperature in the tropics. *J. Atmos. Sci.*, **51**, 2207–2224, [https://doi.org/10.1175/1520-0469\(1994\)051<2207:IBOCTA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<2207:IBOCTA>2.0.CO;2).
- Schreck, C. J., III, 2015: Kelvin waves and tropical cyclogenesis: A global survey. *Mon. Wea. Rev.*, **143**, 3996–4011, <https://doi.org/10.1175/MWR-D-15-0111.1>.
- Straub, K. H., and G. N. Kiladis, 2002: Observations of a convectively coupled Kelvin wave in the eastern Pacific ITCZ. *J. Atmos. Sci.*, **59**, 30–53, [https://doi.org/10.1175/1520-0469\(2002\)059<0030:OOACCK>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<0030:OOACCK>2.0.CO;2).
- , and —, 2003: The observed structure of convectively coupled Kelvin waves: Comparison with simple models of coupled wave instability. *J. Atmos. Sci.*, **60**, 1655–1668, [https://doi.org/10.1175/1520-0469\(2003\)060<1655:TOSOC>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<1655:TOSOC>2.0.CO;2).
- Takayabu, Y. N., 1994: Large-scale cloud disturbances associated with equatorial waves. Part I: Spectral features of the cloud disturbances. *J. Meteor. Soc. Japan*, **72**, 433–449, https://doi.org/10.2151/jmsj1965.72.3_433.
- , and M. Murakami, 1991: The structure of super cloud clusters observed in 1–20 June 1986 and their relationship to easterly waves. *J. Meteor. Soc. Japan*, **69**, 105–125, https://doi.org/10.2151/jmsj1965.69.1_105.
- , G. N. Kiladis, and V. Magaña, 2016: Michio Yanai and tropical waves. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, Meteor. Monogr., No. 56, Amer. Meteor. Soc., <https://doi.org/10.1175/AMSMONOGRAPH5-D-15-0019.1>.
- Ventrone, M. J., C. D. Thorncroft, and C. J. Schreck III, 2012: Impacts of convectively coupled Kelvin waves on environmental conditions for Atlantic tropical cyclogenesis. *Mon. Wea. Rev.*, **140**, 2198–2214, <https://doi.org/10.1175/MWR-D-11-00305.1>.
- , M. C. Wheeler, H. H. Hendon, C. J. Schreck III, C. D. Thorncroft, and G. N. Kiladis, 2013: A modified multivariate Madden–Julian oscillation index using velocity potential. *Mon. Wea. Rev.*, **141**, 4197–4210, <https://doi.org/10.1175/MWR-D-12-00327.1>.
- Wang, H., and R. Fu, 2007: The influence of Amazon rainfall on the Atlantic ITCZ through convectively coupled Kelvin waves. *J. Climate*, **20**, 1188–1201, <https://doi.org/10.1175/JCLI4061.1>.
- Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber–frequency domain. *J. Atmos. Sci.*, **56**, 374–399, [https://doi.org/10.1175/1520-0469\(1999\)056<0374:CCEWAO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2).
- , —, and P. J. Webster, 2000: Large-scale dynamical fields associated with convectively coupled equatorial waves. *J. Atmos. Sci.*, **57**, 613–640, [https://doi.org/10.1175/1520-0469\(2000\)057<0613:LSDFAW>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<0613:LSDFAW>2.0.CO;2).
- Yang, G.-Y., and B. Hoskins, 2017: The equivalent barotropic structure of waves in the tropical atmosphere in the Western Hemisphere. *J. Atmos. Sci.*, **74**, 1689–1704, <https://doi.org/10.1175/JAS-D-16-0267.1>.
- , —, and J. Slingo, 2007: Convectively coupled equatorial waves. Part II: Propagation characteristics. *J. Atmos. Sci.*, **64**, 3424–3437, <https://doi.org/10.1175/JAS4018.1>.
- Yoo, C., and S.-W. Son, 2016: Modulation of the boreal winter-time Madden–Julian oscillation by the stratospheric quasi-biennial oscillation. *Geophys. Res. Lett.*, **43**, 1392–1398, <https://doi.org/10.1002/2016GL067762>.