Changes in the Eastward Movement Speed of the Madden–Julian Oscillation with Fluctuation in the Walker Circulation

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ABSTRACT: The eastward movement of a convectively active region is a distinguishing characteristic of the Madden–Julian oscillation (MJO). However, knowledge about the mechanisms that determine the eastward movement speed remains limited. This study investigates how the background environment modulates the speed of the boreal winter MJO and describes an intrinsic relationship between the MJO and background atmospheric circulation. We calculated the speed of the MJO events from the daily tracking of the locations of the minimum values of the outgoing longwave radiation anomaly in the time–longitude space. These speeds were then used to analyze systematic differences in the sea surface temperature (SST) distribution associated with the MJO speed. The analysis revealed a deceleration of the MJO under low-frequency (>90 days) SST distributions that increased toward the western Pacific from both the Indian Ocean and the eastern Pacific. In contrast, the dependency on SST variability in intraseasonal frequencies (20–90 days) was small. Subsequently, the relationship between the MJO speed and background circulation, which is largely determined by the lower boundary condition set by the low-frequency SST distribution, was analyzed. The analysis counterintuitively revealed that the MJO tends to decelerate when the large-scale zonal circulation with low-level westerlies and upper-level easterlies from the Indian Ocean to the Maritime Continents is strong. The results suggest a novel view that the MJO is an integral component of the Walker circulation and that its eastward movement is modulated by the state of the large-scale flow of the Walker circulation.

KEYWORDS: Atmosphere–ocean interaction; Atmospheric circulation; Madden–Julian oscillation; Walker circulation

1. Introduction

The Madden–Julian oscillation (MJO; [Madden and Julian 1971](#)) is the predominant intraseasonal variability in the tropics, which is characterized by a slow eastward movement of an envelope of a convectively active region that initiates over the Indian Ocean (IO) and dissipates near the central Pacific (CP; [Madden and Julian 1972](#)). The mechanisms of this eastward movement and the factors that determine its speed are not yet fully understood.

Observational studies have revealed that the mean speed of the eastward movement of an MJO varies from event to event. [Weickmann et al. \(1985\)](#) have reported one of the earliest estimates of the speed range of the MJO as $3\text{--}6\text{ m s}^{-1}$, with an average of approximately 5 m s^{-1} . Their results have been confirmed by several studies (e.g., [Weickmann and Khalsa 1990](#); [Rui and Wang 1990](#); [Hendon and Salby 1994](#); [Suematsu 2015](#); [Zhang and Ling 2017](#); [Wang et al. 2019](#); [Wei and Ren 2019](#); [Chen and Wang 2020](#)), and the documented minimum and maximum speeds of MJO convection have been extended to approximately 1 m s^{-1} ([Wang and Rui 1990](#); [Chen and Wang 2020](#)) and 10 m s^{-1} ([Zhang and Ling 2017](#)), respectively. Currently, 5 m s^{-1} is widely accepted as the characteristic speed of the MJO ([Zhang 2005](#)).

The variations in MJO movement have been associated with seasonal cycles. [Wang and Rui \(1990\)](#) tracked convective signals of MJO events, classified them based on their course of progression and strength of the convective signals, and analyzed their seasonal variations. They indicated that the MJO events that occur in the boreal winter months (November–April) move slower and exhibit stronger convective signals than those that occur in the boreal summer months (May–August). Following their pioneering work, comprehensive investigations on the seasonality of the MJO revealed a tendency of the MJO to proceed eastward faster during boreal spring (March–May) than during other times of the year ([Jenken et al. 2011](#); [Suematsu 2015](#)). A few studies have suggested that the timing of the transition of the active region of the MJO convection from the IO to the western Pacific (WP) is regulated by the seasonal evolution of the sea surface temperature (SST) distribution, particularly from November to December ([Bellenger and Duvel 2007](#); [Sobel et al. 2008](#); [Miura et al. 2015](#)). In this season the WP sector of the Indo-Pacific warm pool, defined as the stretch of the ocean above 28°C that bestrides the IO and WP ([Wyrtki 1989](#)), begins its south-eastward extension, which continues through the austral summer months (November–April; [Kim et al. 2012](#)). For the MJO events that occur during November–December, the eastward shift of the convective region is reportedly modulated by the climatological eastward displacement of the location of the warmest SST from the IO to the WP ([Miura et al. 2015](#)).

The SST variability at the interannual and longer time scales has also been demonstrated to influence the characteristics of the eastward movement of the MJO. For example,

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the extent to which the convective activities of an MJO can penetrate the Pacific Ocean is affected by El Niño–Southern Oscillation (ENSO; [Trenberth 1997](#)). Several studies have revealed that the convective activities of an MJO tend to extend eastward beyond the date line during El Niño years, whereas they tend to be confined westward of the date line during La Niña years (e.g., [Fink and Speth 1997](#); [Hendon et al. 1999](#); [Woolnough et al. 2000](#); [Pohl and Matthews 2007](#); [Nishimoto and Shiotani 2013](#)). [Pohl and Matthews \(2007](#); hereafter [PM07](#)) revealed that the duration of MJO events was shorter during El Niño than during La Niña and deduced that MJO should move faster during El Niño events than during La Niña events. This was confirmed by studies that evaluated the mean speed of the MJO events during El Niño to be faster than that during La Niña ([Nishimoto and Shiotani 2013](#); [Wei and Ren 2019](#), hereafter [NS13](#) and [WR19](#)). However, [Roundy and Kravitz \(2009\)](#) and [Gribble-Verhagen and Roundy \(2010\)](#) have shown that the MJO tends to move more slowly over the CP near the onset of El Niño events, suggesting that considering the developmental stages of the ENSO is important for understanding the relationship between ENSO and MJO speed. The Indian Ocean dipole (IOD; [Saji et al. 1999](#)) is another interannual variability that influences MJO frequency. [Izumo et al. \(2010\)](#) revealed that MJO events during positive and negative IOD events have high (35–50 days) and low (55–100 days) frequencies, respectively.

Many studies have focused on the behavior of equatorial waves to investigate the mechanisms influencing the variations in the eastward speed of the MJO. [Miura et al. \(2012\)](#) controlled the entrainment parameter of a cumulus parameterization in an atmospheric general circulation model and showed that the eastward movement of organized convective systems accelerated and decelerated as their coupling to the divergent and rotational wind fields strengthened, respectively. Through aquaplanet experiments, [Kang et al. \(2013\)](#) demonstrated that the velocities of large-scale equatorial convective systems change systematically with the differences in the relative contributions of Rossby and Kelvin waves. They revealed that as the meridional width of the high SST region widens or the location of the highest SST is displaced away from the equator, the relative contribution of the Rossby waves increases and the eastward movement of the convective system slows down. Their results were reconfirmed in a recent study ([Jiang et al. 2020](#)), which suggested that the wider meridional width of the highest SST shifts the velocity of the convective system from eastward to westward.

Observational analyses also suggested an increase in the speed of the MJO with a strong coupling with the Kelvin wave responses ([Wang et al. 2019](#); [WR19](#); [Chen and Wang 2020](#)) and attributed a strong coupling with the Rossby wave response as a characteristic of the slowly proceeding ($\sim 4.1 \text{ m s}^{-1}$) MJO events ([WR19](#)). It has been indicated that the Kelvin wave response to the east of the MJO convection moistens the lower troposphere and enhances shallow and congestus convection, which preconditions an eastward environment favorable for deep convection and induces rapid movement of the MJO ([Wang et al. 2019](#); [WR19](#); [Chen and Wang 2020](#)).

As discussed, various factors such as the seasonal cycle, SST variability, and coupling with equatorial waves have been associated with the eastward movement of the MJO. However, the fundamental properties that interrelate these factors and provide a coherent explanation to the variations in the speed of the MJO remain unclear. [Suematsu and Miura \(2018\)](#) revealed that a quasi-steady background SST distribution for atmospheric convection with a warmer WP than the IO is crucial for the realization of the long-lived convective activities of the MJO. They asserted that the slowly varying SST distribution (>60 days) determines the bottom boundary condition, which can either support or suppress the development of MJO convection.

Slow changes in the zonal SST gradient over the tropics have been associated with variations in the Walker circulation ([Bjerknes 1969](#)). Together with the typically overlooked fact that the active region of the MJO convection coincides with the western branch of the Walker circulation, it is reasonable to expect that the MJO is influenced by slow changes in the SST. [Suematsu and Miura \(2018\)](#) supported this by revealing that the zonal gradient of the background influences the development of large-scale convective activities into an MJO event. Moreover, recent studies ([Setzenfand 2018](#); [Tomoff 2020](#); [Roundy 2021](#)) have indicated that the speed of the MJO is influenced by the global circulation pattern. In particular, they have associated the acceleration of MJO with a stronger subtropical jet stream and deceleration of MJO over the IO with anomalous upper tropospheric easterlies in the tropics. Considering these implications, this study hypothesizes that the variations in the Walker circulation, associated with slow changes in the SST, can be a fundamental factor that regulates the speed of the eastward movement of the MJO.

In this study, we first evaluated the variations in the speed of the MJO movement. Subsequently, we indicated that these variations are associated with the variations in the Walker circulation, which is influenced by SST fluctuations at a time scale longer than the intraseasonal time scale. We focused on the MJO events in the boreal winter months (November–April) when the movement of the MJO is mostly eastward with smaller meridional displacements than those during the boreal summer months (May–October; [Wang and Rui 1990](#)).

2. Data

The MJO events examined in this study were objectively detected using the real-time multivariate MJO index (RMM; [Wheeler and Hendon 2004](#)), which is a proxy that detects the MJO as an entity of active convection coupled to large-scale circulation at the intraseasonal time scale. The data used to calculate the RMM were the interpolated outgoing longwave radiation (OLR; [Liebmann and Smith 1996](#)) from NOAA, and the daily data of lower level (850 hPa) and upper level (200 hPa) zonal wind velocities (U_{850} and U_{200} , respectively) from the NCEP–DOE Reanalysis 2 (NCEP–DOE R2; [Kanamitsu et al. 2002](#)). The RMM indices were calculated for the period from 1 January 1979 to 31 December 2016. However, the period from 1 May 1994 to 31 January 1995 was omitted

from our analysis to eliminate the influence of the unrealistically high OLR values in September 1994 (Suematsu 2015). Multilevel data of zonal and vertical wind velocities of NCEP–DOE R2 were used to examine the large-scale atmospheric circulation during MJO events. The SST data used were the NOAA Optimum Interpolated SST V2 (Reynolds et al. 2002) for the period from 1 January 1982 to 31 December 2016. Note that the $0.25^\circ \times 0.25^\circ$ resolution of the SST data was reduced to $2.5^\circ \times 2.5^\circ$ by area averaging before the analyses. This is because the correlation between convective signals and SST increases with a decrease in resolution, which levels off at approximately 0.6° at a resolution of $2.5^\circ \times 2.5^\circ$ (Suematsu and Miura 2018). We also used the ocean Niño index (ONI) provided by the NOAA/CPC to determine the ENSO phases in which MJO events occurred. ONI is defined as the 3-month running mean of the SST anomaly over the Niño-3.4 region (5°S – 5°N , 170° – 120°W). Periods when ONI was >0.5 K and periods when ONI was <-0.5 K were classified as the episodes of El Niño and La Niña, respectively (NOAA/CPC 2017).

3. Methods

a. MJO detection

In this study, the MJO events were identified by extracting the time sequences that project to the RMM phase space from phases 2 to 7 while satisfying the MJO criteria of Suematsu and Miura (2018) (Table 1). The convectively inactive phases of 1 and 8 were omitted from the analyses. The criteria for MJO detection were configured such that the physical implications of the trajectory on the RMM phase space reflect the generally accepted characteristics of the MJO in the physical space while incorporating temporal drops in the RMM amplitude from other disturbances that project to the zonal wind.

The RMM calculation procedures followed the original method of Wheeler and Hendon (2004), except for simplifying the procedure to eliminate the seasonal cycle to the removal of the long-term trend and passage of the 20–120-day Lanczos bandpass filter (Duchon 1979) with 241 symmetric weights. This simplification was adopted because we were not concerned with real-time application. The days of the initiation and termination of the MJO events were defined as the first day of phase 2 and the last day of phase 7, respectively.

The MJO events that initiated after 1 November and terminated before 30 April were selected as the events that occurred in the boreal winter. Using this classification, 60 MJO events were detected between the boreal winters of 1982/83 and 2015/16.

b. Estimation of MJO speed

Our method of MJO speed evaluation was based on the tracking of MJO convection in the spatiotemporal space. Tracking was conducted by first calculating the meridional averages of the OLR anomaly between 15°S and 15°N and then detecting the longitude of the minimum value of the daily anomaly in the time–longitude space (Fig. 1). The OLR anomaly was calculated as the difference in the OLR from the daily climatology of the 1979–2016 OLR data. The minimum values were detected for restricted longitude ranges, depending on the RMM phases. The specified longitude ranges were 50° – 120°E for phases 2–3, 50° – 150°E for phase 4, 100°E – 150°W for phase 5, and 120°E – 150°W for phases 6–7. An RMM phase is physically meaningless when its amplitude is small. Thus, combined longitude ranges (50°E – 150°W) were searched for the days when the RMM amplitude dropped below 0.8, which is the value at which a sufficiently strong MJO-like atmospheric pattern signal appears to be present (Suematsu and Miura 2018). Note that the longitude ranges for phases 4 and 5 overlap with those of other phases to enable smooth tracking over the Maritime Continents (MC), where the MJO typically stagnates (Wang and Rui 1990; Hendon and Salby 1994; Zhang and Ling 2017), and regions of active convection are typically split into both the eastern and western sides of the MC.

The speeds of the MJO events were evaluated using the regression coefficient of the 2D data comprising the dates and longitudes of the tracked minima of the OLR anomalies. This approach reduces the sensitivity of the results to the location of the minimum OLR anomaly, which is highly variable on a daily basis (cf. Fig. 1). The calculated regression coefficients that passed the Student's *t* test at a confidence level of 95% were determined as the mean speeds of the MJO events during their lifetimes.

Although MJO events were detected in the RMM phase space, which is predominantly determined by U_{850} and U_{200} (Straub 2013), our method of MJO speed estimation only considered the OLR. Therefore, confirming the consistency between the speeds evaluated in the time–longitude space and the trajectory in the RMM phase space will reinforce the

TABLE 1. MJO criteria on RMM phase space and their physical interpretations.

Criteria on RMM phase space	Physical interpretation
Phases proceeds from phase 2 to 7	Convective activity proceeds from the Indian Ocean to the western Pacific
Phases do not skip more than one phase	Convective activity proceeds continuously in the physical space
Phases do not recede by more than one phase	Dismiss convective systems with major westward-propagating signals
Average RMM amplitude is >0.8 .	Maintenance of typical MJO structure
Period of consecutive days with amplitude < 0.8 is below 15 days	Maintenance of typical MJO structure
Tracking is completed between 20 and 90 days	Completion of an event in an intraseasonal time scale

FIG. 1. Hovmöller diagram of 15°S – 15°N averaged OLR anomaly (W m^{-2}) of a MJO event from 21 Dec 2012 to 28 Jan 2013. Five days before and after the initiation and termination of the MJO event are shown for reference. The black and red lines represent the longitudes of the tracked minimum OLR anomalies and their regression line, respectively. The color bar on the right indicates the daily real-time multivariate MJO (RMM) phases: phase 1 (red), phase 2 (yellow), phase 3 (yellow-green), phase 4 (green), phase 5 (cyan), phase 6 (blue), phase 7 (purple), and phase 8 (magenta). The dotted boxes indicate the longitude ranges for the search for the daily minimum OLR anomaly for each RMM phase.

robustness of the evaluated MJO speeds. To ensure consistency between the two, we imposed the constraint that the MJO speeds should have a linear relationship with the mean angular velocities of the trajectories in the RMM phase space. This requirement is based on the expectation that the angular velocity defined in the RMM phase space corresponds to the speed of an MJO in the physical space. This is because the amplification of a specific RMM phase is expected to reflect the enhancement of a large-scale atmospheric circulation coupled with a strong convective activity over a characteristic location depending on the phase.

The mean angular velocity (rad day^{-1}) of an MJO event on the RMM phase space was defined as the difference in the polar angles between the last day of phase 7 and the first day of phase 2 divided by the number of days of the event. The polar angles were calculated from the polar axis, which was defined as the RMM1 axis in the negative direction. The MJO

events were selected by first calculating the regression line between the angular velocities and MJO speeds for all the detected MJO events, and then selecting the MJO events which the distance between the MJO speeds and the regression line was within one standard deviation.

As a result of consistency screening, eight events were removed (Fig. 2). For the remaining 52 MJO events, we obtained a mean speed of 4.4 m s^{-1} , which is consistent with the generally accepted value of the MJO speed of movement at 5 m s^{-1} .

4. Results

a. Evolution of the OLR of slow and fast MJOs

We first compared the five fastest and slowest events (hereafter referred to as the slow MJO and fast MJO, respectively), which were within the 10th percentile range of each extreme to identify systematic differences in the MJO characteristics that are related to their speeds. The mean speeds of the slow and fast MJOs were 1.5 and 7.6 m s^{-1} , respectively.

Figures 3a and 3b compare the temporal evolutions of the convective activities of the slow and fast MJOs from the RMM phase composites of OLR. The composites for each of the phases from 2 to 7 were made for each member of the slow and fast MJOs, and then, they were composited for each phase within each of the groups. Days with an RMM amplitude of <0.8 , were excluded from the composites. Note that the composites of the absolute values of the OLR rather than the anomalies were considered to depict the evolutions of the slow and fast MJOs as they occurred. The composites provided slightly different impressions from those of the OLR anomalies (e.g., Wheeler and Hendon 2004), and the centers of the locations of the low OLR were shifted toward the MC region where OLR is climatologically low.

FIG. 2. Scatterplot of the average MJO speed (m s^{-1}) and angular velocities (rad day^{-1}) of the detected MJO events. The black solid line represents the regression line between the speed and the angular velocities. The dotted lines indicate one standard deviation of the residual from the regression line. The MJO events selected for the analysis are shown in red, and the removed events are shown in blue.

FIG. 3. Real-time multivariate MJO (RMM) phase composite of OLR (W m^{-2}) of the (a) slow MJO and (b) fast MJO.

At the initiation stage (phase 2) of the slow MJO (Fig. 3a), there was a continuous stretch of a low OLR region ($<210 \text{ W m}^{-2}$) from 60°E to the date line with a minimum OLR region beginning to develop over the eastern IO around the southwestern coast of Sumatra (Fig. 3a). In the following developing stages (phases 3 and 4), the OLR continued to decrease over the eastern IO and MC. By phase 4, convective activity reached its maximum intensity with an area of OLR below 170 W m^{-2} , spreading from the eastern IO to the MC. An impressive feature at this stage was that the low OLR region broadly extended from 10°S to 10°N. In phase 5, the OLR signal shifted eastward to the WP (160°E), while maintaining its broad meridional extent. In the decaying stages (phases 6 and 7), convective activity shifted southeastward off the equator.

The evolution of the fast MJO (Fig. 3b) is remarkably different from that of the slow MJO (Fig. 3a). In phase 2, a low OLR region ($<210 \text{ W m}^{-2}$), which takes its minimum over

the central IO, extends from approximately 60°–110°E, and the smaller regions of low OLR over the WP were disconnected from the signal over the IO. In the following phases, the low OLR region shifted toward the eastern IO in phase 3 and extended to the WP beyond 160°E by phase 4. In phase 5, the convective signal intensified to its maximum around 150°E. However, the convective signals appeared weaker than the slow MJO, and the OLR remained above 170 W m^{-2} , except for a small region over the WP. This higher OLR is consistent with a recent finding that faster MJOs are accompanied by smaller condensation heating (Wang et al. 2019). Convective activities continued to extend farther eastward along the equator in the decay phases of 6 and 7. Notably, the convective signals of the fast MJO were bounded within a meridionally narrower range ($<10^\circ$ latitude) from the eastern IO (90°E) to the WP (150°E).

Evidently, the slower MJO events were accompanied by stronger convection that extended meridionally wider,

particularly over the MC, than the faster ones. In the next subsection, we investigate whether these differences are related to the differences in SST distributions.

b. SST distributions under the slow and fast MJOs

We examined whether the contrasts in the convective activities of the slow and fast MJOs were attributable to the differences in SST distributions. First, we confirmed a known relationship between the MJO speed and SST distribution. We then clarified the time scale of the SST variability responsible for the differences in the MJO speed.

The composites of SSTs on the day of the initiation of the slow and fast MJOs are shown in Figs. 4a and 4b, respectively. The SST distribution at the initiation of the slow MJO is evidently characterized by a large temperature difference between the warmer WP and colder IO (Fig. 4a). The Indo-Pacific warm pool region ($>28^{\circ}\text{C}$) was mostly restricted between 10°S and 5°N over the IO but spanned from 15°S to 15°N over the WP. In contrast, the SST distribution at the initiation of fast MJO was characterized by a warmer IO. The Indo-Pacific warm pool region covers almost the entire equatorial IO between 15°S and 15°N and stretches eastward to 130°W with a narrower meridional extent over the WP (Fig. 4b). The SST distributions of the Indo-Pacific warm pool region associated with the slow and fast MJOs were consistent with the respective locations where convection was enhanced, as shown in Fig. 3. The region of active convection spreads meridionally broader, particularly over the MC for the slow MJO and meridionally narrower and zonally elongated along the equator for the fast MJO. The association of a wider meridional breadth of the warmest SST region with the slower proceeding MJO is also supported by the results of the model experiments on the aquaplanet (Kang et al. 2013; Jiang et al. 2020).

The zonal features of the abovementioned SST are clearly shown in Fig. 4c, as the 15°S – 15°N averages of the composited SSTs on the initiation dates of the slow and fast MJOs. The slow MJO was initiated under the characteristic condition that the SST increased toward the WP from both the IO and the eastern Pacific (EP). In contrast, the fast MJO was initiated under the condition that SST distributes more zonally uniformly across the convectively active region of the MJO (60°E – 160°W). Although the SST increased from the EP to the WP in both cases, its magnitude was considerably smaller for the fast MJO than for the slow MJO. The above features of higher and lower SST over EP associated with the fast and slow MJOs, respectively, are consistent with the results of the previous studies that associated faster and slower proceeding MJOs to El Niño and La Niña, respectively (PM07; NS13; WR19).

Although the SSTs on the day of the MJO initiation are shown in Figs. 4a–4c to avoid the direct influence of the MJO, there remains a caveat that it includes SST variabilities of all frequencies. Thus, we cannot discuss the time scales of SST variability, which primarily contributed to their differences. To separate the SST variabilities of different time scales, we applied the Lanczos time filter (Duchon 1979) to SST anomalies (SSTA). The SSTA is defined as the difference in SST

FIG. 4. SST ($^{\circ}\text{C}$) at the initiation of the (a) slow MJO and (b) fast MJO, (c) 15°S – 15°N averaged SST ($^{\circ}\text{C}$), (d) background SSTA ($^{\circ}\text{C}$), and (e) intraseasonal SSTA ($^{\circ}\text{C}$) of the slow MJO (red) and fast MJO (blue). The shadings in (c)–(e) indicate one standard deviation at each longitude.

from the daily climatology calculated from SST data from 1982 to 2016. Because the duration of the detected MJO events was between 20 and 61 days by definition, we regarded the 90-day low-pass-filtered SSTA as the variation slower than the MJO time scale, which constitutes the background condition of the MJO. Thus, we call this SSTA component

the background SSTA. In contrast, the 20–90-day bandpass-filtered SSTA can be expected to reflect the air–sea interaction of the MJO, which we call the intraseasonal SSTA component. These filters were constructed with 241 symmetric weights. The abovementioned time filters were also used to define the background and intraseasonal fields of zonal winds and pressure velocity fields.

Figures 4d and 4e show the 15°S–15°N averaged background SSTA and intraseasonal SSTA on the day of initiation of the slow and fast MJOs. The background SSTAs were clearly different (Fig. 4d), whereas the difference in the intraseasonal SSTAs was surprisingly small between the two (Fig. 4e). The background SSTA of the slow MJO gradually increased from the IO to the MC, reaching a maximum over the WP at approximately 150°E, and decreasing sharply toward the EP. In contrast, the background SSTA of the fast MJO followed a pattern in which a local minimum occurred over the WP and increased toward the IO and EP. Evidently the background SSTAs dominantly contributed to the differences in the total SST distributions (Figs. 4a–c).

Although these results are consistent with the view that ENSO can modulate the speed of the MJO movement, the differences in the background SSTA do not necessarily originate from ENSO. According to the ONI, four of the five events of the slow MJO and one of the five fast MJO events occurred under La Niña and El Niño conditions, respectively. The remaining events classified as slow MJO and fast MJO occurred under weak La Niña and El Niño, respectively, or under neutral ENSO conditions. Therefore, other sources of slow SST variability must be considered. We discuss this in section 4d when the analysis is extended to all events.

The conspicuous differences associated with the MJO speeds in the background SSTA were mostly negligible in the intraseasonal SSTA. The intraseasonal SSTA of each RMM phase also did not exhibit systematic differences between the slow and fast MJOs (data not shown). This implies that the MJO speed was not predominantly determined by the strength of the air–sea interaction. If the differences in the surface moisture flux were responsible for the differences in the MJO speed, the export of latent heat from the sea surface would lead to significant differences in the intraseasonal SSTA. A few recent studies also support the view that the effect of the air–sea interaction on the eastward movement of the MJO is marginal (Suematsu and Miura 2018; Chen et al. 2020).

A plausible explanation for this result is that the variability in the background SSTA, which modifies the zonal SST gradient over the equatorial IO and the Pacific, indirectly influences the MJO by modulating the thermally direct cells of the Walker circulation. To investigate this speculation, we compared the background wind fields between the slow and fast MJOs and examined whether their differences were coherently related to the differences in the background SSTA.

c. Background zonal circulations under the slow and fast MJOs

We examined the background atmospheric circulation at spatiotemporal scales in which both the slow and fast MJOs

were embedded. Figure 5 shows the 5°S–5°N averaged longitude–pressure cross section of the background zonal wind (background U ; m s^{-1}) and vertical pressure velocity (background ω ; Pa s^{-1}) on the initiation day of the slow (Figs. 5a,c) and fast MJOs (Figs. 5b,d).

Background U at the initiation of both slow (Fig. 5a) and fast MJOs (Fig. 5b) exhibited the characteristics of the two cells of the Walker circulation: a baroclinic structure of the zonal winds with a pair of low-level convergence and upper-level divergence near the date line, and two pairs of upper-level convergence and low-level divergence over the western IO at approximately 50°E and over the EP at approximately 90°W, respectively. However, a close comparison between the two indicated that the low- and upper-level westerlies from the IO to MC and from the CP to EP, respectively, were stronger for the slow MJO. This suggests that the slow MJO is embedded within a stronger Walker circulation than that of the fast MJO.

The difference in the strength of the Walker circulation during the slow and fast MJOs is clearly shown by the differences in the background ω of the two. The background ω at the initiation of the slow MJO (Fig. 5c) was characterized by a distinct zonally continuous region of upward motion from the IO to the date line that is bounded by a narrow but strong subsidence at the western edge of the IO (50°E) and by a broad region of subsidence from the date line to the EP (90°W). In contrast, for the fast MJO, the region of upward motion extended eastward to the EP (110°E; Fig. 5d) from the western IO (60°E); however, it appeared to be split into two regions at approximately 120°E, where a relative suppression of the upward motion was observed. The downward motions of the fast MJO, located over the western IO (50°E) and EP (centered around 120°W), were clearly weaker than those of the slow MJO. Interestingly, the downward motion over the EP reached the surface for the slow MJO, whereas it only reached 500 hPa for the fast MJO.

The relationship between a stronger Walker circulation and the slow MJO is consistent with the characteristics of their convective activities and their background SSTAs. Specifically, compared to the fast MJO, the slow MJO was accompanied by strong convection under a large background zonal SST gradient and strong Walker circulation. Such an enhancement of the Walker circulation and decrease in the area fraction of the convective region with the increase in zonal SST gradient, have also been suggested by the results of a sensitivity study using an idealized model (Bretherton and Sobel 2002). In the following subsections, we investigate whether these relationships also hold for the rest of the detected MJO events.

d. Analyses of all detected events

1) BACKGROUND SST AND MJO SPEED

Our analyses were extended to all 52 detected MJO events. We conducted correlation analyses to confirm the robustness of the relationship between the MJO speed and SST. The correlation analysis was employed rather than the regression analysis because our aim was not to quantify the change in

FIG. 5. Pressure–longitude cross section of the 5°S–5°N averaged background U (m s^{-1}) for the (a) slow MJO and (b) fast MJO and background ω (Pa s^{-1}) for the (c) slow MJO and (d) fast MJO. Note that negative (red shade) and positive (blue shade) values in for background ω in (c) and (d) indicate upward and downward motions, respectively. The locations showing differences between the slow MJO and fast MJO that are significant at the 95% and 80% confidence levels are indicated by contours and stipples, respectively. The shaded area on the map at the bottom shows the plotted region for reference.

the MJO speed with the change in the SST distribution, but to evaluate the strength of the relationship between the two.

Figure 6a shows the distribution of the correlation coefficients between the MJO speed and SST averaged over 10 days, leading to the day of the initiation of each MJO event. The 10-day average was used to mitigate the direct influence of the MJO convection. The correlation takes an El Niño–like pattern with areas of significant positive correlations over the IO and EP and negative correlations over the WP. These features are consistent with the results presented in section 4b.

To elucidate the importance of SST variability at a time scale longer than the MJO, the same correlation analysis was conducted for the background and intraseasonal SST separately. Clearly, the correlation pattern of the raw SST (Fig. 6a) can be predominantly explained by that of the background SST (Fig. 6b) rather than the intraseasonal SST (Fig. 6c). Moreover, the correlations between the MJO speed and intraseasonal SST were insignificant over nearly the entire equatorial Indian and Pacific Oceans.

The analyses in the previous sections implied that the magnitudes of the zonal SST gradients between the warmer WP and cooler IO and EP are the aspects of the SST distribution that are associated with the MJO speed. To demonstrate that this correlation is not an artifact of a few extreme events, we defined an index that incorporates the zonal SST gradients toward the WP from both the IO and WP as follows:

$$\Delta\text{SST} = \text{SST}_{\text{WP}} - \frac{\text{SST}_{\text{IO}} + \text{SST}_{\text{EP}}}{2}, \quad (1)$$

where SST_{WP} , SST_{IO} , and SST_{EP} are the area-averaged SST over WP (15°S–15°N, 140°–160°E), IO (15°S–15°N, 60°–100°E), and EP (15°S–15°N, 160°–120°W), respectively. We also examined how their values were distributed across the detected MJO events. In addition, 10-day averages leading to MJO initiation were considered to calculate the SST_{WP} , SST_{IO} , and SST_{EP} .

A scatterplot of MJO speed against ΔSST is shown in Fig. 7, which clearly confirms the negative correlation (−0.66)

FIG. 6. Correlation maps between MJO speed and (a) SST, (b) background SST, and (c) intra-seasonal SST averaged over 10 days leading to the MJO initiations. Locations where the correlations are significant at the 95% confidence level are indicated by the contours.

between the two. The MJO events were distributed evenly across the spectrum of Δ SST and MJO speed without forming any noticeable clusters. This indicates that the tendency of the MJO to decelerate with the increase in Δ SST is a remarkable characteristic that is shared by all the detected events. Moreover, the strength of the correlations between the MJO speed and SST_{IO} , SST_{WP} , and SST_{EP} individually, and SST gradients between IO and WP ($SST_{WP} - SST_{IO}$), and between WP and EP ($SST_{WP} - SST_{EP}$) were nearly comparable to those of the Δ SST (Table 2). This signifies that the MJO speed is modulated, not by one particular region, but by the entire SST distribution across the IO to the EP.

FIG. 7. Scatterplot of MJO speed ($m s^{-1}$) and Δ SST (K).

Figure 8 shows that the MJO speed and Δ SST anomaly (Δ SSTA) are correlated (-0.51). The difference in Δ SST from its daily climatology is defined as Δ SSTA. As shown in Fig. 8, the relationship between the MJO speed and Δ SST is largely retained even after the seasonal cycle is removed, which signifies that their relationship is largely explained by interannual Δ SST variability. However, the decrease in correlation suggests that the seasonal cycle, which also alters Δ SST at a time scale longer than the MJO, may modulate the MJO speed. Therefore, we investigated whether a similar systematic change occurred in MJO speed with the season. In other words, we investigated whether the smaller monthly averaged MJO speed is associated with the larger monthly averaged Δ SST.

The Δ SST and speed of the MJO events averaged for each month are shown in Fig. 9. The day of MJO initiation was determined as the month in which an MJO occurred. There was a sharp decrease in Δ SST from January to April. This is associated with the increase in SST_{IO} and SST_{EP} in April following the annual cycle of variability in the Indo-Pacific warm pool (Kim et al. 2012) and the equatorial EP (Nigam and Chao 1996). Simultaneously, the monthly mean MJO speed increased from January to April. This is consistent with the view that the MJO decelerates with an increase in the Δ SST. The fastest mean speed in April is consistent with findings in previous studies that revealed that faster MJOs are observed in the boreal spring (Jenkner et al. 2011; Suematsu 2015). The large error bar in April is due to the small number of MJO events that both initiated and terminated in April to be classified as boreal winter MJO events analyzed in this study.

TABLE 2. Correlation between MJO speed and SST indices. All correlations are significant at the 95% confidence level.

	SST _{IO}	SST _{WP}	SST _{EP}	SST _{WP} - SST _{IO}	SST _{WP} - SST _{EP}	Δ SST
Correlation	0.45	-0.41	0.54	-0.59	-0.61	-0.66

In summary, we further supported the results of section 4b, in which the MJO speed decreased with the SST distribution such that the WP was warmer than the IO and EP. These results are consistent with the documented relationship between the ENSO and MJO speed (PM07; NS13; WR19). In addition, although such a relationship may be dominated by interannual variability, we established that the same tendency also holds for the seasonal cycle in a consistent manner.

2) BACKGROUND CIRCULATION AND THE MJO SPEED

The relationship between the MJO speed and zonal circulation was examined for all the detected MJO events. Figure 10 shows the correlation between the MJO speed and the longitude–pressure cross section of the 5°S–5°N averaged background U (Fig. 10a) and intraseasonal U (Fig. 10b) on the day of MJO initiation.

The background U pattern indicates that the MJO decelerated with strong background low-level (below approximately 500 hPa) westerlies from the IO (80°E) to the WP (130°E) and strong background low-level easterlies from the WP (150°E) to the EP (130°W; below approximately 700 hPa). Note that the colors represent correlations, not wind speeds. The sign of the correlation is reversed in the upper level, reflecting the baroclinic structure of the background circulation, above approximately 300 hPa to the west of the date line and above approximately 600 hPa to the east. These correlation patterns indicate that the MJO decelerated as the Walker circulation strengthened, which corresponded well with the results presented in section 4c.

In contrast, the correlation pattern of the intraseasonal U and MJO speeds indicates an association of strong low-level (approximately at 900 hPa) easterlies over the WP (160°E)

and upper-level (above 300 hPa) westerlies from the MC (120°E) to the date line to the fast-moving MJO events. This signifies that, at their initiation, the convective activities of the faster moving MJOs are coupled to strong zonal circulation on the eastern side. This is consistent with the previous studies that suggested the MJO speed to be accelerated by coupling to strong zonal circulation leading to MJO convection, which they referred to as the front Walker cell (Chen and Wang 2018; Wang et al. 2019; WR19; Chen and Wang 2020). However, the correlation with intraseasonal U was relatively weaker than that with background U . Therefore, it is reasonable to interpret that the strength of the Walker circulation, which embeds the MJO, rather than the front Walker cell coupled to the MJO, is predominantly associated with the MJO speed.

The results thus far indicate that slow MJOs occur when the pattern of Walker circulation is intensified. To confirm this tendency for all detected events, the area averages of the background U_{200} and background U_{850} were considered over the MC region (5°S–5°N, 100°–140°E) and over the CP region (5°S–5°N, 160°–120°W), respectively, and were averaged over the duration of each event. These four variables were assumed to represent the strength of the western and eastern cells of the Walker circulation that constitute the background circulation of an MJO event.

Figure 11 shows the scatterplots of the averaged zonal wind speeds and MJO speed. The correlations of the MJO speed with the background U_{200} and U_{850} were 0.70 and -0.48, respectively, over the MC (Figs. 11a,c), and were -0.49 and 0.45, respectively, over the CP (Figs. 11b,d). They are all significant at the 95% confidence level and signify that the MJO speed decreases as the Walker circulation intensifies. These results are consistent with a previous study that associated

FIG. 8. Scatterplot of MJO speed (m s^{-1}) and Δ SSTA (K). FIG. 9. Monthly averages of the (a) MJO speeds and (b) Δ SST (K) averaged over 10 days leading to the MJO initiations. The error bars indicate the standard errors of the mean.

FIG. 10. Correlation maps between MJO speed and pressure–zonal cross section of 5°S – 5°N averaged (a) background U and (b) intraseasonal U at the day of initiation of the MJO. Locations where the correlations are significant at the 95% confidence level are indicated by the contours.

slow procession of the MJO over the IO to anomalous easterlies over the MC (Tomoff 2020; Roundy 2021). Interestingly, the background U_{850} over the MC became smaller as the MJO proceeded faster and eventually changed from westerly to easterly (Fig. 11c). This tendency was reversed for the background U_{200} . Considering the structure of the background U of the fast MJO as shown in Fig. 5b, this may indicate that the MJO proceeds faster when the western cell of the Walker circulation is weak and cannot fully extend westward to the IO. Notably, the transitions from the fast MJO to the slow MJO in these figures are continuous, and the tendency of the MJO to decelerate with the strengthening of the Walker circulation is reconfirmed to be a general characteristic shared by all the detected MJO events.

5. Summary and discussion

In this study, we investigated a fundamental factor that modulates the speed of the eastward movement of the MJO. First, to examine the characteristics of the MJO by their speeds, we detected MJO events in boreal winters (November–April) between 1982 and 2016. The speeds of the detected MJOs were estimated by daily tracking the locations of the minimum OLR anomalies, combined with the

requirement that the estimated speeds exhibit a linear relationship with the angular velocities in the RMM phase space. Although our method involved subjective selection of several parameters and was susceptible to misdiagnosis of MJO speeds for cases with erratic movement of convection, it sufficiently provides the statistics of the MJO speeds that depicted the characteristics of slow and fast moving MJO events that were consistent with the existing literature (e.g., PM07; NS13; WR19), thereby serving the purpose of the study.

The characteristics of the slowest and fastest 10th percentile of the detected MJO events (slow MJO and fast MJO) were compared. It was revealed that the slow MJO was characterized by strong convective activities that were distributed over a meridionally wide area, particularly over the MC, whereas the fast MJO was characterized by convective activities that were less intense and distributed along a narrower meridional range. The respective location where the convection was enhanced for each group was related to the spatial distribution of the WP warm pool at their initiations: the slow MJO initiated under meridionally broader and the fast MJO initiated under a zonally more elongated WP warm pool.

The differences in the SST were attributed to SST variations at time scales longer than the MJO. Specifically, the slow and fast MJOs were associated with background SSTAs, which intensified and diminished the positive zonal SST gradient toward the WP from both the IO and EP, respectively. These results correspond with previous studies that identified the modes of interannual variability with a smaller zonal SST gradient (i.e., El Niño and positive IOD) to be associated with faster moving MJO events (PM07; Izumo et al. 2010; NS13; WR19). Indeed, the variations in the MJO speed appeared to be partly attributable to the ENSO phases; however, this study indicated that the variations in MJO speed were not entirely explicable by the ENSO, and the changes in the zonal SST gradient with the seasonal march were also revealed to be associated with the changes in the MJO speed in a consistent manner with the ENSO.

Notable differences associated with the MJO speed in the background SSTA and its decline in the intraseasonal SSTA led us to hypothesize that the eastward movement of the MJO is modulated by the background zonal circulation, the Walker circulation, which is largely determined by the background SST distribution. The slow MJO was associated with an intensified Walker circulation with distinct regions of updrafts and downdrafts to the west and east of the date line, respectively. In contrast, fast MJO was associated with weak Walker circulation with updrafts across the IO to the EP. The slow MJO appeared to be bounded within the western cell of the intensified Walker circulation owing to its strong zonal asymmetry in the upward motion, and the convective activities of the fast MJO appeared to proceed swiftly eastward through weakened Walker circulation.

The robustness of the analyses of the slow and fast MJOs was confirmed when the analyses were extended to all detected MJO events. The results indicated that the MJO speeds were negatively correlated with both ΔSST and the strength of the Walker circulation. Such relationships were missing or considerably weaker in the signals at the

FIG. 11. Scatterplots of MJO speed and (a) background U_{200} over Maritime Continents (MC), (b) background U_{200} over the central Pacific (CP), (c) background U_{850} over MC, and (d) background U_{850} over CP.

intraseasonal time scale. These results reinforced the view that the slow variations in the background SST and the associated changes in the large-scale circulation at time scales longer than the MJO modulate the MJO speed.

Previous studies have suggested that intraseasonal evolution of moisture modulates the eastward movement of the MJO (e.g., Sobel and Maloney 2013; Kim et al. 2014; Adames and Wallace 2015; Adames and Kim 2016; Chen and Wang 2018; Jiang et al. 2018). These studies would suggest that the eastward movement of the MJO will be accelerated by stronger Walker circulation owing to the combined effects of advection by the low-level westerlies coinciding with the MJO convection and enhanced moisture supply by the low-level easterlies leading the MJO convection over warmer SST. However, this study has counterintuitively revealed that slower MJO events manifest with the intensification of the Walker circulation. Although this does not necessarily contradict the mechanism, suggested by previous studies, that moisture advection induced by intraseasonal wind field enhances the eastward movement of the MJO, this study indicated that the influence of the background circulation on the MJO movement is not simply to advect the MJO convection eastward.

Another interesting outcome of this study is that the MJO speed, Δ SST, and associated Walker circulation strength were nearly evenly distributed across the spectrum of their occurrences. Previous studies (e.g., Miura et al. 2012; Kang et al. 2013; WR19; Chen and Wang 2020) indicated that tighter coupling to the westward-moving Rossby type waves decelerates

the MJO. The high correlation (0.70) of the MJO speed with the background U_{200} over the MC (Fig. 11a) suggests that the gradual transition of the MJO speed may be associated with the relative contribution of mixed Rossby–gravity (MRG) and Kelvin waves, which are theoretically expected to be accompanied by easterly and westerly acceleration of the mean flow, respectively, in the upper troposphere to the lower stratosphere (Hayashi 1970).

Based on these inferences, we speculate that slow MJO events with high contributions from MRG manifest as a part of the Walker circulation intensification when the background zonal SST gradient sets a lower boundary condition that demands an intensification of the Walker circulation through the acceleration of the upper-level easterlies. Similarly, under zonally uniform background SST, fast MJO events whose characteristics asymptote to Kelvin waves (Roundy 2012) are expected to be realized concurrently with weakening of the Walker circulation. Such a view conforms with studies that suggest the identity of the MJO as both the MRG (Yang and Ingersoll 2011; Takasuka and Satoh 2020) and Kelvin waves (Roundy 2012), and studies that suggest from numerical experiments (Kang et al. 2013; Jiang et al. 2020) and observations (Wang et al. 2019; WR19; Chen and Wang 2020) that the relative contribution of Rossby type and Kelvin waves modulates the MJO speed.

However, to verify our conjecture, evidence for the transition of the MJO composition depending on the mean large-scale flow needs to be presented, for example from the

comparisons of the differences in the spectra of equatorial waves during the periods of slow and fast proceeding MJO. The remaining questions on the mechanism through which the background large-scale flow modulates the MJO speed should also be addressed by investigating the influence of the background circulation on the moisture evolution during the MJO. The influence of the meridional structure of the background SST and circulation on the moisture evolution and MJO movement would be of particular interest. Bridging the present results, which focused on the circulation in the tropics, to those that addressed the influence of subtropical jets on the MJO (Setzenfand 2018; Tomoff 2020; Roundy 2021) will be considered in future studies to understand the interaction between MJO and the global large-scale circulation.

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Data availability statement. Reanalysis and observational datasets are publicly available at locations cited in the appropriate references. Observed NOAA OLR data are available at https://psl.noaa.gov/data/gridded/data.interp_OLR.html, the NOAA OI SST V2 high-resolution dataset is available at <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>, and ONI data are available at https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.

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