Diversity of the Madden–Julian Oscillation: Initiation Region Modulated by the Interaction between the Intraseasonal and Interannual Variabilities

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ABSTRACT: As one of the aspects of the diversity of the Madden–Julian oscillation (MJO), the modulation of initiation regions of the boreal-winter MJO is studied in terms of the relationship between intraseasonal and interannual variabilities. MJOs are categorized as those initiating in the Indian Ocean (IO), Maritime Continent (MC), and western Pacific (WP), referred to herein as IO-MJOs, MC-MJOs, and WP-MJOs, respectively. The composite analyses for each MJO category using observational data reveal that the diversity of MJO initiation regions directly results from the modulation of areas where horizontal advective premoistening efficiently occurs via intraseasonal/synoptic-scale winds. This is supported by the difference in the zonal location of equatorial intraseasonal circulations established before MJO initiation, which is related to a spatial change in background convection and associated Walker circulations forced by interannual sea surface temperature (SST) variability. Compared to IO-MJOs (favored in the climatological background on average), MC-MJOs tend to be realized under the eastern-Pacific El Niño-like condition, as a result of eastward-shifted intraseasonal convection and circulation patterns induced by background suppressed convection in the eastern MC. WP-MJOs are frequently initiated under the central-Pacific El Niño-like and positive IO dipole-like conditions, in which the WP is selectively moistened with the aid of background enhanced (suppressed) convection over the WP (the southeastern IO and the central-to-eastern Pacific). This major tendency derived from sample-limited observations is verified by a set of 15-yr numerical experiments with a global nonhydrostatic MJO-permitting model under a perpetual boreal-winter condition where observation-based SSTs are prescribed.

KEYWORDS: Madden-Julian oscillation; Interannual variability

1. Introduction

Madden and Julian (1972) first presented a canonical view of tropical intraseasonal convection coupled with a planetary-scale zonal overturning circulation, which is now called the Madden–Julian oscillation (MJO). The MJO is typically characterized by large-scale convective envelopes organized in the equatorial Indian Ocean (IO), which subsequently propagate eastward slowly into the western Pacific (WP) and dissipate around the date line. The candidate mechanisms underlying this canonical MJO have been described in terms of the interactions among convection, dynamical waves, moisture, and surface conditions (Lau and Waliser 2012; Jiang et al. 2020). More recently, studies have focused on what causes the event-to-event variability of MJO features such as the periodicity (Pohl and Matthews 2007; Izumo et al. 2010), propagation speed (Suematsu 2018; Wang et al. 2019; Wei and Ren 2019), and the distribution of MJO convection in the Indo-Pacific region (Bellenger and Duvel 2012; Hirata et al. 2013). Revealing the causes of MJO diversity will be helpful for testing pre-existing MJO theories and better predicting the MJO. Based on this

notion, this study considers the diversity of MJO initiation regions.

Most previous studies of MJO initiation implicitly assume that the IO is the starting location of MJO convection, which leads to the three tropical-origin hypotheses. The first highlights the role of equatorial circumnavigation of Kelvin waves decoupled from MJOs around the Pacific, as first suggested by Knutson and Weickmann (1987). Several subsequent works have pointed out that Kelvin-wave intrusion into the IO helps trigger MJO convection through low-level moisture convergence (Kikuchi and Takayabu 2003; Seo and Kim 2003; Chen and Zhang 2019) and/or atmospheric destabilization due to midtropospheric cooling (Matthews 2008) or weakened large-scale subsidence (Powell and Houze 2015). The second hypothesis is the “discharge–recharge” hypothesis, which emphasizes the importance of basin-scale but local variations in sea surface temperature (SST), surface fluxes, and radiative cooling (e.g., Bladé and Hartmann 1993; Kemball-Cook and Weare 2001; Benedict and Randall 2007). Benedict and Randall (2007) specifically propose that gradual column moistening and heating prompted by the convective development is key to MJO initiation. The third hypothesis posits that horizontal advective moistening in the IO is responsible for free-tropospheric moisture accumulation, which in turn

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supports organized convection (e.g., Maloney 2009; Zhao et al. 2013); moisture advection to the western IO by intraseasonal flows during an MJO-suppressed phase is important. At present, these hypotheses are regarded as major mechanisms of MJO initiation in terms of large-scale intraseasonal physics, although which mechanism is more important may depend on each case. Recently, in studies focusing on cross-scale interaction, it was proposed that MJO initiation in the western IO is primarily triggered by dynamics of mixed Rossby–gravity waves (Takasuka et al. 2019; Takasuka and Satoh 2020).

It is true that MJO convection is most frequently initiated in the IO (Zhang and Ling 2017), but MJO initiation is not limited to this region. For example, Matthews (2008) focused on primary MJO events without an immediately preceding MJO and found that the number of primary MJO initiations in the Maritime Continent (MC) and WP was about half that in the IO in 1974–2005. This means that analyses postulating that the MJO is realized in the IO do not capture the whole picture of MJO initiation. In fact, the three representative hypotheses reviewed above do not explain why MJO initiation regions are modulated; the hypothesis involving circumnavigating Kelvin waves is applicable only to events in the IO because of an upstream-origin mechanism to the IO, and the discharge–recharge hypothesis and the horizontal advective moistening process do not specify where MJO initiation is favored.

Nevertheless, there are only a few studies targeting the diversity of MJO initiation regions. Bellenger and Duvel (2012) suggest that convective and wind perturbations of MJOs tend to be enhanced (reduced) in the WP (IO) under El Niño conditions. This result partly implies that MJO convection sometimes starts from the WP, indicating that El Niño–Southern Oscillation (ENSO) may control MJO initiation regions. However, the authors did not reveal specific processes responsible for MJO initiation in basins other than the IO and did not provide a reason why the MC is also selected as an MJO initiation region. Related to this problem, Hirata et al. (2013) compared the atmospheric and SST variations before MJO onset between the IO and MC. They found that while SST warming associated with suppressed convection is important for the subsequent convective onset in the IO, this process is not detectable for MJO cases in the MC. As such, how MJO initiation is realized outside the IO is still an open question.

To examine this question, we hypothesize that the mutual relationship between intraseasonal processes and interannual variability is a clue to understanding where MJO initiation is favored. Indirect evidence for this hypothesis is that the seasonal mean MJO intensity changes on an interannual time scale. In boreal winter during the typical El Niño years, when an increase in SST over the equatorial eastern Pacific (EP) is mature, active MJO perturbations shift eastward to the east of the date line (e.g., Fink and Speth 1997; Vincent et al. 1998; Hendon et al. 1999; Kessler 2001) or MJO activities around the WP are reduced (e.g., Tam and Lau 2005; Feng et al. 2015; Chen et al. 2016). In the new type of El Niño events known as central-Pacific (CP) El Niño (Ashok et al. 2007; Kao and Yu 2009), characterized by SST warming over the equatorial CP, stronger MJO activities are observed in the WP (e.g., Feng et al. 2015; Chen et al. 2016; Wang et al. 2018). Furthermore,

during a positive phase of the IO dipole mode (IOD), MJOs are disrupted around the MC and weakened in the WP (Wilson et al. 2013; Benedict et al. 2015). These studies indicate that the interannual modulation of circulations induced by SSTs can significantly affect the regional favorableness of MJO activities on average; note, however, that they did not focus on MJO initiation itself. The importance of the interannual variability in promoting MJO initiation was shown by Suematsu and Miura (2018) and Suematsu (2018), who found that the probability of MJO realization in the IO is increased in accordance with the enhancement of a positive background zonal SST gradient from the IO to the WP and associated Walker circulations. This suggests that the atmosphere–ocean coupled variability over time scales longer than those of intraseasonal variations can set the background appropriate for the establishment of MJO circulations.

With the aim of comprehensively understanding the conditions favorable for MJO initiation, this study elucidates a mechanism for the modulation of MJO initiation regions. For this purpose, we perform an observational composite analysis of MJOs that are initiated in the three representative basins (IO, MC, and WP) and a series of 15-yr numerical experiments using a global nonhydrostatic model that can realistically reproduce the MJO; the methodology is presented in section 2. In section 3, the differences and similarities in the intraseasonal processes and their background conditions supporting MJO initiation in the three basins are analyzed using observational data. We propose that the interannual Walker circulation variations forced by SSTs can modulate the areas where intraseasonal moistening is more likely to occur, and that this leads to the diversity of MJO initiation regions. The validity of the proposed mechanism is investigated by numerical experiments in section 4. A summary and discussion are presented in section 5.

2. Observational data, analysis methods, and numerical experimental design

a. Observational data

As a proxy for deep convection, we used interpolated daily outgoing longwave radiation (OLR) data for the period of 1979–2013, obtained from the National Oceanic and Atmospheric Administration satellite (Liebmann and Smith 1996). The spatial resolution is 2.5° latitude $\times$ 2.5° longitude. We also used pentad mean CPC Merged Analysis of Precipitation (CMAP) rainfall (Xie and Arkin 1997) to detect MJOs and analyze the moisture–convection relationship. This is interpolated into a $1.5^\circ \times 1.5^\circ$ horizontal grid from a $2.5^\circ \times 2.5^\circ$ grid with daily values for 1979–2012.

The 6-hourly global atmospheric reanalysis data are from ERA-Interim (Dee et al. 2011) with a horizontal resolution of $1.5^\circ \times 1.5^\circ$, averaged to daily values covering January 1979–December 2012. We used the three-dimensional field variables of horizontal wind components $\mathbf{V}_h = (u, v)$, vertical p -velocity (ω), specific humidity (q), temperature (T), and geopotential (Φ). They have 27 pressure levels spanning from 1000 to 100 hPa. The two-dimensional fields of surface pressure, surface latent and sensible heat fluxes (LHF and SHF), and

TABLE 1. Summary of MJO detection procedures.

Step	Purpose	Methodology
S_1	Identification of MJO initiation regions from IO, MC, and WP	Using probability distributions of MJO initiation longitudes identified by equatorial (15°S–15°N) eastward-propagating precipitation tracking following Zhang and Ling (2017)
S_2	Detection of LCEs in regions identified in S_1	Using time series of 5-day running mean unfiltered OLR anomalies averaged over each MJO initiation region
S_3	Detection of MJOs from LCEs detected in S_2	Tracking of an MJO index constructed from the first two PCs of daily intraseasonal (MJO-filtered) OLR anomalies in 30°S–30°N and all longitudes for observations (simulations)

surface and top-of-atmosphere longwave and shortwave radiative fluxes (LW and SW) were also used to compute column-integrated water vapor (CWV) and moist static energy (MSE) budget in [section 3](#). Furthermore, daily SST data and its anomalies (SSTAs) from NOAA Optimum Interpolation SST version 2 (OISST2) ([Reynolds et al. 2007](#)) from September 1981 to December 2012 were used to examine the influences of interannual SSTs. Note that the SSTAs ($0.25^\circ \times 0.25^\circ$) are provided as deviations from 1971–2000 climatology and re-gridded onto a $1.5^\circ \times 1.5^\circ$ grid by linear interpolation.

b. Analysis methods

1) DEFINITION OF ANOMALIES FOR ATMOSPHERIC VARIABLES

To extract atmospheric variations on various time scales of our interest, we utilize five types of anomaly: unfiltered, low-frequency background (LFB), intraseasonal, high-frequency, and MJO-filtered. The unfiltered anomalies for observations (15-yr numerical simulations) were defined as the deviations relative to the 91-day running mean (the 15-yr mean of a simulation). Note that we used unfiltered anomalies for moisture-related variables (e.g., q , MSE) because it might not be straightforward to distinguish which temporal scales moisture variations have; while it is theoretically guaranteed that dynamics have a specific temporal scale (e.g., equatorial waves and MJO/ENSO-related circulations), moisture experiences various cross-scale processes such as large-scale advection and instant phase change.

The remaining four types of anomaly were obtained by a filtering approach. Before the computation of all filtered anomalies for the observational data, we first removed the daily climatology and its first three harmonics of OLR and all other variables based on the 1979–2013 and 1979–2012 reference period, respectively. For these daily anomalies, LFB, intraseasonal, and high-frequency anomalies were computed using a 100-day low-pass, 20–100-day bandpass, and 20-day high-pass Lanczos filter ([Duchon 1979](#)) with 201 weights, respectively. MJO-filtered anomalies used for robust detection of MJO convection were obtained by a wavenumber-frequency filtering via fast Fourier transforms ([Wheeler and Kiladis](#)

1999). Its filtering band was defined as eastward wavenumbers 1–10 and periods of 20–100 days (cf. [Zhang and Ling 2017](#)).

The aforementioned filtering was also suitably applied to the data from 15-yr numerical simulations, except that their anomalies were from the 15-yr mean in each experiment. The simulation data were averaged to daily values and interpolated to the same resolution as the observational data.

2) DETECTION OF MJO ONSET IN VARIOUS REGIONS

For composite analyses of our targeted MJOs, we constructed the objective method to detect MJO initiation over the Indo-Pacific region. The MJO detection algorithm in this study is an updated version of the one described by [Takasuka and Satoh \(2020\)](#) to analyze the diversity of MJO initiation regions. This algorithm consists of three steps: step 1 (S_1) is identification of MJO initiation regions from the three candidates (IO, MC, and WP); step 2 (S_2) is detection of large-scale convective events (LCEs) in the identified regions; and step 3 (S_3) is identification of MJO initiation events from the detected LCEs. [Table 1](#) summarizes the purposes and procedures of these steps.

The first step, S_1 , determines MJO initiation regions from the three candidate basins, which are subjectively defined in advance: the IO (10°S–10°N, 60°–90°E), MC (15°S–5°N, 90°–130°E), and WP (15°S–5°N, 135°–165°E). These candidates were selected so that they are located to the west of 90°, 130°, and 170°E around the equator, where MJO activities indicated by intraseasonal OLR standard deviations during the December–March (DJFM) peak ([Fig. 1a](#)). Note that our main results are insensitive to the slight difference of choices of longitudes for the candidate basins. For quantitative identification of MJO initiation regions, we used a probability distribution of MJO initiation longitudes identified by [Zhang and Ling's \(2017\)](#) tracking algorithm of equatorial (15°S–15°N) eastward-propagating positive MJO-filtered precipitation anomalies, except that the criterion for propagation speed was changed to $3\text{--}8\text{ m s}^{-1}$. The probability was computed in each bin with a width of 20° based on the number of MJO events in $30^\circ\text{E}\text{--}150^\circ\text{W}$. For the three candidates (IO, MC, and WP), MJO initiation regions were specified as areas within which the

FIG. 1. (a) Map of standard deviations of intraseasonal OLR anomalies during boreal winter [December–March (DJFM)] in 1980–2012. Cyan rectangles indicate the IO, MC, and WP as defined in this study. (b) Number (bar) and probability distribution (red line) of MJO initiation longitudes specified by tracking of MJO precipitation. The longitudinal bin width for the number and probability distribution is 10° and 20° , respectively. The probability is computed as the ratio of the number of events in each bin to their total number in 30°E – 150°W . Circles on the line denote the probability peaks. (c) Phase–longitude diagram of equatorial OLR (shading) and 850-hPa zonal wind anomalies (contours) averaged over 15°S – 5°N on the days with $A \geq 0.8$ during boreal winter. Contour interval is 1 m s^{-1} , with negative (zero) contours dashed (omitted). Cross marks indicate the minima of OLR anomalies, and green rectangles represent phases corresponding to MJO convection in the IO, MC, and WP.

probability peaked. A probability peak was defined such that the probability was equal to or greater than that in the adjacent bins.

As an example, Fig. 1b shows the probability distribution of observed MJO initiation longitudes during DJFM in 1980–2012. Because there are probability peaks in all three basins, they are identified as MJO initiation regions for the observation. In section 4, the same procedure is applied to the simulation data for which it is nontrivial where MJO initiation is favored. Note that we calculated the number distribution with a bin width of 10° (bar in Fig. 1b) and found similar characteristics to those with a bin width of 20° , although the distribution was slightly noisier.

Next, S_2 specifies starting and ending dates of LCEs (D_{start} and D_{end}) in each MJO initiation region identified by S_1 . We used the time series of 5-day running mean domain-averaged unfiltered OLR anomalies in each basin ($\text{OLR}'_{\text{area}}$) and its standard deviation (σ). The date D_{start} (D_{end}) is defined as the first (last) date that satisfies $\text{OLR}'_{\text{area}} \leq -0.8\sigma$ during the period between the first of five consecutive days in which $\text{OLR}'_{\text{area}} < -0.6\sigma$ and the first of five consecutive days in

which $\text{OLR}'_{\text{area}} > -0.6\sigma$ [see Takasuka and Satoh (2020) for details].

Finally, S_3 identifies MJO initiation from LCEs detected in the observation (simulations) by tracking an MJO index constructed from linear combinations of the two leading principal components of daily intraseasonal (MJO-filtered) OLR anomalies in 30°S – 30°N and all longitudes during DJFM (the entire period of a simulation). The derived OLR-based MJO index provides amplitude A ($= \sqrt{\text{PC1}^2 + \text{PC2}^2}$) and phase α ($= \arctan(\text{PC1}/\text{PC2})$ for the observation) divided into eight sections by every $\pi/4$. Note that the reason for the use of MJO-filtered anomalies in the simulations is that the east–west ratio of the OLR spectral power on MJO spatiotemporal scales tends to be degraded in simulations (Takasuka et al. 2018). The phase–longitude diagram of observed equatorial OLR and 850-hPa zonal wind anomalies averaged on boreal winter days with $A \geq 0.8$ (Fig. 1c) suggests that the constructed MJO index captures well the eastward propagation of the convective system coupled to zonal circulations over the warm pool.

The MJO tracking for each LCE was conducted by imposing five criteria for the evolution of A and α . The first criterion (C_1) requires $A \geq 0.8$ in any of phases $k - 1$, k , and $k + 1$ (integer k satisfies $1 \leq$

$k \leq 8$, and $k - 1$ and $k + 1$ are cyclic) during an LCE period ($D_{\text{start}} - D_{\text{end}}$). Note that k is determined such that phases from $k - 1$ to $k + 1$ correspond to enhanced convection in the specified initiation regions. Consequently, for the observation, k equal to 2, 4, and 6 is appropriate for detecting MJO initiation over the IO, MC, and WP, respectively (see cross marks in Fig. 1c denoting the minima of equatorial OLR anomalies). The remaining four criteria for an LCE that satisfies C_1 are as follows: (C_2) $A \geq 0.4$ during tracking; (C_3) $A \geq 0.8$ through phases $k - 1$ to $k + 1$ except that the number of days with $(0.4 \leq) A < 0.8$ is equal to or less than five; (C_4) no phase skipping and no more than one phase recession; and (C_5) success in tracking up to phase $k + 3$ with C_2 – C_4 satisfied. If an LCE satisfies C_1 – C_5 , it is regarded to be an MJO event for which tracking started (terminated) on D_{init} (D_{term}), when C_1 (C_5) is cleared.

The above tracking alone, however, does not necessarily capture MJO events *initiated* in the MC and WP, because it can also detect MJO convection that was initiated to the west of those basins and propagated into the considered regions. We excluded such cases of MJO initiation using the following approach. We first took S_1 and S_2 to LCEs in the most western region (e.g., the IO for the observation) and identified the tracking periods of MJO events (D_{init} – D_{term}) there. The same routine was then applied in order to the eastern regions identified in S_1 . If an MJO tracking period in a target region (except for the most western region) intersected with any tracking periods in regions to the west of the target one, or if the tracking between the D_{term} already assigned to the west of the target region and the D_{init} in the target region satisfied C_2 and C_4 , we concluded that the MJO event in the target region did not correspond to an in situ initiation case.

3) COMPOSITE PROCEDURE

To compare atmospheric and SST fields before MJO initiation between the different regions, we applied lagged-composite analyses to the detected MJO events in each region. The reference for the lagged composites (i.e., day 0) was defined as D_{init} in each case. The unfiltered anomalies used in the composites were presented with 5-day running mean. The statistical significance of composite anomalies was assessed by a two-tailed Student's t test at the 90% confidence level under the assumption that MJO events are independent of each other.

c. Numerical experimental design

We used the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) (Tomita and Satoh 2004; Satoh et al. 2008, 2014) to evaluate the observation-based insights from section 3. We adopted a globally quasi-uniform 28-km horizontal mesh and 38 vertical layers extending to an altitude of about 40 km above the sea surface; the layer thickness increases with height. The effects of turbulent mixing were parameterized by the Mellor–Yamada–Nakanishi–Niino (MYNN) level 2 scheme (Mellor and Yamada 1974; Nakanishi and Niino 2004, 2009). Radiative transfer was calculated using MSTRNX (see Sekiguchi and Nakajima 2008). The computation of surface heat and momentum fluxes followed the bulk formula (Louis 1979; Uno et al. 1995). Land surface processes were treated by the model of Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO; Takata et al. 2003).

Notably, we used the single-moment bulk cloud microphysics scheme (NSW6; Tomita 2008) without any cumulus parameterizations despite the coarse resolution, which means that convection-related instabilities are removed by precipitation from the cloud microphysics scheme alone. Although a global nonhydrostatic model with a grid interval of less than around 15 km can successfully reproduce MJO convection (Miura et al. 2007, 2009; Miyakawa et al. 2014), the validity of enforcing the strong relationship between grid-scale moist processes and local dynamical circulations at this resolution is not physically guaranteed. The authors' previous studies, however, showed that, at least under the aquaplanet configuration of NICAM, MJO-like disturbances can be simulated at horizontal resolutions from 14 to 220 km, even if convection is explicitly simulated without cumulus parameterizations (Takasuka et al. 2015, 2018). This suggests that explicit convection at coarse resolutions provides a moisture–convection relationship suitable for MJO reproduction. Similar results for coarse-resolution models have been reported previously, although the extent of the similarity may depend on specific details of the models (e.g., Holloway et al. 2013; Pilon et al. 2016; Hohenegger et al. 2020). In practical terms, the coarse resolution reduces computational demands and thus enables us to conduct several long-term simulations.

Because our numerical experiments were aimed at validating the influences of the SST-related interannual variability on MJO initiation regions in DJFM, we performed 15-yr simulations in which the model seasonality was perpetually fixed to boreal winter and various SST distributions were prescribed. We set perpetual 7 February solar insolation with diurnal cycles because of the similarity to its DJFM climatology. Prescribed ozone distribution and surface parameters such as albedo and vegetation were derived from their DJFM mean. To avoid excessive land biases caused by the fixed solar insolation, the temperatures at the surface, canopy, and soil, and the canopy and soil water content were nudged to their DJFM mean with a time scale of 1 day. The three SST patterns were used in this study, and are presented in detail in section 4. Each simulation forced by each different SST pattern was initialized from the atmospheric and land states after the 90-day spinup simulation of which the initial condition was the DJFM mean.

3. Observed intraseasonal variations and background conditions supporting MJO initiation in the three regions

The observational analyses in this section are targeted at 47, 20, and 13 MJO cases that were initiated in the IO, MC, and WP, respectively, during DJFM in 1982–2012. We first clarify the differences and similarities in intraseasonal dynamical and moisture variations before MJO initiation among the three regions. We then show that the SST-related interannual variability can support such intraseasonal processes that contribute to the diversity of MJO initiation regions.

a. Intraseasonal dynamical and moisture variations

Figure 2 shows time–longitude diagrams of composite equatorial (15°S – 5°N) unfiltered 850-hPa zonal wind and OLR anomalies associated with MJO events initiating in the IO, MC,

FIG. 2. Time-longitude diagrams of composite unfiltered 850-hPa zonal wind (shading) and OLR anomalies (black contours) averaged over 15°S–5°N for (a) IO-MJO, (b) MC-MJO, and (c) WP-MJO cases. Contour interval is 7.5 W m^{-2} , with positive (zero) contours dashed (omitted). Stippled areas denote statistical significance of zonal wind fields at the 90% level. Green contours in (c) represent OLR anomalies filtered for ERs, and their interval is 4 W m^{-2} . In (a)–(c), vertical cyan broken lines indicate the longitudinal band of the corresponding MJO initiation region.

and WP, hereafter referred to as IO-MJO, MC-MJO, and WP-MJO, respectively. In all categories, large-scale active convection is realized around day 0, and then propagates eastward with strong westerlies; MJO initiation in the three regions is captured. The evolution of convection and circulations leading to MJO initiation is distinct in each region. For IO-MJOs, eastward-propagating convection is enhanced in 120°E–180° from days –30 to –15, and associated convective suppression is developed around 90°E (Fig. 2a). Related to this, anomalous easterlies prevail in the IO after day –15. By contrast, in MC-MJOs (Fig. 2b), convective and wind perturbations in 120°–150°E are absent before day –20. Instead, negative OLR and westerly anomalies are farther east (150°E–150°W) through day –10, and then the easterlies associated with suppressed convection to the east of the MC dominate in 110°E–180°; that is, the spatial pattern of convection and zonal winds before the MC-MJO initiation is shifted overall eastward by about 30° compared to IO-MJOs. Unlike these two cases, the WP-MJO initiation appears to be prompted by westward-propagating convective and dynamical signals (Fig. 2c). It coincides with the westward intrusion of negative OLR anomalies filtered for $n = 1$ equatorial Rossby waves (ERs; westward wavenumbers 1–10; periods of 10–96 days; and equivalent depths 1–90 m; green contours in Fig. 2c).

The above distinctions are clearly presented together with moisture variations in the horizontal patterns of intraseasonal OLR and 850-hPa wind and unfiltered CWV anomalies (Fig. 3). In a comparison of IO- and MC-MJOs at day –24, the longitudinal shift of enhanced convection is reconfirmed: negative OLR anomalies are observed in 120°E–180° for IO-MJOs, while they are in 150°E–150°W for MC-MJOs (Figs. 3a,b). This shifted convection may bring about the difference in the subsequent evolutions of IO- and MC-MJOs, considering that westerlies blowing into active convection can amplify the convective suppression before MJO initiation. For

IO-MJOs, suppressed convection and associated anomalous easterlies prevail over the IO and MC (i.e., to the west of active convection at day –24), and resultant moist anomalies appear in the western IO through day –6. Meanwhile, suppressed convection before the MC-MJO initiation is observed in the MC and WP; this allows for moistening with easterlies in the western MC (yellow square in Fig. 3b) after day –12 where and when positive OLR anomalies are dominant for IO-MJOs. For WP-MJOs (Fig. 3c), westward-propagating ERs with active convection and cyclonic circulations (indicated by the broken arrow) seem to play a role in conveying moisture to the WP.

As for the intraseasonal evolution before the IO- and MC-MJO initiation, one may wonder how decaying convection to the east enhances suppressed convection to the west (e.g., from days –24 to –12). This can be explained by the phase relationship between convection and moisture tendency on the intraseasonal time scale (Inoue and Back 2015). Because a circulation caused by active intraseasonal convection can dry the free troposphere to the west with a certain lag for the maximum convective amplitude, dry anomalies and suppressed convection can be strengthened during the weakening of preceding active convection. This was confirmed by our results (not shown).

The overview of each initiation process suggests that the diversity of MJO initiation regions can arise directly from the difference in equatorial zonal intraseasonal circulations and favorable areas for efficient moistening. This is summarized in Fig. 4, which displays the equatorial zonal-vertical structure of intraseasonal circulations and moisture (Figs. 4a–f) and equatorial zonal distributions of 850–400-hPa integrated moisture without removing the annual cycle (Figs. 4g,h) 10–15 and 0–5 days prior to the MJO initiation. Before the IO-MJO initiation (Fig. 4a), the descending branch connected to ascending motions in 150°E–180° spreads over the IO and MC, and shallow moistening continues at the western edge of the mid- to

FIG. 3. Maps of composite intraseasonal (20–100-day filtered) OLR (shading) and 850-hPa wind anomalies (vectors; m s^{-1}), and unfiltered CWV anomalies (contours) every 6 days from days –24 to 0 (from top to bottom) for (a) IO-MJO, (b) MC-MJO, and (c) WP-MJO cases. Contour interval is 2.5 kg m^{-2} , with negative (zero) values dashed (omitted). Vectors and stippling over shaded areas denote statistical significance at the 90% level, respectively. Yellow squares at day 0 indicate the initiation region of each MJO category. The broken arrow in (c) represents westward-propagating active convection with cyclonic circulations.

lower-tropospheric easterlies. The latter is expected to be due to horizontal moisture advection under the eastward free-tropospheric moisture gradient in the IO (Fig. 4g), which is quantified later in this section. As a result, the amount of moisture accumulation is sufficient for IO-MJO convection (Figs. 4b,h). For MC-MJOs (Fig. 4c), the large-scale descent is prominent in 120°E – 180° , in conjunction with the eastward shift of the circulation seen in IO-MJOs. This is followed by selective moistening and upward motions around the western MC with the low-level easterly anomalies and eastward moisture gradient (Figs. 4d,g,h), even though the western IO has temporarily experienced deep convection (Fig. 4c). In Figs. 4e and 4f, moistening leading to the WP-MJO initiation is induced by the westward intrusion of the ascending branch of the local circulation in 150°E – 150°W from days –15 to –10.

To evaluate the premoistening processes quantitatively, we analyze the daily-mean column-integrated MSE budget using 6-hourly reanalysis data. MSE variations roughly reflect moisture variations under a weak temperature gradient approximation (Sobel et al. 2001), which should be valid on the MJO scale. The MSE used here is

$$h = C_p T + \Phi + L_v q, \quad (1)$$

where C_p is the specific heat at constant pressure, and L_v is the latent heat of vaporization. The budget equation for the column-integrated MSE is expressed as

$$\left\langle \frac{\partial h}{\partial t} \right\rangle = -\langle \mathbf{V}_h \cdot \nabla h \rangle - \left\langle \omega \frac{\partial h}{\partial p} \right\rangle + \langle \text{LW} \rangle + \langle \text{SW} \rangle + \text{LHF} + \text{SHF}, \quad (2)$$

where angle brackets represent mass-weighted vertical integration from the surface to 100 hPa. Figures 5a–c show the time evolution of unfiltered anomalies of MSE budget terms averaged in each MJO initiation region for IO-, MC-, and WP-MJOs. Here, regions subject to MSE averaging are slightly modified from the domains used for MJO detection, considering composite moisture and convection fields (yellow squares in Fig. 3). In all three regions, negative vertical advection and positive net radiation anomalies are clearly found after day –5, consistent with the establishment of large-scale deep convection 0–5 days prior to the initiation (Figs. 4b,d,f). Before that, positive MSE tendency anomalies from days –10 to –5 are recognized in every case, which is mainly due to horizontal advection. Note that positive vertical advection anomalies (i.e., moistening via shallow circulations) are also observed for IO- and WP-MJOs, which implies that the details of three-dimensional moisture advection are worth being revealed by vertically resolved moisture budget analysis (e.g., Benedict and Randall 2007; Takasuka and Satoh 2020).

We further examined the dominant time scale of the flows responsible for horizontal MSE advection, based on the following decomposition in the horizontal advection term:

$$-\langle \mathbf{V}_h \cdot \nabla h \rangle = -\langle [\mathbf{V}_h] \cdot \nabla h \rangle - \langle \mathbf{V}'_h \cdot \nabla h \rangle - \langle \mathbf{V}^*_h \cdot \nabla h \rangle, \quad (3)$$

where $\mathbf{V}'_h$ and $\mathbf{V}^*_h$ are intraseasonal (20–100 days) and high-frequency (<20 days) components of $\mathbf{V}_h$, respectively; and $[\mathbf{V}_h] (= \mathbf{V}_h - \mathbf{V}'_h - \mathbf{V}^*_h)$ is the background horizontal wind including the annual cycle. Figure 5d shows the decomposed horizontal advection anomalies with zonal and meridional components, averaged in each initiation region from days –10

FIG. 4. Longitude–height sections of composite intraseasonal (20–100-day filtered) zonal (m s^{-1}) and vertical wind (Pa s^{-1}) anomalies (vectors and shading for vertical p -velocity), and unfiltered specific humidity anomalies (contours) averaged over 15°S – 5°N for the period (a),(c),(e) from days -15 to -10 and (b),(d),(f) from days -5 to 0 for IO-MJO cases in (a) and (b), MC-MJO cases in (c) and (d), and WP-MJO cases in (e) and (f). Contour interval is 0.18 g kg^{-1} , with negative (zero) values dashed (omitted). Vectors and stippling over shaded areas denote statistical significance at the 90% level. The vertical p -velocity in vectors is multiplied by 500. Zonal distributions of composite 850–400-hPa-integrated water vapor averaged over 15°S – 5°N for the period (g) from days -15 to -10 and (h) from days -5 to 0 for IO-MJO (blue), MC-MJO (green), and WP-MJO cases (cyan).

FIG. 5. Time series of composite unfiltered anomalies of the column-integrated MSE budget terms averaged over the initiation region of (a) IO-MJO (10°S – 10°N , 50° – 80°E), (b) MC-MJO (15°S – 5°N , 80° – 110°E), and (c) WP-MJO cases (15°S – 5°N , 135° – 165°E). The budget terms are composed of the tendency (dashed black), horizontal advection (red), vertical advection (blue), net radiative processes (purple), and surface heat fluxes (green). Horizontal (vertical) MSE advection anomalies integrated over the planetary boundary layer (from the surface to 850 hPa) are also plotted with red (blue) broken lines. (d) Decomposition of column-integrated horizontal advection shown in (a)–(c), averaged from days -10 to -5 , by the LFB ($[\mathbf{V}_h]$), intraseasonal ($\mathbf{V}_h$), and high-frequency ($\mathbf{V}_h^*$) wind variations. Open circles (crosses) denote zonal (meridional) advection anomalies. Blue, green, and cyan bars are for IO-MJO, MC-MJO, and WP-MJO cases, respectively.

to -5 . Intraseasonal flows contribute predominantly to horizontal advection for IO- and MC-MJOs, where zonal advection is more responsible than meridional advection. This process is consistent with the results of previous studies for the IO-MJO initiation (e.g., Zhao et al. 2013; Nasuno et al. 2015). For WP-MJOs, high-frequency winds (intraseasonal) zonal winds act primarily (secondarily) on moistening, which reflects the influence of westward-propagating disturbances that are probably associated with ERs (Figs. 2 and 4). These results indicate that intraseasonal zonal circulations and/or synoptic-to-intraseasonal disturbances play a role in setting the appropriate conditions for MJO initiation in any region through horizontal moisture advection. In addition, this advective moistening is observed mostly in the free-troposphere rather than in the planetary boundary layer (cf. colored broken lines in Figs. 5a–c). In this sense, our results disagree with earlier

studies (e.g., Hsu and Li 2012) that focus on frictional moisture convergence as a primary contributor to MJO destabilization.

To summarize, the MJO initiation processes have a feature common to all three regions: horizontal moisture advection by mid- to lower-tropospheric circulations is key to moisture buildup mainly on the intraseasonal time scale. However, the regional pattern of intraseasonal circulations established before the MJO initiation is different in each MJO category. As a consequence, the area where large-scale advective moistening is more likely to occur is modulated, which directly leads to the diversity of MJO initiation regions.

b. Comparison of the background atmospheric conditions

Here, we raise two questions: What changes the intraseasonal circulation patterns? What environments support the continuous development of MJO convection in response to

FIG. 6. Maps of composite LFB (100-day low-pass filtered) 500-hPa vertical p -velocity (shading) and 850-hPa horizontal wind anomalies (vectors; m s^{-1}), and τ_c^{-1} (contours) for (a) IO-MJO, (b) MC-MJO, and (c) WP-MJO cases. Each field is averaged from days -30 to 0 . Contour interval is 0.6 day^{-1} . Vectors and stippling over shaded areas denote statistical significance at the 90% level. Red solid and dashed rectangles in (b) represent the domains compared in Fig. 7.

moistening in regions other than the IO? Like Suematsu and Miura (2018) and earlier studies, we speculate that interannual variations affect intraseasonal atmospheric variability. We thus examined the difference in LFB anomalous circulations before the IO-, MC- and WP-MJO initiation as a controlling factor of intraseasonal processes.

Figure 6 presents horizontal maps of LFB anomalies of 500-hPa vertical p -velocity and 850-hPa winds averaged from days -30 to 0 for the MJO initiation in each region. While no obvious circulation anomalies are found for IO-MJOs (i.e., almost climatological fields; Fig. 6a), the other two cases have the characteristic modulation of background convection and low-level winds. For MC-MJOs (Fig. 6b), LFB subsidence and low-level divergence anomalies with statistical significance are recognized in 120° – 150°E despite the weak signals. This means that, at least in the composite of all MC-MJOs, large-scale convective organization tends to be more suppressed than usual in the eastern MC. In fact, intraseasonal convective perturbations in 120° – 150°E , 20–30 days prior to day 0 are less

clear for MC-MJOs than for IO-MJOs (Figs. 2a,b). We should note, however, that this relationship between LFB and intraseasonal variations is derived only from the weak tendency in all case composites. This matter is discussed in section 3c. Before the WP-MJO initiation (Fig. 6c), LFB ascent and low-level convergence are enhanced around the WP, and the convective suppression is found in the southwestern MC and to the east of the date line. Hence, the WP is favorable for increased activities of synoptic-to-intraseasonal disturbances such as ER-wave intrusion and MJO convective organization, although it is still uncertain why ERs are selectively enhanced and how ERs dynamically develop into the MJO. Note that the above LFB signals for MC- and WP-MJOs are also statistically significant in terms of their difference from those for IO-MJOs (not shown).

While it is plausible that the WP-MJO initiation is favored because of the more convectively supporting background in the WP than in the adjacent regions, it remains elusive why the MJO convective development for MC-MJOs finally occurs in

FIG. 7. (a) Time series of composite CWV (black) and column-integrated horizontal moisture advection anomalies (red) averaged over the MC (15°S–5°N, 80°–110°E; solid) and IO (10°S–10°N, 50°–80°E; dashed) for MC-MJO cases. (b) As in (a), but for estimated precipitation (i.e., $P' = \langle q' \rangle / \tau_c$; blue) and CMAP rainfall anomalies (black).

the MC rather than in the IO. This question is rooted in the fact that the eastward shift of the intraseasonal circulations alone leaves room for moistening in the IO via advective processes by anomalous easterlies (Figs. 4c,g). In fact, the time evolution of unfiltered CWV and column-integrated horizontal moisture advection anomalies over the MC and IO for MC-MJOs (Fig. 7a) indicates that more anomalous moisture is observed in the IO with horizontal advection until day –8.

To understand why MC-MJOs are realized, we focus on spatial differences of the convective sensitivity to moisture fluctuations, which is related to the background fields under the convective adjustment framework (Betts and Miller 1986). Here, we assume that precipitation variations P' are explained by CWV variations $\langle q' \rangle$ in the form of $P' = \langle q' \rangle / \tau_c$, where τ_c is the adjustment time scale; larger τ_c^{-1} means a higher convective sensitivity to moisture. Based on the observed exponential q – P relationship in the tropics [$P \propto \exp(a\langle q \rangle / \langle q_s \rangle)$] (e.g., Bretherton et al. 2004) and its Taylor expansion around the background (i.e., the sum of the daily climatology and LFB anomalies), τ_c is given as a function of space and slowly varying time (e.g., Adames 2017):

$$\tau_c = \frac{\langle \bar{q}_s \rangle}{a\bar{P}}, \quad (4)$$

where $\langle \bar{q}_s \rangle$ is column-integrated saturated specific humidity, a is constant, and overbars denote the background. Note that τ_c largely depends on $\bar{P}$ because of few variations in $\langle \bar{q}_s \rangle$ under

the weak temperature gradient. We obtained $a = 9.03$ by the exponential curve fit to each dataset in oceanic grids over 20°S–20°N, 30°E–150°W in 1982–2012.

Figure 7b presents the time evolution of precipitation anomalies estimated from τ_c and $\langle q' \rangle$ as well as CMAP precipitation anomalies in the MC and IO for MC-MJOs. The estimated precipitation, which evolves like the CMAP rainfall except for absolute magnitudes and a slight lag, becomes larger in the MC than in the IO even when moisture anomalies are smaller (e.g., around day –10; see also Fig. 7a). This feature results from much larger τ_c^{-1} in the MC-MJO initiation region than in the IO for MC-MJOs (contours in Fig. 6b), although this τ_c^{-1} distribution is also applicable to the other cases (Figs. 6a,c). Hence, moisture perturbations lead to more enhanced convection in the MC than in the IO in association with climatologically active precipitation, which explains how the advective moistening associated with the eastward-shifted intraseasonal circulations for MC-MJOs can selectively promote the convective development in the MC.

c. Influence from the interannual SST variability

Since the modulation of background equatorial circulations described in section 3b can be related to the interannual SST variability, we examined the difference in 91-day running mean SSTA fields between IO- and MC/WP-MJO cases (Fig. 8). The actual SSTAs whose absolute values are more than 0.1 K for MC- and WP-MJOs are also shown with stippling. Note that we take the longer averaging period for SSTAs (from days –60 to 0) than for the atmospheric circulations in Fig. 6 considering a delayed atmospheric response to SSTs. Before the MC-MJO initiation (Fig. 8a), warmer (colder) SSTAs in the equatorial Pacific (the southern WP) are observed; these have the ability to induce convective suppression remotely around the MC. This is consistent with LFB anomalous circulations for MC-MJOs (Fig. 6b), although the expected enhancement of background convection over the Pacific is missing in Fig. 6b (a reason for this is discussed later in this section). For WP-MJOs, SSTAs are warmer (colder) in the equatorial WP/CP (EP), and the SSTA differences in the southern IO have a dipole structure (Fig. 8b). These SSTAs can explain significant LFB ascent anomalies around the WP and descent on both its sides (Fig. 6c).

The interannual SSTAs in the Pacific and the southern IO for MC- and WP-MJOs are reminiscent of the influences of the representative atmosphere–ocean coupled modes. Table 2 presents the differences in the fraction (and number) of IO-, MC-, and WP-MJOs between the positive and negative phases (denoted as P-phase and N-phase, respectively) of three monitoring indices: the Niño-3.4 index, the El Niño Modoki index (EMI; Ashok et al. 2007), and the IOD index (DMI; Saji et al. 1999). Every index is computed with 91-day running mean, and P-phase (N-phase) for each index is assigned when an index averaged from days –60 to 0 is more than 0.2 K (less than –0.2 K). The difference between IO- and MC-MJO fractions is largest for the Niño-3.4 index; the occurrence of MC-MJOs tends to increase (decrease) for its P-phase (N-phase) in comparison with IO-MJOs, which is consistent with positive SSTAs broadly over the equatorial Pacific (Fig. 8a).

FIG. 8. Maps of the difference in composite 91-day running mean SSTAs of (a) MC-MJO and (b) WP-MJO cases from IO-MJO cases (shading). Stippled areas with yellow (blue) dots denote where the actual composite 91-day running mean SSTAs are more (less) than 0.1 K for (a) MC-MJO and (b) WP-MJO cases. Each field is averaged from days -60 to 0 . Broken rectangles in (a) and (b) indicate the regions used to compute Niño 3.4 index and EMI, respectively.

For WP-MJOs, their fractions in P-phase (N-phase) for both EMI and DMI are increased (decreased) most significantly compared to IO-MJOs, which corresponds to the CP El Niño-like pattern and dipole structure in the southern IO (Fig. 8b). Note, however, that the DMI (and the associated dipole pattern in the IO) here does not necessarily reflect the actual IOD variability because it should rapidly dissipate in boreal winter.

As described earlier, one caveat here is that the signals of LFB anomalous circulations for all MC-MJO composites are not as strong as expected from the EP El Niño-like state (cf. Fig. 6b). This is because the contrast between the fraction of MC-MJOs in the EP El Niño-like and La Niña states is not so large (Table 2), although all MC-MJO composites can somewhat capture the characteristics under the EP El Niño-like condition. To show this explicitly, we compare LFB anomalous circulations, interannual SSTAs, and equatorial unfiltered 850-hPa zonal wind and OLR anomalies for the MC-MJO between P-phase and N-phase of Niño-3.4 index (Fig. 9). As expected, for the P-phase we find enhanced and suppressed background convection in the equatorial Pacific (MC) directly (remotely) induced by warm SSTs over the Pacific (Figs. 9a,b). In response to this, there are more (less) convective perturbations in 150°E – 150°W (120° – 150°E) from days -30 to -10 (Fig. 9e),

resembling the feature in Fig. 2b. We should emphasize, however, that a certain number of MC-MJOs are also initiated under the La Niña condition, when background convective enhancement is limited in the MC (Fig. 9b) and MJO convection correspondingly tends to be concentrated there (Fig. 9f). This situation is entirely different from that for MC-MJOs during the EP El Niño-like state, which means that there is another pathway to MC-MJO initiation apart from the mechanism via anomalous horizontal moisture advection observed in all MC-MJO composites. Thus, further detailed analyses for this matter are required to complete our understanding of MJO initiation in all longitude sectors, although the composite of the aforementioned counteracting effects caused by the different ENSO phase produces faint signals associated with the EP El Niño-like condition.

In short, the specific atmosphere–ocean interannual variabilities can promote MJO initiation in regions besides the IO; the MC-MJO (WP-MJO) is more likely to be initiated under the EP El Niño-like (CP El Niño-like and positive IOD-like) condition. Because our primary interest is the *major* relationship between the intraseasonal and interannual variability, the above observed tendency is emphasized in this study. Nevertheless, it is also a fact that the La Niña state has a

TABLE 2. The fraction (number) of IO-, MC-, and WP-MJO cases that are initiated when the Niño-3.4 index, EMI, and DMI averaged from days -60 to 0 is more than 0.2 K (P-phase) and less than -0.2 K (N-phase). The fraction is defined as the ratio of the number of target MJO cases to that of all cases for a specified region. For each index, bold (italic) text indicates the maxima and minima of the fraction for P-phase and N-phase among three regions, respectively.

Region	Niño-3.4 index		EMI		DMI	
	P-phase	N-phase	P-phase	N-phase	P-phase	N-phase
IO	36% (17)	53% (25)	45% (21)	36% (17)	28% (13)	17% (8)
MC	55% (11)	35% (7)	55% (11)	35% (7)	25% (5)	10% (2)
WP	38% (5)	46% (6)	69% (9)	23% (3)	31% (4)	8% (1)

FIG. 9. (a),(b) As in Fig. 8a, but for (a) P-phase and (b) N-phase of Niño-3.4 index and stippled areas denote where absolute values of SSTAs are more than 0.15 K. (c),(d) As in Fig. 6b, but for (c) P-phase and (d) N-phase. (e),(f) As in Fig. 2b, but for (e) P-phase and (f) N-phase.

potential to support the MC-MJO initiation, which should be scrutinized in the future.

d. Summary of the observed diversity of MJO initiation regions

Figure 10 schematically summarizes the major relationships between the intraseasonal and interannual variabilities that can modulate MJO initiation regions. Two key points aid its interpretation: point 1 (P_1) background conditions with temporal scales longer than those of intraseasonal variations can affect the favorableness of convective organization; and point 2 (P_2) convective organization modulates dynamical circulation. In this context, the situation for IO-MJOs is explained as follows (Fig. 10a). Climatological equatorial zonal circulations (purple arrows) tend to support convective organization around the MC/WP on the intraseasonal time scale (gray shaded), following P_1 . The resultant intraseasonal suppressed convection to the west (orange shaded) leads to advective moistening in the western IO by inducing anomalous low-level easterlies (cyan arrows) because of P_2 , which makes the IO preferable for MJO initiation.

As shown in Fig. 10b, MC-MJOs are realized more under the EP El Niño-like pattern, which is also interpreted by both P_1 and P_2 . In terms of P_1 SST-induced background convective suppression over the eastern MC tends to disrupt organized convection there and instead supports it to the east. Thus, eastward-shifted intraseasonal circulations can be easily established through P_2 . This increases the

likelihood of efficient horizontal moisture advection over the MC and convective development in this region associated with the climatologically strong moisture–convection relationship, which can promote the MC-MJO initiation. By contrast, WP-MJOs (Fig. 10c) are favored under the CP Niño-like state and the dipole SST structure in the southern IO. This is probably because the WP can be selectively moistened more easily than usual by enhanced synoptic-to-intraseasonal disturbances there, as a result of the background convective enhancement around the WP/CP region and its suppression in the adjacent areas.

Based on the observational analysis, we infer that the variety of MJO initiation regions is due mainly to the fact that background Walker circulations forced by the interannual SSTAs modulate a preferred moistening area through the change in intraseasonal convection and circulations. However, this hypothesis is derived from sample-limited observations. To overcome this limitation, we validate whether the background SSTs can indeed induce the diversity of MJO initiation regions by using long-term numerical experiments (see next section).

4. Numerical experiments

As described in section 2c, we conducted the 15-yr perpetual-boreal-winter simulations with NICAM to evaluate the sensitivities of background SSTs to MJO initiation regions. The three different SST patterns were prescribed during the entire simulation periods

FIG. 10. Schematic diagrams summarizing the major relationships between the intra-seasonal and low-frequency variabilities inferred from the observational data analyses of (a) IO-MJO, (b) MC-MJO, and (c) WP-MJO cases. See text for details.

(Fig. 11). First, we adopted the DJFM climatology (Fig. 11a) as a control experiment (CTL). In the other two experiments, we used the representative SSTs associated with the MC- and WP-MJO initiation. In one experiment (denoted as EXP-EP), the EP El Niño-like SSTAs were added to the DJFM climatology in the equatorial Pacific (20°S – 20°N , 130°E – 70°W ; Fig. 11b). The other experiment (denoted as EXP-CP_IO) has the CP El Niño-like pattern (20°S – 20°N , 130°E – 70°W) and the dipole SSTAs in the southern IO (20°S – 10°N , 50° – 120°E) (Fig. 11c). The EP (CP) El Niño-like anomalous fields were based on the first two empirical orthogonal functions EOF1 (EOF2) for the 91-day running mean SSTAs over 30°S – 30°N , 110°E – 70°W in 1981–2012. The SSTAs given in the IO were derived from EOF2 for the domain 20°S – 20°N , 30° – 120°E .

Although the EOF-based SSTs are different from the observed distributions in detail (Figs. 8 and 11b,c), we used them for sensitivity experiments because we intended to examine general responses to SSTs that do not depend on the specific situation. We confirmed that the three PCs corresponding to the EOFs, which were equivalent to the Niño-3.4 index, EMI, and DMI, had fractions of MJO cases that were similar to those shown in Table 2 (not shown).

a. Mean Walker circulations and MJO activities

We first analyzed the simulated mean Walker circulations. Figure 12b presents the 15-yr mean equatorial (15°S – 15°N averaged) zonal–vertical mass flux circulations subtracted

from their zonal mean for the CTL. For reference, the corresponding circulations for the DJFM mean in 1979–2012 from ERA-Interim are also plotted in Fig. 12a. The circulations in the CTL are qualitatively consistent with the observation, although the simulated ascending (descending) motions around the MC (the Pacific) are overemphasized and the ascending branch in the IO is not as clear.

Figures 12c and 12d show the difference in the Walker circulation and associated specific humidity between the EXP-EP/CP_IO and the CTL. In Fig. 12c, the EXP-EP has broad and deep subsidence and dry anomalies in 120° – 150°E with the anomalous ascending branch in 170°E – 120°W . In addition, the lower-tropospheric easterly anomalies switch to westerly anomalies around 150°E . These features are similar to the background modulation for MC-MJOs, although LFB ascent anomalies in the Pacific are unclear for observations, as explained in section 3c. The mean-state change in the EXP-CP_IO (Fig. 12d) also captures WP-MJO characteristics, such as strong ascent anomalies over the WP and CP bookended by anomalous subsidence and dry regions, despite the eastward extension of the ascending branch to 150°W and exaggerated descent anomalies around 150°E in the simulation. As for differences between the EXP-EP and EXP-CP_IO (Fig. 12e), the EXP-CP_IO has climatologically more active convection and moist environments in 120°E – 150°W and vice versa in the adjacent areas than the EXP-EP.

FIG. 11. (a) Observed DJFM climatological SST distribution used to force the CTL. (b),(c) SST distribution used for the (b) EXP-EP and (c) EXP-CP_IO (contours) and its difference from the CTL (shading).

We also examined mean MJO activities for the CTL and their modulation by the given SSTAs. Figure 12f compares equatorial MJO-filtered OLR variance for all the experiments and the observation. The distribution of variance in the CTL is relatively well simulated, even though it is underestimated from the IO to the western MC compared to the observation. In a comparison between the EXP-EP and CTL (red), the mean MJO activities for the EXP-EP decreased in 120°–150°E whereas they increased around the MC and to the east of 150°E. As for the EXP-CP_IO (blue), variances increase (decrease) to the east (west) of 130°E. These changes in the mean MJO amplitude correspond to the modulation of intraseasonal convective perturbations for MC- and WP-MJOs shown in section 3a. Thus, we expect that the likelihood of MJO initiation over the Indo-Pacific warm pool is different between the three experiments.

b. Modulation of MJO initiation regions

Figure 13a shows the probability distributions of MJO initiation longitudes identified by the tracking of MJO-filtered precipitation anomalies in each experiment following the method described in section 2b. The statistical significance of the probability difference in each bin between the CTL and EXP-EP/CP_IO is examined by the two-tailed Welch's *t* test assuming that each 120-day segment (i.e., almost the same as the number of days in DJFM) in 15-yr experiments is

independent of each other; a sample size in one experiment is 45 [$\approx 365 \times 15/120$]. The number of MJOs used to compute the probability is 59, 66, and 63 for the CTL, EXP-EP, and EXP-CP_IO, respectively. For the CTL, of the three candidate basins, the IO and WP regions have probability peaks; the IO- and WP-MJO initiation is preferred under a climatological condition during boreal winter. This situation is modulated in the other two experiments, as expected. For the EXP-EP, the probability distribution changes to become convex upward in 80°–160°E, which results in the appearance of a peak in the MC. The comparison between the EXP-CP_IO and CTL reveals that the more significant peak in the WP is recognized for the EXP-CP_IO, although both experiments commonly have two probability peaks over the IO and WP. Hence, SSTAs for the EXP-EP (EXP-CP_IO) have the ability to induce more MC-MJO (WP-MJO) initiation.

For more quantitative evidence of the regions in which the imposed SSTAs have the most impacts on MJO initiation, Fig. 13b displays the difference between the EXP-EP/CP_IO and CTL over the three segments corresponding to the IO, MC, and WP regions. Note that each segment has the same 40° zonal width for fair comparison. For the EXP-EP, the probability of MJO initiation increased (decreased) the most in 90°–130°E (50°–90°E), compared to the CTL. This indicates that the EP El Niño-like SST pattern prompts (suppresses) the MC-MJO (IO-

FIG. 12. Longitude–height sections of 15°S–15°N averaged zonal and vertical mass flux ($\text{kg m}^{-2} \text{s}^{-1}$) subtracted from their zonal mean (vectors and shading for vertical mass flux) in (a) observed DJFM climatology and (b) 15-yr mean states of the CTL, and their difference from the CTL for the (c) EXP-EP and (d) EXP-CP_IO; (c) and (d) also plot the difference of the mean specific humidity with contours. Contour interval is 0.2 g kg^{-1} , with negative (zero) values dashed (omitted). The vertical component of vectors is multiplied by 800. (e) As in (c) and (d), but for the difference between the EXP-EP and EXP-CP_IO (the latter minus the former). Contour interval is 0.1 g kg^{-1} . (f) Zonal distribution of MJO-filtered OLR variance averaged over 15°S–15°N for observation in DJFM (gray dashed) and the CTL (black), and its difference from the CTL for the EXP-EP/CP_IO (red/blue). Color shading represents the longitudinal regions outlined in Fig. 1.

MJO) initiation more than usual, consistent with the observed relationship between the Niño-3.4 index and MJO initiation (Table 2). For the EXP-CP_IO, the difference in the probability is highest in 130°–170° E and lowest in 50°–90°E, which confirms that SSTAs with the CP Niño-like pattern and the dipole warm/cold structure in the southern IO provide the most favorable condition for the WP-MJO

initiation, as is the case for the observation (Fig. 8b and Table 2).

In summary, the three experiments provide an ample number of MJOs under the three SST conditions, and the results clearly support the observational insight that the interannual SST variability impacts on the likelihood of MJO initiation in a particular region.

FIG. 13. (a) Probability distributions of MJO initiation longitudes specified by tracking of MJO precipitation for the CTL (black), EXP-EP (red), and EXP-CP_IO (blue) as well as observation (gray dashed; as in Fig. 1b). The longitudinal bin width is 20°. Circles on the line denote the probability peaks. Stars for the EXP-EP and EXP-CP_IO indicate statistically significant differences from the CTL at the 90% levels. Color shading represents the longitudinal regions outlined in Fig. 1. (b) Difference in the probability in the three segments (50°–90°E, 90°–130°E, and 130°–170°E) from the CTL for the EXP-EP (red) and EXP-CP_IO (blue).

c. Consistency in MJO initiation processes

Since IO-, MC-, and WP-MJO initiation is more probable in the CTL, EXP-EP, and EXP-CP_IO, respectively, we examined whether their MJO initiation processes also follow the observed ones. Table 3 summarizes the MJO initiation regions identified from Fig. 13a and integer k used for MJO tracking (see section 2b) in the target region (indicated by boldface) in each experiment. After we defined the MJO initiation regions for the CTL and EXP-CP_IO as the IO and WP, and for the EXP-EP as all three regions, we detected MJOs in each experiment by setting k shown in Table 3.

The composite results are derived from 34 IO-MJOs, 24 MC-MJOs, and 32 WP-MJOs in the CTL, EXP-EP, and EXP-CP_IO, respectively. In Figs. 14a–c (Figs. 14d–f), we compare the time–longitude diagrams of unfiltered CWV (850-hPa zonal wind) and OLR anomalies averaged over 15°S–10°N. For IO-MJOs in the CTL (Figs. 14a,d), the pair of enhanced/suppressed convection related to wet/dry anomalies appears in 90°E–180° around day –20, which is followed by anomalous easterlies in the IO. Then, significant moist signals with active convection begin to propagate eastward from the IO, despite the disruption of the propagation over the MC, as in many other numerical models (e.g., Wang et al. 2014;

TABLE 3. Identified MJO initiation regions and integer k used to detect MJO events in the target region (boldface) for each experiment.

Experiment	Initiation region (used k)
CTL	IO ($k = 2$), WP
EP	IO ($k = 2$), MC ($k = 4$), WP
CP_IO	IO ($k = 1$), WP ($k = 5$)

Ling et al. 2019). Before the MC-MJO initiation for the EXP-EP (Figs. 14b,e), there is a corresponding pair of convective and moisture anomalies in 130°E–150°W, and associated easterly anomalies are observed around the MC. These features represent the eastward-shifted pattern of those in IO-MJOs for the CTL. The consistency with the observation is also seen for WP-MJOs in the EXP-CP_IO (Figs. 14c,f); MJO convection is initiated in accordance with the westward intrusion of moisture from the Pacific, although the westward propagation is slower than in the observation, and the associated wind variations are not so clear.

To evaluate moisture accumulation processes in each MJO initiation region, we conducted MSE budget analysis using 6-hourly snapshots and Eq. (2). Unlike Eq. (1), the MSE was redefined considering the model formulation

$$h = (C_v + R_d q_d + R_v q)T + \Phi + L_v q - L_f q_i, \quad (5)$$

where C_v is the specific heat at constant volume; R_d and R_v are the gas constant of dry air and water vapor, respectively; L_f is the latent heat of fusion; and q_d and q_i are the specific humidity of dry air and ice condensation, respectively. Figures 15a–c compare the time sequences of unfiltered MSE budget anomalies averaged over the three MJO initiation regions for the corresponding experiments. In all cases, anomalous horizontal MSE advection plays a role in moisture buildup before MJO convective activation indicated by positive net radiation anomalies (gray shading). In Fig. 15d, the decomposition of the horizontal advection term [Eq. (3)] elucidates positive contributions from intraseasonal wind anomalies for every case as well as from high-frequency components for WP-MJOs in the EXP-CP_IO. These features are similarly observed in Fig. 5, although there are several differences from observations: one is that horizontal advection anomalies for the simulated IO-MJOs are smaller than for observed IO-MJOs, partly because of weaker zonal wind anomalies (Fig. 14d vs Fig. 2a). Another difference is that the contribution from intraseasonal winds (especially with meridional components) is larger than from synoptic winds to moistening for simulated WP-MJOs, probably because of more slowly westward-propagating cyclonic disturbances around the WP in the model (cf. Fig. 14c). Note that it is reasonable that background winds do not contribute to anomalous moistening because SSTs are perpetually fixed.

In summary, enhanced intraseasonal/synoptic-scale convection and circulations, the zonal location of which is modulated before MJO initiation in the target regions according to the given background SSTs, are responsible for horizontal advective premoistening, as in the observations (cf. section 3d and Fig. 10). This validates the importance of

FIG. 14. Time-longitude diagrams of composite unfiltered CWV (shading) and OLR anomalies (contours) averaged over 15°S – 10°N for (a) IO-MJOs in the CTL, (b) MC-MJOs in the EXP-EP, and (c) WP-MJOs in the EXP-CP_IO. Contour interval is 6 W m^{-2} , with positive (zero) contours dashed (omitted). Stippled areas denote the statistical significance of CWV fields at the 90% level. Vertical magenta broken lines in each plot indicate the longitudinal band of the corresponding MJO initiation region. (d)–(f) As in (a)–(c), but for unfiltered zonal wind (shading) and OLR anomalies (contours).

the mutual relationship between the intraseasonal and interannual variabilities for enabling the diversity of MJO initiation regions.

5. Summary and discussion

Motivated by the fact that MJOs are not necessarily initiated in the IO, we investigated a potential cause of the diversity of MJO initiation regions in terms of the relationship between intraseasonal and interannual variabilities. First, using observational daily data, we identified MJO initiation in the IO, MC, and WP during DJFM in 1982–2012 (IO-, MC-, and WP-MJO, respectively). We then examined the differences and similarities in initiation processes of detected MJO events between the three regions based on lagged-composite analysis.

The comparisons of intraseasonal dynamical and moisture variations between IO-, MC- and WP-MJOs revealed that they differ in the equatorial zonal circulations prior to the initiation date (day 0), although there is premoistening in every initiation region. For IO-MJOs, there are low-level intraseasonal easterly anomalies over the IO through day -5 in accordance with large-scale suppressed convection around the MC that originates from active convection in the MC and WP after day -30 (120°E – 180° ; Figs. 2a and 3a). As for MC-MJOs, the same intraseasonal circulation and convective patterns shift eastward overall before MJO initiation; anomalous low-level easterlies associated with convective suppression prior to day 0 are observed around the MC, which results from the eastward shift of organized convection seen from days -30 to -10 (150°E – 150°W ; Figs. 2b and 3b). The WP-MJO initiation corresponds

FIG. 15. (a)–(c) As in Figs. 5a–c, but for (a) IO-MJOs in the CTL (10°S–10°N, 50°–80°E), (b) MC-MJOs in the EXP-EP (15°S–5°N, 95°–125°E), and (c) WP-MJOs in the EXP-CP_IO (15°S–5°N, 130°–160°E). (d) As in Fig. 5d, but for IO- (blue), MC- (green), and WP-MJOs (cyan) in the corresponding simulations. In (a)–(c), gray shading indicates the period used to average anomalies of the horizontal MSE advection in each MJO category.

to the westward intrusion of an active convective phase of ERs (Figs. 2c and 3c). Since the MSE budget analysis suggests that horizontal moisture advection mainly by intraseasonal winds contributes to the premoistening for every MJO category (Fig. 5), we can say that the difference in the equatorial intraseasonal circulations directly modulates MJO initiation regions through the change in the preferred moistening areas.

As shown in Fig. 10, the different equatorial intraseasonal circulations responsible for the variety of MJO initiation regions is rooted in the LFB variability. While the background circulations for IO-MJOs have climatological distributions (Fig. 6a), MJO initiation in the other two regions tends to be favored under the specific LFB anomalous circulations. For MC-MJOs, the LFB convective suppression in 120°–150°E (Fig. 6b) leads to less organized convection there and the resultant eastward shift of the intraseasonal circulations before the MC-MJO initiation. This causes efficient horizontal advective moistening in the MC, which results in subsequent convective organization there helped by the climatologically strong convective sensitivity to moisture perturbations. For WP-MJOs, the

enhancement and suppression of background convection is observed in 140°–170°E and on both its sides, respectively (Fig. 6c), which supports the development of convective disturbances in the WP. These background changes are related to interannually varying SSTs. MC-MJOs are favored under the EP El Niño-like condition that induces anomalous subsidence around the eastern MC (Table 2 and Figs. 8a and 10b), although the La Niña state also has a potential for the MC-MJO initiation. WP-MJOs are more realized under the CP El Niño-like and positive IOD-like SST condition, consistent with active (suppressed) convection in the WP (southeastern IO) (Table 2 and Figs. 8b and 10c). Thus, the SST-induced interannual variability of the tropical zonal circulations is expected to give rise to the diversity of MJO initiation regions by modulating the probability of MJO initiation in each region.

The above sample-limited observational finding is further tested by the numerical experiments, in which the three 15-yr perpetual-boreal-winter experiments were conducted using a global nonhydrostatic model with a 28-km mesh. The simulations successfully reproduced MJO events; the CTL

experiment used DJFM climatological SSTs as a reference, and the other two experiments used representative SSTs created by adding the EP El Niño-type pattern (EXP-EP) and both CP El Niño-type pattern and the dipole structure in the southern IO (EXP-CP_IO) to the climatology. By contrast to the CTL, the probability distribution of MJO initiation longitudes in the EXP-EP (EXP-CP_IO) has a clear peak around the MC (WP) (Fig. 13a). In fact, the difference in the probability of MJO initiation between the EXP-EP (EXP-CP_IO) and CTL is highest around the MC (WP) region (Fig. 13b). In addition, the composite analyses for MJOs initiated in the IO, MC, and WP for the CTL, EXP-EP, and EXP-CP_IO, respectively, suggest that intraseasonal circulations and moisture variations before MJO initiation in any categories closely resemble those in the observation. These results support the observation-based view in Fig. 10.

The present study shows for the first time the specific mechanism of the modulation of MJO initiation regions in terms of the relationship between background equatorial zonal circulations forced by the interannual SST variability and intraseasonal dynamical and moisture variations. The resulting implication is that, of the MJO initiation mechanisms proposed by previous studies on the IO-MJO, horizontal moisture advection is more universally important in that it sets a preferred condition for the MJO (e.g., Zhao et al. 2013; Nasuno et al. 2015; Takasuka et al. 2018). Furthermore, the present study emphasizes the influence of the background zonal circulations on intraseasonal fields, which follows the view that the interannual modulation of the Walker circulation affects whether or not the MJO is initiated in the IO (Suematsu and Miura 2018) and alters propagation speeds of the MJO (Suematsu 2018; Wei and Ren 2019). This means that appropriate representation of the interannual variability of the atmosphere–ocean coupled system (e.g., ENSO) leads to better prediction of MJO evolution. We should note, however, that the interannual SST-forced variability does not completely determine where the MJO is initiated, but rather modulates its probability (see Table 2). One possible reason for this is that the MJO itself, once initiated somewhere, also considerably affects atmospheric environments on the intraseasonal time scale through modulation of moisture fields. Further analysis of not only the major characteristics associated with the LFB variability but also the exceptional cases may help advance a complete understanding of the MJO theory.

A long-term numerical experiment using a global non-hydrostatic MJO-permitting model is one of key components of this study to evaluate the MJO initiation quantitatively (section 4). Nevertheless, there are some discrepancies between observations and simulations with regard to the strength of the Walker circulations (Figs. 12a,b) and the barrier effect of the MC for MJO propagation (Figs. 14a,d). To overcome these deficiencies and to achieve more realistic simulations, continuous efforts are needed to improve the model in terms of cumulus convection and turbulent mixing processes and to test the model with various configurations (e.g., Matsugishi et al. 2020).

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