Oceanic Impacts on MJOs Detouring near the Maritime Continent^①

LEI ZHOU

School of Oceanography, Shanghai Jiao Tong University, Shanghai, and Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, China

RAGHU MURTUGUDDE

University of Maryland, College Park, College Park, Maryland

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ABSTRACT

Madden–Julian oscillations (MJOs) are the dominant mode of intraseasonal variability (ISV) in the atmosphere acting as a bridge between weather and climate. During boreal winter, many MJO events are detoured southward while propagating across the Maritime Continent. Although MJO simulations have been greatly improved in recent years, the mechanism and simulation of MJO detouring near the Maritime Continent are still a great scientific challenge. Several mechanisms have been proposed based on atmospheric dynamics and thermodynamics. In this study, the oceanic role in MJO detouring is diagnosed using observations and reanalysis products. It is found that warm sea surface temperature (SST) anomalies occur over the southeastern Indian Ocean that induce a cyclone in the lower troposphere. Due to the westerly background winds, westerly winds are strengthened (weakened) to the north (south) of warm SST anomalies. As a result, the latent heat flux (LHF) is enhanced, and convection is reinforced to the north of warm SST anomalies. In contrast, the LHF is reduced, and SSTs warm to the south of pre-existing warm SST anomalies. Hence, the warm SST anomalies and convection system shift the MJOs southward before they reach the Maritime Continent. The identification of the oceanic influence on the MJO detouring deepens our understanding of the mechanism of their detour and elicits the role of the ocean. It is expected to brighten the prospects for better simulation and forecast of MJOs over the Maritime Continent. The oceanic ISV in the southeastern Indian Ocean is subject to many forcings, such as intraseasonal atmospheric forcing, the Indonesian Throughflow, local oceanic instability, and coastal Kelvin waves along Sumatra. Determining the mechanism of ISV in the southeastern Indian Ocean requires further dedicated studies.

1. Introduction

Madden–Julian oscillations (MJOs) are a major component of tropical intraseasonal variability (ISV) in the atmosphere, which has a typical period of 30–60 days (Madden and Julian 1971, 1972, 1994; Zhang 2005; Li 2014). They bring abundant precipitation to the tropical Indo-Pacific region. Usually, MJOs originate over the western Indian Ocean, propagating eastward at about 5 m s^{-1} , and get strengthened across the Indian Ocean (Wang 2012; Zhang 2013). In the Pacific Ocean, MJOs can modify the amplitude and period of low-frequency

El Niño–Southern Oscillation (ENSO; Batstone and Hendon 2005; Zavala-Garay et al. 2005; Tang and Yu 2008) and enhance the predictability of ENSO (McPhaden et al. 2006; Hendon et al. 2007). They can also have a significant impact on North American climate (Yang et al. 2002; Lorenz and Hartmann 2006; Riddle et al. 2013) and the North Atlantic Oscillation (NAO; Cassou 2008; Jiang et al. 2017). However, MJOs often weaken when entering the Maritime Continent. Some MJO events can propagate through the Maritime Continent in the tropics, but more are detoured southward during the propagation. There are also some MJOs that are blocked and cannot go through the Maritime Continent (Inness and Slingo 2006; Kerns and Chen 2016; Kim et al. 2017; Zhang and Ling 2017). In the state-of-the-art weather and climate models, the strength and trajectory of MJOs over the Maritime Continent are still not rendered realistically and remain a grand scientific

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Corresponding author: Lei Zhou, zhoulei1588@sjtu.edu.cn

challenge for better MJO simulations and predictions (Weaver et al. 2011; Wang et al. 2014; Kim et al. 2016). It has been shown that increasing the model resolution alone is not likely to be the key (Neale and Slingo 2003; Zhu et al. 2017), but a better process understanding of the MJO dynamics around the Maritime Continent is required.

Several mechanisms have been proposed for the detour of MJOs. Complex orography is a typical feature of the Maritime Continent, which can disrupt MJOs. Altitudes of many islands can be over 2000 m, which can result in the topographic blocking via variation in vorticity and convergence (Wu and Hsu 2009; Tan et al. 2018). The land–sea contrast in heat capacity over the Maritime Continent is another possible mechanism for the blocking and detouring effect on MJOs. As argued by Sobel et al. (2010), the land can be regarded as seawater with zero mixed layer depth. Thus, the surface heat (or moist entropy) fluxes have sharp boundaries between the land and the ocean following the complex land–sea distribution over the Maritime Continent, which control the phase relations between surface heat flux and convection during MJOs (Maloney and Sobel 2004) and distort the MJO propagation. Recently, the diurnal variation has been found to have a blocking and detouring impact as well. Due to the different heat capacities of land and ocean, diurnal variabilities are much stronger over land than over the ocean. MJOs are more likely to propagate across the Maritime Continent when soil moisture increases by the vanguard precipitation and the diurnal cycle over land is consequently reduced. This mechanism was proposed as the Maritime Continent convective diurnal cycle (MAC3; Peatman et al. 2014; Ling et al. 2019) and it was supported by the results from a cloud-permitting model (Hagos et al. 2016) and satellite observations (Ling et al. 2019). Besides the blocking and detouring effects due to complex land–sea distributions and contrast between land and ocean heat capacities, the large-scale atmospheric dynamics and thermodynamics also play an important role. In the Pacific Ocean to the east of Maritime Continent, the MJO detouring was partly attributable to the dry anomalies induced by the equatorial Rossby waves originating from the warm pool (Feng et al. 2015; DeMott et al. 2018). In the Indian Ocean to the west of Maritime Continent, Kim et al. (2017) concluded that the advection of moist static energy (MSE) is critical for the detour. Using model simulations, Zhu et al. (2010) found that the meridional advection of MSE and moisture is important, which indicated the importance of impacts from beyond the deep tropics.

The mechanisms for the MJO detouring have thus been extensively studied from the atmospheric dynamics and

thermodynamics. However, oceanic influences, particularly the influence of sea surface temperature (SST) anomalies, have not been fully examined in the context of the MJO detouring around the Maritime Continent but they are receiving more and more attention recently (DeMott et al. 2015). Krishnamurti et al. (1988) was a pioneering study of oceanic impacts on MJOs. They concluded that the surface winds and SSTs were both important for the air–sea interaction on intraseasonal time scales, but the former usually played a more important role. Both observations (Jones et al. 1998; Fu et al. 2003) and model simulations (Waliser et al. 1999; Woolnough et al. 2001; Zhu et al. 2017) have shown evidence to support a significant oceanic influence on the detour of MJOs. Recently, Kim et al. (2016) concluded that in an operational prediction system, appropriate coupling with the ocean could improve MJO simulations over the Maritime Continent. For the detour near the Maritime Continent, Tseng et al. (2017) showed with numerical experiments that warm SST anomalies in the southeastern Indian Ocean (SEIO) were favorable for the southward shift of MJOs, probably by enhancing the low-level moisture convergence and distorting the coupled Rossby–Kelvin waves. Zhang and Ling (2017) also indicated that the influence of low-level moist convergence and its dependence on SST anomalies was likely a promising avenue for a better understanding in the mechanism of detoured MJOs. Nonetheless, there is much to be understood in terms of the oceanic impacts and the corresponding dynamics in steering the MJOs to the south and this provides the motivation of this study. In the following, data are introduced in section 2. Main results are presented in section 3. Discussion is presented in section 4 and conclusions are summarized in section 5.

2. Data and methods

Atmospheric variables, such as wind velocities and precipitation, are obtained from daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). SST data are obtained from National Oceanic and Atmospheric Administration (NOAA) 1/4° daily Optimum Interpolation SST (OISST; Reynolds et al. 2007) and the outgoing longwave radiation (OLR) are from the NOAA satellite data (Liebmann and Smith 1996). All data are from 1982 to 2017 and the ISVs are obtained with a 20–100-day bandpass Butterworth filter. Since precipitation in reanalysis products has considerable uncertainties (Chaudhuri et al. 2013), daily satellite rainfall obtained from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis

FIG. 1. Daily OLR_{diff} (defined as $OLR_{NE} - OLR_{ST}$) during DJF from 1982 to 2017. The two dashed lines mark the mean plus STD and mean minus STD of OLR_{diff} . Blue (red) plus signs mark the significant positive (negative) peaks in OLR_{diff} . Blue (red) circles denote the MJO events that peaks in OLR_{diff} coincide with peaks in RMM1, which indicate that the convection center occurs in the ST (NE) region. See more detailed definition in the main text.

(3B42RT; Huffman et al. 2007) from 1998 to 2017 are used. The sea surface height (SSH) anomalies are obtained from the daily Global Ocean Gridded (L4) data from 1993 to 2017, which are provided by European Union Copernicus Marine Service Information. The horizontal resolution is $1/4^\circ$ in both latitude and longitude. Daily atmospheric variables from ERA-40 (Uppala et al. 2005) and ERA5 (Copernicus Climate Change Service 2017) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) are also used to verify the robustness of the results. Chaudhuri et al. (2013) verified that different reanalysis products have comparable uncertainties when they are calibrated against observations. It is confirmed that the results using ERA-40 and ERA5 are qualitatively the same as the ones using NCEP–NCAR reanalysis. Therefore, results using ERA-40 and ERA5 are not presented below.

Since the southward detour of MJOs is pronounced in boreal winter (Kim et al. 2017; Ling et al. 2019), the analyses in this study focus on the period from December to February (DJF). Following Kim et al. (2017), two boxes are selected to delineate the southward detour of MJOs. One box is the near-equatorial region (NE region; the northern box) within 5°S – 5°N , 100° – 140°E . The other box is the southern tropical region (ST region; the southern box) within 15° – 5°S , 100° – 140°E . The differences between the regional mean intraseasonal OLR anomalies (a common proxy for deep convection) in the two boxes (the NE and ST regions) are defined as $OLR_{diff} = OLR_{NE} - OLR_{ST}$ (black lines in Fig. 1). Since OLR anomalies are negative during deep convection, positive (negative) OLR_{diff} denotes a convection center residing in the ST (NE)

region. In addition, MJOs are represented with the Real-time Multivariate MJO (RMM) index created by Wheeler and Hendon (2004). The whole RMM is defined as $\sqrt{RMM1^2 + RMM2^2}$, where RMM1 and RMM2 stand for the RMM time series 1 and time series 2, respectively. Positive RMM1 indicates that deep convection occurs over the Maritime Continent, while negative RMM2 indicates the deep convection occurs over the open Indian Ocean (Wheeler and Hendon 2004). Since we focus on the MJO detouring around the Maritime Continent, RMM1 is used below. For the following composite analyses, the MJO events are selected when significant peaks in OLR_{diff} coincide with significant positive RMM1 peaks. Specifically, the following three criteria must be satisfied:

- 1) OLR_{diff} (rather than OLR anomalies in either NE region or ST region) are significantly larger than its mean plus its standard deviation (STD) or smaller than its mean minus its STD.
- 2) RMM1 reaches a local maximum. If the interval of two local maxima of RMM1 is less than 30 days, only the maximum of the two peaks is selected.
- 3) RMM1 is larger than its mean plus its STD, so that the MJO convection resides in the Maritime Continent rather than over the open Indian Ocean.

When a significant positive OLR_{diff} (larger than the mean plus STD of OLR_{diff} ; blue plus signs in Fig. 1) coincides with a RMM1 peak, the convection center of the corresponding MJO event occurs in the ST region. Similarly, when a significant negative OLR_{diff} (smaller than the mean minus STD of OLR_{diff} ; red plus signs in Fig. 1) coincides with a RMM1 peak, the convection

TABLE 1. The days (day 0) with a coherence between peaks in OLR_{diff} (defined as $OLR_{NE} - OLR_{ST}$) and positive peaks in RMM1 index for all ST and NE events. Day 0 for ST (NE) events are marked with blue (red) circles and are indexed in blue (red) numbers in Fig. 1.

Event No.	Date of day 0	Event No.	Date of day 0
ST events			
1	30 Dec 1982	8	28 Feb 2007
2	17 Feb 1985	9	26 Dec 2007
3	25 Jan 1989	10	8 Feb 2008
4	28 Feb 1990	11	21 Jan 2012
5	17 Feb 1994	12	21 Feb 2013
6	28 Feb 2000	13	10 Feb 2014
7	28 Feb 2003	14	19 Dec 2015
NE events			
1	31 Jan 1982	6	4 Jan 2005
2	24 Jan 1991	7	27 Dec 2008
3	26 Dec 1991	8	5 Dec 2011
4	28 Feb 1992	9	13 Feb 2016
5	27 Jan 1999		

center of the corresponding MJO event occurs in the NE region. There are 14 (9) MJO events whose convection centers fall distinctly into the ST (NE) region, as shown with the blue (red) circles in Fig. 1. Hereafter, for conciseness, the MJO events marked with blue (red) circles in Fig. 1 are referred to as ST (NE) events. The ST (NE) events are indexed with blue (red) numbers and the corresponding dates are listed in Table 1. The composite intraseasonal OLR anomalies for the ST and NE events, as well as their differences, are shown in Fig. 2. Clearly, for the ST events, pronounced negative OLR anomalies occur in the ST region between 5° and 15° S, which indicates that the MJOs are detoured to the south of the Maritime Continent. In contrast, for the NE events, negative OLR anomalies straddle the equator in the NE region indicating that the MJOs are going directly through the Maritime Continent.

Theoretically, a caveat of the above method is that it does not guarantee that an MJO event is selected by applying RMM1 alone. Since the variances explained by RMM1 and RMM2 are very close [12.8% for RMM1 and 12.2% for RMM2 according to Wheeler and Hendon (2004)], they are not separable (North et al. 1982). Thus, RMM1 alone cannot guarantee an MJO event. On the other hand, not all detoured MJO events are selected with the above method. In fact, using TRMM data, Kerns and Chen (2016) showed that 25% MJO events that could propagate through the Maritime Continent were not well captured by the whole RMM index. Nevertheless, each selected ST and NE event (Fig. 1 and Table 1) is examined. All events can propagate through the Maritime Continent, either in the tropics (NE events)

FIG. 2. Composite intraseasonal OLR anomalies ($W m^{-2}$) for the (a) ST events and (b) NE events, and (c) the differences between ST and NE events. The dotted regions in (c) indicate statistically significant differences at the 95% confidence level. The two red boxes in (c) are the NE region (the northern one) and the ST region (the southern one), respectively, following Kim et al. (2017).

or along a detoured route (ST events). The composite Hovmöller diagrams of intraseasonal OLR anomalies for the NE and ST events are shown in Fig. 3. In the deep tropics (averaged between 5° N and 5° S; Figs. 3a,b), both composite NE and ST events go across the Maritime Continent. In addition, convection becomes weaker after entering the Maritime Continent (between the two dashed lines at 100° and 140° E in Fig. 3), which is consistent with the common characteristics of MJOs. Along the southern route (averaged between 5° and 15° S; Fig. 3c), the propagation through the Maritime Continent is also clear. Convection recovers over the Maritime Continent between 100° and 140° E, which is discussed further below. In addition, the composite

FIG. 3. Hovmöller diagrams of composite intraseasonal OLR anomalies (W m^{-2}) for (a) the NE events averaged between 5°N and 5°S , (b) the ST events averaged between 5°N and 5°S , and (c) the ST events averaged between 5° and 15°S . The longitude range of the Maritime Continent between 100° and 140°E is marked with vertical dashed lines in each panel.

Wheeler–Hendon phase diagrams (Wheeler and Hendon 2004) for the ST and NE events are shown in Fig. S1 in the online supplemental material. Hovmöller diagrams of intraseasonal OLR and rainfall anomalies for some typical ST events are shown in Figs. S2 and S3. More discussion on the method is also presented in the supplemental material. Overall, since we focus on the detoured MJO events, all selected events for the following analyses are MJOs that can go through the Maritime Continent. The propagation range and speed are similar between the ST and NE events. The MJOs that are completely blocked by the Maritime Continent (cannot reach the Pacific) are not addressed in this study, but they deserve a dedicated examination in the future.

3. Results

a. Horizontal advection and local convergence

Low-level moisture convergence is a major feature of detoured MJOs. The vertically integrated specific humidity $\langle q' \rangle$ [the operator $\langle A \rangle$ is defined as $(1/g) \int_{p_t}^{p_b} A dp$, where g is gravitational acceleration, $p_b = 1000 \text{ hPa}$ and $p_t = 300 \text{ hPa}$ are pressures at the bottom and the top of the atmosphere, respectively, and A is a dummy variable] for the NE and ST events are shown in Fig. 4. Clearly, moisture accumulates in the ST region for the ST events (Fig. 4a), and in the NE region for the NE

events (Fig. 4b). As a result, when MJOs detour near the Maritime Continent, there is moisture affluence over the Timor Sea and the northwestern Australia, and a significant moisture deficit in the deep tropics around 100°E (Fig. 4c). Meanwhile, in the lower troposphere, there is a cyclone (clockwise in the Southern Hemisphere) over the Timor Sea during the ST events (arrows in Fig. 4a), which is an important dynamical process for the detouring of MJOs (more discussion is presented below). In contrast, during the NE events, westerly winds from the Indian Ocean and the easterly winds from the Pacific Ocean converge over the Maritime Continent, which is consistent with the positive moisture anomalies (Fig. 4b) and deep convection (negative OLR anomalies; Fig. 2b) in the NE region. In fact, there is a weak anticyclone over the Timor Sea (arrows in Fig. 4b), which is unfavorable for convection over the ST region. The composite vertical profiles of $\text{MSE} = C_p T + gz + Lq$ (C_p is heat capacity at constant pressure, T is air temperature, z is height, L is latent heat of evaporation, and q is specific humidity) averaged within the ST region (within $15^{\circ}\text{--}5^{\circ}\text{S}$, $100^{\circ}\text{--}140^{\circ}\text{E}$) from day -25 to day 25 are shown in Fig. 5a. Starting from day -10 , positive MSE begins to occur in the lower troposphere due to convergence (colors in Fig. 5a), in which the zonal advection of MSE dominates (Fig. 5b; Kim et al. 2017). The atmosphere becomes unstable with the accumulation of MSE and deep convection is triggered. Convergence

FIG. 4. Colors: composite q' (kg m^{-2}) for (a) ST events and (b) NE events, and (c) the differences between ST and NE events. Vectors are the corresponding intraseasonal winds at 850 hPa. The dots represent differences in (c) that are statistically significant at the 95% confidence level. The Timor Sea and Makassar Strait are marked in (b).

and positive MSE anomalies can be seen in the whole air column until about day 8.

Although MJOs propagate eastward from the western tropical Indian Ocean and horizontal advection plays an important role for the detour of MJOs by transporting moisture and MSE (Kim et al. 2017), the differences between ST and NE events are not statistically significant before reaching the Maritime Continent. As shown in the Hovmöller diagrams, for both ST and NE events, negative intraseasonal OLR anomalies (Figs. 6a,b) propagate eastward starting from the western Indian Ocean around 40°E on day -25. Their differences are not significantly different from zero (regions without dots in Fig. 6c).

When approaching the Maritime Continent (to the east of 100°E and between the two dashed lines in Fig. 6), the OLR anomalies for the ST events are much stronger than those for the NE events, which indicate that the deep convection is only enhanced for the ST events. The same conclusion can be drawn for $\langle \text{MSE}' \rangle$ (Figs. 6d,e). For both ST and NE events, positive $\langle \text{MSE}' \rangle$ propagate eastward from about 40°E on day -20, which is mainly due to the moisture convergence (the component Lq in MSE dominates; not shown) associated with the active phase of MJOs. But the differences between ST and NE events are insignificant to the west of 100°E. Over the ST region, $\langle \text{MSE}' \rangle$ for the ST events are much larger than the NE events, which is consistent with the strong convection over ST. For the NE events, OLR anomalies are positive and $\langle \text{MSE}' \rangle$ are close to zero within 100°–140°E on day 0. This is because the average is taken between 5° and 15°S in Fig. 6. If the average is taken between 5°N and 5°S (the latitudinal range for the NE region), the coherence between negative OLR anomalies and positive $\langle \text{MSE}' \rangle$ is clear (not shown). If the meridional averages are taken between 5°N and 5°S (the meridional range of NE region), the Hovmöller diagrams are qualitatively the same as the ones shown in Fig. 6 (not shown); that is, significant differences in OLR anomalies and $\langle \text{MSE}' \rangle$ cannot be found over the Indian Ocean to the west of 100°E. But differences are clearly seen in the NE region over the Maritime Continent. The same conclusions can be drawn for other key variables for the eastward propagation of MJOs, such as the intraseasonal anomalies in zonal winds, $\langle q \rangle$, potential vorticity (Zhang and Ling 2012), low-level convergence, and SSH anomalies (not shown). Consistently, DeMott et al. (2018) found that the amplitudes of MJO events have no significant differences over the Indian Ocean, no matter how they cross the Maritime Continent. Therefore, it can be concluded that the detour of MJO near the Maritime Continent should be mainly attributable to local processes.

b. SST influences on detour of MJOs

Differences in intraseasonal SST anomalies between the ST and NE events are shown in Fig. 7. The patterns of SST anomalies for the ST events alone are similar to those in Fig. 7 (not shown). The intraseasonal OLR anomalies for the composite ST events are superimposed to indicate the locations of convection during the detoured MJOs. On day -25, the SST differences in the SEIO and Maritime Continent are small (Fig. 7a). There are hardly any significant intraseasonal OLR anomalies over the Indian Ocean. Positive SST anomalies begin to occur off Sumatra around 10°S, 100°E on day -20. At the same time, negative OLR anomalies occur over the

FIG. 5. (a) Composite vertical profile of horizontal divergence (colors; 10^{-7} s^{-1}) and intraseasonal MSE anomalies (contours) averaged within the ST region for the ST events. Contours for intraseasonal MSE anomalies start from $2 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ (solid contours) and $-2 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$ (dashed contours), with an interval of $2 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$. (b) As in (a), but for the intraseasonal zonal advection of MSE ($10^{-3} \text{ m}^2 \text{ s}^{-3}$). The dotted regions and black contours indicate the composite are significantly different from zero at the 95% confidence level.

southwestern Indian Ocean around 20°S , 70°E , which indicate the MJO genesis but do not seem to be related to the warm SST anomalies off Sumatra. Then, the positive SST anomalies get enhanced, extending south-eastward to southern Java Sea and Timor Sea, from day -15 to day -5 (Figs. 7c–e), which was first noticed by Zhang and Ling (2017). During this period, negative OLR anomalies extend eastward through the Indian Ocean, as an MJO event (Hovmöller diagrams in Fig. 3). On day -15 , negative OLR anomalies reach Sumatra, but in the deep tropics (between 10°N and the equator around 100°E ; Fig. 7c). On day -10 , when SST anomalies reach the maximum over SEIO, negative OLR anomalies are detoured southward to SEIO (Fig. 7d) and get strengthened rapidly over SEIO (Fig. 7e). On day 0, when the RMM1 index reaches the local maximum and convection is fully developed, intraseasonal SST anomalies diminish. Comparing with the convergence and MSE anomalies in Fig. 5, one can see that convection does not occur simultaneously with warm SST anomalies. At a specific location, the warm SST anomalies lead the convection by about 10 days, since SST anomalies reach the maximum on day -10 (Fig. 7d). Equivalently, in space, the warm SST anomalies are to the south of convection at a specific time, because the whole system is detoured southward. After day 0, the convection system keeps propagating eastward through the Maritime Continent (Fig. 7g; also see the supplemental material). By day 15, the convection center

(negative OLR anomalies) moves to the western Pacific but becomes much weaker (Fig. 7h).

In addition, during boreal winter (DJF), there is a significant lag correlation between intraseasonal SST anomalies and precipitation (Fig. 8a) over the ST region, when the SST anomalies lead precipitation by 10 days. The simultaneous correlations between intraseasonal SST and rainfall anomalies are not statistically significant over the SEIO (not shown). The same conclusion can be drawn using TRMM data from 1998 to 2017 (Fig. 8b). Deep convection after warm SST anomalies can be clearly seen in Fig. 9, because warm SST anomalies reach maximum on day -10 (Fig. 7d). Since we focus on the southward detour of MJOs, the vertical profiles in the meridional direction are shown, although MJOs mainly propagate eastward (Adames and Wallace 2014; Kim et al. 2014; Adames and Wallace 2015). On day 0, positive intraseasonal MSE anomalies occur between 10° and 20°S in the entire air column, and thus the atmosphere over SEIO becomes unstable. Due to the air density differences at different vertical levels, momentum ρv and $\rho \omega$ (where ρ is the air density, and v and ω are the meridional and vertical velocities in the pressure coordinate, respectively) are shown in Fig. 9, rather than the velocities v and ω . The vertical momentum anomalies are pronounced. However, the meridional momentum anomalies are only discernible in the boundary layer below 850 hPa. There is no significant downdraft to the north of convection (10° – 20°S) in the troposphere.

FIG. 6. Hovmöller diagrams of intraseasonal OLR anomalies (W m^{-2}) averaged between 5° and 15°S for the (a) ST events and (b) NE events, and (c) their differences. The dotted differences in (c) are the ones that are statistically significant at the 95% confidence level. The two dashed lines in each panel mark 100° and 140°E , which are the meridional boundaries of the ST and NE boxes. (d)–(f) As in (a)–(c), but for MSE' (10^6 J m^{-2}).

Therefore, the convection is mainly attributable to local impacts of air–sea fluxes, but not to the atmospheric meridional circulation in the vertical (akin to a local Hadley cell). The same conclusion can be drawn with the latitude–vertical profiles on other composite days (not shown) and it is consistent with the previous findings

that the horizontal advection is essential for the detour of MJOs (Kim et al. 2017).

The lead–lag relation between warm SST anomalies and atmospheric convection can be untangled by applying the classical wind–evaporation–SST (WES) mechanism (Xie and Philander 1994) at intraseasonal

FIG. 7. Composite differences in intraseasonal SST anomalies ($^{\circ}\text{C}$) between the ST and NE events ($\text{ST} - \text{NT}$). The dotted differences are the ones that are statistically significant at the 95% confidence level. The red contours denote intraseasonal OLR anomalies for the composite ST event, starting from 0 W m^{-2} with an interval of -10 W m^{-2} . The thick contours are statistically significant at the 95% confidence level.

FIG. 8. Lag correlation coefficients between intraseasonal SST anomalies and precipitation, when the SST anomalies lead precipitation by 10 days. SST anomalies are from OISST data, where precipitation is (a) the convective rainfall from NCEP–NCAR reanalysis and (b) from TRMM data. Correlation coefficients larger than 0.28 are statistically significant at the 95% confidence level. The reduction in degree of freedom due to bandpass filtering is considered following Bretherton et al. (1999).

time scales. The fundamental process in the WES mechanism is that surface evaporation and associated LHF are modified by SST anomalies and surface wind speed anomalies, so that the SST and surface winds are coupled, and air–sea interactions are sustained. Over the warm intraseasonal SST anomalies, a cyclone is organized as shown with the arrows in Fig. 10 (also shown with the arrows in Fig. 4). The background winds (obtained using a low-pass filtering with a cutoff period of 100 days) are westerlies (solid white contours in Fig. 10) over the Timor Sea and northwestern Australia. In the northern branch of the cyclone over the warm SST anomalies in the Timor Sea (approximately between 10° and 5°S), intraseasonal wind anomalies reinforce the background westerlies. Meanwhile, in the southern branch of the cyclone (around 20°S), intraseasonal wind anomalies are opposite to the background zonal winds, reducing the total zonal winds. As a result of the enhanced (reduced) wind speed in the northern (southern) branch of the cyclone, surface heat flux is reinforced (suppressed). The phase relation between anomalies in SST and LHF (the major component of surface heat flux)

FIG. 9. Composite intraseasonal MSE anomalies (colors) and momentum anomalies (arrows) on day 0 averaged between 100° and 140°E (the longitude range of the two boxes in Fig. 2). The unit is $10^{-3} \text{ m}^2 \text{ s}^{-2}$ for MSE anomalies, $\text{kg m}^{-2} \text{ s}^{-1}$ for meridional momentum anomalies, and $\text{kg Pa m}^{-3} \text{ s}^{-1}$ for vertical momentum anomalies. The dotted MSE anomalies and black arrows are statistically significant at the 95% confidence level.

is shown in Fig. 11. Warm SST anomalies begin to occur on about day -20 at 5°S. Then the warm SST anomalies propagate southward. Since this propagation speed is relatively high, it is not well resolved in daily data. To the north of positive SST anomalies, the total westerly winds are enhanced. Therefore, at the same latitude, enhancement in total winds lags the warm SST anomalies by about 10 days. In a few days after the enhancement of wind anomalies, LHF increases (black contours in both Figs. 11a and 11b), which is favorable for deep convection. To the south of warm SST anomalies, easterly wind anomalies weaken the background westerly winds. As a result, the total wind is reduced and LHF decreases due to the differences of ocean–atmosphere interaction between the northern and the southern branches of the cyclone, via the interactions between atmospheric cyclones and warm SST anomalies in the context of background westerly winds. The entire system thus moves southward, including the warm SST anomalies, cyclone in the atmosphere, LHF, and deep convection. Hence, the MJO also detours southward.

The phase relation between vertical velocity and surface heat flux (the major component is LHF; Emanuel et al. 1994; Sobel et al. 2010) is critical for the accumulation

FIG. 10. Intraseasonal SST anomalies (colors; $^{\circ}\text{C}$) and intraseasonal sea surface winds (vectors) for the ST events on day -5 . The background zonal winds (obtained with a low pass filtering at 100 days) during ST events are superimposed with white contours. Solid white contours start from 1 m s^{-1} with an interval of 1 m s^{-1} ; dashed white contours start from -1 m s^{-1} with an interval of -1 m s^{-1} . The dotted SST anomalies and black arrows are statistically significant at the 95% confidence level.

of potential energy in the atmosphere. Neglecting the small terms such as the nonlinear advection terms, the linear thermodynamic equation for the atmosphere is $(\partial T'/\partial t) - \omega' S_p = J'/C_p$, where T is air temperature, ω is vertical velocity, S_p is a parameter for static stability, J is the convective heating, C_p is the heat capacity at a constant pressure, and the prime denotes the intraseasonal component of each variable. The potential energy is proportional to $\overline{T'^2}/2$, where the overbar denotes an average over a sufficiently long period.

Multiplying T' on both sides of the thermodynamic equation and taking the average over a long period, one obtains $(\partial/\partial t)(\overline{T'^2}/2) - \overline{T'\omega' S_p} = \overline{T'J'}/C_p$. The phase difference between anomalies in air temperature and heating term is critical for the generation of potential energy (i.e., a nonnegligible $\overline{T'J'}$). The phase differences can be clearly seen in Fig. 11b. After the accumulation of potential energy, it can be transferred directly to kinetic energy on intraseasonal time scales. The kinetic energy budget of MJOs was examined in Zhou et al. (2012), showing that the energy gain from the potential energy is a major source for the kinetic energy on intraseasonal time scales. This conclusion remains true for the detoured MJOs. Overall, the phase relation adjusted by the SST influence enables the accumulation of potential energy and creates a favorable condition for MJOs to detour southward when reaching the Maritime Continent.

4. Discussion

a. SST anomalies over SEIO and MJO-associated SST anomalies

Usually, there are warm SST anomalies ahead of the MJO convection center (e.g., Shinoda et al. 1998; Woolnough et al. 2000) with an amplitude $\sim 1/3^{\circ}\text{C}$ (Hendon and Glick 1997). However, the warm SST anomalies over SEIO that play a key role in the processes discussed in this study are not generally attributable the SST anomalies associated with MJOs.

FIG. 11. (a) Latitude–time diagram for composite ST events averaged between 110° and 130°E . Colors are intraseasonal SST anomalies. Black contours denote intraseasonal LHF, solid (dashed) contours are for positive (negative) anomalies. The black contours start from $\pm 10 \text{ W m}^{-2}$ with an interval of 10 W m^{-2} . White contours denote total sea surface zonal winds and start from 1 m s^{-1} with an interval of 1 m s^{-1} . (b) Colors are intraseasonal surface air temperature (at 1000 hPa) anomalies ($^{\circ}\text{C}$). Solid and dashed contours are as in (a).

FIG. 12. Hovmöller diagrams of intraseasonal SST anomalies ($^{\circ}\text{C}$) averaged over (a) 5°N to 5°S and (b) 5° to 15°S for the ST events. The black contours are 0.1°C in both panels. The Maritime Continent is between the two dashed lines at 100° and 140°E in each panel. The dotted regions are statistically significant at a 95% confidence level.

The Hovmöller diagrams of intraseasonal SST anomalies during the composite ST event, averaged from 5°N to 5°S and from 5° to 15°S , are shown in Fig. 12. In both panels, the large SST anomalies between 40° and 50°E are attributable to the strong Somali Current and associated instabilities (e.g., Schott et al. 2009). Between 60° and 70°E around day -40 , the composite SST anomalies are larger than 0.1°C , which may be related to MJO genesis over the western Indian Ocean (Zhou et al. 2008b; Webber et al. 2012). However, the composite SST anomalies are weak, being smaller than 0.1°C , from 70°E to the Maritime Continent (100°E ; dashed lines in Fig. 12). In Fig. 12b, there are almost no eastward-propagating SST anomalies, which is consistent with observations (e.g., Hendon and Glick 1997). In contrast, the SST anomalies over the Maritime Continent (between 100° and 140°E ; two dashed lines in each panel in Fig. 12) are distinct. Particularly, in the SEIO (Fig. 12b), they can be larger than 0.5°C . Therefore, the large warm SST anomalies over SEIO should not be the same as the SST anomalies ahead of MJOs. In fact, the conclusion that the warm SST anomalies over the SEIO are not associated with MJOs is consistent with the fact that there is a similar possibility for MJOs to go through the Maritime Continent or to detour near the Maritime Continent (Inness and Slingo 2006; Kerns and Chen 2016; Zhang and Ling 2017). Further ocean process studies are needed to understand if some of these SST anomalies are indeed associated with MJOs and, if so, why some MJOs are able to sow the seeds for their own detour while others are not.

In addition, the STDs of intraseasonal SST anomalies in the Indian Ocean are shown in Fig. 13. Generally, the STDs of intraseasonal SSTs are large over the SEIO, which can reach 0.6°C in boreal winter (Fig. 13b), but small in tropical Indian Ocean, where the STDs of intraseasonal SST are about 0.3°C throughout the year (Fig. 13a) and boreal winter (Fig. 13b). The energetic oceanic ISVs in the SEIO and the Maritime Continent have been extensively studied. For example, the oceanic ISV over the SEIO is mainly attributable to ocean instabilities that are related to the ocean current shears and ocean stratification (e.g., Feng and Wijffels 2002; Zhou et al. 2008a; Ogata and Masumoto 2011). Within the Maritime Continent, the ISVs are found to be attributable to remote and local wind forcing, tropical waves and their resonance in the ocean, and thermocline changes (Qiu et al. 1999; Schiller et al. 2010; Pujiana et al. 2013). MJO is surely one driver for oceanic ISVs over the Maritime Continent (e.g., Zhou and Murtugudde 2010), but it is not the only driver. There are abundant and energetic ISVs in SEIO and within the Maritime Continent that do not depend on MJOs, and the ocean dynamics associated with these variabilities are complex.

b. Possible influence from Indonesian Throughflow

The warm SST anomalies over the SEIO can also be related to the Indonesian Throughflow (ITF). Although eastward-propagating MJOs can leave footprints on the ocean via sequential equatorial Kelvin waves translating

FIG. 13. STDs of intraseasonal SST anomalies ($^{\circ}\text{C}$) during (a) all seasons and (b) boreal winter (DJF) from 1982 to 2017. The intraseasonal SST anomalies are obtained from daily OISST data with a bandpass filter between 20 and 100 days.

to coastal Kelvin waves along Sumatra (Waliser et al. 2003; Zhou and Murtugudde 2010), during detoured MJOs the differences between ST and NE events in the ocean (such as the SST anomalies and SSH anomalies; similar to Fig. 6) are not significant over the tropical Indian Ocean. Therefore, the local oceanic processes in the SEIO and the impacts from the ITF are good likely candidates for explaining the intraseasonal SST anomalies in the Timor Sea. Even though the Makassar Strait (marked in Fig. 4b) is the major pathway of the ITF, its volume and its impact on the Indian Ocean are modulated by SSH in the Karimata Strait and the Java Sea, which acts like a freshwater plug for the Makassar Strait throughflow (Gordon et al. 2003; Zhou and Murtugudde 2009). When SSH is high (low) in the Karimata Strait and the Java Sea, warm Makassar Strait throughflow is hindered (unobstructed), and the ITF becomes cooler (warmer) than normal. There is also an intraseasonal component to this Karimata–Makassar interplay (Zhou and Murtugudde 2009; Pujiana et al. 2013). As shown in Fig. 14, SSH anomalies during the ST events are significantly lower than those during the NE events, which should be favorable for warm intraseasonal SST anomalies over the SEIO. Significant

negative differences (dotted regions) occur over the Karimata Strait (red box in Fig. 14a) on day -20 and extend to the Java Sea from day -15 to day 0 , reaching a maximum around day -5 . Meanwhile, in the tropical regions and along Sumatra (white boxes in Fig. 14), SSH anomalies are not significantly different between the ST and NE events (no dotted regions in the white boxes), with an occasional exception on day -15 (Fig. 14b). This is one more piece of evidence supporting the conclusion that there are no significant differences between MJOs that can and cannot go through the Maritime Continent when they are still traveling over the Indian Ocean (Fig. 6; DeMott et al. 2018). Moreover, the thermocline intensification is a pronounced feature of the ITF (Tozuka et al. 2007; Zhou et al. 2008b). After entering the Indian Ocean, the ITF can modify the vertical structure in the SEIO, triggering baroclinic instability and enhancing oceanic ISVs (Feng and Wijffels 2002; Zhou et al. 2008a). Therefore, based on current results, it is reasonable to assume that the intraseasonal SST anomalies over the SEIO are possibly attributable to oceanic variabilities and the influence of the ITF. They do not appear to depend on the eastward-propagating MJOs,

FIG. 14. (a)–(e) Differences in SSH anomalies (m) between the composite NE events and the composite ST events from day –20 to day 0. (f) The mean SSH anomalies over the Karimata Strait [red box in (a)]. The dotted differences are statistically significant at a 95% confidence level. The white boxes in (a)–(e) mark the equatorial region and the coastal region along Sumatra.

although the atmospheric impacts cannot be fully excluded.

c. Active roles of the ocean

The relation between SST anomalies and surface heat flux during MJOs has been widely discussed, such as in Shinoda et al. (1998), Waliser et al. (2003), Zheng et al. (2004), and de Szoek et al. (2015), and many others. The mechanism unveiled in this study also involves anomalies in SST and LHF, which are coupled by the low-level cyclone and background winds. Nevertheless, the forcing and response relation between surface heat flux and SST in this study is different from the typical MJO process. During normal MJOs, the ocean mostly plays a passive role. For example, in a suppressed phase of MJO, LHF is reduced and shortwave radiation is

enhanced due to weak winds and a clear sky (Hendon et al. 2012). SST increases accordingly. Thus, the SST anomalies are responses to the atmospheric forcing and then they feed back to the atmosphere. In contrast, for detoured MJOs, the ocean plays an active role. The SST anomalies over SEIO are not mainly attributable to the MJO forcing. They induce a low-level cyclone. The background westerlies are reinforced in the northern branch of the cyclone, while they are reduced in the southern branch. According to the WES mechanism, the LHF is enhanced (reduced) in the northern (southern) branch of the cyclone, and the whole system is detoured southward. Moreover, the rapid increases of negative OLR anomalies (Figs. 3c and 6c) and positive $\langle \text{MSE}' \rangle$ (Fig. 6f) occur in the ST region between 100° and 140°E, which is not expected for regular MJOs. Therefore, they

FIG. 15. Sketch for detoured MJOs. Red oval denotes warm SST anomalies. As a result, a cyclonic circulation generates due to the low surface pressure. Given the mean westerlies in the tropics during austral summer, LHF increases and SST decreases in the northern branch of the cyclone. In contrast, LHF decreases and SST increases in the southern branch of the cyclone. As a result, the convection center shifts southward and the MJO detours southward.

can only be attributable to the oceanic ISVs over the SEIO, which are distinctly different from SST anomalies induced by MJOs themselves.

Although the warm SST anomalies over the SEIO are not the ones associated with MJOs based on the current results, the influence of MJO convection (e.g., via the downwelling Kelvin waves along Sumatra) cannot be completely ruled out. For the ST events, after being detoured southward around the Maritime Continent, they continue to propagate eastward through the Maritime Continent (Fig. 3; also see the online supplemental material). The MJO convection is expected to play a role for the eastward propagation, probably by interacting with the local environment. However, the relative contribution between MJO convection and oceanic ISVs over SEIO to the eastward propagation can be hardly quantified with observations or reanalysis products alone. Some well-designed numerical model experiments are required.

5. Conclusions

MJOs are the dominant atmospheric ISVs in the tropics. During boreal winter, MJOs mainly propagate eastward. However, a large portion of MJOs detour southward near the western edge of the Maritime Continent. In this study, the oceanic impacts via the intraseasonal SST anomalies on the detour of MJOs are diagnosed using observations and reanalysis products. It is found that the warm SST anomalies over the SEIO can lead to a cyclone in the lower troposphere. Since the background winds during boreal winter are westerlies,

to the north (south) of the cyclone, the westerly (easterly) wind anomalies enhance (reduce) the background winds. As a result, the total winds become stronger (weaker) and LHF is enhanced (reduced) to the north (south) of the SST anomalies. As a result, convection in the atmosphere is triggered to the north, rather than the center, of warm SST anomalies. Meanwhile, convection is suppressed to the south of the warm SST anomalies, which leads to a temperature increase and induces the whole ocean–atmosphere coupled system to move southward. The entire process of the oceanic influence, as illustrated in Fig. 15, follows the principle of the WES mechanism albeit at intraseasonal time scales. The influences of the orography of the Maritime Continent on MJOs have been discussed in earlier studies (Inness and Slingo 2006; Wu and Hsu 2009). The obstacle effects of the Maritime Continent for the MJOs have also been widely examined (Oh et al. 2012; Peatman et al. 2014; Ling et al. 2019) as well as the mechanisms involving the diurnal cycle, land–sea contrast in surface heat flux, and so on. In this study, it is shown that the MJO system is steered southward by warm SST anomalies in SEIO. Since the total SSTs are not warm enough in this region (not well above 27.5°C; Graham and Barnett 1987), the SST anomalies do not trigger deep convection directly. Instead, the warm SSTs induce the cyclone and modify the general circulation in the atmosphere, which can induce the horizontal advection emphasized in previous studies, such as Kim et al. (2017). As a result, the advection by the general circulation in the atmosphere plays a critical role in the detour of MJOs (Zhu et al. 2010). Therefore, it can be concluded that there are two potentially favorable conditions for the

detour of MJOs. One is the obstacle in the pathway of the MJO eastward propagation over the Maritime Continent. The other one is the warm ocean environment over SEIO and the feedbacks it triggers via WES.

The mechanisms for the SST anomalies are not examined in detail in this study, due to the complex ocean dynamics (such as the ocean instabilities and ocean mixing) and ocean–atmosphere interactions in this region. A comprehensive heat budget analysis (including the ocean advection, entrainment, and ocean mixing) is necessary for unveiling the mechanisms of the warm SST anomalies in SEIO. It is also necessary for quantifying the relative contributions of ocean dynamics (such as ocean instabilities and the ITF influences) and MJO impacts (such as the coastal Kelvin waves along Sumatra) to the warm SST anomalies over SEIO. So far, the rendition of oceanic ISVs in ocean reanalysis products is hardly satisfactory for such detailed analysis (Zhang et al. 2016; Jayasankar et al. 2019). Hence, more studies using systematic observations and well-designed high-resolution models are needed in the future. Since oceanic impacts on the MJO detours are essential and independent from the atmospheric forcing, a fully coupled ocean–atmosphere model, rather than an atmosphere-only model, is likely indispensable for better simulations and forecasts of MJO trajectories near the Maritime Continent, especially considering the ocean warming and the recently reported trends in the Indo-Pacific warm pool and the residence times of MJO over the Indian Ocean and the Maritime Continent (Subramanian et al. 2014; Roxy et al. 2019).

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