Impacts of Detoured Madden–Julian Oscillations on the South Pacific Convergence Zone

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ABSTRACT: Madden–Julian oscillations (MJOs) are a major component of tropical intraseasonal variabilities. There are two paths for MJOs across the Maritime Continent; one is a detoured route into the Southern Hemisphere and the other one is around the equator across the Maritime Continent. Here, it is shown that the detoured and nondetoured MJOs have significantly different impacts on the South Pacific convergence zone (SPCZ). The detoured MJOs trigger strong cross-equatorial meridional winds from the Northern Hemisphere into the Southern Hemisphere. The associated meridional moisture and energy transports due to the background states carried by the intraseasonal meridional winds are favorable for reinforcing the SPCZ. In contrast, the influences of nondetoured MJOs on either hemisphere or the meridional transports across the equator are much weaker. The detoured MJOs can extend their impacts to the surrounding regions by shedding Rossby waves. Due to different background vorticity during detoured MJOs in boreal winter, more ray paths of Rossby waves traverse the Maritime Continent connecting the southern Pacific Ocean and the eastern Indian Ocean, but far fewer Rossby wave paths traverse Australia. Further studies on such processes are expected to contribute to a better understanding of extreme climate and natural disasters on the rim of the southern Pacific and Indian Oceans.

KEYWORDS: Atmosphere; Indian Ocean; Southern Hemisphere; Advection; Convection; Intraseasonal variability

1. Introduction

Madden–Julian oscillations (MJOs; Madden and Julian 1971, 1972; Zhang 2005) are a major component of intraseasonal variabilities in the tropics, which have a typical period of 30–60 days. Usually, MJOs originate over the western Indian Ocean. In boreal winter, most MJOs propagate eastward from the Indian Ocean into the Pacific Ocean via the Maritime Continent (Wang and Rui 1990). However, MJO trajectories diverge near the Maritime Continent. A portion of MJOs go through the Maritime Continent near the equator, while some are detoured southward and cross the Maritime Continent around 10°S. There are also cases where MJOs are blocked by the Maritime Continent and cannot reach the Pacific Ocean (DeMott et al. 2015; Feng et al. 2015; Kerns and Chen 2016; Kim et al. 2016; Zhang and Ling 2017). The complex land–sea distributions and orography with multiscale air–sea interactions over the Maritime Continent have resulted in different mechanisms being proposed, such as the influence of land–sea contrast and orography (Wu and Hsu 2009; Tseng et al. 2017; Tan et al. 2018), the diurnal cycle of convection and its impacts on vanguard precipitation (Oh et al. 2011; Peatman et al. 2014; Ling et al. 2019), the large-scale atmospheric dynamics and thermodynamics (Feng et al. 2015; Kim et al. 2017; DeMott et al. 2018), and the oceanic impacts (Marshall and Hendon 2013; Zhou and Murtugudde 2020).

After traversing the Maritime Continent, MJOs have active interactions with climate processes over the Pacific Ocean at multiple time scales. In the western Pacific, the composite SST anomalies due to MJOs are about 0.25°C (Shinoda et al. 1998). MJOs also explain a large number of westerly wind bursts (Takayabu et al. 1999; Seiki and Takayabu 2007; Puy et al. 2015), which are critical for the irregularity and diversity of El Niño–Southern Oscillation (ENSO; e.g., Gebbie et al. 2007; Chen et al. 2015; Thual et al. 2016). In the eastern tropical Pacific Ocean, MJOs can perturb SSTs by −0.5°C (Maloney and Kiehl 2002; Waliser et al. 2003) and modify the tropical cyclogenesis over the northeastern Pacific Ocean by generating eddy kinetic energy (Maloney and Hartmann 2000).

The South Pacific convergence zone (SPCZ) is a distinct and dominant feature in the southern Pacific Ocean. It consists of strong convection and large precipitation, and plays an important role in regional weather and climate (Trenberth 1976; Vincent 1994). The seasonality of SPCZ is coherent with that of eastward-propagating MJOs; that is, they both exist during all seasons but are more active in boreal winter (Wang and Rui 1990; Zhang and Dong 2004; Widlansky et al. 2010; Kidwell...
The MJOs can influence the SPCZ via the subtropical Rossby wave propagation and advection of air masses with high potential vorticity in the upper troposphere (Matthews et al. 1996). Matthews (2012) found that the active MJO phase shifted the SPCZ westward. Such a modification was confirmed by Haffke and Magnusdottir (2013) using satellite data. Numerical simulations confirmed that the MJO convection can migrate into the SPCZ (Sperber et al. 1997) and implied that the SPCZ was prone to be stronger when MJOs were stronger (Kim et al. 2011). The symmetry of MJOs with respect to the equator in different seasons was noted by Hendon et al. (2007), and its relations with SST variation and ENSO were discussed. However, the different impacts of MJOs along the two distinct paths (i.e., the detoured and nondetoured MJOs over the Maritime Continent) onto the SPCZ have not been examined thus far, to the best of our knowledge. In this study, our results show that the detoured MJOs have a significant impact on the SPCZ and lead to pronounced meridional cross-equatorial transports from the Northern into the Southern Hemisphere. In contrast, the impacts of nondetoured MJOs on the subtropics are relatively small. Variabilities of SPCZ can have impacts on the surrounding regions via Rossby waves (Lintner and Neelin 2008; van der Wiel et al. 2016; Lee and Seo 2019). Therefore, the deconvolution of the influences of different types of MJOs on the SPCZ will advance the comprehensive understanding of weather and climate in the entire southern Pacific Ocean. In the following, data and methods are introduced in section 2. The results are described in section 3. Conclusions and discussion are presented in section 4.

2. Data and methods

Atmospheric variables, such as wind velocities and specific humidity, are obtained from ERA5 (Copernicus Climate Change Service 2017) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The outgoing longwave radiation (OLR) is from the NOAA satellite data (Liebmann and Smith 1996). All data are from 1982 to 2019 and the intraseasonal variabilities are obtained with a 20–100-day bandpass Butterworth filter. Two other reanalysis products from ERA-40 (Uppala et al. 2005) and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) are used to verify the robustness of the following results and conclusions. Since the results are qualitatively the same, only the results using ERA5 are shown below. The results and conclusions are robust and not sensitive to the products.

Following Kim et al. (2017), two boxes are chosen to delineate the detoured and nondetoured MJO events. The northern box is near the equator within 5°S–5°N, 100°–140°E (referred to as the NE region hereafter), and the southern box is in the southern tropics within 15°–5°S, 100°–140°E (referred to as the ST region hereafter; white boxes in Fig. 1a). When the OLR anomalies are positive (negative) in the NE region but negative (positive) in the ST region, the convection center of an MJO event is over the ST (NE) region. Hence, the difference between the regional mean intraseasonal OLR anomalies in the two boxes (i.e., OLR_{diff} = OLR_{NE} - OLR_{ST}) is defined for diagnosing the impacts of detoured MJOs. There are five cases in which both OLR_{NE} and OLR_{ST} are significantly negative, but their difference is small. These cases are not regarded as either typical detoured events or typical nondetoured events. Thus, large positive (negative) OLR_{diff} is one requirement for a detoured (nondetoured) MJO event. The Real-time Multivariate MJO (RMM) index created by Wheeler and Hendon (2004) is applied to identify MJOs. The convection center of MJOs is over the Maritime Continent (western Pacific) when RMM1 (RMM2) is significantly positive.
and the RMM index. Specifically, the following criteria are required to be satisfied:

1) RMM1 reaches the local maximum and is larger than 1. If there is more than one local maximum of RMM1 in 30 consecutive days, only the maximum of the peaks is selected. Such days with maximal RMM1 are regarded as day 0 for an MJO event.

2) In 20 days after the RMM1 peak day (day 0 from criterion 1 above), RMM2 is larger than 1 for more than 5 days, which guarantees that the MJO event traverses the Maritime Continent and the convection center associated with the MJO reaches the western Pacific.

3) For a detoured (nondetoured) MJO event, OLR_{diff} is larger (smaller) than its mean plus (minus) its standard deviation (STD).

All detoured and nondetoured MJO events from 1982 to 2019, which satisfy the above criteria, are listed in Table 1. There are 23 (26) detoured (nondetoured) MJO events, out of which 21 (12) events (the events in bold in Table 1) occur in boreal winter from November to April. Since the seasonalities of both MJOs (Zhang and Dong 2004) and detoured MJO events are clear (Kim et al. 2017; Zhang and Ling 2017; Li et al. 2020), boreal winter is selected in this study. Therefore, the 21 detoured MJO events and the 12 nondetoured MJO events from November to April (the events in bold in Table 1) are used for the following analyses. In the following analysis, the bandpass-filtered intraseasonal variabilities are focused on, so that the impacts of seasonality are minimized. For the nondetoured MJOs, 5 out of 12 events are in November (Table 1). It is verified that there are no significant differences between the 5 nondetoured events in November and the other 7 nondetoured events from December to April over the SPCZ, although some differences exist in the eastern equatorial Indian Ocean (not shown).

3. Results

The composite intraseasonal OLR anomalies on day 0 for the detoured and the nondetoured events are shown in Figs. 1a and 1b, along with their differences in Fig. 1c. For the detoured MJO events, negative OLR anomalies occur in the Southern Hemisphere centered around 10°S. For the nondetoured events, the negative OLR anomalies are in the Northern Hemisphere between the equator and 10°N and they hardly occur over the SPCZ region. The eastward propagation of the composite detoured MJO event from the eastern Indian Ocean to the western Pacific Ocean is shown in Fig. 2a, which is meridionally averaged between 5°S and 15°S. The eastward propagation of detoured and nondetoured events across the Maritime Continent can also be seen if the average is taken within the latitudinal range of the NE region (between 5°N and 5°S; Figs. 2b,c). The intraseasonal OLR anomalies between 5°N and 5°S tend to weaken for the detoured MJOs, while they maintain their intensity for the nondetoured MJOs. Although there are only 12 nondetoured MJO events (bold in Table 1), the eastward-propagating OLR anomalies are statistically significant in Fig. 2c and their eastward propagation is mainly near the equator.

The composite intraseasonal OLR anomalies and precipitation after day 0 for the detoured and the nondetoured MJOs are shown in the online supplemental material. Their differences are shown in Fig. 3. On day 0 and day 5 (Figs. 3a,b),
convection and the corresponding rainfall occur over the Maritime Continent. On day 10 (Fig. 3c), the convection system moves to the southern Pacific between 10° and 20°S. In the following 10 days until day 20 (Figs. 3d,e), OLR anomalies and precipitation occur over the SPCZ. On day 25 (Fig. 3f), all variabilities become weak and there are almost no significant OLR anomalies (no thick red contours in Fig. 3f). Thus, the detoured MJO events reach the Pacific Ocean in about 10 days after day 0 and the following analyses on the MJO’s impacts over the southern Pacific focus on the composite from day 10 to day 20.

**a. Impacts of detoured MJOs on SPCZ**

The composite intraseasonal OLR anomalies during days 10–20 for the detoured and nondetoured events are shown in Figs. 4a and 4b. Their differences are shown in Fig. 4c. The diagonal pattern of negative OLR anomalies for the composite of detoured MJO events is distinct in the southern Pacific. It starts from 140°E near the equator and extends southeastward to about 20°S, 160°W, which coincides with the location of the SPCZ (Vincent 1994). In contrast, for the composite of nondetoured MJO events, the diagonal pattern of negative OLR anomalies is not discernible. There are just weak OLR anomalies, although significant along 5°S and to the northeast of Australia (dotted region in the southwestern Pacific in Fig. 4b). The same figures for intraseasonal precipitation anomalies are shown in Figs. 4d–f. In the SPCZ region, the intraseasonal rainfall anomalies are much stronger during the detoured MJO events than they are during the nondetoured events, which indicates enhanced deep convection and latent heat release over the SPCZ during the detoured MJOs. The intraseasonal wind anomalies in the lower troposphere (850 hPa) averaged from day 10 to day 20 for the detoured MJOs are superimposed in Fig. 4a with white arrows. A cyclonic circulation occurs within 10°–30°S, 150°E–160°W, which indicates a low-level convergence to the southwest of the deep convection over the SPCZ (OLR and precipitation in Fig. 4), which is typical of SPCZ (Kiladis et al. 1989). The intraseasonal wind anomalies at 850 hPa for the nondetoured MJO events are shown in Fig. 4b, which are small. As a result, their differences resemble those for the detoured MJOs (white arrows in Fig. 4c) and the low-level cyclonic circulation near SPCZ is clear. The wind anomalies can simply be explained by the classical Gill response (Gill 1980) with a heat source in the Southern Hemisphere (Vallis 2006; not shown).

**b. Meridional transport across the equator**

Deep convection associated with MJOs tend to follow moisture recharging with a lag of roughly 5–10 days. The composite vertical profiles of intraseasonal specific humidity for the detoured and the nondetoured MJOs over the SPCZ (averaged between 5° and 15°S) are shown in Figs. 5a and 5b, respectively. For the detoured MJOs, significant positive humidity anomalies occur in the entire air column from a few days after day 0 until about day 15 (Fig. 5a). In contrast, for the nondetoured MJOs, moisture depletion happens from day 10 to day 20 (Fig. 5b), since the convection center is near the equator, which is to the north of the SPCZ. As a result, pronounced differences in specific humidity can be seen between the two types of MJOs from day 10 to day 20 (Fig. 5c), which is consistent with the differences in the OLR and precipitation anomalies over the SPCZ (Figs. 4c,f).

The meridional wind anomalies during detoured MJOs can transport moisture and energy from the Northern Hemisphere to the Southern Hemisphere. The budget equation for intraseasonal moisture anomalies in the total air column is (Yanai et al. 1973; Neelin and Held 1987)

\[
\frac{\partial q}{\partial t} = -\nabla_h \cdot (u_h q) - \left( \frac{\partial (\omega q)}{\partial p} \right) + E - P, \tag{1}
\]

**FIG. 2.** (a) Hovmöller diagram of intraseasonal OLR anomalies for the composite detoured MJOs averaged between 5° and 15°S. (b) As in (a), but for detoured MJOs averaged between 5°N and 5°S. (c) As in (a), but for nondetoured MJOs averaged between 5°N and 5°S. Two dashed lines mark the Maritime Continent between 100° and 140°E. The unit is W m⁻². The composite OLR anomalies in the dotted regions are statistically significant at 95% confidence level.
where \( q \) is specific humidity, \( \mathbf{u}_H = \mathbf{u} + \mathbf{u}_q \) is the horizontal wind vector, \( \omega \) is the vertical velocity in an isobaric coordinate, \( E \) is evaporation, \( P \) is precipitation, the prime denotes the intraseasonal anomaly; \( h/C_1 \) is \([1/(g \Delta p)]_{pt} - pt, \) where \( pt = 100 \text{ hPa} \) is the pressure at the top of the atmosphere and \( pb = 1000 \text{ hPa} \) is the pressure at the bottom of the atmosphere. All terms in Eq. (1) for the detoured MJOs are shown in Fig. 6. Positive moisture tendency \( \frac{\partial q}{\partial t} \) is discernible in the southern Pacific between \( 10^\circ \) and \( 20^\circ \) S around \( 170^\circ \) E. Over the SPCZ, the horizontal advection is the dominant term (Fig. 6b), which is mainly balanced by precipitation (Fig. 6d). The vertical advection stands out around \( 10^\circ \) S and \( 20^\circ \) W. More detailed processes of advection can be unveiled by decomposing all variables into three scales (Maloney 2009; Zhou et al. 2012b; Dubey et al. 2018): the background state (obtained with a 100-day low-pass filter; denoted with a bar), the intraseasonal anomaly (obtained with a bandpass filter between 20–100 days; denoted with a prime), and the high-frequency component (obtained with a 20-day high-pass filter; denoted with a double prime). For example, the specific humidity is decomposed as \( q = \overline{q} + q' + q'' \). Thus, the horizontal advection on the intraseasonal time scales becomes

\[
- \langle \nabla_H \cdot (\mathbf{u}_H q) \rangle = - \langle \nabla_H \cdot (\mathbf{u}_H q' + \mathbf{u}_H \overline{q} + \mathbf{u}_H q'') \rangle - \langle \nabla_H \cdot (\mathbf{u}_H q' + \mathbf{u}_H q' + \mathbf{u}_H q'') \rangle - \langle \nabla_H \cdot (\mathbf{u}_H q' + \mathbf{u}_H q'') \rangle.
\]

The term \( - \langle \nabla_H \cdot (\mathbf{u}_H q) \rangle \) is not included in Eq. (2), because it belongs to the background state. The major terms in Eq. (2) averaged between days 10 and 20 for the detoured MJO events are shown in Fig. 7. The meridional transports of \( - \partial (\mathbf{u}_H q)/\partial y \) (Fig. 7e), which is the transport of background moisture by the intraseasonal meridional wind anomalies during the detoured MJOs (white arrows in Fig. 4a), dominate over SPCZ. Correspondingly, the positive moisture tendency to the southwest of SPCZ, a northwest–southeast diagonal region from \( 10^\circ \) S, \( 160^\circ \) E to \( 30^\circ \) S, \( 160^\circ \) W, is pronounced.

The background moisture carried by the intraseasonal zonal
wind anomalies \((-\partial (\alpha'/\bar{v})/\partial x; \text{Fig. 7a})\) is also significant over SPCZ, which is consistent with the eastward propagation of MJOs. The apparent alternative positive and negative pattern in \(-\partial (\alpha'/\bar{v})/\partial x\) (Fig. 7a) over SPCZ is likely attributable to the short averaging period (from day 10 to day 20) of eastward-propagating MJOs. They are not related to Rossby waves, which are discussed below, since the spatial scale is much smaller than the zonal wavelength of Rossby waves, which span wavenumber 1–4 (see below). The pronounced moisture advection by the background moisture and intraseasonal wind anomalies were identified in many previous MJO studies, such as those of Jiang (2017), Ahn et al. (2020), and Kang et al. (2020). The horizontal advection of \(q'\) by the background winds (\(\bar{u}\) and \(\bar{v}\); Figs. 7b,f) is small. The interactions between \(q'\) and the intraseasonal wind anomalies (\(u'\) and \(v'\); Figs. 7c,g) are also small. However, the coherence between high-frequency variabilities leads to significantly negative \(-\partial (\alpha'q')/\partial y\) over the SPCZ region (Fig. 7h), which is consistent with many previous studies (Benedict et al. 2015; Jiang et al. 2017; Zhu et al. 2019) that pointed out that the meridional moisture advection by high-frequency wind anomalies is important for MJOs in the western Pacific Ocean.

During MJOs, convection is favored by large moist static energy (MSE) due to the moisture anomalies (e.g., Kiranmayi and Maloney 2011; Sobel et al. 2014; Cui and Li 2019). The MSE (\(h\)) is the sum of dry static energy (DSE) and moisture (\(q\)); that is, \(h = s + Lq\), where \(s\) denotes DSE (Holton and Hakim 2013). The budget for DSE is (Yanai et al. 1973; Neelin and Held 1987; Sobel et al. 2014)

\[
\frac{\partial s}{\partial t} = -\nabla_H \cdot (\bar{u}_H \bar{s}) - \frac{\partial (\alpha \bar{s})}{\partial p} + Q_H + Q_{SH} + LP,
\]

where \(Q_H\) denotes radiative heating, \(Q_{SH}\) is the sensible heat flux, and \(L\) is the latent heat of vaporization. All terms in
The major components in Eq. (4) during the detoured MJOs are shown in Fig. 9. The meridional advection of DSE in terms of $-\partial (\nu' q')/\partial y$ (Fig. 9e) still dominates in Eq. (4) in the diagonal region over the southwest SPCZ, although the zonal advection term $-\partial (\nu' \phi')/\partial x$ (Fig. 9a) along with the eastward-propagating MJOs is also an evident contributor. A difference from the moisture budget is that the meridional DSE advection by high-frequency wind anomalies ($-\partial (\nu' q')/\partial y$ in Fig. 9b) does not stand out in the SPCZ. During the detoured MJOs, the MSE is dominated by $q$. Thus, the structure of MSE has a similar pattern to those of $q$. For conciseness, only the pronounced terms during the detoured MJOs in the MSE budget are shown in Fig. 10. The advection of MSE ($-\nabla_H \cdot (\mathbf{u}_H s)$; Fig. 10a) dominates the MSE budget at intraseasonal time scales. The positive MSE advection over the diagonal SPCZ region is mainly attributable to the meridional MSE advection of $-\partial (\nu \bar{H})/\partial y$ (Fig. 10c), which is partly offset by the zonal advection of $-\partial (\nu \bar{H})/\partial x$ (Fig. 10b). Due to the high-frequency variabilities in moisture and wind anomalies ($-\partial (\nu' q')/\partial y$ in Fig. 7h), negative $-\partial (\nu' H')/\partial y$ is noticeable over SPCZ. It indicates an energy transfer from the intraseasonal variabilities to the high-frequency components, which can support the enhancement of eddies and cyclones in the western Pacific Ocean (Maloney 2009; Andersen and Kuang 2012).

The meridional transports during detoured MJOs are significant over the SPCZ region. The zonal mean of $-\partial (\nu \bar{H})/\partial y$ across the entire SPCZ (150$^\circ$E−120$^\circ$W; Vincent 1994) and averaged from day 10 to day 20 is shown in Fig. 11a. The blue line is for the detoured MJOs and the red line is for the nondetoured MJOs. The corresponding STD with respect to their mean are marked with blue and red shades, respectively. During the detoured MJOs, negative $-\partial (\nu \bar{H})/\partial y$ around the equator and positive $-\partial (\nu \bar{H})/\partial y$ around 20$^\circ$S are distinct from zero, which indicates a pronounced southward moisture transport across the equator. In contrast, during nondetoured MJOs, the southward moisture transport in the Southern Hemisphere is much smaller and it is not significantly different from zero (the black dashed line in Fig. 11a). The corresponding meridional transports of DSE are shown in Fig. 11b. The weak negative tendency shows a peak around the equator (slightly shifted into the Southern Hemisphere). Thus, there are poleward transports in both hemispheres in the tropics during the detoured MJOs (blue line and blue shades in Fig. 11b). Around 20$^\circ$S, positive values of $-\partial (\nu \bar{H})/\partial y$ are significantly different from zero. During the nondetoured MJOs, the zonal mean transports across SPCZ are generally significant between the detoured and the nondetoured MJOs at the 95% confidence level.
small in the Northern Hemisphere (red line and red shading in Fig. 11b). There are moderate negative values of \(-\partial(\nu'\zeta)/\partial y\) near the equator and positive values of \(-\partial(\nu'\zeta)/\partial y\) to the north of 10°S, which is consistent with the fact that the southward spread of low OLR diminishes around 10°S (Fig. 4b).

However, the values of \(-\partial(\nu'\zeta)/\partial y\) during nondetoured MJOs (red shading in Fig. 11b) embrace the zero line (dashed line in Fig. 10b) at all latitudes. Therefore, the nondetoured MJOs have limited impacts on either the northern or the southern Pacific Ocean. In contrast, during the detoured MJOs, the southern Pacific Ocean is a “recipient” of moisture and energy from the Northern Hemisphere at intraseasonal time scales.

c. Rossby waves radiating from SPCZ

Deep convection can shed Rossby waves which transmit the perturbation quite far under certain conditions. Over the SPCZ, the MJO-induced deep convection can also trigger Rossby waves and the local impacts can travel over the southern Pacific Ocean and around the globe. Considering the background winds \(\mathbf{u}\) and \(\mathbf{v}\), which are obtained with a low-pass filtering at 100 days, the dispersion relation of Rossby waves is (Hoskins and Ambrizzi 1993; Lee and Seo 2019)

\[
\omega = k\pi + \mathbf{u} + \frac{\bar{L} \mathbf{z}/\partial x - k(\beta + \bar{\omega} \mathbf{z}/\partial y)}{k^2 + F^2},
\]

where \(k\) and \(l\) are the zonal and meridional wavenumbers, respectively; \(\beta\) is the meridional gradient of the Coriolis parameter; and \(\bar{\zeta} = \bar{\mathbf{u}}/\partial x - \bar{\mathbf{u}}/\partial y\) is the relative vorticity of background winds. The zonal and meridional group velocities are as follows:

\[
c_g = \frac{\partial \omega}{\partial k} = \pi + \frac{(\beta + \bar{\omega} \mathbf{z}/\partial y)(k^2 - F^2) - 2k\bar{L} \mathbf{z}/\partial x}{(k^2 + F^2)^2},
\]

\[
c_g = \frac{\partial \omega}{\partial l} = \pi + \frac{(k^2 - F^2) \bar{L} \mathbf{z}/\partial x + 2k(\beta + \bar{\omega} \mathbf{z}/\partial y)}{(k^2 + F^2)^2}.
\]

The ray path of Rossby waves is determined by \(dx/dt = c_g x\) and \(dy/dt = c_g y\). During the propagation, the wavenumbers change due to variation in background winds and associated vorticities: that is,

\[
\frac{dk}{dt} = -k\pi - \mathbf{u} \cdot \frac{\bar{L} \mathbf{z}/\partial x - k\bar{L} \mathbf{z}/\partial x \mathbf{y}}{k^2 + F^2},
\]

\[
\frac{dl}{dt} = -k\pi - \mathbf{u} \cdot \frac{\bar{L} \mathbf{z}/\partial x \mathbf{y} - k\bar{L} \mathbf{z}/\partial y^2}{k^2 + F^2}.
\]
Considering that the perturbation is produced by deep convection, the background winds are chosen to be the winds in the upper troposphere. The mean background winds ($u$ and $v$) at 200 hPa averaged between day 10 and day 20 during detoured MJOs are shown in Figs. 12a and 12b. The background winds are obtained with a low-pass filter of 100 days, and they do not change significantly during the entire lifetime of MJOs. Over most of the SPCZ region, mean $u$ during detoured MJOs are weak westerlies, which are favorable for the eastward propagation of MJOs (Jones 2009; Zhou et al. 2012a). However, the seasonal mean $u$ during boreal winter (from November to April) are stronger westerlies (not shown), so that the differences in $u$ between the detoured MJOs and the seasonal mean in boreal winter are significant easterlies over SPCZ (Fig. 12c). In the meridional direction, mean $v$ during detoured MJOs are southerlies in the upper troposphere (Fig. 12b) and their deviations from the seasonal mean $v$ in boreal winter are also significant southerlies (Fig. 12d).

The Rossby waves are traced using Eqs. (6) and (7). The mean background winds averaged between day 10 and day 20 during detoured MJOs (Figs. 12a,b) and associated vorticity ($\zeta$) are used to calculate the ray paths shown in Fig. 12e. The seasonal mean background winds during boreal winter (November–April from 1982 to 2019; not shown) are used to
obtain the ray paths in Fig. 12f. Since the nondetoured MJOs propagate near the equator (Fig. 2c) and do not have significant impacts on the SPCZ (Fig. 3), the mean convection, circulations, and the associated ray paths of Rossby waves are similar to the seasonal mean (not shown). Therefore, in the analysis below, the detoured MJOs are compared with the background state, rather than with the nondetoured MJOs. The significant differences in background winds between the detoured MJOs and the seasonal mean (Figs. 12c,d) indicate a rectification by the detoured MJOs onto the low-frequency variabilities. Such an upscale impact can be important but is beyond the scope of this study. The related mechanisms deserve dedicated research in the future. For both the detoured MJOs and the background state, initial positions are evenly selected within the SPCZ, which are denoted with red circles in Figs. 12e and 12f. Three initial zonal wavenumbers (3, 4, and 5) and three periods of Rossby waves (20, 30, and 40 days) are tested for each initial location. Such selections on zonal wavenumbers and periods are common to MJOs. The initial meridional wavenumber ($l$) is obtained by solving the dispersion relation of Rossby waves [Eq. (5)] with given initial zonal wavenumber and period and the real solution is selected. Therefore, for each initial position (each red circle in Figs. 12e,f), nine rays are emanated.

For the detoured MJOs and the seasonal mean in boreal winter, there are three common directions for Rossby waves. The first one is the westward one, going across the Maritime Continent and traversing the Indian Ocean. The second one is the northwestward one, circulating through the South China Sea and turning northeastward across the Pacific Ocean in the Northern Hemisphere. The third is the eastward one, which travels across the tropical Pacific. A distinct feature of Rossby waves during detoured MJOs is the relatively small number of paths spreading southward. Under seasonal mean winds in boreal winter, a significant number of rays travel southward (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019). However, during detoured MJOs in boreal winter, the easterly zonal wind deviations from the seasonal mean (Fig. 12f), covering Australia. They can extend to the Southern Ocean and the Antarctic (Lee and Seo 2019).
southward. As a result, there are almost no rays over Australia in Fig. 12e.

4. Discussion and conclusions

There are two routes for MJOs to cross the Maritime Continent; one is near the equator (nondetoured events) and the other one is around 10°S (detoured events). In this study, the different impacts of the two categories of MJOs over the Pacific Ocean are examined. It is found that the detoured MJOs are a heat source in the Southern Hemisphere leading to strong meridional wind anomalies across the equator. As a result, convection and precipitation over the SPCZ region are enhanced and a cyclonic gyre is generated to the southwest of SPCZ. In addition, meridional winds carry moisture and energy into the southern subtropics between 15° and 30°S. In contrast, the impacts of nondetoured MJOs are restricted to the tropical region and their influence on the two hemispheres is relatively small. Convection over the SPCZ can radiate Rossby waves and teleconnect their impacts worldwide. Due to the background wind anomalies associated with the detoured MJOs, Rossby waves originating over the SPCZ have a lower probability of propagating southward and spreading over Australia and the southern Pacific Ocean to the south of SPCZ. On the other hand, the oceanic and the atmospheric environments near Australia have impacts on the separation of detoured and nondetoured MJOs, such as the

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**Fig. 9.** Major terms of DSE advection in Eq. (4), averaged between day 10 and day 20 for the detoured MJOs. The unit is 10^2 kg s^{-3}. The terms in Eq. (4) that are not shown are not significant.
intraseasonal warm SST anomalies in the southeastern Indian Ocean (Zhang and Ling 2017; Zhou and Murtugudde 2020) and the onset of the Australian monsoon (Kim et al. 2017). Hence, there may be a coupling between the SPCZ and the eastern Indian Ocean on the two sides of Australia via the detoured MJOs. The details of the mechanisms require further explorations.

Kim et al. (2017) examined moisture advection by anomalous winds when MJOs transit over the Maritime Continent. In this study, we focus on the impacts of MJOs on the SPCZ after the MJOs have crossed the Maritime Continent. The different influences of detoured and nondetoured MJOs on SPCZ are mainly due to different latitudinal positions of convection.
associated with the two types of MJO. Thus, during the suppressed phase over the SPCZ before the eastward-propagating MJOs arrive, there are no significantly different influences between the detoured and nondetoured MJOs (e.g., no significant differences in $q_0$ in Fig. 5c before day 10). Besides the impacts of eastward-propagating MJOs, there are also strong local convection and intraseasonal variabilities over SPCZ (Vincent 1994; Widlansky et al. 2010; Brown et al. 2020). Nevertheless, since all events discussed in this study are selected based on the MJO index (Wheeler and Hendon 2004), the intraseasonal variabilities are associated with MJOs. Moreover, in the context of global warming, MJOs were found to stay longer in the Pacific Ocean but stay shorter in the Indian Ocean due to the expansion of Pacific warm pool (Roxy et al. 2019). Cai et al. (2012) argued that small variation in SPCZ could have significant local consequences, especially in terms of the extreme events and devastating natural disasters, since gradients are large in this region in both the atmosphere and the ocean. Therefore, it is important to explore the trend of the detoured and nondetoured MJOs and the possible changes in their impacts on the southern Pacific Ocean in the future.

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