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ABSTRACT

Mechanisms for extratropical influences on the initiation of the Madden–Julian oscillation (MJO) are investigated using numerical simulations and a global reanalysis product. Previous simulations by a tropical channel model captured the timing and gross features of the initiations of two MJO events and suggested that the initiations were due to influences from the extratropics. In this study, latitudinal transport of momentum from the extratropics is found to be crucial in generating the lower tropospheric westerlies in the tropics associated with the MJO initiation. The diagnoses of the zonal momentum budget for the MJO initiation region revealed that the advection by meridional winds could be important prior to the initiation of the MJO. The time evolution of the wave activity identifies its source over the southern Indian Ocean where it grows by extracting kinetic energy from the mean flow. The time scale of the lateral boundary conditions that is responsible for the MJO initiation is also investigated. The implications of the results and limitations of the approach are discussed.

1. Introduction

The mechanism of initiation of the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) remains a challenging problem for research. This is highly relevant to operational forecast of the MJO, since the MJO is connected to a variety of events around the globe [see references in Lau and Waliser (2005) and Zhang (2005)]. The time scale of the MJO relates to the subseasonal predictability and affects medium- and extended-range weather forecasts in both the tropics and extratropics (e.g., Ferranti et al. 1990; Mo and Higgins 1998; Jones and Schemm 2000). Major features of the extratropical low-frequency variability could be reproduced by specifying a time-dependent tropical forcing that mimics the convective heating associated with the MJO (Matthews et al. 2004). Thus, forecast of the MJO is essential for the skillful prediction in the tropics and extratropics on the intraseasonal time scale. An important step toward achieving this is to understand the initiation mechanism of the MJO.

Proposed hypotheses to explain the MJO initiation include local recharge–discharge processes (i.e., tropical internal dynamics), upstream effects of circumnavigating waves (i.e., previous MJO event), extratropical influences, and stochastic forcing. A review of these hypotheses was summarized in Zhang (2005). Here we confine our discussion to the extratropical/lateral influences on the MJO initiation. Liebmann and Hartmann (1984) showed that changes in convection in the tropics lag that of the extratropical 500-hPa height, indicating that the midlatitude flow affects the tropics. Hsu et al. (1990) observed evidence suggesting that Rossby wave trains propagating into the tropics from the midlatitudes may play a role in initiating a particular MJO event in the Indian Ocean. Matthews and Kiladis (1999) also observed similar triggering of convection by high-frequency Rossby waves over the central Pacific. Coherent fluctuations between the extratropical circulation and tropical convection on the intraseasonal time scale were reported (e.g., Liebmann and Hartmann 1984; Lau and Philips 1986; Carvalho et al. 2005). Weickmann and Berry (2009) revealed the tropics–extratropics interactions on intraseasonal time scales and their role in creating tropical convective anomalies and slowly evolving global-scale circulation. Using a two-layer linear model, Frederiksen and Frederiksen (1997) hypothesized that the MJO is a tropical–extratropical coupled mode resulting from moist barotropic–baroclinic instability. Whether the observed relationship between the extratropical and tropical...
intraseasonal signal is statistically significant is, however, controversial (e.g., Ghil and Mo 1991; Straus and Lindzen 2000). Wave propagations from the mid and high latitudes into the tropics were found to be largely determined by the structure of the zonal flow (e.g., Webster and Holton 1982). But Hoskins and Yang (2000) questioned the need of a particular background zonal flow for Rossby wave propagation by demonstrating that the extratropics can influence the tropics directly in the presence of easterlies as well as westerlies. These studies in general have indicated possible influences on the tropics from the extratropics, but it is not clear how the MJO is initiated by them.

Recently, two independent studies by Lin et al. (2007) and Ray et al. (2009, hereafter R09), using different models, pointed out that extratropical influences could be an efficient mechanism to initiate the MJO. Using a primitive equation dry global model, Lin et al. (2007) showed that an MJO-like oscillation could be generated in the absence of moisture and convection. They found that the extratropical flows were critical for the simulated intraseasonal variability in the tropics. Using a tropical channel model, R09 showed that simulated MJO initiations in the zonal wind of two observed events did not critically depend on detailed characteristics of the sea surface temperature (SST; varying versus constant in time, mean distribution from boreal spring versus winter), the initial conditions (within a 10-day period), the latitudinal location of the lateral boundaries (21°–38°N and S), or latent heating and moist processes. The only factor found to be critical to the reproduction of the MJO initiation in zonal wind was time-varying lateral boundary conditions. When such lateral boundary conditions were replaced by constant (in time) ones, the model failed to reproduce the MJO initiation.

The current study is an extension of R09 to investigate the mechanisms for extratropical influences on the initiation of one MJO event. Following R09, the MJO initiation is defined in terms of the appearance of MJO-associated intraseasonal westerly wind anomalies at 850 hPa over the western Indian Ocean, irrespective of whether or not it is preceded by a previous event. A tropical channel model (see section 2a) is used. The main advantage of this channel model is that, without east–west boundaries, it isolates the external effects arriving solely from the extratropics. Thus, this model is an ideal tool to investigate the possible influences from the extratropics.

Individual MJO events have received very little attention. In particular, numerical simulations addressing individual events are rare. Thus, a case study approach, like this one, investigating individual MJO events, with the help of reanalysis boundary conditions, is useful to provide unique perspectives on the MJO mechanism. While the representativeness of case studies might be in question given the large variations from event to event (e.g., Salby and Hendon 1994; Yano et al. 2004), a case study can suggest research targets for further studies to establish statistical significance of the results from individual cases.

Section 2 provides brief descriptions of the model, numerical simulations, and data used. Section 3 assesses the mechanism of intraseasonal variability in the tropics–extratropics system. Discussions and a summary are given in sections 4 and 5, respectively.

In short, our results demonstrate that extratropical influences are essential to initiate the anomalous westerlies in the lower troposphere for the MJO event considered in this study. The results challenge the prevailing belief that the tropical internal dynamics is the sole reason for the MJO initiation.

2. Model and data
   a. Model

A brief description of the model used is given here (see Ray 2008 and R09 for details). A tropical channel model was developed based on the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Dudhia 1993; Grell et al. 1995). This model is referred as tropical MM5 (TMM5). The model domain covers the entire tropics using a Mercator projection, and the north–south boundaries can be set at any latitudes. There are 28 unevenly spaced full-sigma levels, with the model top at 50 hPa. The model output is taken every 3 h. As in R09, the selected parameterizations for this study are: Betts–Miller convective scheme (Betts and Miller 1986), explicit moisture calculations using a simple ice scheme (Dudhia 1993), the planetary boundary layer scheme of the National Centers for Environmental Prediction (NCEP) eta model (Janjic 1994), and Rapid Radiative Transfer Model (RRTM) longwave (Mlawer et al. 1997) and Dudhia (1989) shortwave radiation. A model domain (21°S–21°N, 0°–360°) with a horizontal resolution of 111 km comprises the control simulation (CS) in this study. In all simulations, sea surface temperature is constant in time with the same spatial pattern at the initial time. Hereafter, the terms constant and varying refer to time.

The MJO event considered in this study appears in April–May 2002 (Fig. 1a). For computational efficiency, all tests and the reference control simulation started from 10 April 2002 (Fig. 1b); they are listed in Table 1. This event was chosen randomly by R09. We use the
zonal wind at 850 hPa (U850) to measure the MJO and its initiation to make consistent comparisons among different simulations, including those without latent heating and moist processes (NO_LH and NO_MOIST in Table 1).

b. Data

Model validation is conducted using the NCEP–NCAR reanalysis (hereafter simply reanalysis; Kalnay et al. 1996) data. The NCEP global tropospheric analyses (final or FNL data, 1° × 1°, 6 hourly) are used to provide initial and lateral boundary conditions for the model. The SST data are also from the reanalysis, which contains intraseasonal fluctuations. However, we have used constant SSTs in the simulations.

3. Results

R09 indicated the unique role of extratropical influences in the initiation of the MJO event in April–May 2002. To further confirm the fact that the lateral boundary conditions at given latitudes from the reanalysis are dominant and independent of the MJO itself, we conduct an experiment (PBC2 in Table 1) in which the lateral boundary conditions at any time \( t \) are replaced by those of \( t - 30 \) days (e.g., the lateral boundary conditions of 11 April 2002 are replaced by those of 12 March 2002). However, the boundary conditions at \( t = 0 \) (i.e., 0000 UTC 10 April) are not changed, so that the initial conditions are not disturbed. The model completely misses the anomalous westerly winds seen in Fig. 1 associated with the MJO (Fig. 2). It seems that the simulation PBC2 (Fig. 2b) is lagging by about 20–30 days compared to the reanalysis (Fig. 2a) and CS. However, the simulation PBC2 follows closely the applied lateral boundary conditions. Although these results show importance of the lateral boundary conditions, they do not provide any information about its nature or time scale, and its dynamical connections, if any, to the MJO initiation.

Mechanisms of extratropical influences on the MJO initiation are presented here in terms of zonal wind anomalies, meridional momentum transport, zonal momentum budget, wave activity flux, and the associated energy exchange processes. The origin of the lower tropospheric anomalous westerlies in the tropics associated

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>CS</td>
<td>Control simulation. Time-independent SST. Time-dependent lateral boundaries at 21°S and 21°N.</td>
</tr>
<tr>
<td>NO_LH</td>
<td>Same as CS, but with no latent heating.</td>
</tr>
<tr>
<td>NO_MOIST</td>
<td>Same as CS, but with no moisture.</td>
</tr>
<tr>
<td>FBC</td>
<td>Same as CS, but with time-independent lateral boundary conditions.</td>
</tr>
<tr>
<td>MBV1</td>
<td>Same as CS, but with lateral boundaries at 28°S and N.</td>
</tr>
<tr>
<td>MBV2</td>
<td>Same as CS, but with lateral boundaries at 38°S and N.</td>
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<tr>
<td>PBC1</td>
<td>Same as CS, but with perturbations in lateral boundaries.</td>
</tr>
<tr>
<td>PBC2</td>
<td>Same as CS, but with boundary conditions from 30 days back.</td>
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![Fig. 1](image1.png)

![Fig. 2](image2.png)
with this MJO initiation is found to be in the extratropics and to be brought to the tropics by meridional transport of anomalous westerly momentum. An analysis of the zonal momentum budget reveals the importance of meridional advection in controlling the local tendency of the anomalous zonal winds prior to the MJO initiation. The time evolution of wave activity relevant to the MJO initiation identifies its source over the extratropical southern Indian Ocean, where it grows by extracting kinetic energy from the mean flow.

a. Zonal and meridional wind anomalies

We find a clear signal of propagation of U850 from the midlatitude toward the tropics in a wide longitudinal band covering 30°–60°E in the Southern Hemisphere. An example in the 40°–50°E longitudinal band from the reanalysis is shown in Fig. 3a. Perturbations in U850 appear around 30°S about three weeks before the MJO initiation. Then they propagate northward (indicated by the solid line) and reach near the equator at the end of
April prior to the MJO initiation. This is also observed in the CS (Fig. 3b) and other test runs (Figs. 3c–e), except the one with constant boundary conditions (Fig. 3f). Similar features can also be found at 925 and 700 hPa in the region 30°–60°E (not shown). Thus, such propagation of anomalous zonal wind is taking place over a large portion of the lower troposphere. For simulations in which lateral boundaries are within 30° (all simulations except MBV2 in Table 1), this feature can directly enter the model domain through the prescribed boundary conditions given by the reanalysis.

It is interesting to note that a large area of positive perturbations in Fig. 3a between 20° to 30°S appears within the model domain for the test run MBV2 with lateral boundaries at 38° (Fig. 3c). One may wonder how the MJO was initiated in this test run. Was there any dynamical control from the lateral boundary conditions at 38°S for this test run that helped carry this perturbation toward the tropics? To address this question, we first show the meridional winds at 850 hPa (V850) from the reanalysis (Fig. 4a). Interestingly, the meridional wind anomalies also propagate from higher latitudes to the equator (indicated by the solid line). In the test run MBV2 (Fig. 4b) and other simulations (not shown), this feature in meridional winds enters the model domain through southern boundary conditions. The latitudinal extent of the positive anomalies in the meridional winds is beyond 70°S in the reanalysis. Thus, the origin of the anomalous meridional winds that enter the model domain through its southern boundaries is not tropical. One may speculate that the positive anomalies of meridional winds in the presence of positive anomalies in zonal winds may transport westerly momentum toward the equator in the Southern Hemisphere. In section 3b, we show that this is indeed the case for this MJO event. We did not find any evidence of propagation toward the equator in the Northern Hemisphere in the same region prior to the initiation.

b. Momentum transport

The meridional transport of zonal momentum due to the transients ($u'v'$; Weickmann et al. 1997) is calculated using the reanalysis. Similar to the $u'$ (Fig. 3a) and $v'$ (Fig. 4a) propagation, one notices the northward transport of zonal momentum (Fig. 5) in the Southern Hemisphere. Positive $v'$ around 15 April is found at high latitudes up to about 80°S (Fig. 4a). This positive $v'$ in the Southern Hemisphere can transport momentum northward. In contrast, positive $u'$ before the MJO initiation is confined within 20°–30°S, which is outside the region of maximum MJO variance, since almost all the MJO variance is confined within 20 degrees of latitude (Zhang and Dong 2004). Thus, the origin of the momentum perturbations is outside the tropics, and at a time when there is no MJO activity in the Indian Ocean.

The MJO index based on Wheeler and Hendon (2004) on 20 April (0.53) indicates the lack of MJO activity at this time. The time evolution of the perturbations shows that a positive $u'v'$ appears around 30°S, south of Madagascar on the second week of April. It then propagates northward to reach around 20°S on the third week of April and further reaches the equatorial region on the last week of April, when the MJO initiates (the MJO

![Fig. 4. As in Fig. 3, but for V850 anomalies from (a) the reanalysis and (b) test run MBV2 with lateral boundaries at 38°S and N. The dashed lines in (a) indicate the location of the lateral boundaries (38°S and N) in the test run MBV2.](image-url)
index is 1.8 on 30 April and becomes >2 on 2 May). The result indicates the importance of the meridional momentum transport in modulating the lower tropospheric zonal winds associated with the MJO initiation. However, there might be other factors (e.g., Moncrieff and Klinker 1997; Carr and Bretherton 2001) that can influence the local tendency of the zonal wind in the tropics. An analysis of the zonal momentum budget, which is presented next, may help identify those factors.

c. Zonal momentum budget

Here we estimate various components of the zonal momentum budget and compare them to the local tendency of the zonal winds. The zonal momentum budget is given by

$$\frac{\partial u'}{\partial t} = -\frac{\partial \phi'}{\partial x} + f v' - u' \frac{\partial u'}{\partial x} - v' \frac{\partial u'}{\partial y} - \omega \frac{\partial u'}{\partial p} + R,$$

where $u$ is the zonal wind, $v$ the meridional wind, $\omega$ the vertical pressure velocity, $\mathcal{f}$ the Coriolis parameter, and $\phi$ the geopotential; $R$ is the residual, which represents acceleration due to subgrid-scale processes but also includes all errors in the estimate and in the data used. After subtracting the time mean of the constituent variables of the zonal momentum budget, Eq. (1) can be written as

$$\frac{\partial u'}{\partial t} = -\frac{\partial \phi'}{\partial x} + f v' - \left(u' \frac{\partial u'}{\partial x} + u' \frac{\partial \phi'}{\partial x}ight) - \left(v' \frac{\partial u'}{\partial y} + v' \frac{\partial \phi'}{\partial y}\right)$$

$$- \left(\omega \frac{\partial u'}{\partial p} + w' \frac{\partial \phi'}{\partial p}\right) + R', \quad (2)$$

where the overbar denotes time mean and the prime denotes perturbation from the mean. The time mean quantities were computed over the simulation period (10 April–10 June 2002). The terms in the parentheses are advective tendencies contributed by the zonal, meridional, and vertical winds, respectively. Here the results are presented for 850 hPa since the MJO initiation is described primarily with respect to U850. The zonal momentum budget is computed for the region $10^\circ$S–$10^\circ$N, $40^\circ$–$50^\circ$E. The choice of this region is based on the fact that MJO-associated U850 anomalies appeared first in this region (see Fig. 1).

Figure 6 shows the major terms of the momentum budget equation including the local tendencies ($\partial u' / \partial t$) from the reanalysis (Fig. 6a, solid) and CS (Fig. 6a, short dashed). The local tendency is generally much smaller than the other terms. The positive tendencies around 29 April from the reanalysis are associated with the MJO initiation in the western Indian Ocean and are captured well by CS. The pressure gradient and residual are generally larger than others, but they compensate each other. Note that an order of magnitude difference among the several reanalysis datasets, particularly in the pressure gradient terms, was found by Carr and Bretherton (2001). As a result, there is more confidence in the calculation of other terms than pressure gradient and residual. The sum of pressure gradient and residual is negative prior to the MJO initiation (Fig. 6a, dotted–dashed), whereas local tendency increases gradually following the meridional advection (Fig. 6a, long dashed), indicating the importance of meridional advection on the MJO initiation.

The meridional advection in the deep tropics ($10^\circ$S–$10^\circ$N; Fig. 6b, dashed) could be traced back to the southern boundary of the model (Fig. 6b, thick solid), whereas the contribution from the northern boundary is negligible (Fig. 6b, thin solid). Contrary to the CS, in the test run with fixed boundary conditions (FBC), the sum of pressure gradient and residual is positive and large (Fig. 6c, dotted–dashed), but no MJO initiation occurs. The local tendency in FBC (Fig. 6c, short dashed) is

![Fig. 5. Latitude-time diagram of $u' v'$ (m$^2$ s$^{-2}$) at 850 hPa (averaged over $40^\circ$–$50^\circ$E, 3-day running mean) from the reanalysis. The solid line indicates the meridional propagation.](image-url)
much smaller than that from CS (Fig. 6a, short dashed). The meridional advection term in FBC is also large before the MJO initiation compared to that of control simulation but with the opposite sign (Fig. 6c, long dashed). The differences between the simulation and the reanalysis become large after the MJO initiation, particularly for the pressure gradient term. However, the transition from negative to positive pressure gradient during the MJO initiation (e.g., Lin et al. 2005) is captured well by the control simulation. The role of the meridional advection is more prominent in the Southern Hemisphere (10°S–0°; Fig. 6d), indicating the influences from the southern boundary conditions. The large positive values of meridional advection are compensated by the combined term (pressure gradient + residual), resulting in much smaller local tendency.

The previous section demonstrated the importance of the meridional transport of the zonal momentum from the extratropics to the tropics. The results in this section indicate that the advection terms—in particular, advection by meridional winds—can be important in the MJO initiation region prior to the MJO initiation.
The evolution of extratropical circulation anomalies can be described by the wave activity flux vector $\mathbf{W}$ (Takaya and Nakamura 1997, 2001). The horizontal component of $\mathbf{W}$ is given by

$$W = \frac{1}{2|\mathbf{U}|} \left[ u(\psi_x^c - \psi_x^y, x, y) + v(\psi_y^c - \psi_y^x, x, y) \right],$$

where $\mathbf{U} = (u, v)$ is the two-dimensional time mean flow, $\psi$ is the perturbation streamfunction, and subscripts represent partial derivatives. Note that $\mathbf{W}$ can be used as a diagnostic tool to indicate an instantaneous moment of a propagating packet of wave disturbances and thereby to infer the source and sink of the packet. Divergence (convergence) of $\mathbf{W}$ indicates a source (sink) region.

We present results related to wave activity from the reanalysis only, since the model boundaries do not extend to the higher latitudes far enough to cover the wave source. Figure 7 shows $\mathbf{W}$ at 200 hPa calculated from the reanalysis. We confine our discussion primarily over the western Indian Ocean. On 10 April (Fig. 7a), there is little wave activity over the southern Indian Ocean. The $\mathbf{W}$ vector is large around 25°N, 30°E but points north-eastward (away from the tropics). On 13 April (Fig. 7b) $\mathbf{W}$ becomes prominent over the southern Indian Ocean with a strong eastward component. The northward component of $\mathbf{W}$ then grows rapidly over the next two days (Figs. 7c,d), indicating significant wave activity from the midlatitudes toward the tropics. Interestingly, this is the same time that positive perturbations in the zonal and meridional winds appear in the reanalysis and simulations (see Figs. 3 and 4). The timing also coincides with the start of the northward transport of zonal momentum as seen in Fig. 5. The wave pattern then moves northward from 40°S and is supplemented further by another wave source (located around 30°S, 25°E) over the next three days (Figs. 7e–g) and reaches around 25°S on 19 April (Fig. 7h). This wave source moves eastward (Figs. 8a–c) and is located around 25°S, 45°E on 23 April (Fig. 8d). It seems that this wave source supplements the wave packet seen on 19 April, which moves northward and reaches the equatorial region of MJO initiation during 26–29 April (Figs. 8e–h). The wave activity over the southern Indian Ocean diminishes significantly beyond 29 April and can be traced only over the south-central and southeastern Indian Ocean (not shown). A wave packet analysis at 300 hPa shows a similar behavior of $\mathbf{W}$, which seems to reach the equatorial Indian Ocean just before the initiation of the MJO. The propagation signal of $\mathbf{W}$ is not clear in the lower troposphere.

Wave activity flux from the extratropics to the tropics is not limited in the Southern Hemisphere only. Around 25°N, 30°E, there is an apparent source from which wave activity moves southward, reaching east Africa (Figs. 7b,c). However, no further southward propagation can be detected. Thus, this source region of wave activity flux does not influence the MJO initiation region. Note that the mean zonal wind at 200 hPa (U200) is westerly in the Indian Ocean south of the equator (Fig. 9a), thus providing a westerly duct for the propagation of waves from the extratropics to the tropics (Webster and Holton 1982). However, U850 is easterly in the Indian Ocean around 20°–10°S (Fig. 9b), where no propagation of $\mathbf{W}$ is found toward tropics at 850 hPa. The regions where westerlies are prevalent seem to be the source region for the wave activity flux as well. Interestingly, U850 is also predominantly westerly beyond 20° latitudes (Fig. 9b). Since the model simulated the mean conditions well, these wave activities can enter the interior of the model domain through the lateral boundary conditions.

Wave activity flux toward the equator was previously found by several studies (e.g., Schubert and Park 1991; Magnusdottir and Haynes 1996). Using a dry model, Lin et al. (2007) observed extratropical influence in the North Atlantic area with a southward wave activity flux into the tropics. In our case, the dominant wave activity is found over southern Indian Ocean and propagates northward toward tropics. The differences in the two studies are obvious. Lin et al. (2007) presented composite behaviors of a dry model simulation. Our approach is to diagnose the initiation for an individual MJO event. The obvious question is: What is the source of energy that created the extratropical perturbations eventually affecting the tropics? This question is addressed next.
Fig. 7. Time evolution of wave activity flux $W$ (m$^2$ s$^{-2}$) at 200 hPa from the reanalysis from 10 to 19 Apr; $W$ is plotted only when it is $>$0.15. The rectangles in each panel indicate the points of interest.
FIG. 8. As in Fig. 7, but for 20–29 Apr.
The barotropic conversion of kinetic energy from the mean flow to a disturbance can be described by (Simmons et al. 1983)

\[ C = E \cdot \nabla u = -(u'^2 - v'^2) \frac{\partial \overline{u}}{\partial x} - u'u' \frac{\partial \overline{u}}{\partial y} = (C1 + C2), \tag{4} \]

where \( \mathbf{E} = -(u'^2 - v'^2, u'u') = -(E1, E2) \) is the extended Eliassen–Palm flux or \( \mathbf{E} \) vector. The overbar represents the time mean and the prime denotes deviation from the time mean. Here \( -\mathbf{E} \) may be viewed as the effective horizontal flux of westerly momentum due to transient eddies. The direction of \( \mathbf{E} \) pointing from weak to strong zonal velocity implies a positive contribution to the net growth of eddy energy.

We have shown in Figs. 3 and 4 that the positive anomalies in zonal (i.e., westerly) and meridional (i.e., southerly) winds appear in the second week of April in the southern Indian Ocean. Examples are shown for the \( \mathbf{E} \) vector (arrows) and the energy conversion \( C \) (shaded) at two different times in Fig. 10. We confine our discussion of the \( \mathbf{E} \) vector over the southern Indian Ocean because we found propagation of wave activities (\( \mathbf{W} \)) toward the tropics prior to the MJO initiation only in this region (see Fig. 7). On 10 April (Fig. 10a), no significant \( \mathbf{E} \) vector is found over the southern Indian Ocean, resulting in very little conversion of energy between the mean flow and eddies. No wave activities can be detected then either (see Fig. 7a). On 13 April (Fig. 10b), the \( \mathbf{E} \) vector and energy conversion \( C \) become significant around 55°S, 30°E. The \( \mathbf{E} \) vector in this region points predominantly northward in the direction of gradient of the mean zonal wind (see Fig. 9a), suggesting that the mean state is supplying energy for the growth of the perturbations. The conversion term \( C \) is dominated by the second term \( C2 \) in Eq. (4) in the presence of a weak zonal gradient of mean zonal flow (small \( \partial \overline{u}/\partial x \); Fig. 9a). This is comparable to the abundance of wave activity flux at this time in the same region (Figs. 7b,c). During this time \( \mathbf{W} \) in the southern Indian Ocean is toward the tropics (Figs. 7b,c), and the growth of perturbation energy comes from the mean flow.

The above results confirm that the source of the energy for perturbation is over the extratropics through internal nonlinear processes. However, this result does not say much about the time scale of the perturbations that are essential to the initiation of the chosen MJO event. This aspect is discussed in section 4. A spectrum analysis of \( \mathbf{W} \) and \( C \) along different latitudinal bands indicates that there is a peak at the intraseasonal time
scale in the region 40°–60°S (not shown). However, the propagation of $W$ critically depends on the ambient conditions during individual MJO events. As a result, the true effects of $W$ can be studied only after considering each event separately.

4. Discussion

The results presented in this paper are similar in many respects with that of Lin et al. (2007) (see section 1). They are also similar in some ways to that presented by Frederiksen and Frederiksen (1997). This is interesting particularly because the approach adopted in our study is significantly different from their approach. They used a linear framework with no prescribed boundary conditions; our study, on the other hand, is constructed on the basis of a complex nonlinear numerical model with prescribed boundary conditions from a reanalysis. In their study, the interactions with convection are included using a simple parameterization, whereas our test runs with no latent heating and no moisture have no interactions with convection. Supporting evidence has also been found where this MJO event was captured in a multiyear simulation by a nested regional climate model forced laterally by the reanalysis boundary conditions.

It is instructive to discuss the temporal frequency at which the extratropical influence through the model boundary conditions controls the MJO initiation for this event. We conduct a simulation (PBC1 in Table 1) by perturbing the lateral boundary conditions only (no changes in the surface conditions and in the initial conditions). The lateral boundaries at $t$ and $t + 6$ h are interchanged for each pair. The initiation of the MJO in the model is not affected (not shown). This indicates that the minute details of the spatiotemporal structures of the boundary conditions are not essential, but the gross features of the time-varying lateral boundary conditions, possibly of the intraseasonal time scale, must be present in the data to have a successful simulation of the initiation of this MJO event. This might enhance our ability to forecast the MJO using a combination of GCMs that can produce the gross atmospheric features and higher-resolution mesoscale models.

In a recent study, Gustafson and Weare (2004a,b) performed a composite study using 2-yr MM5 simulations with and without filtered (30–70 day) boundary conditions. They used the standard regional version of MM5 with a domain covering 44°–181°E and 24°S–24°N. The simulated MJO did not change appreciably when 30–70-day filtered boundary conditions were used. However, higher-frequency transients or stochastic forcing from the extratropics could not be ruled out. They have shown that the lateral influences on the intraseasonal time scale from the extratropics may not be necessary for MJO initiation. Our results in this study and in R09 suggest that the lateral influences can be sufficient for MJO initiation.

It is natural to ponder the fraction of MJO events that are affected by extratropical influences. Matthews (2008) classified all MJO events from 29 September 1974 to 2 September 2005 as either primary (with no preceding MJO events) or successive (with preceding events). He found that 40% are primary and 60% are successive events. He observed that the successive events are systematically influenced by the extratropics, whereas no such extratropical influence was found for primary events.
It would be interesting to find out whether his observations can be confirmed by model simulations as done here but covering all MJO events during the same period.

Despite the use of a unique and novel approach, there are biases and limitations in our simulations and approach. Therefore, a systematic study is needed to assess the role of lateral influences for all observed MJO events in different seasons (Zhang and Dong 2004), mean states (El Niño versus non–El Niño years, strong versus weak monsoon years; Inness et al. 2003), place of origin (western, central, and eastern Indian Ocean, west Pacific; Matthews 2008), and strengths (strong versus weak anomalies; Rui and Wang 1990), and in relation to previous events (primary versus successive MJO events; Matthews 2008).

5. Summary

Mechanisms for extratropical influences on the MJO initiation are investigated for an MJO event during April–May 2002 using a global reanalysis and a tropical channel model. With given time-dependent lateral boundary conditions from the reanalysis, this model is able to reproduce the timing of the MJO initiation over the western Indian Ocean as marked by the intraseasonal transition from easterly to westerly anomalies in U850.

Latitudinal transport of the westerly momentum from the extratropics into the tropics is found to be crucial in generating the lower tropospheric westerly anomalies in the reanalysis and simulations. An analysis of the zonal momentum budget for the MJO initiation region reveals that the advection by the meridional winds is important at the initiation of this event. Extratropical influences on this event are not limited to the lower troposphere. Such interactions are also revealed at the upper troposphere by diagnosing the time evolution of the horizontal component of extratropical wave activity flux (W). This flux is shown to have a major source region over the southern Indian Ocean that resulted in W propagating toward the tropical initiation region of the MJO. The energy source for the extratropical perturbation is through extraction of kinetic energy from the mean flow.

The local thermodynamic state in the tropics obviously plays a major role in the strength and maintenance of the MJO event. The results indicate that the origin of this MJO event cannot be explained solely by the internal dynamics of the tropical atmosphere, and they support the hypothesis that extratropical processes and extratropical–tropical interactions can be essential ingredients in the MJO dynamics (e.g., Liebmann and Hartmann 1984; Hsu et al. 1990; Frederiksen and Frederiksen 1997; Matthews and Kiladis 1999; Straus and Lindzen 2000; Lin et al. 2007).

In conclusion, our results demonstrate that extratropical influences are essential for the initiation of the considered MJO event. They raise several fundamental questions about our understanding of the MJO initiation mechanism and call for further research attention toward comparing internal dynamics to the extratropical influence on the MJO.

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