MJO-like Coherent Structures: Sensitivity Simulations Using the Cloud-Resolving Convection Parameterization (CRCP)

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ABSTRACT

Interaction between equatorially trapped disturbances and tropical convection is investigated using a non-hydrostatic global model that applies the cloud-resolving convection parameterization (CRCP). The CRCP represents subgrid scales of the global model by embedding a 2D cloud-resolving model in each column of the global model. The modeling setup is a constant-SST aquaplanet, with the size and rotation of earth, in radiative-convective quasi equilibrium. The global atmosphere is assumed to be initially at rest. No large-scale organization of convection is present outside the equatorial waveguide. Inside the waveguide, on the other hand, the model simulates spontaneous formation of coherent structures with deep convection on the leading edge and strong surface westerly winds to the west, the westerly wind bursts. These coherent structures resemble the Madden-Julian oscillation (MJO) observed in the terrestrial Tropics and are present in simulations applying prescribed and interactive radiation, and increased horizontal resolution of the global model. The MJO-like structures are essential for the development of the mean westerly flow, the superrotation, within the equatorial waveguide. Sensitivity simulations suggest that the coupling among deep convection, free-tropospheric moisture, and the large-scale flow is essential for coherence of the MJO-like structures. When large-scale fluctuations of convectively generated free-tropospheric moisture are removed on a timescale of a few hours, the coherent structures do not develop and, if already present, these structures disintegrate rapidly. It follows that the moisture-convection feedback, postulated previously to explain the large-scale organization of tropical convection and its coupling with SST fluctuations, operates very efficiently in the CRCP global model. It is also argued that the feedback plays a role in sensitivity simulations with horizontally uniform surface fluxes, where horizontal variability of the fluxes is required for the development, but not the maintenance, of MJO-like coherent structures. These results are discussed in the context of existing theories and modeling studies, which aim to explain the coupling between convection and the large-scale dynamics in the Tropics on intraseasonal timescales.

1. Introduction

Convective-radiative quasi equilibrium, a balance between radiative processes and moist convection, is a useful paradigm for the tropical atmosphere. In the Tropics, the warming due to absorption of solar radiation in the troposphere offsets only part of the cooling associated with emission of terrestrial longwave radiation. As a result, radiative processes cool the troposphere at a typical rate of about 1 K day\(^{−1}\). This cooling is balanced by the sensible and latent energy fluxes from the surface, with the latent flux constituting about 90% of the total flux. The latent energy is released within convective clouds with most of the condensed water returning to the surface as precipitation. Deep convection, spanning the entire depth of the troposphere, is a key in the energy and water budgets. Although the horizontal export of energy out of the Tropics (both in the atmosphere and in the ocean) is essential for the earth’s climate, it represents only a fraction of the vertical fluxes associated with the tropical convective-radiative quasi equilibrium. Consequently, to a first approximation, one may study the Tropics without considering their interaction with the extratropics.

Tropical deep convection is observed to be organized on a wide range of scales, from a single cumulonimbus to intraseasonal oscillations (e.g., Nakazawa 1988; Sui and Lau 1992; Hendon and Liebmann 1994; Chen et al. 1996; among many others). However, the mechanisms responsible for this multiscale organization and, more generally, the coupling between convection and the large-scale tropical dynamics, are poorly understood. The most spectacular example of tropical variability on intraseasonal timescales is the so-called Madden-Julian oscillation (MJO; Madden and Julian 1994, and references therein). The MJO is a large-scale perturbation (zonal wavenumber one or two) of surface pressure,
cloudiness, precipitation, and winds discovered by Madden and Julian in the early 1970s by a careful analysis of tropical sounding data, and subsequently confirmed by satellite observations of tropical cloudiness (e.g., Nakazawa 1988). The MJO has drawn considerable interest from both the weather forecasting and climate communities. The MJO dominates the intraseasonal variability in the Tropics, but it also impacts the extratropics. Moreover, its role in longer timescale climate variations, such as the famous El Niño–Southern Oscillation (ENSO), remains unclear. The MJO affects convection and surface winds only over the warm waters of the Indian Ocean and the tropical western Pacific, whereas the upper-tropospheric winds show the global impact. The MJO propagates west to east with typical speeds between 5 and 10 m s$^{-1}$; that is, it circumnavigates the earth in several tens of days. Besides the MJO, a rich variety of equatorially trapped, convectively coupled waves (such as Rossby, Kelvin, mixed Rossby–gravity, etc.) affect the large-scale organization of convection in the Tropics (see Wheeler et al. 2000 for a recent discussion).

A wide range of mechanisms is involved in the large-scale organization of tropical convection. Mechanisms previously considered include coupling of convection with large-scale equatorial perturbations (e.g., Lindzen 1974; Chang and Lin 1988; Lau et al. 1989; Brown and Bretherton 1995; Chao and Deng 1998; Majda and Shefter 2001; Grabowski and Moncrieff 2001); impact of clouds and moisture on radiative transfer (e.g., Nilsson and Emanuel 1999; Raymond 2000a; Raymond and Zeng 2000; Grabowski and Moncrieff 2002); impact of environmental moisture on convective dynamics (e.g., Raymond 2000b; Tompkins 2001a,b); impact of convectively generated gravity waves on subsequent convective development (e.g., Mapes 1993, 1998; Oouchi 1999); and atmosphere–ocean interactions (e.g., Neelin et al. 1987; Emanuel 1987; Platau et al. 1997). However, despite vigorous research in past decades, the mechanisms of large-scale organization of tropical convection remain enigmatic. In particular, there is no generally accepted theory that accounts for tropical intraseasonal oscillations and the MJO. The major impediment is the vast range of interacting scales involved. In numerical modeling, the spectrum of scales can be truncated by using convective parameterization, which is how the coupling between convection and large-scale dynamics has traditionally been examined (e.g., Hayashi and Sumi 1986; Chao and Lin 1994; Kuma 1994; Brown and Bretherton 1995; Chao and Deng 1998; Raymond 2000a, 2001). However, the results are compromised by their sensitivity to the particular parameterization scheme employed and scheme parameters (e.g., Chao and Lin 1994; Slingo et al. 1994; Chao and Deng 1998; Maloney and Hartmann 2001; Lee et al. 2001).

Grabowski and Smolarkiewicz (1999) and Grabowski (2001, hereafter G01) proposed a novel approach that includes elements of cloud and mesoscale dynamics into numerical models of weather and climate. The key is to apply a 2D cloud-scale model in each column of the 3D large-scale model. Availability of the cloud-scale data allows for explicit coupling of moist convection with radiative and surface processes. This approach was termed the cloud-resolving convection parameterization (CRCP). G01 (section 4) and Grabowski (2002, hereafter G02) applied CRCP to the idealized problem of convective–radiative quasi equilibrium on the earth-sized rotating constant-SST aquaplanet (cf. Sumi 1992; Kirtman and Schneider 2000). The global CRCP simulations featured pronounced large-scale organization of convection within the equatorial waveguide, where coherent structures, resembling tropical MJO, spontaneously developed.

The simulations discussed in G01 and G02 raise important questions as far as generality of these results and mechanisms behind convection organization are concerned. How sensitive are MJO-like coherent structures to the horizontal resolution of the global model? Will these results change when an interactive radiation transfer model replaces the prescribed radiation (cf. Raymond 2001)? What role do interactive surface heat fluxes play in the coherence of the MJO-like structures (cf. Neelin et al. 1987; Emanuel 1987)? Does the tropospheric moisture impact large-scale organization of convection (cf. Raymond 2000b; Tompkins 2001a,b)?

This paper aims to address these questions by presenting a set of sensitivity simulations similar to those discussed in G01 and G02.

The paper is organized as follows. We start with a brief discussion of CRCP in the next section. Section 3 introduces the model and provides details of model simulations. Sections 4 and 5 present the results. Discussion of model results follows in section 6, and conclusions are drawn in section 7.

2. The cloud-resolving convection parameterization

The CRCP applies a 2D cloud-resolving model in each column of a 3D large-scale or global model [Grabowski and Smolarkiewicz (1999); G01; see also Khairoutdinov and Randall (2001) for an example of the application of this technique to a climate model]. In the spirit of classical convection parameterization, which assumes scale separation between convection and large-scale flow, the cloud-resolving models from neighboring columns interact only through the large-scale dynamics. In a nutshell, CRCP involves many two-dimensional cloud-resolving models that interact according to the large-scale dynamics. Details of CRCP were presented in section 2 of G02.

The scientific basis of CRCP comes from numerous numerical studies of moist tropical convection driven by observed large-scale conditions over a period of $\mathcal{O}$(10) days (see Grabowski et al. 1996, 1998; Wu et al. 1998, 1999; among many others). These modeling stud-
ies demonstrate that a 2D computational framework oriented along the east–west direction results in tropical cloud systems whose integral effects (including effects on surface and radiative processes) reproduce both observations and 3D simulations. Thus, a 2D cloud-scale model inside each column of the 3D large-scale model should be capable of explicitly representing the interaction between moist convection and large-scale flow, convection organization, and the effects of convection on surface and radiative processes. However, limitations of the CRCP associated with the assumed scale separation between large-scale and cloud-scale dynamics (a cornerstone of all convection parameterization schemes) are pertinent. For instance, a mesoscale convective system is not capable of propagating from one model column into the neighboring one (see section 3 of G01 for a discussion). Although a large-scale model featuring CRCP is less computationally demanding than a hypothetical cloud-resolving model of 3D large-scale tropical dynamics, this approach is computationally demanding compared to traditional convection parameterizations. The cost of running a large-scale model featuring CRCP is almost entirely due to cloud-resolving calculations (see also a discussion in Khairoutdinov and Randall 2001).

The coupling between the large-scale model and CRCP 2D cloud-resolving models is motivated by a traditional approach to convection parameterization in which large-scale dynamics provide the so-called large-scale forcing for convection, and convection feeds back the so-called convective response (e.g., section 2 in Grabowski et al. 1996). Because temperature and moisture budgets are essential for the convective heating and moistening that drive the large-scale dynamics, all thermodynamic fields are coupled instantaneously using consistent averaging procedures. In contrast, insofar as the kinematics are concerned, the large-scale flow is assumed to organize convection while the cloud-scale flow should transport the large-scale momentum. In effect, the cloud-scale and large-scale velocities in either zonal or meridional direction (depending upon the orientation of 2D CRCP domains) are coupled simply by relaxing one to the other on a finite timescale (taken as 1 h in all simulations discussed in this paper). It should also be mentioned that the role of large-scale flow in convection organization is seldom considered in traditional convection parameterization schemes.

3. The numerical model, modeling setup, and model simulations

The numerical model and simulation procedures are the same as in G01 (section 4) and in G02. Thus, only a brief discussion is included here, and the emphasis is on the modifications applied in specific sensitivity simulations.

The global model is the anelastic nonhydrostatic two-time-level nonoscillatory forward-in-time Eulerian/semi-Lagrangian Navier–Stokes solver in spherical geometry (Smolarkiewicz et al. 2001; Grabowski and Smolarkiewicz 2002), the same as in G01 and G02. The Eulerian version of the model is used in the CRCP simulations. All simulations have 51 levels in the vertical with a uniform gridlength of 0.5 km. The global model time step is 12 min.

As in G01 and G02, the 2D cloud-scale models in each column of the global model have horizontal periodic domains of 200 km with a 2-km gridlength (see a brief discussion in section 4 of G01). The vertical grid is the same as in the global model and the model time step is 20 s. In addition, the gravity wave absorber is used in the uppermost 9 km of each cloud model with an inverse of the characteristic timescale increasing linearly from zero at the bottom of the absorber to 1/600 s$^{-1}$ at the top of each model domain. The fact that the global model and cloud-scale models solve exactly the same (nonhydrostatic) equations with the same vertical grid simplifies the coupling between the two models.

The globally uniform SST is 30°C (303.16 K). In all but one simulation, the effects of radiative processes on the atmosphere are prescribed by applying a constant-in-time cooling rate profile. The prescribed cooling rate is 1.5 K day$^{-1}$ below 12 km, linearly decreasing from 1.5 K day$^{-1}$ to zero between 12 and 15 km, and is zero above 15 km. One simulation applies an interactive radiation (INRAD) transfer model (Kiehl et al. 1994) inside the CRCP domains. However, the globally averaged profile of the temperature tendency associated with radiative transfer is adjusted to match that applied in prescribed radiation simulations [see (1) in Grabowski et al. 2000]. Equinox conditions, no diurnal cycle, and a zero zenith angle are assumed over the entire aquaplanet. The radiation transfer model calculates radiative tendencies once every global model time step (i.e., every 12 min). We stress that the radiative transfer applies cloud-scale fields supplied by CRCP and does not involve any subgrid-scale representation of cloud structure and overlap.

The initial thermodynamic profiles as well as the reference profiles are taken from the 0000 UTC, 1 September 1974 Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) sounding (i.e., as in Grabowski et al. 1996, 1998). The atmosphere is initially at rest. Free-slip lower boundary conditions are applied (i.e., no surface friction). The thermodynamic fields are initiated by applying instantaneous cloud-scale fields from a 2D convective–radiative quasi-equilibrium simulation to all columns of the global model (see section 4 in G01). The simulations are typically run for 80 days.

Table 1 lists the simulations. The control simulation (CTRL) is that discussed in G01 (section 4) and in G02 (simulation EW therein). Simulation HIRES (high resolution) is the same as CTRL, except for the higher horizontal resolution of the global model (48 × 32 rather than 32 × 16). In INRAD, the prescribed radiative ten-
dencies applied in CTRL are replaced by the interactive radiation transfer model, as discussed above. The next two simulations [constant surface fluxes (CONFL) and restarted constant surface fluxes (R-CONFL)] are similar to CTRL, but apply horizontally uniform (i.e., noninteractive) surface heat fluxes. The horizontally uniform surface fluxes in CONFL and R-CONFL are average surface fluxes derived from the surface flux algorithm over the entire planet. In other words, the same interactive flux scheme is used in CONFL and R-CONFL as in all other simulations, but only the globally averaged surface fluxes are applied in every column of the global model. CONFL starts from \( t = 0 \) (as CTRL, HIRES, and INRAD), whereas R-CONFL is restarted from day 60 of a simulation featuring a well-developed MJO-like coherent structure and run for an additional 20 days. Finally, QVRLX \( (q_r \text{ relaxation}) \) and R-QVRLX (restarted \( q_r \text{ relaxation} \)) explore the role of free-tropospheric moisture on the large-scale organization of convection (Tompkins 2001a,b). In these simulations, large-scale fluctuations of the free-tropospheric moisture are removed by applying a relaxation term in the global moisture equation:

\[
\frac{\partial q_r}{\partial t}\big|_{\text{rel}} = -q_r - \langle q_r \rangle \frac{\tau}{\tau},
\]

where \( \langle \cdot \rangle \) denotes global average at a given level, and \( \tau \) is the relaxation timescale. This term is applied only for model levels above 2 km (i.e., above the boundary layer). Simulations QVRLX and R-QVRLX are motivated by numerical studies of the impact of relative humidity on moist convection (e.g., S.H. Derbyshire et al. 2002, personal communication). The timescale \( \tau \) is taken as 1 h in QVRLX and 3 h in R-QVRLX. In a nutshell, the relaxation suppresses development of large-scale fluctuations of free-tropospheric moisture. As illustrated in the next section, these fluctuations are created through the interaction between convection and the large-scale flow in CTRL, HIRES, and INRAD. In R-QVRLX, on the other hand, the already existing large-scale moisture fluctuations are removed over the first several hours of the simulation. In both cases, the focus is on the impact of this procedure on the large-scale convection organization.

4. Impact of horizontal resolution

a. Simulation CTRL

Simulation CTRL was discussed in detail in G01, so only features relevant to the analysis here will be presented. Figure 1 shows the Hovmöller (time–space) diagrams of the surface precipitation and precipitable water at the equator for the duration of the simulation CTRL, as well as snapshots of vertical and horizontal flow in the vertical equatorial plane at day 80. The figure also shows distribution of the surface precipitation and the total surface flux along the equator at day 80. Zonal distribution of surface precipitation at a given latitude and at a given time is obtained by combining cloud-scale data from CRCP domains located at this latitude. The surface precipitation and precipitable water diagrams shown in Fig. 1, as well as all others shown in this paper, use averages from two zonal belts adjacent to the equator because the global model does not have grid points located exactly at the equator. (Note that Fig. 14 in G01 shows the surface precipitation in CTRL for these zonal belts separately.)

Figure 1 illustrates development of wavenumber-1 coherent structure as the simulation progresses. The structure, evident in the last 20 days of the simulation, is embedded in a considerably moister environment as documented by the precipitable water plot. It features deep convection on the leading edge of strong surface westerly flow and easterly upper-tropospheric winds behind. The structure is also associated with enhanced surface fluxes. The meridional distribution of the surface precipitation and surface winds, illustrating that the coherent structure is limited to the equatorial waveguide, is shown in Fig. 17a of G01. As noticed in G01, such a pattern of convection, large-scale flow, and surface heat fluxes is reminiscent of the MJO and an associated westerly wind burst (e.g., Fig. 13 in Lau et al. 1989, Fig. 16 in Lin and Johnson 1996). This pattern will be referred to as the ‘‘MJO-like coherent structure’’ throughout the paper, in order to distinguish it from the MJO observed on earth.

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1 Ideally, one would prefer to restart from CTRL. Unfortunately, only a fraction of CRCP data was archived from the simulation CTRL, not enough for a smooth restart. A simulation that provided data for the restart was one of sensitivity simulations, which featured strong MJO-like coherent structures and can be considered as just another realization of CTRL.

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Table 1. Model simulations discussed in this paper.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>Simulation described in section 4 of G01</td>
</tr>
<tr>
<td>HIRES</td>
<td>As in CTRL, but with increased horizontal resolution of global model</td>
</tr>
<tr>
<td>INRAD</td>
<td>As in CTRL, but with interactive radiation transfer model</td>
</tr>
<tr>
<td>CONFL</td>
<td>As in CTRL, but with horizontally uniform surface fluxes</td>
</tr>
<tr>
<td>R-CONFL</td>
<td>As in CONFL, but restarted from day 60 of a simulation with a strong MJO-like structure, run till day 80</td>
</tr>
<tr>
<td>QVRL</td>
<td>As in CTRL, but with moisture relaxation as described in the text</td>
</tr>
<tr>
<td>R-QVRLX</td>
<td>As in QVRLX, but restarted from day 60 of a simulation with a strong MJO-like structure, run till day 70</td>
</tr>
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</table>
b. Simulation HIRES

This simulation was performed to investigate sensitivity of model results to the horizontal resolution of the global model. Figure 2, in the same format as Fig. 1 above, shows results from the simulation HIRES. As in simulations with lower horizontal resolution, HIRES features various convectively coupled equatorially trapped large-scale perturbations in the first 20 days of the simulation. Subsequently, strong eastward-propagating coherent structures develop within the waveguide (a pair around day 20 and a single one around day 50). These structures dominate the large-scale pattern throughout the rest of the simulation. As one can expect, higher resolution of the global model in HIRES allows for a more diverse response in terms of horizontal scale and propagation speed of various perturbations than in CTRL.

An intriguing feature of Fig. 2 is that the equatorial surface precipitation diminishes for a period between days 35 and 45. (It also decreases at day 80; this is why the middle and bottom panels in Fig. 2 show data for day 77, and not for day 80 as in CTRL.) This feature is explained in Fig. 3, which shows meridional distributions of zonally averaged surface precipitation, time averaged for days 33–44 and days 69–80. The first period corresponds to the diminished equatorial precipitation, whereas the latter period features a typical MJO-like pattern (cf. Fig. 2). The period with the MJO-like pattern (days 69–80) shows a fairly uniform meridional distribution of the averaged surface precipitation. When the mean surface precipitation diminishes at the equator, however, the pattern features two maxima away from the equator. The latter pattern resembles the double intertropical convergence zone (ITCZ) pattern often ob-
Fig. 2. As in Fig. 1, but for the simulation HIRES. The precipitable water thresholds for the grayscale are 61 and 71 kg m$^{-2}$. The middle and bottom panels are at day 77 and vertical velocity contour interval is 4 cm s$^{-1}$ starting at 2 cm s$^{-1}$.

Served in GCM idealized simulations (see a review in Liu and Moncrieff 2002, manuscript submitted to J. Atmos. Sci., hereafter LM). A pattern of stronger off-equatorial convection similar to HIRES was also observed in a lower-resolution simulation that will not be discussed in this paper.

Spatial distributions of surface precipitation and surface zonal winds are illustrated in Fig. 4, which shows snapshots of model results at days 40 and 77. Day 40 features suppressed equatorial convection and enhanced convection off the equator. At day 77, on the other hand, a strong MJO-like coherent structure is present in the eastern part of the waveguide. It features leading-edge convection and strong westerly flow at the surface (a westerly wind burst) to the west of the surface precipitation (cf. Fig. 2). A significant difference between HIRES and lower-resolution simulations (e.g., Fig. 17 for CTRL in G01, Fig. 5 for INRAD herein) is that MJO-like structures have a smaller meridional extent in HIRES. A similar impact of the horizontal resolution is evident in meridional distributions of the mean zonal flow, temperature, and moisture between lower-resolution simulations (e.g., Fig. 12 in G01 for CTRL) and HIRES (not shown).

5. Effects of physical processes

a. Interactive radiation

Raymond (2001, section 4a) suggested that cloud-radiative interactions are essential for the development of MJO-like coherent structures. As already demonstrated in G01 and G02, this is not the case when CRCP is used in place of a traditional convective parameterization because strong MJO-like structures develop in simulations with prescribed radiative cooling. On the other hand, Lee et al. (2001) discussed idealized aquaplanet simulations where transition from prescribed to interactive radiation resulted in a rather significant impact on the large-scale organization of convection. These two studies motivated the simulation INRAD using the interactive radiation transfer model.

Figure 5, in the same format as Fig. 1, shows the Hovmöller diagrams of the surface precipitation and
precipitable water at the equator, and the large-scale flow at day 80 for INRAD. Figure 6, on the other hand, shows a snapshot (at day 80) of the spatial distribution of surface precipitation and zonal winds, respectively. The two figures should be compared to Figs. 2 and 3 for HIRES, and Fig. 1 herein and Fig. 17a in G01 for CTRL. The large-scale organization of convection, spatial distribution of precipitable water, and large-scale flow in INRAD is similar to CTRL and HIRES, and it is dominated by the MJO-like coherent structures. Thus, it is concluded that cloud–radiative interactions have an insignificant impact on the MJO-like coherent structures.

The evolution of mean zonal and meridional velocities at the equator for INRAD is shown in Fig. 7. Similar to CTRL (Fig. 13 in G01), INRAD features gradual development of equatorial westerly flow throughout the entire troposphere, starting at upper levels and descending into the lower troposphere. This mean westerly flow is accompanied by the mean easterly flow outside the waveguide (not shown; cf. Fig. 12 in G01 for CTRL), which is expected from the conservation of angular momentum of the atmosphere. The mean westerly flow within the waveguide will be referred to as the superrotation, as the westerly flow relative to the ground implies that the zonal flow is faster than the planetary rotation. The superrotation will be discussed in more detail in the following section.

**Fig. 3.** Meridional distribution of the zonally averaged surface precipitation rate averaged over (a) days 33–44, and (b) days 69–80 for HIRES. Vertical bars show twice the standard deviation of the mean from the temporal evolution at a given latitude.

**Fig. 4.** Results for (top) day 40 and (bottom) day 77 of the simulation HIRES. Instantaneous fields of the surface zonal winds (solid and dashed contours for positive and negative values, respectively; contour interval of 10 m s\(^{-1}\) starting from 5 m s\(^{-1}\)) and spatial distributions of the surface precipitation rate derived from CRCP cloud-scale data (gray shading; precipitation rate larger than 1.5 and 15 mm h\(^{-1}\) is shown using light and dark shading, respectively). The plots show data from the zonal belt between 45°S and 45°N only.
FIG. 5. As in Fig. 1, but for the simulation INRAD. The precipitable water thresholds for the grayscale are 61 and 71 kg m$^{-2}$, and vertical velocity contour interval is 1 cm s$^{-1}$ starting at 0.5 cm s$^{-1}$.

detail in section 5d. The mean meridional velocity, which represents the globally averaged mass exchange between the hemispheres, shows fluctuations similar to CTRL, but weaker and less organized (cf. Fig. 13 in G01). As noted in G01 (page 989, right column), this variability is consistent with the wavenumber 0 mixed Rossby–gravity wave observed in the terrestrial atmosphere.

b. Interactive surface fluxes

Surface exchange was postulated in the past as an important factor in the MJO dynamics. There are two distinct mechanisms involved. The first one is associated with the impact of surface winds on sensible and latent heat fluxes from the ocean surface. This is the so-called wind-induced surface heat exchange (WISHE) mechanism (Emanuel 1987; Neelin et al. 1987). The second mechanism concerns the impact of spatially and temporally varying SST on the atmosphere–ocean coupling (e.g., Flatau et al. 1997). The second mechanism is not relevant herein because the SST is uniform in space and time.

As illustrated by Figs. 1, 2, and 5 (as well as Fig. 17b in G01), the enhanced surface fluxes associated with the MJO-like coherent structures occur near the surface precipitation maxima and are typically shifted toward the westerly wind burst area. This is different from a simple model of intraseasonal oscillations proposed by Emanuel (1987) that implies surface flux enhancement to the east of enhanced surface precipitation. However, surface fluxes are not only affected by the surface winds, but also by the thermodynamic properties of the air near the ocean surface. The latter are strongly affected by convection through the impact of convective and mesoscale downdrafts. This is likely why the maximum surface fluxes in Figs. 1, 2, and 5 are only slightly shifted toward the westerly wind burst area.

By applying horizontally uniform surface fluxes, simulations CONFL and R-CONFL explore the impact of the interactive surface fluxes on the MJO development and maintenance. Figure 8 shows that CONFL differs dramatically from other simulations because weak MJO-like structures develop. However, the organization at day 80 is strengthening and it is unclear if a coherent MJO-like structure, similar to those in Figs. 1, 2, and
5, can eventually develop. The zonal flow at the equatorial plane at day 80 resembles westerly wind bursts in CTRL, HIRES, and INRAD, but of much smaller amplitude (note that the contour intervals are different in Figs. 1, 2, 5, and 8). Deep convection is organized into wide bands, which is different from the simulations discussed previously. These bands are characterized by only slightly higher precipitable water than areas with suppressed convection (again, the grayscale in Fig. 8 is different from previous figures). Large-scale perturbations that propagate toward the west are also evident. These are likely convectively coupled equatorially trapped large-scale waves (cf. Wheeler et al. 2000).

Lack of coherence of the MJO also has a dramatic impact on the mean large-scale flow within the equatorial waveguide. Figure 9 shows the evolution of mean zonal and meridional velocities at the equator in CONFL in the same format as Fig. 7 for INRAD (cf. Fig. 13 in G01 for CTRL). Contrary to CTRL, HIRES, and INRAD, CONFL features only weak westerly flow. The mean meridional velocity, on the other hand, features strong and regular fluctuations, more coherent than CTRL (cf. Fig. 13 in G01). As already noted, such a variability is consistent with a wavenumber-0 mixed Rossby–gravity wave with a period of about 4 days, as observed in the terrestrial atmosphere.

Figure 10 shows the evolution of surface precipitation in R-CONFL (days 60–80) and a simulation from which R-CONFL was restarted at day 60 (days 50–60). The spatially uniform surface flux is capable of maintaining a coherent MJO-like structure as well as large-scale moisture fluctuations, provided the MJO-like structure already exists when the simulation begins.

c. Large-scale fluctuations of free-tropospheric moisture

Free-tropospheric moisture is conjectured to have a strong impact on large-scale organization of moist convection (e.g., Raymond 2000b; Tompkins 2001a,b). As illustrated by several figures herein, significant large-scale fluctuations of precipitable water are associated with simulated MJO-like coherent structures. The QVRLX and R-QVRLX simulations investigate if this aspect has any effect on the simulated large-scale organization of convection. As explained in section 3, simulations QVRLX and R-QVRLX apply moisture relaxation in the global model using a short (1 and 3 h) relaxation timescale. This ensures only small fluctuations of water vapor above the boundary layer occur over the entire aquaplanet. Furthermore, as in Tompkins (2001a,b), only dynamic feedback is considered because QVRLX and R-QVRLX apply prescribed radiative cooling.

Figure 11 shows results for QVRLX. In general, the impact of the moisture relaxation is dramatic because extremely weak (if any) large-scale MJO-like structures develop and the precipitation pattern is dominated by westward-propagating perturbations resembling those in CONFL. The maximum surface westerly winds (1–2 m s$^{-1}$) are even weaker than in CONFL and the mean zonal flow (cf. Fig. 9 for CONFL) is only a few tenths of a meter per second at day 80. This suggests that feedback between convection and free-tropospheric moisture is critical for the development of MJO-like coherent structures.

Relaxation of the free-tropospheric moisture has also dramatic impact when the model is restarted from a simulation having a strong MJO-like coherent structure (Fig. 12). The figure shows that the strong convection on the leading edge of the MJO-like coherent structure (evident before day 60) rapidly disintegrates into a wide band of convection once the moisture relaxation is turned on. The band keeps propagating with the MJO-like speed (which suggests that the large-scale coherence of the zonal flow is maintained for a long time), and it seems to feature westward-propagating perturbations that resemble the dominant organization in QVRLX. The zonal extent of the band corresponds to the area of surface westerly flow and enhanced surface fluxes.
The rapid disintegration of the leading-edge convection in simulation R-QVRXL is further illustrated in Figs. 13, 14, and 15. Figure 13 shows the Hovmöller diagrams of the convective available potential energy (CAPE) and convective inhibition (CI) for the same period as Fig. 12. CAPE and CI are calculated as vertical integrals of parcel buoyancy (from near the surface to the level of neutral buoyancy in the upper troposphere for CAPE and from near the surface to the level of free convection for CI) using reversible thermodynamics that includes ice physics (consistent with the CRCP thermodynamics), but with the condensate loading limited to 3 g kg$^{-1}$. CAPE and CI are calculated using global model data and applying an average of the two lowest model levels (i.e., the surface and 500 m) as initial conditions for the parcel calculations. During the period of days 50–60, the area with the leading-edge convection associated with the MJO-like structure features the lowest values of CAPE and CI. The areas ahead and behind the leading edge feature higher CAPE. High values of CI ahead of the coherent structure (right-hand side of the domain) is consistent with suppressed convection there, despite the high values of CAPE. The low CI behind the coherent structure, where CAPE is high, is somewhat surprising. However, this area is characterized by substantial vertical shear of the horizontal
wind, which is likely to suppress development of deep convection through enhancing mixing and entrainment, especially in poorly resolved clouds. The spatial pattern of CAPE and CI after day 60 does not change much. However, the disintegration of the coherent structure leads to lower CAPE (i.e., less black) and higher CI (i.e., less white) in the second half of the period shown in Fig. 13.

Figure 14 illustrates the remarkably rapid disintegration of the large-scale ascent associated with the leading-edge convection of the MJO-like coherent structure. The strong large-scale ascent at day 60 is much weaker after just 6 h into the simulation R-QVRLX, and it is practically nonexistent at the end of the first day. Such a rapid change is an adjustment of the large-scale flow to spread out tropical convective heating. Since the large-scale temperature perturbation required to drive the large-scale flow associated with the MJO-like coherent structure is of order 1 K and the large-scale radiative cooling is about 1 K day$^{-1}$, the adjustment should take place on a timescale of about 1 day.

Figure 15 further illustrates the change of the surface precipitation and surface zonal flow. At the start of R-QVRLX (day 60, Fig. 15a), the pattern features the leading-edge convection and accompanying sharp zonal gradient of surface winds (cf. Figs. 1, 2, and 5). After 5 days of simulation, the maximum surface flow is as strong as at day 60, but the sharp gradient at the leading edge is absent and convection is spread over the entire area of enhanced surface westerly flow, which is consistent with Fig. 12.

d. Superrotation and MJO-like coherent structures

The results discussed above suggest that the coherence of the MJO-like structures impacts the development of the mean westerly flow in the equatorial waveguide (cf. Figs. 7 and 9 herein, and Fig. 13 in G01). Figure 16 shows the development of the superrotation measured by the density-weighted zonal flow across the troposphere (defined as $\int \rho u dz / \int \rho dz$, where $u$ is the zonal velocity component, and $\rho$ is the air density integrated from $z = 0$ to $z = 16$ km), averaged over the two zonal belts adjacent to the equator. In simulations with strong MJO-like coherent structures (CTRL, INRAD, HIRES), the mean westerly flow near the equator progressively increases, with the exception of HIRES near day 40, when the mean westerly flow weakens. As shown in section 4b, the latter is characterized by convection located away from the equator. In comparison with other simulations, the increase of the mean westerly flow in CONFL is insignificant (cf. Fig. 9). No superrotation develops in QVRLX.

The rate of change of the superrotation (Fig. 16) ap-
Fig. 11. As in Fig. 1, but for the simulation QVRLX. The precipitable water thresholds for the grayscale are 72 and 74 kg m$^{-2}$. The vertical velocity contour interval is 0.5 cm s$^{-1}$ starting at 0.25 cm s$^{-1}$. The horizontal velocity contour interval is 2 m s$^{-1}$ starting at 1 m s$^{-1}$.

pears to be correlated with the coherence of the MJO-like coherent structures, as measured, for example, by the strength of westerly wind bursts or intensity of the surface precipitation at the leading edge of the coherent structure. For instance, rapid development of the superrotation after day 60 in CTRL corresponds to strong MJO-like coherent structure shown in Fig. 1 during this period. Similarly, rapid increase of the superrotation around day 15 and day 37 in INRAD corresponds to enhanced westerly wind bursts around these days (not shown). The same applies for the period between days 20 and 30 in HIRES. At the same time, however, lack of the superrotation in QVRLX, slow development of the superrotation for CONFL, and during the initial 50 days of CTRL are all associated with weak (or nonexisting in QVRLX) westerly wind bursts. This association can be further quantified by correlating the change of the superrotation with the maximum westerly wind burst intensities. This fully supports the relationship between development of the superrotation and the coherence of MJO-like structures (not shown).

6. Discussion

a. MJO-like coherent structures and the role of water vapor

Simulations presented in this paper, as well as those in G01 and G02, demonstrate that the MJO-like coherent structures simulated by the global model with CRCP are very robust. The most significant impact on the coherence of MJO-like structures turned out to be associated with horizontal variability of the free-tropospheric moisture. The MJO-like coherent structures could not develop, and coherence of existing structures was practically eliminated in simulations that applied a procedure to remove large-scale moisture fluctuation in the free troposphere. In general, free-tropospheric humidity has been long recognized as an important factor modulating moist convection. The most spectacular example is the impact of dry intrusions on the tropical convection (e.g., Redelsperger et al. 2002, and references therein). The impact on organized convection can be particularly strong (Lucas et al. 2000). On the other hand, convection...
is the only source of free-tropospheric moisture in the Tropics. By moistening its immediate environment, convection renders it more favorable for future convection because clouds growing in a more humid environment lose their positive buoyancy (as a result of entrainment of dry environmental air) more slowly than clouds growing in a drier environment. This moisture conditioning of the tropical environment by convective detrainment is an important delay mechanism in the evolution of the tropical convection. This has long been known observationally (e.g., Yanai et al. 1973) and was highlighted in many studies of moist convection (e.g., Dudhia and Moncrieff 1987).

The impact of moisture fluctuations on MJO-like coherent structure, as simulated herein, can be understood as a feedback process that involves moist convection, free-tropospheric moisture, and the large-scale flow. This feedback causes perturbations in moist convection to strengthen perturbations of the free-tropospheric moisture, which, in turn, affect the spatial distribution of moist convection. The large-scale circulation, which develops in response to spatial fluctuations of convec-
Fig. 14. Instantaneous vertical velocities in the vertical equatorial plane of the global model at the start of the simulation R-QVRLX (day 60), and after 6, 12, and 24 h of the simulation R-QVRLX, from top to bottom, respectively. Contour interval is 1 cm s\(^{-1}\) starting at 0.5 cm s\(^{-1}\). Positive (negative) values are shown using solid (dashed) lines.

Fig. 15. As in Figs. 4 and 6, but for (top) the start of the simulation R-QVRLX (day 60) and (bottom) after 5 days of the simulation R-QVRLX (day 65).

Fig. 16. Evolution of the density-weighted zonal flow on the equator for simulations CTRL, INRAD, HIRES, CONFL, and QVRLX.

Interactive radiation, used neither in the simulation QVRLX herein nor in simulations described in Tompkins (2001a,b), makes the convection–moisture feedback even stronger because of the impact of water vapor and clouds on radiative transfer. This “convection–moisture feedback” was shown to operate efficiently in cloud-resolving simulations discussed in Tompkins (2001a,b). Apparently, it is remarkably efficient in CRCP global simulations discussed herein.

Interactive radiation, used neither in the simulation QVRLX herein nor in simulations described in Tompkins (2001a,b), makes the convection–moisture feedback even stronger because of the impact of water vapor and clouds on radiative transfer. This impact is illustrated in cloud-resolving simulations of convective–radiative quasi equilibrium discussed in Grabowski and Moncrieff (2002). These simulations demonstrate that differential heating due to both longwave and shortwave radiative transfer tends to strengthen large-scale circulations created by spatial fluctuations of convective heating. The minimal impact of the interactive radiation on large-scale organization of convection in CRCP global simulations (simulation INRAD) might be related to the fact that the convection–moisture feedback is already very efficient even without interactive radiation.

In light of the above discussion, the outcome of simulations applying horizontally uniform surface fluxes can also be interpreted as related to the convection–moisture feedback. It has long been recognized that deep convection significantly impacts atmosphere–ocean exchange on the meso- and synoptic scales (see a discussion in Jabouille et al. 1996). The enhanced surface fluxes in aquaplanet simulations presented herein coincide with the deep convection phase and, to a smaller extent, with the westerly wind burst phase of MJO-like coherent structures (see also Fig. 16 in Lin and Johnson 1996). Because they are dominated by the latent flux, surface fluxes contribute to the water vapor feedback by enhancing the surface evaporation in convectively active (perturbed) areas compared to areas of suppressed deep convection. Such an argument seems to explain why MJO-like coherent structures tend to develop much

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slower in the simulation CONFL. However, once present, the MJO-like structures can survive even if surface fluxes are horizontally uniform, as in R-CONFL.

b. MJO in climate models

Sensitivity simulations discussed in this paper were designed to make the MJO-like coherent structures weaken or disappear altogether. This is in contrast to global simulations applying traditional convective parameterizations (in either idealized or realistic setups), which typically struggle with climate variability on intraseasonal timescales (e.g., Slingo et al. 1996). If our results can be extended to the MJO on earth, then the feedback between deep convection and the free-tropospheric moisture has to be a focal point. It follows that the sensitivity of traditional convection parameterizations to the free-tropospheric moisture becomes important for a successful simulation of MJO in traditional climate models. This very issue motivated a systematic investigation into the impact of free-tropospheric humidity on deep convection, using cloud-resolving and single-column models, within the European Cloud Systems (EUROCS) project (see Web site http://www.cnrm.meteo.fr/gcse/EUROCS/EUROCS.html; S.H. Derbyshire et al. 2002, personal communication). The overall strategy is to use sensitivity in simulations using cloud-resolving models as a reference for improving sensitivity of convective parameterizations applied in single-column models.

Are results from previous studies concerning the sensitivity of MJO to convective parameterization consistent with the role of the convection–moisture feedback? Raymond (2001) studied large-scale organization of parameterized convection on the equatorial beta plane and showed development of strong MJO-like structures much in line with results discussed in this paper. The inverse relationship between surface precipitation and free-tropospheric moisture, a feature of the Raymond’s convective parameterization (cf. Fig. 13 therein), was argued to play an important role in the simulations. However, unlike the study reported herein, the convection–moisture feedback had to be aided by the interactive radiation to obtain strong MJO-like structures. According to S. Derbyshire et al. (2002, personal communication), the convection scheme applied in the Met Office model (the Gregory–Rowntree scheme; Gregory and Rowntree 1990) captures the dependence of surface precipitation on the free-tropospheric humidity. Thus, the Gregory–Rowntree scheme has a potential to represent the convection–moisture feedback. This is consistent with the Met Office climate model having a comparatively good MJO signal (S. H. Derbyshire 2002, personal communication). On the other hand, results of Maloney and Hartman (2001) show a more complicated relationship between convection parameterization and the MJO in the National Center for Atmospheric Research’s (NCAR) Community Climate System Model. E.D. Maloney (2002, personal communication) suggests that the impact of convection parameterization in their study is mostly through the improvement of the mean state of the model. Overall, results presented in this paper suggest that systematic evaluation of the sensitivity of traditional convective parameterizations used in climate models to the free-tropospheric moisture, and corresponding evaluation of the impact of convection–moisture feedback operating in these schemes on the strength of MJO, should be undertaken. However, there are other elements of the climate model physics that have impact on tropical climate simulations (e.g., the boundary layer scheme, the cloud scheme). Thus, isolating impacts of a convection scheme might be simpler in idealized simulations of the type discussed in this paper.

Flatau et al. (1997) showed that including interactive SST in a climate model significantly improves the strength of the MJO signal. On the one hand, allowing SST to vary aids the convection–moisture feedback in a similar way as interactive surface fluxes aid development of MJO-like coherent structures in the simulations discussed here. This is because warmer SSTs typically result in positive perturbations of the surface fluxes. On the other hand, as argued by Tompkins (2001b), the coupling between SST anomalies and deep convection simulated by the cloud-resolving model requires the convection–moisture feedback to explain a rather slow response of convection to the SST change.

Finally, results presented in this paper suggest a possible explanation for a surprising result obtained in simulations which apply CRCP technique in a climate model (M. Khairoutdinov 2002, personal communication). A preliminary analysis shows that operating a cloud-resolving model in each column of a climate model enhances tropical climate variability on timescales between diurnal and intraseasonal. However, the intraseasonal timescales seem to show too strong a variability because fluctuations of the outgoing longwave radiation in the climate model with the superparameterization are stronger than in observations. Since the cloud-scale model used in the superparameterization applies a low horizontal resolution (4 km; M. Khairoutdinov 2002, personal communication), the convection–moisture feedback is likely to be exaggerated. The impact of environmental humidity on cloud dynamics (through the entrainment mechanism) will not be captured using a cloud model with such a low horizontal resolution. This point equally applies to the simulations presented in this paper because 2-km horizontal resolution is also insufficient in this regard. Moreover, if the issue is indeed the impact of free-tropospheric moisture on the convective mass flux, then the question whether this impact can be properly captured using a 2D modeling framework is pertinent.

c. Superrotation

A surprising result of the constant-SST aquaplanet simulations is the formation of a significant mean west-
erly flow within the equatorial waveguide (the superrotation) in simulations featuring strong MJO-like coherent structures. The MJO-like coherent structures are associated with propagating heating anomalies, which are zonally highly localized. The impact of such heating anomalies on the large-scale flow has long been considered a prototype model of the intraseasonal oscillations (e.g., Gill 1980; Chao 1987). However, one may argue that the development of the zonally averaged flow should be associated with the zonally averaged heating, that is, without considering the zonal fluctuations associated with the MJO. Such a framework was applied by LM to study mechanisms associated with development of ITCZ on a constant-SST equatorial beta plane. They applied a 2D cloud-resolving model aligned in the meridional direction and obtained two possible configurations of the ITCZ, with convection localized either at the equator or at two ITCZs located approximately 2000 km off the equator. Development of the mean zonal flow in these simulations was interpreted as a result of geostrophic adjustment. In particular, the double ITCZ simulation resulted in off-equatorial warm anomalies and led to the development of easterly flow over the equator.

The results of LM have relevance to the simulations discussed in this paper. Following their argument, the off-equatorial convection around day 40 in HIRES should result in the westward acceleration of the mean flow near the equator (i.e., reduction of the mean zonal flow). As illustrated in Fig. 16, this indeed occurs. However, LM's results cannot explain the relationship between mean eastward acceleration and the MJO-like coherent structures. This is because, as illustrated in Fig. 3b, these structures are associated with a uniform heating across the equatorial waveguide. In other words, eastward acceleration cannot be explained by zonally averaged heating centered at the equator because heating distribution is uniform. Moreover, as illustrated by the difference between simulations with weak superrotation (CONFL and QVRLX) and all other simulations that feature significant superrotation, the issue is not in the meridional distribution of the heating, but rather in the zonal localization of the heating. This can only be investigated in a 3D framework.

7. Conclusions

This paper presents numerical simulations performed to extend discussions in G01 and G02. A novel aspect of these investigations is application of a nonhydrostatic global model that uses the cloud-resolving convection parameterization (CRCP). CRCP represents subgrid scales of the global model by embedding a 2D cloud-resolving model in each column of the global model. As in G01 and G02, the focus is on the organization of convection within the equatorial waveguide on a rotating earth-size constant-SST aquaplanet. The simulations start with the atmosphere at rest and large-scale winds are allowed to evolve freely. Free-slip conditions are applied at the surface. In several simulations, the organization of convection near the equator resembles that in G01 and G02 and it features the large-scale MJO-like coherent structures (wavenumber 1 or 2) that propagate along the equator toward the east with typical speeds between 5 and 10 m s\(^{-1}\) and circumnavigate the planet in several tens of days. Similar MJO-like coherent structures are simulated using higher spatial resolution of the global model (simulation HIRES) and applying either the prescribed radiative cooling (simulation CTRL) or the interactive radiative transfer model (simulation INRAD). We stress that the radiative transfer in INRAD uses cloud-scale fields supplied by CRCP and it does not involve any subgrid-scale representation of cloud structure and overlap. This is different from Khairoutdinov and Randall (2001) where a cloud-resolving model was applied in the climate model to replace only the deep convection parameterization scheme.

Sensitivity simulations, exploring the effects of the coupling among convection, surface exchange, and the free-tropospheric moisture, are illuminating. When interactive surface fluxes are replaced by their globally averaged values (simulation CONFL), the MJO-like structures develop slowly and they are quite different from coherent structures observed in other simulations. However, if already present, these coherent structures are able to survive even with horizontally uniform surface fluxes (simulation R-CONFL). The most dramatic impact occurs when large-scale fluctuations of the free-tropospheric moisture are artificially removed on a short timescale (1 to 3 h). The MJO-like coherent structures do not develop at all (simulation QVRLX), and existing structures in R-QVRLX rapidly disintegrate into wide bands of convection resembling weak MJO-like structures in CONFL. Simulations QVRLX and R-QVRLX suggest that the feedback between deep convection and the tropospheric moisture (the convection–moisture feedback) is essential for the large-scale organization of tropical convection. This conclusion echoes discussions in Raymond (2000b) and Tompkins (2001a,b). It is possible, however, that the convection–moisture feedback is too strong in the global model because of a low spatial resolution of the CRCP cloud models and their 2D geometry. This issue needs to be investigated.

MJO-like coherent structures in CRCP global simulations have significant impact on the mean flow within the equatorial waveguide. The mean westerly flow, the superrotation, develops in simulations with coherent MJO-like structures and it strengthens during periods with particularly strong MJO-like structures. The impact of MJO-like coherent structures on the mean zonal circulation in the Tropics raises important issues concerning the zonal momentum budget in large-scale and climate models that struggle to capture MJO.

As already stated in G01, understanding the mechanisms behind the MJO formation, maintenance, and propagation has challenged tropical meteorology since
detection of the MJO in the early 1970s (see Madden and Julian 1994, and references therein). On the one hand, the simulations presented here suggest that the feedback between convection and the free-tropospheric moisture, postulated as important for large-scale convection organization in previous studies (Raymond 2000b; Tompkins 2001a,b), is crucial for the coherence of the MJO-like coherent structures. On the other hand, the results suggest that at least some of the mechanisms postulated previously (such as meridional or zonal SST gradients, surface friction, interaction between clouds and radiation, or interaction between convection and the SST) are not necessary for the development and maintenance of the MJO-like coherent structures. However, these processes are likely important in bringing idealized MJO-like coherent structures closer to the MJO observed on earth.

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