A Tri-mode of Mock-Walker Cells

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Abstract

This work uses cloud-resolving simulations to study mock-Walker cells driven by a specified sea surface temperature (SST). The associated precipitation in the mock-Walker cells exhibits three different modes, including a single peak of precipitation over the SST maximum (mode 1), symmetric double peaks of precipitation straddling the SST maximum (mode 2), and a single peak of precipitation on one side of the SST maximum (mode 3). The three modes are caused by three distinct convective activity center migration traits. Analyses indicate that the virtual effect of water vapor plays an important role in differentiating the three modes. When the SST gradient is large, the virtual effect may be strong enough to overcome the temperature effect, generating a low-level low-pressure anomaly below the ascending branch of the Walker cell off the center. The results here highlight the importance of the virtual effect of water vapor and its interaction with convection and large-scale circulation in the Walker circulation.

Key words: Walker circulation, cloud-resolving simulation, virtual effect

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Article Highlights:

- Simulations of mock-Walker cells show three different modes.
- The three modes represent different convective activity center migration traits.
- The virtual effect of water vapor plays an important role in differentiating the three modes.
1. Introduction

A common and useful way to understand the tropical large-scale dynamics is to consider a circulation driven by prescribed sea surface temperature (SST). There has been a long history of attempting to explain the tropical mean circulation and precipitation by the distribution of SST (e.g., see Sobel, 2007 for a review). Previous studies may be classified into three groups of ideas. The first idea notes that due to the weak temperature gradient (WTG) in the free tropical troposphere, air columns over higher SST should be more convectively unstable and have greater rainfall (e.g., Sobel et al., 2001; Chiang and Sobel, 2002; Bretherton and Sobel, 2002). The second idea, represented by Lindzen and Nigam (1987), argues that the SST gradient drives low-level winds, and its associated convergence leads to precipitation. The first and second ideas predict precipitation maxima over SST maxima and regions of large SST gradient, respectively. The observational relationship between SST and climatological rainfall suggests a mixture of the above two situations. Thus, the third idea combines the above two ideas by including a deep and a shallow mode of convection (e.g., Neelin and Held, 1987; Back and Bretherton, 2009ab). Despite previous advances in linking tropical mean circulation and SST, the problem remains unresolved. For example, the models in many previous studies are still diagnostic models with posteriori parameters. The double inter-tropical convergence zone (double-ITCZ) bias is still a persistent problem in many climate models (Samanta et al., 2019; Fiedler et al., 2020; Tian and Dong, 2020).

The complexity of tropical dynamics largely comes from interactions between large-scale circulation and small-scale convection (Raymond, 1994; Singh and Neogi, 2022; Emanuel et al., 1994). A useful prototype for studying such problem is the mock-Walker circulation (or cell): a two-dimensional non-rotating circulation forced by specified zonally varying SST (Bretherton et al., 2006). The mock-Walker circulation is an idealized simplification of the tropical Walker circulation, which is the equatorial overturning circulation cell ascending over the west Pacific warm pool.
and descending over the east Pacific cold pool (Bjerknes, 1969; Dong and Lu, 2013; Ma and Zhou, 2016). The Walker cell plays an important role in tropical and global climate. For example, the interannual variability of the Walker cell is the atmospheric component of the El Niño Southern Oscillation (Bjerknes, 1969; Bayr et al., 2014; Williams and Funk, 2011), the change in the Walker cell under global warming greatly impact regional climate in the tropics (Kousky et al., 1984; McGregor et al., 2014).

The mock-Walker cell has been investigated by several studies. Liu and Moncrieff (2008) found that boundary layer processes of friction and wind-induced surface flux variability play an important role in determining the precipitation distribution in mock- Walker cells. Kuang (2012) found that increasing the domain size strengthens the mock-Walker cell and alters its vertical structure. With uniform increases of SST, which mimic global warming, the precipitation of mock-Walker cell increases and the width of precipitation band narrows (Bretherton et al., 2006; Wofsy and Kuang, 2012). These studies usually used high-resolution Cloud-Resolving Models to better represent the small-scale convection and its interaction with large-scale dynamics. An interesting observation in these studies, yet has not been explored, is the behavior of precipitation distribution. In some simulations, there is one precipitation peak over the SST maximum, while in other simulations with different settings, precipitation shows a double-peak distribution (Bellon and Sobel, 2010; Bretherton et al., 2006; Chao and Chen, 2004; Gastineau et al., 2011; Harrop and Hartmann, 2016; Möbis and Stevens, 2012; Silvers and Robinson, 2021). This behavior is analogous to the single versus double ITCZ problem in aqua-planet simulations (e.g., Voigt and Shaw, 2015; Chao and Chen, 2004), even though there is no Coriolis force in the mock-Walker cell.

In this study, we explore the characteristics of mock-Walker cells, particularly the associated precipitation distribution, over a variety of SST and domain sizes to achieve a better understanding of the key dynamics of the mock-Walker cells. In section 2, we briefly describe the numerical model and experimental design. In section 3, we show an unreported, third type of mock-Walker cell with a single precipitation peaking at one flank of the SST maximum. Together with the single- and
double-peak precipitation shown in previous studies, it consists of a tri-mode of mock-Walker cells. In section 4, we elaborate the key mechanism of the tri-mode of mock-Walker cells, the virtual effect of water vapor. Conclusion and discussion are in Section 5.

2. Numerical model and experimental design

The model used here is the System of Atmospheric Modeling (Khairoutdinov and Randall, 2003), version 6.10.4. There are six water species in the microphysics scheme: water vapor, cloud liquid, cloud ice, snow, rain, and graupel. The interactive radiation scheme is from the National Center for Atmospheric Research Community Climate Model (Kiehl et al., 1998). The height of mode top is 27 km with 64 vertical levels. The vertical grid spacing gradually increasing from 37.5 m at the surface to 500 m above the middle troposphere. The SST is prescribed, and the surface fluxes are interactively computed using Monin–Obukhov similarity theory. The solar insolation is similar to that in Bretherton et al. (2006), which is a temporally and horizontally uniform insolation of 413.6 W/m². The simulation domain is a horizontally double-periodic narrow channel in which the meridional extent of the domain (64 km) is much smaller than the zonal extent (Table 1). In all the experiments, the horizontal resolution is 4km. The height of mode top is 27 km with 64 vertical levels. The vertical grid spacing gradually increasing from 37.5 m at the surface to 500 m above the middle troposphere. The Coriolis parameter equals to zero. The initial profiles for temperature and water vapor are taken from the steady state of radiative convective equilibrium simulation under the same SST. The initial vertical profiles of winds are set to zeros.

The circulation is forced with a zonally Gaussian-distributed SST in all the cases:

\[ SST(x) = 298 + \delta e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]

In Eq. (1), \( \mu \) is half of the zonal domain length, so the SST peaks at the center. \( \delta \) and \( \sigma \) set the amplitude and half-width of the SST distribution, respectively. The SST is uniform in the y direction. Interested in examining the behavior of
mock-Walker cells in different parameter regimes, we carried out three groups of experiments with different zonal domain sizes, $\delta$, and $\sigma$ (Table 1). Cases in the first group of experiments (named S) are in a small domain (1024km in the x direction) with $\sigma = 128$km. Each case has a different $\delta$ varying from 1K to 16K. The second group (named L) has both zonal domain and $\sigma$ being four times larger than those of the first group. It includes five cases with $\delta$ varying from 2K to 14K. The third group (named LW) is the same as the second group, except the half-width of the Gaussian distribution is 1.5 times wider ($\sigma = 768$km). Each case is named as the group name followed by its $\delta$. For example, case “LW2” refers to the case in the group LW with $\delta = 2$K. All cases are run until a statistical equilibrium state (300 to 1000 days) is reached, and the first 100 days are discarded as spin-up. In the following analyses, the variables are averaged in the meridional direction.

Table 1. Experimental setup.

<table>
<thead>
<tr>
<th>Group name</th>
<th>Setup</th>
<th>Zonal size (km)</th>
<th>$\delta$ (K)</th>
<th>$\sigma$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Small domain</td>
<td>1024</td>
<td>6, 8, 10, 12, 14, 16</td>
<td>128</td>
</tr>
<tr>
<td>L</td>
<td>Large domain</td>
<td>4096</td>
<td>2, 4, 6, 10, 14</td>
<td>512</td>
</tr>
<tr>
<td>LW</td>
<td>Large domain and Wide Gaussian SST</td>
<td>4096</td>
<td>2, 4, 6, 10, 14</td>
<td>768</td>
</tr>
</tbody>
</table>
3. The tri-mode of mock-Walker cells

The mean precipitation shows three different modes of the mock-Walker cells (Fig. 1). In group S (Fig. 1a), there is a single precipitation peak over the SST maximum when \( \delta \leq 8K \), and there are two peaks of rainfall over the two sides of the SST maximum when \( 10K \leq \delta \leq 16K \). In the group L (Fig. 1b), there is a single precipitation peak over the SST maximum when \( \delta \leq 6K \); however, as \( \delta \geq 10K \), the precipitation peak is off the center. The cases in group LW (Fig. 1c) are similar to those in group L, but the transition from the central peak to the off-center peak occurs at a smaller \( \delta (4K) \). The single precipitation peak over the SST maximum when the SST gradient is weak may be named mode 1, which is consistent with the WTG argument. A large SST gradient leads to the double-peak precipitation (named mode 2) in the small domain simulations (group S) and the off-center single-peak precipitation (named mode 3) in the large domain simulations (group L and LW). The double-peak precipitation over the large SST gradient region (i.e., the flank of SST maximum) is consistent with the Lindzen and Nigam model. The off-center-peak precipitation in the Walker cell is a new mode that has not been reported before. It is intriguing since asymmetric circulation develops under a symmetric setup. In addition, within each group, as SST differences increase, the convective regions tend
to become narrower and stronger, consistent with Bretherton and Sobel (2002).

The circulation of mock-Walker cells also shows a tri-mode corresponding to the precipitation (Fig. 2). In the following analyses, we shall use one case for each mode as example; other cases show qualitatively similar results. For mode 1 (Fig. 2a), the rising branch of the Walker cell is strongest, and the associated relative humidity is highest at the domain center. The maximum of upper-tropospheric cloud condensate at the center indicates strong deep convection associated with the ascending air of the Walker cell. For mode 2 (Fig. 2b), the maximum of ascending air, relative humidity, and cloud condensate are strongest at the flank of the domain center. For mode 3 (Fig. 2c), the Walker cell is asymmetric. The rising branch and the associated deep convection locate on one side of the domain center.

Figure 2. The relative humidity, stream function and non-precipitating condensate of case (a) L2, (b) S14 and (c) LW14. The black solid/dashed contours show the positive/negative value of mass stream function, with black bold lines for zero values. The contour interval is 300kg/m/s for group S and 600kg/m/s for the rest cases. Color shading denotes relative humidity. The white contours denote non-precipitating condensate, with contour levels of 0.01, 0.03, 0.05, 0.2, and 0.5 g/kg. White dashed lines denoting domain center are shown for reference.
Figure 3. The Hovmöller plots of precipitation for three representative cases. The black lines show the centers of domain, which are also the location of SST maxima.

The Hovmöller plots of precipitation clearly show the different characteristics of the three modes (Fig 3). The precipitation oscillates around the domain center, representing propagating convectively coupled gravity wave (e.g., Kuang, 2012). In mode 1 (Fig 3a), since the SST gradient is relatively weak, the convectively coupled gravity wave can propagate far away from the center. Precipitation rate is stronger over the higher SST regions; thus, the time-averaged precipitation shows a relatively flat distribution with the peak at the center. In mode 2 (Fig 3b), the large SST gradient confines the precipitation to be close to the domain center. The rainfall band traverses through the domain center fast while staying at the flank for a longer time period. As a result, the time mean precipitation shows double peaks. The distribution of precipitation reflects the duration that convection stays. In mode 3 (Fig. 3c), the rainfall band persistently stays at one side off the center. Occasionally, it migrates to the other side, then moves back shortly, leading to an off-center precipitation peak after time average. In some cases, we also observed the situations that the rainfall band migrates to the other side and stay for a long time, which may lead to double-peak precipitation if averaging over certain time period. However, this
situation is also mode 3, since it significantly different from the periodic oscillating rain belt in model 2. To test the robustness of mode 3, we have carried out three ensemble runs for the LW6 case with different random initial perturbations. The resulting Walker cells are all in mode 3. However, for the mode 3 cases, whether the precipitation peak locates at the left or right side of the center is randomly depending on initial conditions.

Based on the above observations, we may have the following conjecture. When the SST gradient is weak, the activity of convection is mainly controlled by instability due to SST following the WTG argument (mode 1). When the SST gradient is large, deep convection preferentially stays at the region of the large SST gradient (this state is called the off-center state). The off-center state is a common feature of mode 2 and mode 3. The difference is whether the off-center state can be sustained. In mode 3, the off-center state can be self-sustained, leading to an asymmetric Walker cell. In mode 2, the off-center state cannot be self-sustained, and the rainfall band oscillates between the two sides of the center, leading to two mean precipitation peaks. In the following section, we will illustrate the basic characteristic of the off-center state and examine its sustaining mechanism.

Figure 4. A schematic for defining the off-center state. The Hovmöller plot of precipitation for case S16 is superposed with magenta triangles which denote precipitation centroids at each time step. The grey zone with margins of black dashed line indicates the middle zone, outside which is the region of the off-center state.
4. The dynamics of the off-center state

To examine the off-center state, an objective and quantitative definition is needed. Using the S16 case as an example (Fig. 4), we treat the time period when the distance between the precipitation centroids (magenta triangles) and the domain center is greater than a threshold (the black dashed lines) as the off-center state. The distance threshold is chosen dynamically for each case so that the time period of the left-side off-center state, right-side off-center state, and the rest (i.e., the at-center state) each occupies one-third of the total time period. As seen in Fig. 4, this method of separation works well. However, for the cases of mode 3 (e.g., Fig. 3c), since precipitation is at one side for most of the time, the threshold is adjusted so that the time period of the at-center state occupies one-fifth of the total time period. Our results are not sensitive to reasonable perturbations of the choice of the threshold. The at-center states of all cases are similar; the precipitation maximum, the rising branch of the Walker cell, and the minimum of surface pressure are all at the domain center. We shall mainly focus on the off-center state.

The differences between the three models of the mock-Walker cell may be illustrated by considering the moisture budget of the off-center state. Fig. 5 shows the domain mean surface evaporation (i.e., latent heat flux) and precipitation of all cases at the off-center state. For the cases of mode 1 (red markers in Fig. 5), the evaporation is greater than precipitation; thus, atmospheric moisture is charged during the off-center state and discharged during the at-center state. For the cases of mode 2 (blue markers in Fig. 5), the situation is the opposite. Precipitation is stronger than evaporation during the off-center state, indicating that the off-center state is not sustainable. For mode 3 (green markers in Fig. 5), the evaporation closely balances precipitation and thus the off-center state is sustainable as an equilibrium state.
Figure 5. Scatter plot of time-and-domain-average latent heat flux and precipitation for all cases under the off-center state. Cases of mode 1, mode 2, and mode 3 are denoted with red, blue and green markers, respectively. Cases in the three experimental groups are denoted with triangles, squares, and circles, respectively. The sizes of markers indicate the SST difference (\( \Delta \)) of each case. The black line is the one-to-one line for reference.

Figure 6. The composite off-center state. Each column is for case L2, S14, and LW14,
for demonstration. In each row, the black contours are for virtual temperature anomalies, temperature anomalies, and moisture, respectively. In all panels, the color shading shows the pressure anomalies. The vertical lines on the right of each panel show the differences of variables that the ascending branch average minus the central profile. In the panels of profiles, the bottom axes are for pressure differences (red lines), while the top axes are for other variables (black lines).

Fig. 6 shows the composites of anomalous pressure of the off-center state. Here, anomalies refer to removing horizontal means. We only show the results of the off-center state when precipitation peaks at the left-hand side; the results of the right-side off-center state are flipped using mirror transformation to increase the signal-to-noise ratio. At the off-center state, the low-level low-pressure center is at the domain center for mode 1 and mode 2. However, for mode 3, the low-level low-pressure center co-locates with the rising branch of the Walker cell off the center. The low-level winds flow toward the low-level low-pressure center, converge and ascend there, leading to large precipitation. The co-location between the pressure anomalies and precipitation is a fundamental feature of mode 3. It indicates that the off-center Walker cell may be maintained as a quasi-steady state. For mode 1 and mode 2, when the precipitation is off the center, its low-level pressure minimum is still at the center. Thus, this state is not sustainable and the rising branch of the Walker cell will migrate toward the domain center.

What causes the off-center low-level low-pressure center in mode 3? The reason may be answered by examining the planetary boundary layer (PBL) thermodynamic variables (Fig. 6). Due to the lack of the Coriolis effect, the horizontal pressure gradients are very weak above the PBL (Fig. 6). The surface pressure distribution may be calculated by the pressure lapse rate in PBL, which is determined by air density. Mathematically, it may be written as,

\[ P_s(x) = P_{TBL} + \int_{PBL}^{} \frac{Pg}{RT_v} dz, \sum(2) \]
where $P_s$ and $P_{TBL}$ are pressure at the surface and top of the boundary layer, respectively. $g$ is gravitational acceleration, and $R$ is the ideal gas constant. In Eq. 2, we use virtual temperature $T_v = T(1 + 0.608q - q_c)$ to calculate air density, since it depends on both temperature ($T$, units of K) and moisture ($q$, units of kg/kg). $q_c$ stands for non-precipitating condensate and its influence is negligible. The air column with higher (lower) $T_v$ in the PBL has lower (higher) surface pressure.

The argument by Eq. 2 is confirmed by the distribution of $T_v$ anomalies in Fig. 6 (first row). The PBL pressure anomalies are closely correlated with $T_v$ anomalies. In mode 1 and 2, the PBL $T_v$ is strongest at the center, while for mode 3, the PBL $T_v$ is strongest off the center. $T_v$ is determined by both $T$ and $q$. The PBL $T$ is strongly constrained by SST, and it is strongest at the center for all the cases (second row of Fig. 6). However, $q$ closely follows the ascending branch of Walker cells and has maximum off the center for all the cases under the off-center state (third row of Fig. 6). Moreover, as SST gradient increases, the anomalous $q$ becomes larger. At the same time, the diabatic heating associated with the anomalous $q$ also provides positive feedback for the vertical motion at the ascending the branch of the Walker cells. In mode 3, the anomalous $q$ at the ascending branch is large enough so that its effect on air density (the virtual effect of water vapor) dominates. As a result, the surface low-pressure center locates under the rising branch of the off-center Walker cell instead of at the domain center over the SST peak.

The adjustment of Walker cell and convection to off-center area is sustainable since the water vapor anomaly generated is large enough. This virtual effect also explains why precipitations in Group LW switch to mode 3 at a smaller SST gradient than Group L. The $\sigma$ is larger in Group LW, leading to smaller SST gradient around the domain center and warmer average SST. Within the same group of cases (Group L and LW), SST gradient drives the transition to mode 3. While comparing different groups, the average SST should also be considered. Warmer SST generate more water vapor that indicates stronger virtual effect.
Figure 7. Color shading in all panels show pressure perturbation reconstructed using
deviated field of temperature (the first row) and specific humidity (the second row).
The three columns are for L2, S14 and LW14, respectively. Adjacent to the contours
are profile difference between average ascending branch and central profile of
reconstructed pressure.

We may quantitatively decompose the contribution of temperature and moisture
on the PBL pressure anomalies to better demonstrate their competing effects. We
integrate Eq. 2 downward from a free tropospheric level (700 hPa). The conclusions are
not affected if we start from a different free tropospheric level). To evaluate the
contribution of temperature on PBL pressure anomalies, we calculate the $T_v$ with the
horizontally averaged $q$, and then integrate Eq. 2 downward to the surface level.
Similarly, the contribution of moisture is calculated by using horizontally averaged $T$.
The results show that temperature anomalies generate PBL high-pressure anomalies at
the center compared with ascending branch (profiles in the first row of Fig. 7),
consistent with the distribution of PBL $T$ (the second row of Fig. 6). On the other
hand, the moisture anomalies generate PBL low-pressure anomalies off the center
(second row of Fig. 7) consistent with the distribution of PBL $q$ (third row of Fig. 6).
By comparing each column in Fig. 7, one can notice that for mode 1 and mode 2, the
contribution of temperature anomalies dominates. While for mode 3, the virtual effect
dominates. Thus, this analysis confirms the key role of virtual effects in the three modes of mock-Walker cells. A schematic in Fig. 8 summarizes the key feature and processes of the tri-mode of the mock-Walker cells.

Figure 8. A schematic for three modes of precipitation. The red shading denotes warm anomalies, the blue shading denotes moist anomalies, and LPC denotes surface low-pressure center.

Lastly, we performed two series of additional simulations to test the sensitivity of our results to model resolution and background SST, respectively. In the first test, we repeated a couple of cases with doubled horizontal resolution (i.e., grid spacing of 2km). The cases are selected around the transition points in the original cases. The results (Fig. 9a, b, c) show three modes of precipitation distribution, similar with that in Fig. 1. In the second test, we repeated cases in Group L but with the background SST increased from 298K (Eq. 1) to 300K. The results (Fig. 9d) also show a transition from model 1 to model 3 when $\delta \geq 6K$, qualitatively similar with the results in Fig. 1. Those sensitivity tests indicate that the transition point may depends on the background SST or model resolution, but the tri-mode characteristic of the mock-Walker cells are robust.
Figure 9. The selected cases from (a) Group S, (b) Group L and (c) Group LW under simulations with horizontal resolution of 2km. (d) shows the simulations of Group L with warmer background SST of 300K. The rest settings are the same as that in corresponding original cases. A 4-point running mean is applied to (a) and (d); a 32-point running mean is applied to (b) and (c).

5. Conclusions and discussion

This study examines the mock-Walker cells driven by prescribed Gaussian SST using cloud-resolving simulations. With different amplitudes and widths of SST anomalies and domain sizes, the mock-Walker cells and associated precipitation in show three different modes, namely, the single precipitation peak over the SST maximum (mode 1), the symmetric double precipitation peaks straddling the SST maximum (mode 2), and the single precipitation peak at one side of the SST maximum (mode 3). The three modes are due to different characteristics of the migration of convective activity centers. When convective activity moves to the flank of SST maximum, the virtual effect of water vapor leads to surface low-pressure anomalies that further enhance convection. On the other hand, the surface
low-pressure anomalies forced by the prescribed SST always locate over the SST maximum. When the SST gradient is weak, the virtual effect is weak and the mock-Walker cell is in mode 1. As SST gradients increase, depending on whether the virtual effect may overcome the effects of SST, the convective activity may be trapped quasi-steady on one side of the SST maximum (mode 3) or migrates between two sides (mode 2). The off-center state precipitation mechanism might be related to the reduction of convection with high SST mentioned in previous studies (Lau et al., 1997).

There are some limitations in this study. For example, the SST anomalies in some experiments here are unrealistically large. Besides, we are only able to examine three groups of experiments and two series of supplementary tests; SST anomalies with other distributions are not examined due to the limitation of time and computational resources. In addition, the ocean heat transport by oceanic dynamics and atmospheric feedbacks to the SST are not included in this study. If an interactive ocean model instead of using the prescribed SST, the SST anomaly may be modified or damped. Nevertheless, our conclusions may be generalized and have implications for the tropical large-scale circulations (including the Hadley circulation) in the realistic atmosphere as well as general circulation models. The importance of the virtual effect of water vapor in the tropics is supported by other studies (e.g., Seidel and Yang, 2020; Yang et al., 2022). Moreover, the virtual effect increases as the climate warms. It is of interest to further explore the role of virtual effect in the real tropical atmosphere under global warming.

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