The Madden-Julian Oscillation and Mean Easterly Winds

Stipo Sentic1, Željka Fuchs-Stone1,2, and David J. Raymond1,2

1Climate and Water Consortium, New Mexico Tech, Socorro, NM, USA, 2Physics Department, New Mexico Tech, Socorro, NM, USA

Abstract A recent analytical model of the Madden-Julian Oscillation (MJO), the WISHE-moisture mode theory, successfully models all the main characteristics of the MJO, namely, that it is a planetary, unstable, and eastward propagating tropical mode. The main assumption of the WISHE-moisture mode theory is that an interplay between the global mean easterly zonal winds and moisture leads to the propagation and destabilization of the MJO. We investigate this theory by building a climatological MJO using reanalysis, OAFlux surface latent heat fluxes, and outgoing longwave radiation data and compare it to the WISHE-moisture mode. The necessary condition for the WISHE-moisture mode theory—easterly global mean zonal winds—is always present in the tropics. Comparing the zonal wind, moisture, and moisture tendency anomalies to the WISHE-moisture mode, we find that the WISHE-moisture mode theory is in agreement with the reanalysis-derived climatological MJO. Reanalysis and OAFlux surface latent heat fluxes are in agreement with the WISHE-moisture mode theory. Although meridional surface winds seem to contribute negatively to the surface latent heat flux anomaly, we show that their effect is secondary in the region of enhanced surface latent heat fluxes which moisten the boundary layer and lead to the propagation of the MJO.

1. Introduction

The Madden-Julian Oscillation (MJO Madden & Julian, 1972) is a 30–90 day equatorially trapped intraseasonal oscillation that influences the weather and climate both in the tropics and the extratropics (Zhang, 2013). Weather and climate prediction models do not simulate the MJO sufficiently well (Benedict et al., 2014; Jiang et al., 2015; Kim et al., 2014), which introduces uncertainty in model predictions for both the tropics and the extratropics. To better model the MJO, and consequently the weather and climate, researchers have focused on understanding the underlying mechanisms of the MJO using reanalysis, observations, and numerical and analytical models. The main mechanisms considered here are the moistening of the troposphere, the effect of mean easterlies, and their interplay.

The literature remains divided on matters of maintenance and initiation of the MJO. When it comes to moisture, some studies argue the importance of horizontal and vertical tropospheric moisture transport in propagation of the MJO (Hagos et al., 2014; Pritchard & Bretherton, 2014; Tseng et al., 2015; Zermeño Diaz et al., 2015), while others emphasize a combination of advection and surface fluxes (Maloney, 2009) or other processes like radiative feedbacks (Arnold & Randall, 2015). We focus here on discussion of maintenance and propagation and refer the reader to review papers like Zhang (2005) and Wang et al. (2018) for an exhaustive review of our current knowledge of the MJO.

For example, supporting the first school of thought, Pritchard and Bretherton (2014) did a numerical study in which they changed the intensity of the rotational component of moisture advection. Increasing that component led to a stronger and faster MJO, while decreasing that component made the MJO shut down. The authors argue that the rotational flow component is critical in MJO propagation. Other studies also emphasize horizontal and vertical advection as dominant mechanisms of MJO propagation. Adames and Wallace (2015), Chikira (2014), DeMott et al. (2014), Hsu and Li (2012), Kim et al. (2014), Maloney (2009), Tseng et al. (2015), and Zhao et al. (2013) suggest that horizontal advection of moisture is the most important term in either initiation or propagation of the MJO. Jiang (2017) suggests that determining mechanism for the eastward propagation of the MJO is vertically integrated horizontal advection of seasonal mean moist entropy by the MJO wind anomaly in the lower troposphere, while Kiranmaya and Maloney (2011) found that vertical advection has the same or larger magnitude than horizontal advection in reanalysis data.
In numerical (Andersen & Kuang, 2012; Cai et al., 2013; Pritchard & Yang, 2016; Zhang & Song, 2009) and reanalysis and observational (Benedict & Randall, 2007; Bellenger et al., 2015; Janiga & Zhang, 2016; Wolding & Maloney, 2015) studies, vertical advection of moisture and moist static energy is found to be an alternative mechanism for the MJO moistening and propagation. For example, aquaplanet global circulation model simulations by Hsu et al. (2014) suggest that the primary contributor to the boundary layer moisture budget is vertical advection of moisture, even though horizontal advection also contributes. In their simulations, the MJO becomes quasi stationary if they remove the zonal asymmetry in the moisture field from 1,000 to 850 hPa, that is, a more moist boundary layer east of the MJO and a dry boundary layer west of it.

Other studies emphasize column radiative and surface processes as more important for the MJO propagation and destabilization (Arnold & Randall, 2015; Wang et al., 2017; Wolding et al., 2016). For example, Arnold and Randall (2015) find that longwave radiation feedbacks (heating anomalies) support MJO-like disturbances in their aquaplanet simulations, more so than horizontal or vertical advection. Wolding et al. (2016) find that MJO instability is supported by radiative feedbacks and dampened by horizontal advection. Numerical simulations of Wang et al. (2017) find that vertical velocity second-order baroclinic mode contributes to the propagation of the MJO via contribution to the zonal asymmetry in the moist static energy tendency. Wolding and Maloney (2015) find that anomalous surface latent heat fluxes contribute to increased moisture content at the precipitation maximum but also that they are insufficient to destabilize the MJO without radiative feedbacks. All these studies used complex numerical models of varying degrees or reanalysis and observations to investigate propagation and maintenance of the MJO.

An alternative to complex numerical and reanalysis studies for understanding the MJO is to build simplified analytical models. An analytical model that captures the main characteristics of the MJO, that is, its eastward propagation and instability mechanism, could suggest the main mechanism behind the MJO initiation and eastward propagation. A number of idealized studies have tried to explain the main properties of the MJO, namely, that it is an eastward propagating tropical wave unstable for large planetary wave-lengths (Adames & Kim, 2016; Emanuel, 1987; 1993; Fuchs & Raymond, 2002, 2005, 2007; Lindzen, 1974; Neelin et al., 1987; Neelin & Yu, 1994; Sugiyama, 2009a; Sobel & Maloney, 2012; Wang & Rui, 1990; Yano & Emanuel, 1991; Yu & Neelin, 1994). For example, some of these models use a range of zonally varying mean zonal wind as surface forcing attempting to model the MJO, based on observed variations between the convective center of the MJO and the mean surface zonal wind (perhaps best summarized in Zhang, 2005). Lindzen (1974) assumed a stationary basic state (mean zonal wind zero) and perturbations thereof which did not lead to recreating MJO characteristics. Emanuel (1987), on the other hand, assumed a mean zonal easterly wind with the convection in phase with the strongest surface fluxes. This model reproduced some MJO characteristics. Sobel and Maloney (2012) assumed a mean westerly zonal wind characteristic of the Indo-Pacific warm pool, which produced a disturbance traveling westward, opposite of the eastward MJO propagation. Subsequent modifications of their model (Adames & Kim, 2016; Sobel & Maloney, 2013), that is, the meridional advection of moisture, led to improved modeling of the MJO characteristics. A study by Sobel et al. (2001) first introduced the idea of the MJO as a moisture mode, that is, that maximum tropospheric heating is associated with the maximum in tropospheric moisture content. Subsequent studies developed the moisture mode theory and instability further (Adames & Kim, 2016; Fuchs & Raymond, 2002, 2005, 2007; Sugiyama, 2009b; Sobel & Maloney, 2012, 2013). Other MJO theories propose that the MJO is destabilized by mesoscale convective forcing. To name a few, Majda and Stechmann (2009) present a model which reproduces the main characteristics of the MJO. The main assumption which produces this solution is that synoptic scale wave activity moistens the atmosphere and acts as a heating source for upscale transport of energy to planetary scales. Yang and Ingersoll (2013) present a nonlinear two-dimensional shallow water model of the MJO. Their results suggest that the MJO is an interference pattern of eastward and westward propagating inertia gravity waves. They argue that the MJO is not a low-frequency wave but an interference pattern of high-frequency waves. Finally, Yang and Ingersoll (2014) construct a scaling theory based on a 1-D version of the Yang and Ingersoll (2013) model, in which the horizontal scale of the MJO is proportional to the convective forcing and inversely proportional to Kelvin wave speed, suggesting that the convective forcing and high-frequency waves produce the MJO envelope. These studies reproduced some of the main characteristics of the MJO.

A recent study by Fuchs and Raymond (2017) developed a simple analytical model that captures the main characteristics of the MJO, namely, that it is an eastward propagating unstable global mode of wavenumber 1. The main assumption in their model is a form of wind-induced surface heat exchange
Figure 1. The eastward propagating WISHE-moisture mode of Fuchs and Raymond (2017).
Figure 3. Number density of MJOs for (a) OLR values of filtered OLR minima and (b) longitude position of the filtered OLR minima.

We also test the sensitivity of the zonal wind mean to the choice of latitudinal averaging boundaries. Figure 2b shows the FNL mean zonal wind for four latitude ranges: 5°S to 5°N, 10°S to 10°N, 15°S to 15°N, and 20°S to 20°N. The magnitude of the average zonal wind increases with increasing latitudinal range; the yearly average values for the zonal winds are −1.92, −2.24, −2.69, and −2.94 ms⁻¹ for 5°S to 5°N, 10°S to 10°N, 15°S to 15°N, and 20°S to 20°N, respectively. Despite this sensitivity to the choice of the latitude range, in this paper we focus on the 10°S to 10°N range because qualitatively the zonal winds for higher values of latitude behave similarly, and for comparison with other studies since this is a customary range for latitudinal averaging. Also, we focus on FNL data since the other reanalyses show qualitatively similar results.

Figure 2 shows that the globally averaged mean zonal winds are always easterly and never globally westerly, for all the days of the year, which suggests that the necessary conditions for the development of the MJO in the WISHE-moisture mode paradigm (Fuchs & Raymond, 2017) are always present.

3. MJO Composite

In this section we construct a composite MJO from a large set of MJOs from reanalysis and OAFlux data, and compare it to the Fuchs and Raymond (2017) WISHE-moisture mode. Here we use only FNL reanalysis out of the reanalysis used in the previous section.

3.1. Data and Method

We use the Wheeler-Kiladis space-time spectral analysis (Wheeler & Kiladis, 1999) to identify the location of each MJO in the NOAA Interpolated Outgoing Longwave Radiation (OLR, Liebmann & Smith, 1996) for the time period from 2000 to 2016. First we use the Wheeler-Kiladis filter to produce the anomalous OLR for wavenumbers 1 to 5 and periods from 30 to 90 days. From the filtered anomalous OLR we can find the position of the local minima in space and time as the reference point for each MJO case. The climatology below is done by collocating all the variable fields relative to the reference point for each MJO case (minimum of the anomalous OLR) and averaging them, thus producing a longitude-time map of the variables relative to the MJO OLR minimum. Variables we use are the 10 m zonal and meridional wind (u and v, respectively), water vapor mixing ratio (mr), water vapor mixing ratio tendency (\(\partial m_r / \partial t\)), and surface latent heat flux from the FNL reanalysis and the OAFlux data set (F). In the figures below the reference point is always at 0 day time and 0° longitude.

The Wheeler-Kiladis objective identification of the MJO leads to detection of both weak and strong signals, and for this data set we get filtered anomalous OLR minimum values between −38 and −1 W m⁻². Figure 3 shows the number distribution of detected MJOs versus OLR values of filtered OLR minima and longitude position of the filtered OLR minima. Most of the detected MJO cases occur between 50° and 200° longitude. Cases outside this range could be false signals so we exclude them. We also exclude OLR signals weaker than −11 W m⁻² to exclude further possible false signals. Thus, out of 190 detected signals for the period from 2000 to 2016 we keep 109 cases. Out of the 109 cases we remove 7 due to double counting.
when the same MJO has two local minima in the filtered OLR. This gives us six MJO cases per year, which is consistent with the frequency of MJOs reported in other studies (e.g., Zhang, 2005, reports 2–12 MJOs per year). We produce anomalies of the variables by subtracting a 3 month climatology for each MJO case to remove seasonal and annual Hadley cell changes (e.g., if a case occurs in November, we subtract the September–October–November climatology from each variable for that case). The 3 month climatology corresponds to December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON) periods.

We analyze surface latent heat fluxes for the WISHE mechanism of Fuchs and Raymond (2017). Since the WISHE-moisture mode has zero meridional wind solution, it would be interesting to see which surface wind component dominantly contributes to the surface fluxes in the reanalysis. First, we compute the bulk surface latent heat flux (Yu et al., 2008):

\[ F = (u^2 + v^2)^{1/2}CL_v \rho_0 (m^*_v - m_r), \]  

where \( m^*_v \) is the saturated water vapor mixing ratio, \( \rho \) is density, \( L_v \) is the latent heat of vaporization, and \( C \) the turbulent exchange coefficient. Due to predominantly zonal mean horizontal wind, we can define the wind components as follows: \( u = U + u', v = v' \), where \( U \) is the mean zonal wind, and \( u' \) and \( v' \) the zonal and meridional wind anomalies, respectively. Then,

\[ (u^2 + v^2)^{1/2} = (U^2 + 2Uu' + u'^2 + v'^2)^{1/2} \approx U(1 + 2u'/U)^{1/2} \approx |U(1 + u'/U)| \approx |U + u'|, \]  

which suggests that the meridional wind effect on surface latent heat fluxes goes away in the low-amplitude limit and that the dominant component contributing to the surface latent heat fluxes is the zonal wind. While the globally averaged zonal wind is certainly easterly, the mean zonal wind varies longitudinally. While it is strongly easterly in the Pacific, it is weak and sometimes weak westerly in the warm pool. This suggests that equation (2) holds over the Pacific where \( U \ll U \) and in the warm pool both wind components can contribute to the bulk surface flux due to low zonal wind strength. Furthermore, the anomalies of the surface latent heat flux should show a dependence on the anomalies of the wind components. The wind contribution to the bulk surface latent heat flux is \( |\vec{v}| = (U + u')^2 + v'^2)^{1/2} \), which can be approximated by a zonal and a meridional contribution:

\[ \Delta |\vec{v}| \approx [(U + u')^2 + 1 - U = u' \left( \frac{u'}{U} \right) U, \]  

\[ \Delta |\vec{v}| \approx [U^2 + v'^2]^{1/2} - U = \left[ (1 + \frac{v'^2}{U^2})^{1/2} - 1 \right] U, \]  

where \( [(1 + v'/U)^2 - 1] < v'/U \) since \( 1 + v'/U > (1 + v'^2/U^2)^{1/2} \) due to the Pythagoras theorem. The meridional wind contribution to the bulk surface latent heat flux anomaly is mathematically much smaller for strong zonal winds, that is, in the Pacific, outside of the warm pool. To quantify the influence of zonal wind on the surface flux, we use

\[ F_Z = |u|CL_v \rho_0 (m^*_v - m_r), \]  

and we quantify the contribution of the meridional wind to the surface flux by

\[ F_M = F - F_Z. \]  

Note that we use \( u \), not \( u' \), for calculating the zonal component of the surface latent heat flux \( F_Z \). In the next subsection we show the anomalies of the surface latent heat flux and its components (\( \Delta F, \Delta F_Z \), and \( \Delta F_M \)), obtained with the same compositing procedure discussed above.

### 3.2. Reanalysis Anomalies

First we look at the MJO composite obtained from all 102 identified MJO cases. In the next subsection we test the sensitivity of our results to the global mean zonal wind strength.

Figure 4 shows anomalies of the 10 m zonal wind, the water vapor mixing ratio, the water vapor mixing ratio tendency averaged from 100 to 850 hPa, and the water vapor mixing ratio tendency averaged from 850 to 1,000 hPa, relative to the anomalous OLR minimum found at zero time and longitude. Previous research
has identified the MJO standard characteristics (e.g., Benedict & Randall, 2007; Hsu et al., 2014; Madden & Julian, 1972; Sentic et al., 2015; Zhang, 2013), some of which are enhanced westerly wind anomaly west of and enhanced easterly wind anomalies east of the OLR minimum (Figure 4a), a high water vapor mixing ratio associated with the precipitating region of the MJO (Figure 4b), and a 7 m s$^{-1}$ propagation speed (Figures 4a–4d). We also identify moistening and drying in the free troposphere (850 to 100 hPa, Figure 4c), and the boundary layer (1,000 to 850 hPa, Figure 4d). There is a positive tropospheric mixing ratio tendency east of and a negative west of the MJO convective center propagating at the speed of 7 m s$^{-1}$. The boundary layer tendency shows a similar pattern propagating at approximately 20 m s$^{-1}$. The boundary layer moistening extends further to the east than the tropospheric moistening. The WISHE-moisture theory is consistent with lower atmospheric moistening well east of the convecting region and the transition of this moistening into the troposphere supporting deep convection observed in the reanalysis data. Hsu et al. (2014) found that if they remove the boundary layer moisture dipole (a positive moisture anomaly east of and a negative west of the MJO convective center) in their simulations from 850 to 1,000 hPa, the MJO-like phenomenon becomes quasi stationary. This suggests that the boundary layer moisture in their model is important for the propagation of the MJO. To test the WISHE part of the theory, we next look at surface fluxes.
Figure 5. (a) OAFlux surface latent heat flux anomaly, (b) FNL reanalysis surface latent heat flux anomaly, (c) FNL surface latent heat flux anomaly calculated using only the zonal wind, and (d) a measure of the meridional wind influence on the FNL surface latent heat flux anomaly. The white guide lines are the same as in Figure 4. Only data significant to the 95th percentile are shown.

Figure 5 shows OAFlux surface latent heat flux anomalies, reanalysis FNL surface latent heat flux anomalies, the FNL surface flux anomaly calculated using only the zonal wind (equation (5)), and the contribution of the meridional wind to the FNL surface fluxes (equation (6)) derived in section 3.1. While we notice a similar spatial pattern in both OAFlux and FNL surface fluxes (Figures 5a and 5b), the FNL reanalysis seems to overestimate the strength of the surface fluxes. The full latent heat surface fluxes and the zonal component (Figures 5a–5c) show similar moistening features: enhanced surfaces fluxes around 0° and 90° longitude in the time period from −10 to 10 days. We see, however, that the 90° longitude signal is dominantly stronger over a larger surface in the zonal surface flux component (Figure 5c). The meridional wind contribution to the surface fluxes (Figure 5d) is much smaller east of the convective center (east of the slanted white line), consistent with our mathematical decomposition shown in section 3.1. The meridional component contributes positively to the surface fluxes west of the convective center, with a slightly higher magnitude than the zonal contribution. Again, this is consistent with the mathematical explanation from section 3.1; the region around the convective center (0 day time and 0° longitude) is usually found in the warm pool region (Figure 3c) where the mean zonal wind is climatologically low in magnitude (|U| ≈ 0) which makes the zonal component of the surface flux anomaly similar in magnitude to the meridional component. Out toward 90° latitude is the mean zonal wind climatologically strong (|U| ≫ 0) which gives a much stronger zonal wind influence on the surface heat flux than the meridional wind component (equations (3) and (4).
The position of the surface flux maximum (Figures 5a–5c), about 90° longitude, coincides with the region of minimum easterly zonal wind anomaly (Figure 4a). The boundary layer moistening (Figure 4d), however, is displaced a few days prior to the surface flux maximum seen in Figure 5. This suggests that the moistening might be influenced by effects other than just the surface fluxes. Fuchs and Raymond (2017) acknowledge that nonlinear effects like advection need to be implemented in the WISHE-moisture mode theory in future work; these nonlinearities could affect the phase between the moistening in the boundary layer and surface fluxes. As other research suggests (Adames & Wallace, 2015; Chikira, 2014; DeMott et al., 2014; Hsu & Li, 2012; Kim et al., 2014; Maloney, 2009; Tseng et al., 2015; Zhao et al., 2013), horizontal advection of moisture might be an important influence on the boundary moisture content which might influence the relationship between the boundary layer moistening and surface fluxes.

These results suggest that the WISHE-moisture mode explains the influence of the surface zonal wind on the MJO. Moistening of the boundary layer east of the MJO convective center is associated with the increased anomalous surface fluxes east of the MJO convective center. Further refinements need to be made to the Fuchs and Raymond (2017) model to capture the effects of the meridional wind and nonlinearities which influence the phase between boundary layer moistening and surface fluxes.

### 3.3. Sensitivity to Global Mean Zonal Wind Strength

The WISHE-moisture mode is sensitive to the strength of the mean zonal wind. It is unstable only for strong enough mean zonal winds (Fuchs & Raymond, 2017). As shown in section 2, global mean zonal winds are...
always easterly in the tropics. In this section we compare composite MJOs for weak and strong mean global easterly winds. We first filter the zonal wind in time with a low pass Lanczos filter (with a 60 day cutoff period), in order to filter out variations of the zonal wind due to changes induced by the MJO. Next, we define the strength of the zonal winds as the strength of the globally mean zonal winds on the day of the minimum OLR for each detected MJO event (there is little difference if we average over a 20 day period). After ordering the cases by the strength of the zonal wind, we select the cases for two quartiles. The first quartile of globally mean zonal winds gives weak zonal wind cases (Q1, mean of $-1.9 \text{ ms}^{-1}$ for 25 cases), and the fourth quartile gives stronger zonal wind cases (Q4, mean of $-2.6 \text{ m s}^{-1}$ for 25 cases).

Figure 6 shows the same fields as Figure 4, left panels for weak mean global zonal winds (Q1) and right panels for strong mean global zonal winds (Q4). While the strong zonal wind cases have characteristics similar to the full composite from section 3.2 (Figure 4), the weak zonal wind cases have significant differences. The zonal wind anomaly shows a stronger westerly component, while the mixing ratio and mixing ratio tendencies show a weaker moisture mode and less statistically significant moistening-drying pattern compared to the strong zonal wind case.

We compare the surface fluxes for weak and strong zonal wind cases in Figure 7. Again, the strong zonal wind cases have the same surface flux characteristics as the full composite from section 3.2 (Figure 5). The weak zonal wind cases show a statistically less significant pattern, differing also in pattern from Figure 5.
meridional component of the wind dominates the surface flux pattern, while the zonal component barely shows a signal compared to the strong zonal wind case.

These results suggest that the strength of the mean global zonal wind does play a significant role in the MJO destabilization and propagation and that the WISHE-moisture mode mechanism of moistening and propagation does exist in reanalysis and OAFlux data, for stronger mean zonal winds.

4. Summary and Conclusions

In this paper, we compare the WISHE-moisture mode of Fuchs and Raymond (2017) as a model for the MJO with reanalysis and OAFlux data. The simple analytical theory of Fuchs and Raymond (2017) models three main characteristics of the MJO, namely, that it is a planetary, unstable, and eastward propagating mode. The main hypothesis of the Fuchs and Raymond (2017) model is that enhanced surface latent heat fluxes, associated with global easterly zonal winds, and their interplay with tropospheric moisture destabilize the atmosphere east of the MJO center of convective activity and induce an instability and moistening which propagates the MJO. Their model assumes mean easterlies moistening the atmosphere east of the MJO. This premoistening at some point reaches its critical value at which time deep convection develops. Deep convection then acts to enhance the surface fluxes to the east of the MJO. It is this interplay between moisture and surface fluxes that governs the MJO’s eastward propagation and instability mechanism. We check reanalysis and OAFlux data for the presence of the WISHE-moisture mode.

Zonal wind reanalysis averages (section 2) show that the necessary condition for the MJO existence suggested by Fuchs and Raymond (2017), namely, that mean zonal winds are easterly on the global scale in the tropics, is always present. From reanalysis we computed a composite (section 3) over a large number of identified MJOs (190 cases, using Wheeler-Kiladis filtering of observed OLR, of which we used 102 in this study). We find that the composite MJO characteristics are in agreement with the WISHE-moisture mode theory of Fuchs and Raymond (2017). Easterly zonal wind anomaly minimum is associated with a positive latent heat surface flux anomaly. We mathematically show that the zonal wind component contributes more to the surface flux and the surface flux anomaly, while the meridional wind contribution to the surface fluxes can be significant in areas where the mean zonal wind is low (e.g., in the warm pool). We found this to hold for the surface flux anomalies in reanalysis data. These results suggest that the WISHE-moisture mode is consistent with the zonal component of the MJO in reanalysis data, but it requires further refinement to capture the meridional wind effects on the surface fluxes.

We tested the sensitivity of the composite MJO to global zonal wind strength. The composite MJOs under weak (first quartile of the zonal wind magnitude) and strong (fourth quartile of the zonal wind magnitude) mean global zonal winds show significant differences. While strong zonal wind cases preserve the WISHE-moisture mode characteristics present in the full composite, the weak zonal winds case loses many of the characteristics. This suggests the presence of the WISHE-moisture mode in reanalysis and OAFlux data. However, OAFlux data suggest the reanalysis surface latent heat fluxes are overestimated. Despite this, qualitative patterns are present in both data sets.

While the reanalysis data captures many aspects of the simplified model, there is room for improvement. Fuchs and Raymond (2017) suggest that future versions of their model should include nonlinear effects like advection and warm pool dynamics in order to better represent the MJO. Furthermore, these results are consistent with the numerical studies by Khairoutdinov and Emanuel (2018) and Shi et al. (2018), who found that homogenizing surface fluxes and removing the WISHE mechanism completely removes the MJO-like disturbance in their simulations. Hsu et al. (2014) found that removing the 850 to 1,000 hPa moisture dipole anomaly in their simulations produces a quasi stationary MJO. While these studies are idealized and do not include areas of mean state westerlies, they still show the importance of the WISHE mechanism for the MJO. Maloney and Sobel (2004) do include regions of mean state westerlies and show with sensitivity numerical experiments that the WISHE mechanism is important in their simulations. They get a much weaker MJO-like disturbance if they prescribe a climatologically fixed surface forcing.

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