Radiative Feedbacks Associated with the Madden–Julian Oscillation

BOSONG ZHANG

Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida

RYAN J. KRAMER

Climate and Radiation Laboratory, NASA Goddard Space Flight Center, Greenbelt, and Universities Space Research Association, Columbia, Maryland

BRIAN J. SODEN

Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 20 February 2019, in final form 16 July 2019)

ABSTRACT

Radiative kernels derived from *CloudSat/CALIPSO* measurements are used to diagnose radiative feedbacks induced by the Madden–Julian oscillation (MJO). Over the Indo-Pacific warm pool, positive cloud and water vapor feedbacks are coincident with the convective envelope of the MJO during its active phases, whereas the lapse rate feedback shows faster eastward propagation than the convective envelope. During phase 2/3, when the convective envelope is over the Indian Ocean, water vapor exhibits a vertically coherent response, with the largest anomalies and strongest feedback in the midtroposphere. Though spatial structures of the feedbacks vary, the most prominent difference lies in the magnitude. Cloud changes induce the largest radiative perturbations associated with the MJO. It is also found that the strength of the cloud feedback per unit of precipitation is greater for strong MJO events, suggesting that the strength of individual MJO events is largely dictated by the magnitude of cloud radiative heating of the atmosphere. In addition, stronger radiative heating due to water vapor and clouds helps the MJO survive the barrier effect of the Maritime Continent, leading to farther eastward propagation. These results offer process-oriented metrics that could help to improve model simulations and predictions of the MJO in the future.

1. Introduction

The Madden–Julian oscillation (MJO; Madden and Julian 1972; Zhang 2005) is an important driver of tropical intraseasonal variability. The active phase of the MJO is characterized by numerous convective systems that form a large eastward-propagating convective envelope through interactions between circulation, clouds, radiation, and water vapor. However, our understanding of the MJO is limited and it is poorly simulated in most general circulation models (GCMs; Lin et al. 2006; Kim et al. 2009; Hung et al. 2013; Jiang et al. 2015).

Theories related to the MJO have been debated over the last several decades. Recent studies have viewed the MJO as a coupled Kelvin–Rossby wave (B. Wang et al. 2016; Liu and Wang 2017), a large-scale envelope of small-scale gravity waves (Yang and Ingersoll 2013, 2014), or a large-scale envelope of synoptic-scale waves (Majda and Stechmann 2009). On the other hand, previous studies have viewed the MJO as a moisture mode (Neelin and Yu 1994; Raymond 2001; Sobel et al. 2001; Maloney 2009; Raymond and Fuchs 2009; Sobel and Maloney 2012, 2013; Adames and Kim 2016). Considering the importance of moisture, column-integrated moist static energy (MSE) is often used to diagnose the MJO (Sobel and Maloney 2013; Sobel et al. 2014). MSE (denoted as h) is defined as

$$h = c_p T + gz + L_v q,$$

where c_p is the specific heat of dry air, T is the air temperature, g is the gravitational acceleration, z is the

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-19-0144.s1>.

Corresponding author: Bosong Zhang, bosong.zhang@rsmas.miami.edu

height above the surface, L_v is the latent heat of vaporization, and q is the specific humidity. The budget of the column-integrated MSE (denoted as $\langle h \rangle$) is computed as

$$\frac{\partial h}{\partial t} = \text{THF} + \text{SW} + \text{LW} - \nabla_h \cdot \mathbf{v}h$$

where THF is the surface turbulent heat flux including latent and sensible heat flux, SW and LW are the net shortwave and longwave heating, and $\nabla_h \cdot \mathbf{v}h$ is the horizontal divergence of the column-integrated flux of h . Angle brackets represent column integration. In the budget equation, one major source of SW and LW is cloud- and water-vapor-induced radiative changes. During active phases of the MJO, an enhanced amount of cloud and water vapor reduces radiative cooling of the atmosphere. Together with diabatic heating due to condensation, this anomalous heating is balanced by stronger upward convection, which further increases moisture in the atmosphere. This cloud–moisture–radiation interaction provides a positive feedback to maintain the enhanced convection associated with the MJO (Chikira 2014; Kim et al. 2015; Wolding and Maloney 2015; Janiga and Zhang 2016; S. Wang et al. 2016; Wolding et al. 2016; Adames 2017).

Multiple past studies have considered the importance of radiative feedbacks as a driver of the MJO. Ciesielski et al. (2017) found that cloud–radiative feedbacks help maintain a mature MJO as it moves eastward based on in situ observations, while Del Genio and Chen (2015), using radar and satellite data, found that positive radiative heating anomalies become large before the MJO peak and remain high afterward. In numerical model simulations, it has been found that cloud–radiation interactions are necessary for intraseasonal moisture modes (Sobel and Maloney 2013) and make large-scale convective instability possible (Raymond 2001; Fuchs and Raymond 2002; Fuchs and Raymond 2005). Similarly, Kim et al. (2015) evaluated simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) and suggested that the cloud–radiation interaction is a crucial process for GCMs to correctly represent the MJO. Based on a linear wave theory developed by Sobel and Maloney (2013), Adames and Kim (2016) found a dependence of the MJO's spatial scale on the cloud–radiative feedbacks. In mechanism-denial experiments where radiative processes are eliminated or suppressed, cloud–radiation interactions are also found to be essential to MJO-like disturbances (Arnold and Randall 2015; Khairoutdinov and Emanuel 2018). By comparing simulations in which clouds are transparent to radiation versus those where

clouds are allowed to interact with radiation, Crueger and Stevens (2015) found that cloud radiative effects lead to a more realistic mean state and a stronger MJO. In aquaplanet simulations, when longwave cloud–radiative feedbacks are turned off, the MJO-like disturbances become weaker with a smaller zonal scale (Shi et al. 2018), or disappear completely (Andersen and Kuang 2012).

Despite these efforts to clarify the effects of radiative changes on the MJO, the relative contributions from individual feedbacks have not been evaluated yet. Kim et al. (2015) examined the role of longwave radiative changes using a ratio of the outgoing longwave radiation (OLR) anomaly to precipitation anomaly, while Del Genio and Chen (2015) separated radiative heating into its LW and SW components. However, these approaches assess total heating changes only. Such radiative heating changes can be further decomposed into contributions from different components such as temperature, albedo, water vapor, and cloud. Doing so quantitatively can provide greater insights into the processes by which radiative changes drive the MJO. Thus, a detailed feedback analysis including illustrations of its spatial and temporal evolution is worthwhile.

In this study, the MJO-related feedbacks (including the Planck, lapse rate, water vapor, albedo, and cloud feedbacks) are investigated separately using observationally derived radiative kernels. To explore the extent to which a single feedback influences the MJO, both the magnitude and spatial structure of these feedbacks are examined. We show that cloud radiative heating of the atmosphere, coincident with the convective envelope of the MJO, dictates the strength of individual MJO events, as measured by the magnitude of precipitation. In addition, we show how water vapor feedback and cloud feedback coevolve zonally with precipitation for MJO events that propagate across the Maritime Continent (MC) and compare to those blocked by it. The results indicate that stronger radiative heating over the MC favors farther eastward propagation of the MJO.

The paper is structured as follows. Section 2 includes methods and data used in this study. Main results are presented in section 3 with an analysis of the spatial structure of individual feedbacks and their correlations with the MJO. A summary of the results and discussion are presented in section 4.

2. Methods and data

a. Definition of the MJO

To identify active phases of the MJO, the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) is used in this study. It is based on a pair of

empirical orthogonal functions (EOFs) of the combined fields of 850-hPa zonal wind, 200-hPa zonal wind, and OLR. Two leading time series from the EOFs are called RMM1 and RMM2, and the amplitude of the RMM index is defined as $|\text{RMM}| = \sqrt{\text{RMM1}^2 + \text{RMM2}^2}$. Following common practice, when the amplitude of the RMM index is greater than one, we consider the MJO to be strong. In addition, RMM1 and RMM2 are used to locate the enhanced convective envelope of the MJO, in which a two-dimensional phase space defined by them is separated into 8 phases: specifically, phases 8 and 1 for the Western Hemisphere and Africa, phases 2 and 3 for the Indian Ocean, phases 4 and 5 for the Maritime Continent, and phases 6 and 7 for the western Pacific [Fig. 7 in [Wheeler and Hendon \(2004\)](#)]. We note that the results of this analysis are not sensitive to the choice of the MJO index used. For example, similar conclusions are obtained if we use the OLR-based MJO index (OMI; [Kiladis et al. 2014](#)) instead of the RMM index (not shown).

To investigate connections between water vapor feedback, cloud feedback, and MJO-related precipitation, an MJO tracking method developed by [Ling et al. \(2014\)](#) is used to identify individual MJO events [also outlined in detail by [Zhang and Ling \(2017\)](#)]. This method provides quantitative information of individual MJO events, including its starting and ending longitudes and dates. Thus, corresponding feedbacks during individual MJO events can be quantified. The pentad mean Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) rainfall ([Xie and Arkin 1997](#)) is used to track the MJO events.

b. Radiative kernels

In this study, radiative kernels are used to diagnose the MJO-related feedbacks. Radiative kernels describe the differential response of the radiative fluxes to incremental perturbations in the radiative feedback variables (e.g., temperature, water vapor, clouds, and surface albedo). The use of radiative kernels enables one to decompose a feedback into two parts: one that depends on the radiative transfer algorithm and the unperturbed climate state, and a second factor that arises from the climate response of the feedback variables. By cleanly separating the radiative feedbacks in this manner, the relative importance of different responses in the feedback variables can be readily quantified. Here, we use radiative kernels derived from *CloudSat*/*CALIPSO* measurements ([Kramer et al. 2019](#)), which are free from GCM bias and thus better suited for evaluating feedbacks in observations. Further details regarding the radiative kernel method can be found in [Soden et al. \(2008\)](#).

The radiative kernel for a particular feedback variable x is defined as $K^x = \partial R / \partial x$, where R is the net top-of-atmosphere (TOA) or surface radiative flux, and x is an individual radiative state variable (e.g., temperature, water vapor, clouds, or surface albedo). We separate the temperature change into two components: $x_T = x_0 + x_L$, where x_0 refers to vertically uniform temperature change throughout the troposphere, and x_L refers to the departure of the temperature change from that at the surface. Following [Soden et al. \(2008\)](#), the feedback associated with x_0 is referred to as the Planck feedback, and that with x_L is the lapse rate feedback. The TOA radiative perturbation induced by a change Δx is then approximated as $K^x \Delta x$. For the changes in x associated with the propagation of the MJO, we use two different data sources. One is daily output of temperature, water vapor and surface albedo from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-I; [Dee et al. 2011](#)), which have a horizontal resolution of $2.5^\circ \times 2.5^\circ$. We use the reanalysis data from 1979 to 2016, providing a long period of record. In addition to the ERA-I, we use daily retrievals of temperature and water vapor from the Atmospheric Infrared Sounder (AIRS) Version 6 (V6) Level 3 (L3) product ([Tian et al. 2013](#)), and radiative fluxes from Clouds and the Earth's Radiant Energy System (CERES; [Wielicki et al. 1996](#)) Synoptic Radiative Fluxes and Clouds product (SYN; [Doelling et al. 2013](#); [Rutan et al. 2015](#)) to verify the robustness of our results. These data range from 2003 to 2015. Each variable is composited into eight phases of the MJO to represent the perturbation state. We define the long-term average of each variable as the base state. The climate response of x is computed as the difference between the perturbation state and the base state.

Using the radiative kernel technique, feedbacks can be defined at the TOA or the surface (SFC). Differencing the net radiative fluxes between the TOA and SFC gives the impact of changes in a feedback variable on the radiative heating within the atmospheric column (ATM). In the tropics, model simulations suggest that changes in atmospheric radiative heating are important for convective aggregation ([Muller and Bony 2015](#)). In observations, it has been found that radiative feedbacks play significant roles in the MJO ([Kim et al. 2014](#); [Sobel et al. 2014](#)). Further, [Arnold and Randall \(2015\)](#) suggested that convective aggregation and the MJO show similar MSE budgets, and both are supported by diabatic feedbacks. The MJO, consisting of clusters of self-organized convection, is thus tightly connected with radiative conditions of the atmosphere. In this sense, we focus on feedbacks in ATM, which are also known to constrain condensational heating, and thus precipitation changes

FIG. 1. Maps of the atmospheric radiative feedbacks: (a) Planck, (b) lapse rate, (c) water vapor, (d) cloud feedbacks (unit: W m^{-2}), and (e) precipitation anomalies (unit: mm day^{-1}).

(Held and Soden 2006; Pendergrass and Hartmann 2014; Fläschner et al. 2016).

3. Results

Figure 1 shows maps of the Planck feedback (Fig. 1a), lapse rate feedback (Fig. 1b), water vapor feedback (Fig. 1c), cloud feedback (Fig. 1d), and precipitation (Fig. 1e) composited for phases 1/8, 2/3, 4/5, and 6/7. Here, positive (negative) values indicate anomalous radiative heating (cooling) of the atmosphere. We note that compared to the feedbacks illustrated in Fig. 1, the albedo feedback is the weakest with a magnitude of $\sim 0.01 \text{ W m}^{-2}$ (not shown). This is consistent with previous evaluations of the atmospheric albedo feedback in model simulations of anthropogenic climate change (Fläschner et al. 2016). Since the albedo feedback is negligible, it will not be discussed further in this study. Through the MJO's lifetime, the water vapor and cloud feedbacks show overall eastward-propagating patterns, which generally follow the convective envelope of the MJO (where precipitation anomalies are positive). In contrast, eastward propagation is not present in the Planck feedback while the lapse rate feedback exhibits faster eastward propagation than the convective envelope. In both cases maximum values do not overlap with the convective envelope of the MJO. However, the spatial pattern in the lapse rate feedback is reminiscent of the first baroclinic structure of the MJO, in which the first baroclinic structure in geopotential height corresponds to the largest temperature anomalies in the MJO (Rui and Wang 1990; Hendon and Salby 1994; Kiladis et al. 2005; Adames and Wallace 2014). A further assessment of vertical profiles of the lapse rate feedback over the tropics (not shown) suggests that the feedback

changes signs at different atmospheric levels during phase 2/3, which, when integrated vertically through the entire atmospheric column, leads to a near-neutral to slightly negative feedback over the Indian Ocean as shown in Fig. 1.

Figure 2 shows vertical profiles of water vapor anomalies (Fig. 2, top) and water vapor feedback (Fig. 2, bottom) averaged over regions noted in the caption, which correspond to the typical location of the MJO's convective envelope for each phase. To equate perturbations in water vapor with perturbations in temperature while maintaining a fixed mean relative humidity at each level, we define $\delta\omega = \delta w/\xi$, in which $\xi = (\bar{w}/\bar{w}^s)(dw^s/dT)$; here w is specific humidity and w^s is saturation specific humidity (Soden et al. 2008). The water vapor anomalies ($\delta\omega$) are expressed in units of kelvin to more clearly reveal their impact on heating rates. The readers are referred to Fig. S1 in the online supplemental material for a comparison between the original water vapor anomalies, the scaled water vapor anomalies and the water vapor feedback throughout the eight phases of the MJO, in which evolution of the original water vapor anomalies is in agreement with previous studies using reanalysis, radiosonde or satellite data (Kiladis et al. 2005; Tian et al. 2006; Tian et al. 2010).

Here, we find that the profiles exhibit a uniform structure in the troposphere throughout the MJO's lifetime. During phase 2/3, positive values of water vapor extend from the surface to about 200 hPa, with a peak of about 2 K in the midtroposphere. However, the water vapor feedback does not exactly match the structure of the water vapor profile. For example, the feedback is negative in the lower troposphere (from the surface to 700 hPa) except during phase 6/7. The magnitude of the negative feedback

FIG. 2. Composites of (top) vertical profile of water vapor anomalies (unit: K) and (bottom) vertical profile of water vapor feedbacks (unit: W m^{-2}) during phases (from left to right) 1/8, 2/3, 4/5, and 6/7. Each profile is averaged over a latitude belt of 15°S – 15°N , and 15° – 45°E for phase 1/8, 60° – 90°E for phase 2/3, 105° – 135°E for phase 4/5, and 150°E – 180° for phase 6/7.

is much smaller than the positive feedback in higher levels, however. Thus, the vertically integrated net water vapor feedback is positive, and coincident with the convective envelope of the MJO, as shown in Fig. 1.

Spatial structure of the feedbacks is important during different MJO phases. On the other hand, we note that these feedbacks are of different orders of magnitude, which implies varied levels of contribution to the MJO. The Planck feedback, lapse rate feedback, and water vapor feedback exhibit an order of 1.0 W m^{-2} , whereas the cloud feedback dominates over the convectively active regions of the MJO with an order of about 10.0 W m^{-2} , roughly 10 times as strong as the other feedbacks. In Fig. 1, the cloud feedback exhibits positive values coincident with the convective envelope of the MJO, indicating significant radiative heating of the atmosphere due to cloud changes. This radiative heating can be attributable to specific types of clouds.

To quantify the extent to which different cloud changes contribute to the total cloud feedback, we separate the MJO-related cloud feedback into contributions from high, middle, and low clouds based on the relative contributions from their LW and SW components. Details of this classification method can be found in Webb et al. (2006). Here, Fig. 3 displays feedbacks from high cloud changes (Fig. 3, left) and low plus middle cloud changes (Fig. 3, right). Positive values of

high cloud feedback are largest and coincident with regions of strong convection, while low and middle clouds contribute only a small fraction to the total feedback during active phases of the MJO. Therefore, high cloud feedback plays a more important role in the radiative heating of the atmosphere compared to the other cloud feedbacks.

The dominance of high cloud feedback shown here is in line with previous studies. Tian and Ramanathan (2002) showed that tropical high clouds play an important role in the atmospheric radiative heating. Using radar and sounding observations, Ciesielski et al. (2017) showed that during the MJO active phase, fluctuations in the cloud radiative forcing are sensitive to changes in high clouds. From another perspective, the MJO can be viewed as clusters of aggregated convection. In numerical simulations, cloud radiative heating is found to be essential to convective aggregation and the MJO-like disturbances (Lin and Mapes 2004; Andersen and Kuang 2012; Sobel and Maloney 2013; Arnold and Randall 2015; Crueger and Stevens 2015; Muller and Bony 2015; Khairoutdinov and Emanuel 2018).

To compare the MJO-related feedbacks and its convective activity more precisely, we investigate the relationship between the daily radiative heating of the atmosphere due to water vapor and clouds, and the strength of individual MJO events. Daily resolved

FIG. 3. Maps of (left) high cloud feedback, and (right) low plus middle cloud feedback during phases (from top to bottom) 1/8, 2/3, 4/5, and 6/7 (unit: W m^{-2}).

feedbacks are computed using radiative kernels and the corresponding daily perturbations in temperature, water vapor and cloud radiative effects (computed relative to their corresponding daily resolved climatology). We identify an ensemble of individual MJO events, and the starting and ending dates of each event, using the precipitation-based tracking method outlined in section 2. Since the MJO is an intraseasonal variability, both the precipitation and daily feedbacks are filtered by a two-dimensional fast Fourier transform to obtain the large-scale (zonal wavenumbers 1–10) eastward-propagating intraseasonal (20–100 day) signals (Kiladis et al. 2005). With the retrieved starting and ending dates, we match the daily feedbacks with the identified MJO events temporally and spatially.

Over the Indo-Pacific warm pool, the interaction of an individual MJO event with the MC is found to be crucial for dictating both the strength and zonal propagation of the MJO. Previous studies have shown that the MJO tends to weaken over the MC, and several possible reasons have been suggested for this barrier effect of the MC (Rui and Wang 1990; Hendon and Salby 1994; Maloney and Sobel 2004; Hsu and Lee 2005; Sobel et al. 2008; Adames and Kim 2016; Kim et al. 2016; Zhang and Ling 2017). Here, we show the zonal evolution of the feedbacks associated with the tracked MJO events, with particular attention to their strengths over the MC. Following Zhang and Ling (2017), we analyze the MJO events initiated over the Indian Ocean with starting longitudes between 30° – 100°E , and separate them into

two groups based on their ending longitudes; that is, MJO-C events that propagate across the MC (ending longitude greater than 150°E) and MJO-B events that are blocked by the MC (ending longitude less than 150°E). To examine the coevolution of the feedbacks and the strength of the MJO, the daily feedbacks and the MJO-related precipitation are computed as a function of longitude after a meridional average over 15°S – 15°N .

The composite magnitude of the precipitation and feedbacks are illustrated in Fig. 4 for the two MJO groups. In Fig. 4a, the MJO-related precipitation declines from about 90° to 120°E for both MJO-B and MJO-C, indicating a weakening of convection as the MJO approaches the MC. From 120° to 160°E , precipitation restrengthens for MJO-C only. In addition to zonal differences in trend at a local scale, MJO-C shows more precipitation than MJO-B on average. This also holds true for the water vapor feedback and cloud feedback computed from ERA-I (Figs. 4b,d), in which the longer-lived MJO-C exhibits stronger feedbacks than MJO-B.

To ensure these results are not an artifact of the reanalysis, we also compute the radiative feedbacks from AIRS retrievals of temperature, water vapor profiles and CERES observations of TOA and surface radiative fluxes. The satellite-observed feedbacks are consistent with those inferred from the ERA-I. For example, the water vapor feedback declines by roughly 50% in magnitude over the western Pacific compared to its peak value over the Indian Ocean for MJO-C (Fig. 4c), which

FIG. 4. Evolutions of the filtered (a) precipitation (mm day^{-1}); (b),(c) water vapor feedback (W m^{-2}); (d),(e) cloud feedback (W m^{-2}); and (f),(g) normalized cloud feedback by precipitation [$(\text{W m}^{-2}) (\text{mm day}^{-1})^{-1}$] as a function of longitude averaged over a latitude belt of 15°S – 15°N composited for the group of MJO-B (red line) and MJO-C (blue line). Solid lines in (b), (d), and (f) are computed from ERA-I, while dashed lines in (c), (e), and (g) are from AIRS and CERES SYN. The gray-filled regions mark the location of the MC. The filled colors show standard error for each curve.

is analogous to the evolution of water vapor feedback computed from ERA-I (Fig. 4b). The cloud feedback remains strong for MJO-C when it is propagating across the MC (Fig. 4e), and closely emulates the evolution of cloud feedback derived from ERA-I (Fig. 4d).

The comparison between MJO-B and MJO-C indicates that MJO events with larger water vapor and cloud feedback tend to better survive the barrier effect of the MC. The water vapor feedback is much smaller in magnitude than the cloud feedback throughout the

lifetime of the MJO, indicating a significantly greater contribution of atmospheric radiative heating by clouds to the MJO.

When considering the longer-lived MJO-C events, we note that the precipitation and radiative feedbacks show different zonal structures. The precipitation exhibits a two-peak structure with a decrease as the MJO approaches the MC, but an increase again as the MJO enters the western Pacific (Fig. 4a). However, the two-peak structure is not present in the water vapor and cloud feedbacks computed from ERA-I (Figs. 4b,d). The water vapor feedback reaches its peak over the Indian Ocean for MJO-C but exhibits an approximate 50% decrease around 160°E compared to its peak value. However, the cloud feedback shows less weakening over the MC, suggesting that the cloud feedback remains strong with a continuous heating of the atmosphere.

This is consistent with Ciesielski et al. (2017) who found that as the MJO convective envelope weakens over the Indian Ocean, cloud-radiative feedbacks help maintain the mature MJO as it moves eastward. Similarly, Muller and Bony (2015) showed that high clouds' interaction with radiation is necessary for maintenance of the aggregated convection in model simulations. Here we find that when convection is propagating across the MC, the cloud feedback stays nearly unaffected in magnitude, indicating that the atmosphere is being heated continuously by clouds for the longer-lived MJO-C events, which provides a more favorable environment for the re-strengthening of precipitation. In contrast, MJO-B events exhibit a weakening of cloud feedback and associated radiative heating. Therefore, precipitation does not re-strengthen east of the MC.

The differing evolution of the feedbacks between MJO-B and MJO-C imply that radiative heating can both impact the strength of the MJO and play an important role in modulating how far the MJO propagates eastward. Previous studies have used a linear relationship, $Q'_R = rP'$, to scale anomalous radiative heating to precipitation (e.g., Fuchs and Raymond 2002; Peters and Bretherton 2005) in which Q'_R refers to anomalous radiative heating and P' refers to anomalous precipitation. In terms of the MJO amplification, theoretical studies have suggested that it is the value of r that matters rather than the magnitude of Q'_R itself (Fuchs and Raymond 2005; Sobel and Maloney 2013; Adames and Kim 2016). Here, we scale the cloud radiative heating to precipitation for MJO-B and MJO-C. In Figs. 4f and 4g, MJO-C exhibits larger r (~20% larger than that of MJO-B), suggesting that for similar precipitation events, a stronger cloud feedback helps the MJO propagate across the MC.

To further examine the relationships between the feedbacks and the MJO, Fig. 5a compares the precipitation and

FIG. 5. Scatterplots of (a) mean cloud feedback (x axis; W m^{-2}) vs mean precipitation (y axis; mm day^{-1}) in which cloud feedback and precipitation are averaged over a latitudinal belt of 15°S–15°N first, and then from each MJO's starting to ending dates; (b) ending longitude (x axis) vs domain-averaged cloud feedback (y axis; W m^{-2}) over the MC (15°S–15°N, 100°–150°E). Each black dot represents an individual MJO event. The red lines show significant linear relationships.

cloud feedback averaged over the lifetime of each individual MJO event, using the starting and ending dates derived from the tracking algorithm. The strong positive correlation indicates that the lifetime-averaged intensity of the MJO event is in general proportional to the magnitude of the cloud feedback.

Recall that the cloud radiative feedback tends to be stronger for the longer-lived MJO-C events, which also holds true over the critical MC region. This is further demonstrated in Fig. 5b, which examines how the cloud feedback each MJO event experiences over the MC domain (15°S–15°N, 100°–150°E) influences the zonal propagation of the event. Here, ending longitude retrieved from the tracking method is used to represent how far the MJO propagates eastward. Again, we find that MJO events with larger cloud feedback over the MC tend to propagate farther eastward. Positive relationships are also found between water vapor feedback and the MJO intensity and extent of eastward propagation (not shown), although the correlations and magnitude of the

feedback are noticeably weaker. This again confirms the dominant role of cloud radiative heating over water vapor in maintaining the MJO events.

4. Summary

Previous studies have suggested a positive radiative feedback occurs during the MJO (Lin and Mapes 2004; Kim et al. 2011; Ma and Kuang 2011; Sobel et al. 2014; Crueger and Stevens 2015; Del Genio and Chen 2015; Kim et al. 2015; Ciesielski et al. 2017). However, individual feedbacks contributing to the total radiative change have not been previously diagnosed. In this study, the Planck, lapse rate, water vapor, and cloud feedbacks on atmospheric radiative heating during MJO events are examined using radiative kernels. We find that positive cloud feedback, which is coincident with the MJO's convective envelope, is the most dominant driver of this intraseasonal variability. With peak feedback magnitudes of 10 W m^{-2} , the cloud radiative feedback on atmospheric heating is roughly an order of magnitude larger than the other radiative feedbacks.

Water vapor feedback shows a positive peak centered around 400 hPa over the Indo-Pacific warm pool, which is similar to the top-heavy radiative heating found in observations (Ciesielski et al. 2017) and model simulations (Crueger and Stevens 2015). Though negative water vapor feedback also occurs in the boundary layer, the column-integrated water vapor feedback is positive, and follows the convective envelope of the MJO.

Increased deep convection is one major feature of the MJO during its active phases, which leads to more prevalent and thicker high clouds. In this study, we separate the total cloud feedback into high, middle, and low cloud feedbacks. The results indicate that positive high cloud feedback accounts for most of the total cloud feedback, whereas feedbacks associated with low and middle cloud changes are small during the active phases of the MJO. Furthermore, we use a tracking method to identify individual MJO events and diagnose daily radiative feedbacks associated with the MJO. We find a significant positive linear relationship between the strength of the MJO and the cloud feedback, suggesting that the magnitude of cloud radiative heating of the atmosphere may be an important factor in regulating the strength of MJO events. We show that on average, stronger radiative feedbacks better help the MJO survive the barrier effect of the MC; MJO events with larger cloud radiative heating over the MC tend to be stronger and propagate farther eastward than those with weaker cloud heating.

In agreement with the conclusions of previous studies (Sobel and Maloney 2013; Kim et al. 2014; Sobel et al.

2014; Arnold and Randall 2015; Crueger and Stevens 2015; Del Genio and Chen 2015; Ciesielski et al. 2017; Khairoutdinov and Emanuel 2018), the relationships diagnosed here between convection, clouds, and radiation can serve as useful tests of these critical processes in models. For example, the tight connection between the strength of cloud radiative heating and the MJO-related precipitation should be represented consistently over the Indo-Pacific warm pool in model simulations. Also, by a manipulation of the strength of cloud radiative heating over the MC while keeping other conditions unchanged, it would be interesting to examine whether cloud radiative heating there is the only factor affecting the MJO's zonal propagation. If not, how much does it contribute compared to other factors such as low-level moisture convergence or sea surface temperature. One recent study showed that planetary boundary layer (PBL) feedbacks are key to the development of self-aggregation using an idealized cloud-resolving model (Yang 2018). However, the mechanism-denial experiments in that study mainly address how PBL feedbacks affect the process from disaggregated convection to an aggregated state over a fixed domain, while our results focus on a decomposition of the all radiative feedbacks during active phases of the MJO, rather than which mechanism is more important for triggering the MJO-related convection. In addition, though the magnitude of radiative heating induced by water vapor is small, the water vapor itself is intrinsically related to precipitation. Therefore, an accurate representation of water vapor content in the atmosphere, together with radiative heating and latent heating induced by it, is also crucial for the MJO simulations.

Acknowledgments. This research was supported by NASA Grants NNX14AB19G and 80NSSC18K1032. R.J.K. is supported by NASA Graduate Fellowship Grant 18-EARTH-18R-039 and an appointment to the NASA Postdoctoral Program at NASA Goddard Space Flight Center.

REFERENCES

- Adames, Á. F., 2017: Precipitation budget of the Madden-Julian oscillation. *J. Atmos. Sci.*, **74**, 1799–1817, <https://doi.org/10.1175/JAS-D-16-0242.1>.
- , and J. M. Wallace, 2014: Three-dimensional structure and evolution of the MJO and its relation to the mean flow. *J. Atmos. Sci.*, **71**, 2007–2026, <https://doi.org/10.1175/JAS-D-13-0254.1>.
- , and D. Kim, 2016: The MJO as a dispersive, convectively coupled moisture wave: Theory and observations. *J. Atmos. Sci.*, **73**, 913–941, <https://doi.org/10.1175/JAS-D-15-0170.1>.
- Andersen, J. A., and Z. Kuang, 2012: Moist static energy budget of MJO-like disturbances in the atmosphere of a zonally

- symmetric aquaplanet. *J. Climate*, **25**, 2782–2804, <https://doi.org/10.1175/JCLI-D-11-00168.1>.
- Arnold, N. P., and D. A. Randall, 2015: Global-scale convective aggregation: Implications for the Madden–Julian Oscillation. *J. Adv. Model. Earth Syst.*, **7**, 1499–1518, <https://doi.org/10.1002/2015MS000498>.
- Chikira, M., 2014: Eastward-propagating intraseasonal oscillation represented by Chikira–Sugiyama cumulus parameterization. Part II: Understanding moisture variation under weak temperature gradient balance. *J. Atmos. Sci.*, **71**, 615–639, <https://doi.org/10.1175/JAS-D-13-038.1>.
- Ciesielski, P. E., R. H. Johnson, X. Jiang, Y. Zhang, and S. Xie, 2017: Relationships between radiation, clouds, and convection during DYNAMO. *J. Geophys. Res.*, **122**, 2529–2548, <https://doi.org/10.1002/2016JD025965>.
- Crueger, T., and B. Stevens, 2015: The effect of atmospheric radiative heating by clouds on the Madden–Julian Oscillation. *J. Adv. Model. Earth Syst.*, **7**, 854–864, <https://doi.org/10.1002/2015MS000434>.
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.
- Del Genio, A. D., and Y. Chen, 2015: Cloud-radiative driving of the Madden–Julian oscillation as seen by the A-Train. *J. Geophys. Res.*, **120**, 5344–5356, <https://doi.org/10.1002/2015JD023278>.
- Doelling, D. R., and Coauthors, 2013: Geostationary enhanced temporal interpolation for CERES flux products. *J. Atmos. Oceanic Technol.*, **30**, 1072–1090, <https://doi.org/10.1175/JTECH-D-12-00136.1>.
- Fläschner, D., T. Mauritsen, and B. Stevens, 2016: Understanding the intermodel spread in global-mean hydrological sensitivity. *J. Climate*, **29**, 801–817, <https://doi.org/10.1175/JCLI-D-15-0351.1>.
- Fuchs, Ž., and D. J. Raymond, 2002: Large-scale modes of a non-rotating atmosphere with water vapor and cloud–radiation feedbacks. *J. Atmos. Sci.*, **59**, 1669–1679, [https://doi.org/10.1175/1520-0469\(2002\)059<1669:LSMOAN>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<1669:LSMOAN>2.0.CO;2).
- , and —, 2005: Large-scale modes in a rotating atmosphere with radiative–convective instability and WISHE. *J. Atmos. Sci.*, **62**, 4084–4094, <https://doi.org/10.1175/JAS3582.1>.
- Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Climate*, **19**, 5686–5699, <https://doi.org/10.1175/JCLI3990.1>.
- Hendon, H. H., and M. L. Salby, 1994: The life cycle of the Madden–Julian oscillation. *J. Atmos. Sci.*, **51**, 2225–2237, [https://doi.org/10.1175/1520-0469\(1994\)051<2225:TLCOTM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<2225:TLCOTM>2.0.CO;2).
- Hsu, H.-H., and M.-Y. Lee, 2005: Topographic effects on the eastward propagation and initiation of the Madden–Julian oscillation. *J. Climate*, **18**, 795–809, <https://doi.org/10.1175/JCLI-3292.1>.
- Hung, M.-P., J.-L. Lin, W. Wang, D. Kim, T. Shinoda, and S. J. Weaver, 2013: MJO and convectively coupled equatorial waves simulated by CMIP5 climate models. *J. Climate*, **26**, 6185–6214, <https://doi.org/10.1175/JCLI-D-12-00541.1>.
- Janiga, M. A., and C. Zhang, 2016: MJO moisture budget during DYNAMO in a cloud-resolving model. *J. Atmos. Sci.*, **73**, 2257–2278, <https://doi.org/10.1175/JAS-D-14-0379.1>.
- Jiang, X., and Coauthors, 2015: Vertical structure and physical processes of the Madden–Julian oscillation: Exploring key model physics in climate simulations. *J. Geophys. Res. Atmos.*, **120**, 4718–4748, <https://doi.org/10.1002/2014JD022375>.
- Khairoutdinov, M. F., and K. Emanuel, 2018: Intraseasonal variability in a cloud-permitting near-global equatorial aquaplanet model. *J. Atmos. Sci.*, **75**, 4337–4355, <https://doi.org/10.1175/JAS-D-18-0152.1>.
- Kiladis, G. N., K. H. Straub, and P. T. Haertel, 2005: Zonal and vertical structure of the Madden–Julian oscillation. *J. Atmos. Sci.*, **62**, 2790–2809, <https://doi.org/10.1175/JAS3520.1>.
- , J. Dias, K. H. Straub, M. C. Wheeler, S. N. Tulich, K. Kikuchi, K. M. Weickmann, and M. J. Ventrice, 2014: A comparison of OLR and circulation-based indices for tracking the MJO. *Mon. Wea. Rev.*, **142**, 1697–1715, <https://doi.org/10.1175/MWR-D-13-00301.1>.
- Kim, D., and Coauthors, 2009: Application of MJO simulation diagnostics to climate models. *J. Climate*, **22**, 6413–6436, <https://doi.org/10.1175/2009JCLI3063.1>.
- , A. H. Sobel, and I. S. Kang, 2011: A mechanism denial study on the Madden–Julian Oscillation. *J. Adv. Model. Earth Syst.*, **3**, <https://doi.org/10.1029/2011MS000081>.
- , J.-S. Kug, and A. H. Sobel, 2014: Propagating versus non-propagating Madden–Julian oscillation events. *J. Climate*, **27**, 111–125, <https://doi.org/10.1175/JCLI-D-13-00084.1>.
- , M.-S. Ahn, I.-S. Kang, and A. D. Del Genio, 2015: Role of longwave cloud–radiation feedback in the simulation of the Madden–Julian oscillation. *J. Climate*, **28**, 6979–6994, <https://doi.org/10.1175/JCLI-D-14-00767.1>.
- Kim, H.-M., D. Kim, F. Vitart, V. E. Toma, J.-S. Kug, and P. J. Webster, 2016: MJO propagation across the Maritime Continent in the ECMWF ensemble prediction system. *J. Climate*, **29**, 3973–3988, <https://doi.org/10.1175/JCLI-D-15-0862.1>.
- Kramer, R. J., A. V. Matus, B. J. Soden, and T. S. L’Ecuyer, 2019: Observation-based radiative kernels from CloudSat/CALIPSO. *J. Geophys. Res. Atmos.*, **124**, 5431–5444, <https://doi.org/10.1029/2018JD029021>.
- Lin, J.-L., and B. E. Mapes, 2004: Radiation budget of the tropical intraseasonal oscillation. *J. Atmos. Sci.*, **61**, 2050–2062, [https://doi.org/10.1175/1520-0469\(2004\)061<2050:RBOTTI>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<2050:RBOTTI>2.0.CO;2).
- , and Coauthors, 2006: Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals. *J. Climate*, **19**, 2665–2690, <https://doi.org/10.1175/JCLI3735.1>.
- Ling, J., P. Bauer, P. Bechtold, A. Beljaars, R. Forbes, F. Vitart, M. Ulate, and C. Zhang, 2014: Global versus local MJO forecast skill of the ECMWF model during DYNAMO. *Mon. Wea. Rev.*, **142**, 2228–2247, <https://doi.org/10.1175/MWR-D-13-00292.1>.
- Liu, F., and B. Wang, 2017: Effects of moisture feedback in a frictional coupled Kelvin–Rossby wave model and implication in the Madden–Julian oscillation dynamics. *Climate Dyn.*, **48**, 513–522, <https://doi.org/10.1007/s00382-016-3090-y>.
- Ma, D., and Z. Kuang, 2011: Modulation of radiative heating by the Madden–Julian Oscillation and convectively coupled Kelvin waves as observed by CloudSat. *Geophys. Res. Lett.*, **38**, <https://doi.org/10.1029/2011GL049734>.
- Madden, R. A., and P. R. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.*, **29**, 1109–1123, [https://doi.org/10.1175/1520-0469\(1972\)029<1109:DOGGSC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<1109:DOGGSC>2.0.CO;2).
- Majda, A. J., and S. N. Stechmann, 2009: The skeleton of tropical intraseasonal oscillations. *Proc. Natl. Acad. Sci. USA*, **106**, 8417–8422, <https://doi.org/10.1073/pnas.0903367106>.
- Maloney, E. D., 2009: The moist static energy budget of a composite tropical intraseasonal oscillation in a climate model. *J. Climate*, **22**, 711–729, <https://doi.org/10.1175/2008JCLI2542.1>.
- , and A. H. Sobel, 2004: Surface fluxes and ocean coupling in the tropical intraseasonal oscillation. *J. Climate*, **17**, 4368–4386, <https://doi.org/10.1175/JCLI-3212.1>.

- Muller, C., and S. Bony, 2015: What favors convective aggregation and why? *Geophys. Res. Lett.*, **42**, 5626–5634, <https://doi.org/10.1002/2015GL064260>.
- Neelin, J. D., and J.-Y. Yu, 1994: Modes of tropical variability under convective adjustment and the Madden–Julian oscillation. Part I: Analytical theory. *J. Atmos. Sci.*, **51**, 1876–1894, [https://doi.org/10.1175/1520-0469\(1994\)051<1876:MOTVUC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<1876:MOTVUC>2.0.CO;2).
- Pendergrass, A. G., and D. L. Hartmann, 2014: The atmospheric energy constraint on global-mean precipitation change. *J. Climate*, **27**, 757–768, <https://doi.org/10.1175/JCLI-D-13-00163.1>.
- Peters, M. E., and C. S. Bretherton, 2005: A simplified model of the Walker circulation with an interactive ocean mixed layer and cloud-radiative feedbacks. *J. Climate*, **18**, 4216–4234, <https://doi.org/10.1175/JCLI3534.1>.
- Raymond, D. J., 2001: A new model of the Madden–Julian oscillation. *J. Atmos. Sci.*, **58**, 2807–2819, [https://doi.org/10.1175/1520-0469\(2001\)058<2807:ANMOTM>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<2807:ANMOTM>2.0.CO;2).
- , and Ž. Fuchs, 2009: Moisture modes and the Madden–Julian oscillation. *J. Climate*, **22**, 3031–3046, <https://doi.org/10.1175/2008JCLI2739.1>.
- Rui, H., and B. Wang, 1990: Development characteristics and dynamic structure of tropical intraseasonal convection anomalies. *J. Atmos. Sci.*, **47**, 357–379, [https://doi.org/10.1175/1520-0469\(1990\)047<0357:DCADSO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1990)047<0357:DCADSO>2.0.CO;2).
- Rutan, D. A., S. Kato, D. R. Doelling, F. G. Rose, L. T. Nguyen, T. E. Caldwell, and N. G. Loeb, 2015: CERES synoptic product: Methodology and validation of surface radiant flux. *J. Atmos. Oceanic Technol.*, **32**, 1121–1143, <https://doi.org/10.1175/JTECH-D-14-00165.1>.
- Shi, X., D. Kim, Á. F. Adames, and J. Sukhatme, 2018: WISHE-moisture mode in an aquaplanet simulation. *J. Adv. Model. Earth Syst.*, **10**, 2393–2407, <https://doi.org/10.1029/2018MS001441>.
- Sobel, A., and E. Maloney, 2012: An idealized semi-empirical framework for modeling the Madden–Julian oscillation. *J. Atmos. Sci.*, **69**, 1691–1705, <https://doi.org/10.1175/JAS-D-11-0118.1>.
- , and —, 2013: Moisture modes and the eastward propagation of the MJO. *J. Atmos. Sci.*, **70**, 187–192, <https://doi.org/10.1175/JAS-D-12-0189.1>.
- , J. Nilsson, and L. M. Polvani, 2001: The weak temperature gradient approximation and balanced tropical moisture waves. *J. Atmos. Sci.*, **58**, 3650–3665, [https://doi.org/10.1175/1520-0469\(2001\)058<3650:TWTGAA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<3650:TWTGAA>2.0.CO;2).
- , E. D. Maloney, G. Bellon, and D. M. Frierson, 2008: The role of surface heat fluxes in tropical intraseasonal oscillations. *Nat. Geosci.*, **1**, 653, <https://doi.org/10.1038/ngeo312>.
- , S. Wang, and D. Kim, 2014: Moist static energy budget of the MJO during DYNAMO. *J. Atmos. Sci.*, **71**, 4276–4291, <https://doi.org/10.1175/JAS-D-14-0052.1>.
- Soden, B. J., I. M. Held, R. Colman, K. M. Shell, J. T. Kiehl, and C. A. Shields, 2008: Quantifying climate feedbacks using radiative kernels. *J. Climate*, **21**, 3504–3520, <https://doi.org/10.1175/2007JCLI2110.1>.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- Tian, B., and V. Ramanathan, 2002: Role of tropical clouds in surface and atmospheric energy budget. *J. Climate*, **15**, 296–305, [https://doi.org/10.1175/1520-0442\(2002\)015<0296:ROTCIS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<0296:ROTCIS>2.0.CO;2).
- , D. E. Waliser, E. J. Fetzer, B. H. Lambrigtsen, Y. L. Yung, and B. Wang, 2006: Vertical moist thermodynamic structure and spatial–temporal evolution of the MJO in AIRS observations. *J. Atmos. Sci.*, **63**, 2462–2485, <https://doi.org/10.1175/JAS3782.1>.
- , —, —, and Y. L. Yung, 2010: Vertical moist thermodynamic structure of the Madden–Julian oscillation in atmospheric infrared sounder retrievals: An update and a comparison to ECMWF Interim Re-Analysis. *Mon. Wea. Rev.*, **138**, 4576–4582, <https://doi.org/10.1175/2010MWR3486.1>.
- , E. Manning, E. Fetzer, E. Olsen, S. Wong, J. Susskind, and L. Iredell, 2013: AIRS/AMSU/HSB version 6 level 3 product user guide. Jet Propulsion Laboratory Tech. Rep., 37 pp.
- Wang, B., F. Liu, and G. Chen, 2016: A trio-interaction theory for Madden–Julian oscillation. *Geosci. Lett.*, **3**, 34, <https://doi.org/10.1186/s40562-016-0066-z>.
- Wang, S., A. H. Sobel, and J. Nie, 2016: Modeling the MJO in a cloud-resolving model with parameterized large-scale dynamics: Vertical structure, radiation, and horizontal advection of dry air. *J. Adv. Model. Earth Syst.*, **8**, 121–139, <https://doi.org/10.1002/2015MS000529>.
- Webb, M. J., and Coauthors, 2006: On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles. *Climate Dyn.*, **27**, 17–38, <https://doi.org/10.1007/s00382-006-0111-2>.
- Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, **132**, 1917–1932, [https://doi.org/10.1175/1520-0493\(2004\)132<1917:AARMMI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2).
- Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth’s Radiant Energy System (CERES): An earth observing system experiment. *Bull. Amer. Meteor. Soc.*, **77**, 853–868, [https://doi.org/10.1175/1520-0477\(1996\)077<0853:CATERE>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2).
- Wolding, B. O., and E. D. Maloney, 2015: Objective diagnostics and the Madden–Julian oscillation. Part II: Application to moist static energy and moisture budgets. *J. Climate*, **28**, 7786–7808, <https://doi.org/10.1175/JCLI-D-14-00689.1>.
- , —, and M. Branson, 2016: Vertically resolved weak temperature gradient analysis of the Madden–Julian Oscillation in SP-CESM. *J. Adv. Model. Earth Syst.*, **8**, 1586–1619, <https://doi.org/10.1002/2016MS000724>.
- Xie, P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539–2558, [https://doi.org/10.1175/1520-0477\(1997\)078<2539:GPAYMA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2539:GPAYMA>2.0.CO;2).
- Yang, D., 2018: Boundary layer diabatic processes, the virtual effect, and convective self-aggregation. *J. Adv. Model. Earth Syst.*, **10**, 2163–2176, <https://doi.org/10.1029/2017MS001261>.
- , and A. P. Ingersoll, 2013: Triggered convection, gravity waves, and the MJO: A shallow-water model. *J. Atmos. Sci.*, **70**, 2476–2486, <https://doi.org/10.1175/JAS-D-12-0255.1>.
- , and —, 2014: A theory of the MJO horizontal scale. *Geophys. Res. Lett.*, **41**, 1059–1064, <https://doi.org/10.1002/2013GL058542>.
- Zhang, C., 2005: Madden–Julian oscillation. *Rev. Geophys.*, **43**, <https://doi.org/10.1029/2004RG000158>.
- , and J. Ling, 2017: Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. *J. Climate*, **30**, 3439–3459, <https://doi.org/10.1175/JCLI-D-16-0614.1>.