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Perspective

Recent advances in understanding MJO propagation dynamics

Tim Li [a,b,*], Lu Wang [a], Feng Hu [c]

[a] Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environmental Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

[b] International Pacific Research Center and Department of Atmospheric Sciences, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822, USA

[c] School of Geography and Tourism, Chuzhou University, Chuzhou 239000, China

The Madden–Julian Oscillation (MJO) [1,2] is the most prominent intraseasonal mode in the tropics and is characterized by a slow eastward phase speed, a planetary zonal scale and a period of 30–60 d. Although the main convection of the MJO is confined to the tropics, it can exert a large remote impact on weather and climate around the globe [3]. The MJO is the major source of predictability for sub-seasonal forecasts. It is therefore important to understand the fundamental dynamics of the MJO.

Various theories have been developed to understand the mechanisms of the eastward propagation of the MJO (see [3–5]). So far the most accepted theory is the moisture mode theory, which emphasizes the effect of moisture perturbation [6–8]. The moisture mode theory may, in general, be separated into two types [4,9]. The first type emphasizes the zonal asymmetry of the moisture perturbation in the planetary boundary layer (PBL) [6]. Moisture leading in the PBL is primarily attributed to the advection of mean moisture by the anomalous ascending velocity associated with boundary layer convergence. The PBL convergence leading results from a free atmospheric Kelvin wave response to MJO heating and a warm sea surface temperature (SST) anomaly east of the MJO center [6]. Moistening of the boundary layer in front of the convection helps to trigger local shallow convection [9], promoting the eastward propagation of the MJO.

The second type of moisture mode theory stresses the importance of the zonal asymmetry of the column-integrated moisture or moist static energy (MSE) tendency; the asymmetry of the PBL moisture anomaly is not crucial in this theory. A simple theoretical model was developed by Sobel and Maloney [7] using a column-integrated specific humidity tendency equation. However, the phase speed derived from this model was too slow compared to the observed MJO. Adames and Kim [8] improved the framework of this model by considering the anomalous meridional advection and scale-selective cloud radiative feedback.

Various important issues relevant to the moisture mode theory still need to be resolved. For example, regarding the second type, a number of studies have stressed the importance of horizontal advection while ignoring the role of vertical MSE advection (e.g., [10]). However, other studies have considered that vertical MSE advection has an important role (e.g., [11]). By analyzing observational data and 26 general circulation models (GCM) outputs, Wang et al. [11] showed that a positive column-integrated MSE tendency east of the MJO convection may be attributed to the advection of the mean MSE via a pronounced descent anomaly. The role of vertical MSE advection is therefore still unclear.

A prominent feature of the MJO is a horizontal Kelvin–Rossby wave couplet, with a Rossby wave gyre (Kelvin wave easterly) to the west (east) of MJO convective center [12]. There is some controversy about the effects of the Rossby wave. One school of thought suggests a "drag" effect because equatorial Rossby waves always move westward [13]. This "drag" effect is purely based on free wave dynamics point of view. The other school of thought suggests an "acceleration" effect because a larger Rossby wave component strengthens the zonal asymmetry of the column-integrated MSE tendency through enhanced horizontal MSE advection asymmetry [11].

The goal of this review paper is to resolve the controversy about the roles of vertical MSE advection and the Rossby wave component and to reveal the detailed characteristics of the phase evolution of the MJO.

Role of vertical MSE advection in eastward propagation. Fig. 1a shows the observed column-integrated MSE tendency field when the MJO center is located over the eastern equatorial Indian Ocean (80°E). There is a clear zonal asymmetry in the MSE tendency field. Two different analysis domains have been used to measure this asymmetry. One is the small purple box (50°–110°E, 15°S–5°N) adopted by Jiang [10] and the other is the large black box (40°–160°E, 15°S–5°N) used by Wang et al. [11].

By projecting each of the MSE budget terms into the observed MSE tendency pattern shown in Fig. 1a, Wang and Li [9] assessed the relative roles of horizontal and vertical advection, surface flux and atmospheric radiation in contributing to the asymmetry of the MSE tendency. Their results showed that when a small analysis domain is used (Fig. 1b), horizontal MSE advection is the most important factor in the east–west asymmetry and vertical MSE advection is negligible. The contribution of vertical MSE advection becomes as important as horizontal advection when a large domain is used (Fig. 1c).

Why do different analysis domains yield conflicting assessments of the role of vertical advection? To address this question,

* Corresponding author.
E-mail address: timli@hawaii.edu (T. Li).

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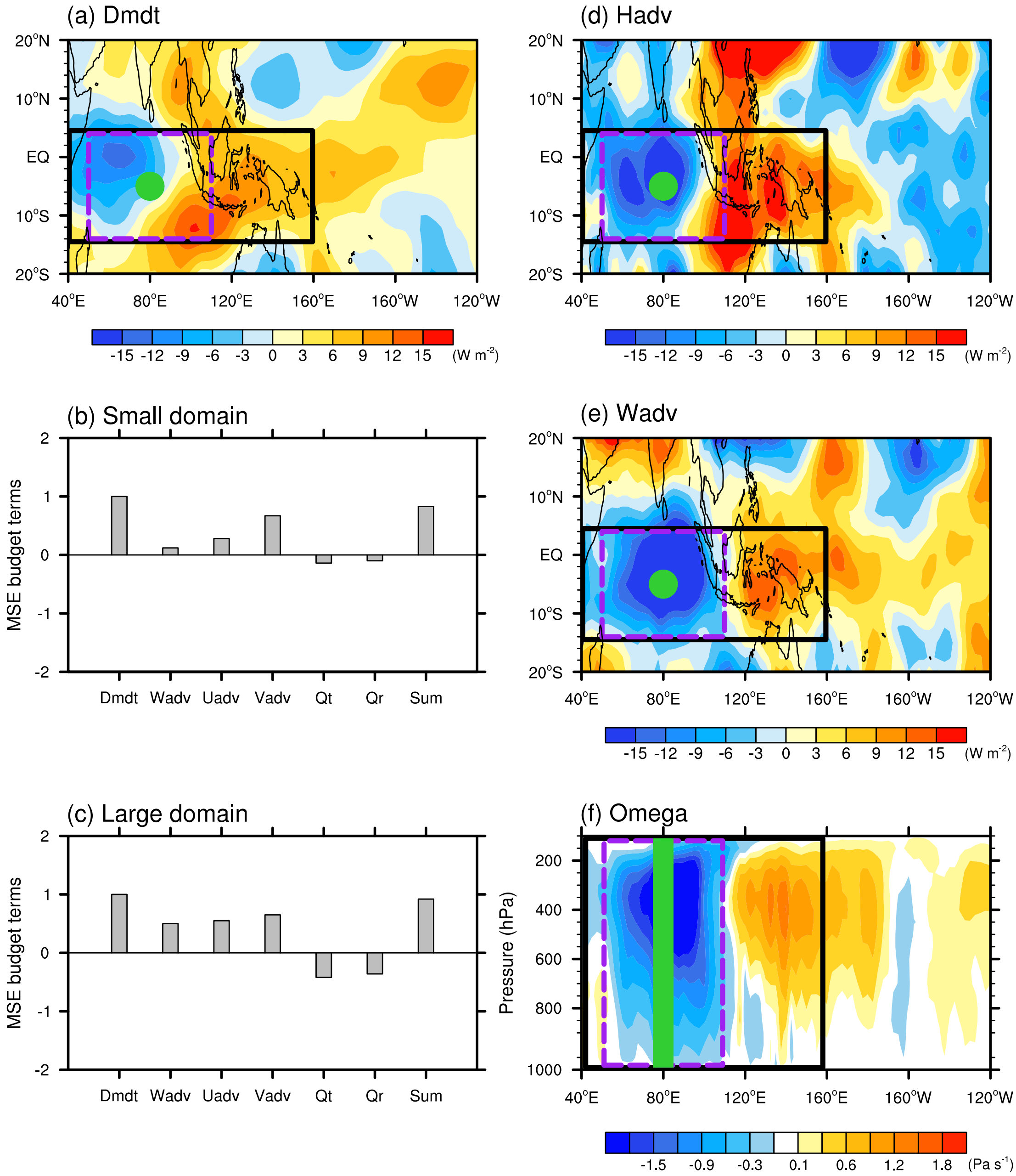

Fig. 1. (a) Horizontal patterns of the column-integrated MSE tendency anomaly (W m^{-2}) regressed onto the MJO rainfall over the region (75°–85°E, 10°S–0°). (b) Fractional contributions of each MSE budget component to the MSE tendency field over a small domain (purple box in (a)). (c) Same as (b) except for a large domain (black box in (a)). In (b) and (c), the value "1" represents a 100% contribution to the observed MSE tendency term. The first bar is the MSE tendency itself and thus its contribution is 100%. The second to sixth bars represent the vertical (Wadv), zonal (Uadv) and meridional (Vadv) MSE advection, surface heat flux (Qt) and atmospheric radiative heating (Qr) terms. The last bar is the sum of the second to sixth bars. (d–f) Same as (a) except for column-integrated horizontal and vertical MSE advection terms respectively. (f) Longitude–vertical cross-section of the vertical velocity anomaly (Pa s^{-1}) associated with the MJO center over the region (80°E, 5°S, green closed dot or green bar). From Wang and Li [9].

Wang and Li [9] examined the horizontal patterns of the horizontal and vertical MSE advection fields (Fig. 1d, e). Both the horizontal and vertical MSE advection fields show a clear zonal asymmetry with a positive anomaly to the east and a negative anomaly to the west, which resembles the total MSE tendency pattern. Such asymmetric patterns indicate that both the horizontal and vertical advection terms contribute to the asymmetry of the MSE tendency and thus the propagation of the MJO.

The zonal extent of the positive vertical and horizontal MSE advection anomalies to the east of the MJO convective center appears greater than that of the negative anomalies to the west. As a result, only a large zonally asymmetrical analysis domain (Fig. 1a, black box) can capture the asymmetry of the tendency, whereas the small domain (purple box) hardly captures the asymmetry, particularly in the vertical advection field.

The zonally asymmetrical vertical advection pattern can be interpreted using the anomalous vertical velocity field. Fig. 1f shows the longitude–vertical cross-section of the anomalous vertical velocity field associated with the MJO. A zonally asymmetric pattern of the vertical velocity anomaly is clearly seen. Anomalous descent (ascent) appears to the east (west) in the upper troposphere. Because the mean MSE is at a minimum in the mid-troposphere, the descent (ascent) to the east (west) could generate a positive (negative) vertical MSE advection anomaly to the east (west). The column-integrated vertical advection anomaly is mainly contributed by the upper level component because both the mean MSE gradient and the vertical velocity anomaly have a top-heavy structure [11].

This analysis clearly indicates that the large domain is able to cover the zonally asymmetric vertical velocity pattern while the small domain cannot. Physically, the zonally asymmetrical vertical velocity pattern can be understood through equatorial wave dynamics. Eastward-propagating Kelvin waves and westward-propagating Rossby waves are generated in response to MJO heating. Because the phase speed of the Kelvin waves is three times that of the Rossby waves, the horizontal extent of the circulation response to the east is about three times that to the west. Thus it is crucial to use a zonally asymmetric domain to describe the MJO circulation and analyze the MSE budget. The proper description of the Kelvin wave response is also crucial for convergence of the PBL and moisture leading [6].

Another way to demonstrate the role of vertical MSE advection is through idealized Aqua-Planet simulations [9]. A zonally symmetric SST profile with a maximum SST at the equator is specified. Under this idealized SST distribution, the model is able to capture the MJO-like signal in the idealized Aqua-Planet simulation. The model-simulated zonally asymmetric MSE tendency pattern is similar to the observed.

An MSE budget analysis has shown the role of vertical MSE advection in causing the zonally asymmetric MSE tendency [9]. The contribution from horizontal MSE advection is much smaller as a result of the pronounced mean easterly flow in the tropics in the Aqua-Planet climate model.

Effect of the Rossby wave component of MJO circulation. Whether the Rossby wave component has a “drag” or an “acceleration” effect on the eastward propagation has been investigated through both idealized Aqua-Planet simulations and the analysis of 26 state-of-the-art climate models [13]. An atmospheric general circulation model (ECHAM 4.6) was used in the Aqua-Planet experiments. This model had a horizontal resolution of T42 and 19 vertical levels (extending from the surface to 10 hPa).

Three sensitivity experiments with different meridional SST profiles were designed [13]. The first experiment was a “broad SST” (BS) experiment, in which the maximum SST (29 °C) appears at the equator and decays slowly with latitude. The second experiment was a “narrow SST” (NS) experiment in which the SST had the same amplitude at the equator, but decayed more rapidly with latitude. The third experiment had an SST profile between the other two (WS experiment). Numerical experiments indicated that this model was able to simulate MJO-like eastward-propagating modes with phase speeds of 8, 11 and 14 m s^{-1} in the BS, WS and NS experiments, respectively.

Given the higher SST in the off-equatorial region in the BS experiment, one may speculate that the intensity of the MJO Rossby wave component is strongest. However, the results of the model simulation are the opposite, that is, the Rossby wave intensity is the greatest in the NS experiment, followed by the WS and BS experiments. All the experiments reproduced the observed Rossby–Kelvin wave couple or a quadrature structure, with the Rossby wave component associated with westerly anomalies at the equator and equatorward meridional wind anomalies converging into the equator to the west of the MJO rainfall center.

Although the MJO circulation patterns look similar, the major difference among the three experiments arises from their intensity. The strength of the Rossby wave component can be measured by an equatorial zonal wind index, an equatorward flow index off the equator, or a relative vorticity index over the Rossby wave gyre region. Regardless of which index is used, they all indicate that the intensity of the Rossby wave component is the strongest in the NS experiment, followed by the WS and BS experiments.

To further evaluate the Rossby wave effect, Wang et al. [14] analyzed 26 state-of-the-art climate models participating in the MJO Task Force multi-model comparison project [11]. Two methods were used to measure the MJO simulation skills. One was based on the pattern correlation coefficient (PCC) between the observed and simulated Hovmöller diagrams of the lead–lag regressed MJO precipitation field along the equator. A higher PCC corresponded to a more systematic eastward phase propagation. Another method was directly based on the MJO phase speed estimated from a linearly fitted slope in the Hovmöller diagrams.

The correlation coefficients between the MJO simulation skills and the intensity of the Rossby wave component were calculated among the 26 GCMs [14]. The Rossby wave strength was measured by four different indices, including an equatorial zonal wind index and two off-equatorial meridional wind indices [14]. The indices were designed such that a greater value indicated a stronger Rossby wave component. This analysis indicated that there was a significant positive correlation between the strength of the Rossby wave and the MJO simulation skills. Significant positive correlations occurred in the lower troposphere (800–500 hPa), suggesting that the lower tropospheric circulation anomaly was crucial in conveying the Rossby wave effect to MJO propagation. This result is consistent with the MSE budget analysis of Wang et al. [11], who showed that horizontal MSE advection had the highest contribution in the lower troposphere.

Maximum phase evolution characteristics. An important assumption of the second type of moisture mode theory is that the eastward propagation of the MJO depends on the MSE tendency asymmetry, while the MSE itself is in phase with the MJO convection. This is analogous to a simple one-dimensional advection equation:

$$\mathrm{d}u/\mathrm{d}t + C\mathrm{d}u/\mathrm{d}x = 0, \quad (1)$$

where C is a constant. There is an analytical solution for this equation: a sine wave solution with a constant phase speed of C. For positive values of C, when the peak phase of the sine wave is at 0°, its time tendency maximum (minimum) must be at +90° (−90°), indicating an eastward phase propagation. The theoretical models of Sobel and Maloney [7] used a MSE tendency equation, which, to a large extent, resembles this advection equation. A positive (negative) MSE tendency to the east (west) causes a continuous and smooth eastward propagation.

This propagation characteristic differs from the first type of the moisture mode theory, which emphasizes PBL moisture leading [6]. In this scenario, perturbation moisture accumulates and congestus clouds develop in a region ahead of the convection [12]. Under this scenario, the movement of the MJO is discontinuous.

Motivated by this physical rationale, Wang and Li [15] developed a novel method to illustrate the detailed phase evolution of the MJO. Fig. 2 compares the phase evolution characteristics from both a conventional linear fitting method and a new temporal normalization method. Fig. 2a shows the time–longitude diagrams of the 20–100-day filtered precipitation and the column-integrated MSE (hereafter <m>) anomalies regressed onto a reference point in the eastern equatorial Indian Ocean (5°S–5°N, 75°–85°E). The MSE and precipitation anomalies move smoothly eastward, as shown by the green line. Fig. 2b shows the MJO maximum phase evolution after applying the normalization method. The black and green dots represent the maximum centers on each day. The maximum precipitation and <m> anomaly centers show a distinctive propagation feature.

These phase diagrams show that the maximum MJO phases do not move smoothly, but instead “jump”. To further explore this “jump” feature, Wang and Li [15] examined the temporal evolution of the longitudinal profiles of the regressed <m> anomalies at the equator from Day 0 to Day 18. They found that the <m> anomaly

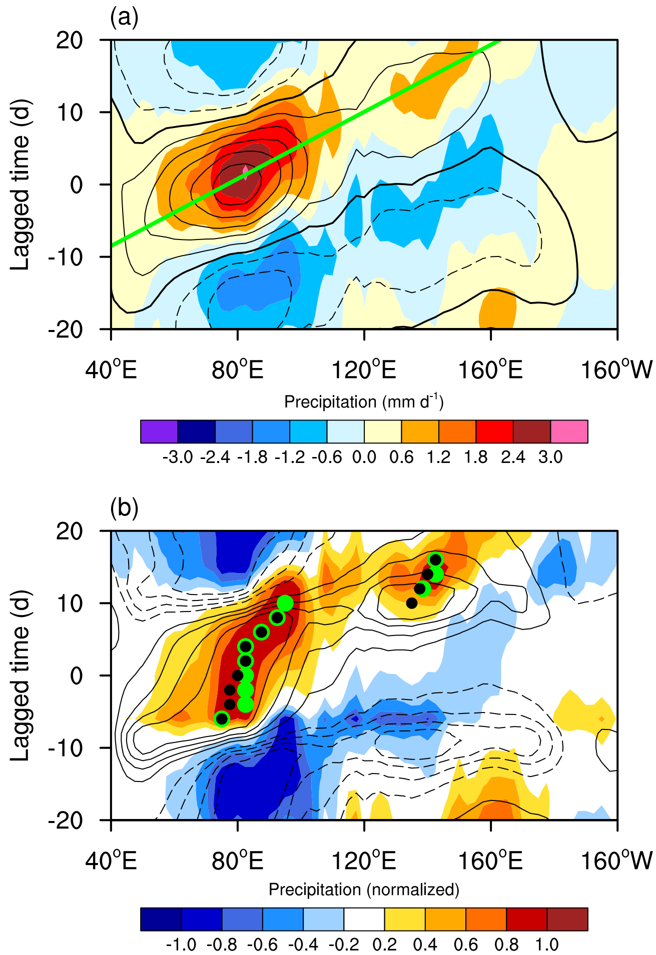

Fig. 2. (a) Time–longitude cross-section of precipitation (shading; mm d^{-1}) and column-integrated MSE (contours with an interval of 1.5×10^6 J m^{-2}; negative values are shown as dashed lines) anomalies along the equator regressed onto the standardized time series of the 20–100-day filtered MSE anomaly over the region (5°S–5°N, 75°–85°E). The slope of the green line denotes the average phase speed. (b) As in (a), except that the regressed fields are normalized by their maximum amplitude at each time level. Black (green) dots denote the centers of maximum MSE (precipitation) anomalies from Day 6 to Day 16 with an interval of two days. From Wang and Li [15].

peaks at 80°E on Day 0 and stays near this area as the amplitude decays. A center develops at 140°E on Day 6. The newly developed center becomes the strongest over the entire region on Day 9, signifying a "jump" of MJO convection from 80° to 140°E. This phase evolution feature is consistent with that shown in Fig. 2b.

What controls the preferred length and temporal scales of this "jump"? We argue that the distance between the old and new convective centers is determined by the characteristic length scale of the Kelvin wave response because a low-pressure anomaly associated with the Kelvin wave response induces PBL convergence in front of the MJO convection, which further increases the perturbation moisture through vertical advection [6,12]. The timescale (around 10 d) inferred from Fig. 2 represents a period during which the PBL moistens and congestus clouds develop. The combined effect of the Kelvin wave length scale (~5000 km) and the convective adjustment timescale (~10 d) leads to an average speed of about 5° longitude per day (Fig. 2a).

Concluding remarks. We discussed three important issues in MJO propagation dynamics: (1) what is the role of vertical MSE advection in causing the east–west asymmetry of the column-integrated MSE tendency anomalies; (2) does the Rossby wave component of the MJO circulation have a "drag" or "acceleration" effect; and (3) does the MJO phase propagate smoothly or "jump"? To address these issues, we relied on combined observational analyses and numerical model experiments. The main conclusions are as follows.

A proper selection of a zonally asymmetrical analysis domain is crucial in assessing the MSE budget terms. Using such a domain, the vertical MSE advection is important in contributing to the zonal asymmetry of the MSE tendency, accounting for about 60% of the total observed MSE tendency asymmetry. Its contribution was substantially underestimated in some previous studies as a result of the incorrect selection of the analysis domain. The physical reasoning is that the characteristic length scales of the Kelvin and Rossby wave response to MJO heating are different. The role of vertical MSE advection has been demonstrated in idealized Aqua-Planet simulations.

The effect of the Rossby wave component on the eastward propagation was examined through idealized Aqua-Planet experiments. A narrower SST meridional profile favors a stronger Rossby wave component and a faster eastward phase speed, implying an "acceleration" effect. Further analysis of 26 GCMs participating in the MJO Task Force multi-model inter-comparison project showed a significant positive correlation between the strength of the Rossby wave and eastward propagation skills, confirming the "acceleration" hypothesis.

A temporal normalization method was used to illustrate the evolution of the maximum MJO phases. It was shown that the maximum phases of the MJO do not move smoothly, but instead "jump". Such an evolution characteristic is consistent with the first type of the moisture mode theory, which emphasizes the phase leading of PBL moisture and the development of congestus convection east of the MJO center. The horizontal extent of the "jump" is determined by the length scale of the Kelvin wave response, whereas its timescale represents PBL moistening and congestus clouds in front of the convection. The combined time and length scales determine the average MJO phase speed.

A number of issues in MJO propagation dynamics remain open. For example, the majority of current operational models have difficulty in predicting the propagation of the MJO over the Maritime Continent (MC). What causes this barrier effect? Given that the MC barrier effect appears stronger in the boreal summer, what is the role of the seasonal mean state (including the zonal and meridional distributions of the mean moisture and precipitation) over the MC in affecting MJO propagation? What controls the diversity of the propagation, intensity and initiation of the MJO? Given the rich spectrum of atmospheric and oceanic variability, including the diurnal cycles over the MC, how and to what extent do the diurnal cycles and high-frequency disturbances feed back to the MJO? Further in-depth observational, theoretical and modeling studies are needed to address these issues.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.08.005.

References

[1] Madden RA, Julian PR. Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. J Atmos Sci 1971;28:702–8.
[2] Madden RA, Julian PR. Description of global-scale circulation cells in the tropics with a 40–50 day period. J Atmos Sci 1972;29:1109–23.
[3] Jiang X, Adames ÁF, Kim D, et al. Fifty years of research on the Madden-Julian Oscillation: recent progress, challenges, and perspectives. J Geophys Res Atmos 2020;17:e2019JD030911.
[4] Li T, Ling J, Hsu P. Madden-Julian Oscillation: its discovery, dynamics, and impact on East Asia. J Meteorol Res 2020;34:20–42.
[5] Zhang C, Adames ÁF, Khouider B, et al. Four theories of the Madden-Julian Oscillation. Rev Geophy 2020;58:e2019RG000685.
[6] Hsu P-C, Li T. Role of the boundary layer moisture asymmetry in causing the eastward propagation of the Madden-Julian Oscillation. J Clim 2012;25:4914–31.
[7] Sobel A, Maloney E. Moisture modes and the eastward propagation of the MJO. J Atmos Sci 2013;70:187–92.
[8] Adames ÁF, Kim D. The MJO as a dispersive, convectively coupled moisture wave: theory and observations. J Atmos Sci 2016;73:913–41.
[9] Wang L, Li T. Effect of vertical moist static energy advection on MJO eastward propagation: sensitivity to analysis domain. Clim Dyn 2020;54:2029–39.
[10] Jiang X. Key processes for the eastward propagation of the Madden-Julian Oscillation based on multimodel simulations. J Geophys Res Atmos 2017;122:755–70.
[11] Wang L, Li T, Maloney E, et al. Fundamental causes of propagating and nonpropagating MJOs in MJOTF/GASS models. J Clim 2017;30:3743–69.
[12] Li T. Recent advance in understanding the dynamics of the Madden-Julian oscillation. J Meteorol Res 2014;28:1–33.
[13] Kang I-S, Liu F, Ahn M-S, et al. The role of SST structure in convectively coupled Kelvin-Rossby waves and its implications for MJO formation. J Clim 2013;26:5915–5930.
[14] Wang L, Li T, Nasuno T. Impact of Rossby and Kelvin wave components on MJO eastward propagation. J Clim 2018;31:6913–31.
[15] Wang L, Li T. Reexamining the MJO moisture mode theories with normalized phase evolutions. J Clim 2020;33:1–40.

Tim Li is a professor at Department of Atmospheric Sciences and International Pacific Research Center (IPRC), University of Hawaii at Manoa. His general research interest areas are tropical meteorology, climate dynamics, atmosphere-ocean interaction and numerical weather prediction. The current research topics include: (1) dynamics of ENSO and inter-basin teleconnection, (2) Asian-Australian monsoon and Tropospheric Biennial Oscillation (TBO), (3) climate change, (4) Madden-Julian Oscillation (MJO), (5) tropical cyclone, and (6) multi-scale interaction.