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Moisture Mode Theory's Contribution to Advances in our Understanding of the Madden-Julian Oscillation and Other Tropical Disturbances

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Abstract

Purpose of Review Our understanding of the Madden-Julian Oscillation (MJO) and other tropical motion systems has significantly improved in recent years. This article reviews the contribution of moisture mode theory to this progress.

Recent Findings Two realizations have contributed significantly to our understanding of the MJO: (1) Free tropospheric water vapor plays an important role in the occurrence and organization of tropical deep convection. (2) The latent heat released in convection is quickly transported around the tropics by gravity waves, the physical mechanism underpinning the weak temperature gradient (WTG) approximation. Simple models of the tropics that include (1) and (2) revealed the existence of moisture modes, waves in which water vapor plays a dominant role in their evolution. It was soon recognized that the MJO exhibits properties of moisture modes. The ensuing development and application of the so-called moisture mode theory of the MJO have led to the recognition that horizontal and vertical moisture advections are central to the propagation of the MJO, and that cloud-radiative heating is at least partially responsible for its maintenance. Moisture mode theory has also been applied to understand the MJO's seasonality, Maritime Continent transit, and response to increasing CO_2. Recent work suggests that moisture mode theory can be extended beyond the MJO in order to explain the observed diversity of tropical motion systems.

Summary A mounting body of evidence indicates that the MJO has properties of moisture modes. Extension of the theory beyond the MJO may help us further understand the processes that drive large-scale tropical circulations.

Keywords Madden-Julian Oscillation · Convectively coupled waves · Moisture modes · Tropical convection

Introduction

Tropical atmospheric variability is characterized by a multitude of atmospheric motion systems that are coupled to convection. At the day-to-day timescale, we observe a myriad of convectively coupled equatorial waves akin to the shallow water wave solutions found by Matsuno [1, 2], as well as off-equatorial easterly waves [3]. At the intraseasonal (week-to-week) timescale, precipitation variability over the Indo-Pacific warm pool (60° E–180°) is largely the result of a phenomenon known as the Madden-Julian Oscillation (MJO) [4]. As the MJO's convective signature propagates eastward over the Indo-Pacific warm pool, its circulation can excite Rossby wave trains that modulate weather around the globe [5, 6].

Since its discovery in the 1960s and 1970s [7–9], the MJO has perplexed scientists. Its planetary-scale structure, slow eastward propagation at $\sim$5 m s^{-1} over the warm pool, and intraseasonal timescale were unlike any previously documented wave. Studies that took place soon after the MJO's discovery acknowledged that deep convection played a central role in its dynamics, yet no proposed framework

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explained all of the MJO's key features [10]. Even after decades of research, many global climate models (GCMs) continue to struggle in simulating a realistic MJO [10–12]. The challenge to understand the MJO has become synonymous with a challenge to better understand the processes in which the large-scale tropical circulation couples to deep convection [13], being referred to as one of the "holy grails" of tropical meteorology [14].

Despite its elusiveness, our understanding of the MJO has progressed considerably in recent decades [15]. This progress has been facilitated by the formalization of the Weak Temperature Gradient (WTG) approximation [16] and its application in the development of moisture mode theory [17, 18]. The theory emphasizes the role that free tropospheric water vapor plays in supporting intraseasonal precipitation anomalies. It is now recognized that convective parameterizations that are more sensitive to free tropospheric water vapor lead to improved MJO simulation [19]. The advection of moisture is critical to the propagation of the MJO [20–23], and cloud-radiative feedbacks play an important role in its maintenance [24–27]. The insights of moisture mode theory have led to more realistic MJO simulation and improved forecasts at the seasonal-to-subseasonal scale [28–31]. Moisture mode theory also provides clues about the nature of large-scale tropical atmospheric motions: how several key parameters could be used to understand the diversity of convectively coupled tropical waves and how the tropical circulation will respond to increasing CO_2 [32–34].

In this article, we review some of the salient features of the MJO and introduce the foundations of moisture mode theory. We will discuss how the theory has advanced our understanding of the MJO, explaining features such as eastward propagation, growth and maintenance, and seasonality. We will elucidate how tropical atmospheric dynamics allows for the emergence of moisture modes, and how they differ from other types of convectively coupled waves. We will synthesize the theory and its potential applications to other tropical motion systems. Finally, we will also discuss shortcomings of the theory, unanswered questions, competing views, and how future work may be able to address these issues.

A Short Review on MJO Structure and Teleconnections

The initial depiction of the MJO by Madden and Julian [4] showed an overturning circulation in the equatorial plane. The rising branch is coupled with enhanced deep convection, while the subsiding branch is associated with suppressed convection. Subsequent studies revealed that the horizontal structure of the MJO also exhibits significant meridional winds associated with Rossby waves [35, 36]. The lower tropospheric structure is reminiscent of the wave response to a stationary equatorially symmetric heat source [1, 37]. The structure, shown in Fig. 1b, consists of a pair of Rossby wave cyclones to the west of the maximum heating and Kelvin wave easterlies to the east. Regions of anomalous cooling exhibit the same aforementioned wave response structure, but of the opposite polarity.

In the upper troposphere Kelvin and Rossby waves, responses are still observed, but exhibit a reversed polarity from the lower troposphere (Fig. 1a). The upper tropospheric Rossby waves also differ from the lower tropospheric waves in their horizontal structure. Unlike the lower tropospheric cyclones, which are centered 10–15° from the equator, upper tropospheric Rossby waves are centered near the equatorward edges of the subtropical jet streams ∼ 28° N/S [38]. Furthermore, these waves exhibit a

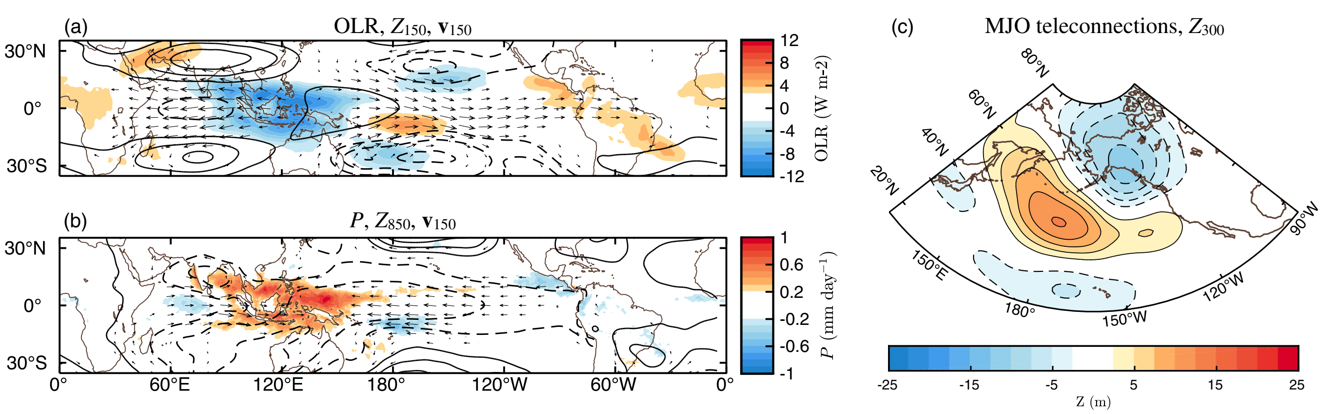

Fig. 1 **a** Outgoing longwave radiation (OLR, shading), 150 hPa geopotential height anomalies (contours) and 150 hPa horizontal winds (arrows) for the time when the MJO is active over the Maritime Continent (MJO phase 5). **b** Precipitation (shaded) and 850 hPa geopotential height (contours) and horizontal winds for the same MJO phase. The contour interval is 2 m for (**a**) and 1 m for (**b**). The maps are linear regressions based on the first OLR-based MJO index (OMI1, Kiladis et al. 2014). **c** 300 hPa geopotential height anomalies corresponding to the MJO phase shown in panels (**a**) and (**b**). Contour interval is 2.5 m

larger zonal extent than the lower tropospheric counterparts, with each cyclonic anomaly extending ∼5000 km. The lower tropospheric Rossby waves are maintained by vortex stretching from the convection and planetary vorticity advection, a balance that is reminiscent of Sverdrup balance [37]. In the upper troposphere, the advection of vorticity imparted by the subtropical jet streams also plays an important role in the vorticity budget of the Rossby waves [39].

The aforementioned reversal of polarity between the upper and lower tropospheric wind and geopotential fields is often referred to as a "first baroclinic mode" [40]. Through mass continuity, this structure is related to a vertical velocity field with a single polarity that reaches a maximum in the midtroposphere (∼400 hPa), akin to the heating profiles seen in tropical deep convection [41]. Vertical velocity profiles consistent with shallow and stratiform convection are also observed during the MJO cycle [42]. However, the role that these vertical velocity profiles play in the MJO cycle remains a topic of active research [10].

The upper tropospheric divergence and divergent wind fields associated with the MJO interact with the North Pacific jet stream to force a Rossby wave teleconnection to higher latitudes [43]. The teleconnection resembles the Pacific-North America pattern (Fig. 1c), and is most efficiently forced when MJO heating has a dipole-like structure with opposite-signed anomalies in the Indian and West Pacific Oceans [44, 45]. Geopotential height and associated flow perturbations produced by this teleconnection have been shown to modulate extratropical temperatures, precipitation, atmospheric river activity, blocking, severe weather, and the North Atlantic Oscillation, among other features [6, 46–51]. The precise nature of the MJO teleconnection and its impacts varies as MJO characteristics and the North Pacific basic state change with ENSO and the QBO [52–54].

Role of Water Vapor in Tropical Convection and the Weak Temperature Gradient Approximation

Tropical rainfall is largely the result of cumulonimbus clouds whose updrafts are initiated from acceleration due to positive buoyancy (see Johnson et al. [55] and references therein). It was hypothesized that the processes that create a favorable environment for updrafts may explain the coupling between the MJO-related precipitation anomalies and the planetary-scale circulation. In parcel theory, the buoyancy of rising parcels is determined by the environmental static stability and the moist static energy (MSE) (or equivalent potential temperature) of the subcloud layer [56, 57].

However, studies showed that tropical deep convection is also sensitive to the concentration of water vapor above the planetary boundary layer [58–60]. Two physical processes are thought to explain the coupling between free tropospheric water vapor and precipitation. First, rising cumulus clouds in the tropics tend to lose buoyancy as they entrain air from the surrounding environment, and dry environments are more effective at diluting the updraft than moist environments [61–63]. Another explanation is based on the observation that MSE tends to remain fixed within the tropical boundary layer, which forms the basis of a concept known as boundary-layer quasi-equilibrium (BLQE) [64, 65]. In precipitating regions, convective downdrafts import low MSE air from the free troposphere, balancing the MSE gain from surface fluxes. The MSE that downdrafts import is higher if the free troposphere is more humid, so more convection is required to create the downdrafts necessary to maintain BLQE [66]. The processes that lead to BLQE are not dependent on entrainment and detrainment of clouds above the boundary layer. However, it is nonetheless possible that the two explanations for the water vapor-precipitation relation may be physically related: less diluted updrafts in a humid-free troposphere create the larger amount of convection that is needed to maintain BLQE.

Observations and idealized simulations of tropical deep convection showed that temperatures within the clouds are similar to those of the surrounding environment [67, 68]. The near homogeneous horizontal temperature distribution suggested that the latent heating within the clouds is balanced by updraft-driven adiabatic cooling. This balance can be extended to any kind of diabatic heating so that the leading thermodynamic balance of the tropics can be written as

$$\omega \frac{\partial s}{\partial p} \approx Q \tag{1}$$

where ω is the pressure velocity, s is the dry static energy, and Q is the diabatic heating rate. This thermodynamic balance, known as the Weak Temperature Gradient (WTG) approximation [16], has been extensively used to understand tropical atmospheric motions [69–71].

WTG balance is achieved in the troposphere through an adjustment process in which internal gravity waves redistribute the energy of latent heating in convection throughout the tropics [67, 72, 73]. The energy is distributed through a large area because the Coriolis force is weak and adjustment to geostrophic balance is therefore slow (i.e., the Rossby radius of deformation is large). An example of how a two-dimensional troposphere adjusts to WTG balance is shown in Fig. 2. It shows the response to anomalous tropospheric heat/cooling in a vertically truncated version of the equations discussed by [73]. Further details about the model are shown in the Supplementary Material.

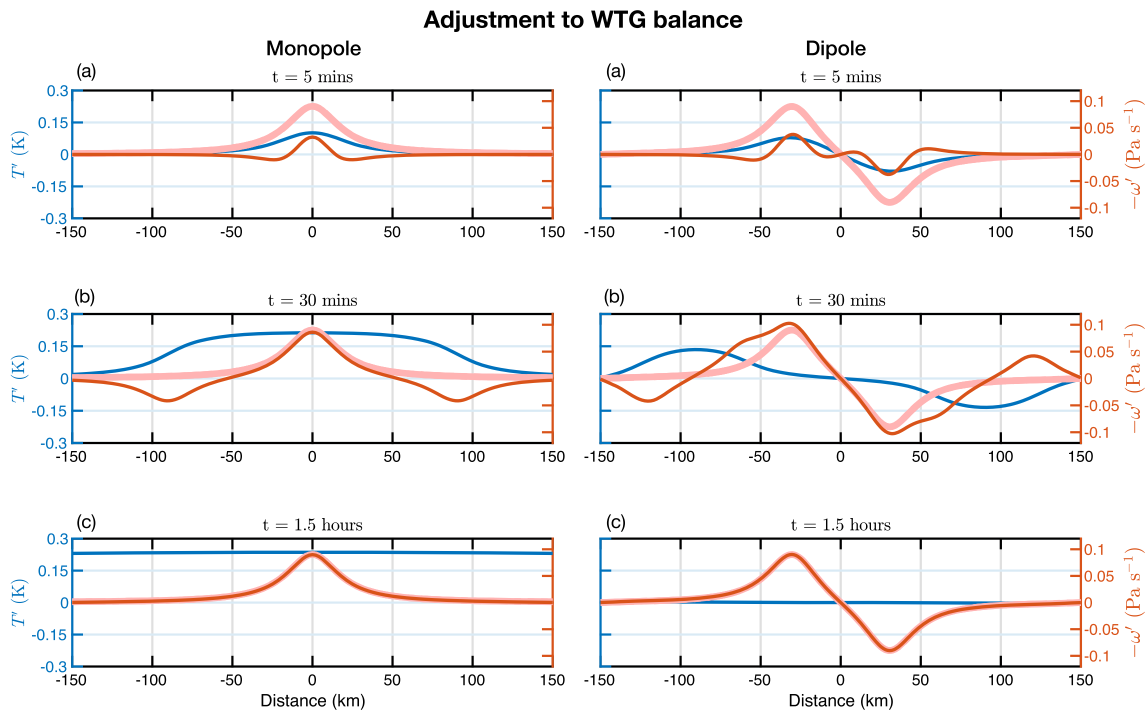

Fig. 2 Anomalous tropospheric response to (left) a horizontal monopole heat source and (right) a horizontal dipole in heating/cooling after (**a**) t=5 min after the heating/cooling is turned on, **b** t = 30 min, and (**c**) t= 1.5 h. The blue line shows the mid-tropospheric temperature anomalies while the red line shows the vertical velocity anomalies. The thick pink line shows the vertical velocity that would balance the heat source exactly. The solutions shown are obtained following Nicholls et al. [73]

Within minutes of turning on an anomalous heat source, an overturning circulation develops consisting of rising air near the center of the heating flanked by regions of subsidence. This circulation is composed of a convectively driven ascent, and a front of adiabatic subsidence driven by gravity waves. While the ascent remains fixed to the heat source, the gravity waves propagate away from the region of heating, warming it through adiabatic compression. Thirty minutes after the heat source is turned on, the region of ascent approximately satisfies WTG balance, while the subsidence front has propagated approximately 90 km from the center of heating. After 1.5 h, the waves have propagated far away enough that the convectively driven ascent and the diabatic heating are in balance over the whole region, satisfying (1). It is important to note that for a horizontal monopole of heating the balanced state results in a change in the domain-mean temperature while for a horizontal dipole of anomalous heating and cooling the temperature anomalies are completely eliminated (right column of Fig. 2). The adjustment towards WTG balance is more complicated in a three-dimensional atmosphere and with the addition of the Coriolis force [67, 72]. Nonetheless, Fig. 2 is still useful in helping us understand why the free-tropospheric temperature distribution in the tropics is so uniform.

The results of Fig. 2 reveal that the timescale in which a given region of the atmosphere adjusts towards WTG balance (τ_{WTG}) is determined by the ratio between the propagation speed of gravity waves (c) and the region's horizontal scale L, so that $\tau_{WTG} = L/c$. For $c = 50$ m/s and $L = 300$ km, the parameters that correspond to Fig. 3, τ_{WTG} is roughly 1.6 h. The timescale τ_{WTG} can be on the order of minutes for mesoscale convection to days in the case of planetary-scale circulations [32, 74, 75]. It is also shorter for first baroclinic modes than higher order modes since the gravity wave speed decreases with decreasing vertical wavelength [72, 74]. The application of τ_{WTG} gives us a qualitative picture of the motion systems that are approximately in WTG balance. These are systems whose timescales much longer than the WTG adjustment time scale [32], such as slowly propagating synoptic-scale systems and the MJO [76].

The tendency of the tropical troposphere to adjust to WTG balance has important implications on how the large-scale circulation couples to convection. If free-tropospheric temperature anomalies are smoothed quickly, and the boundary layer MSE remains approximately fixed [77, 78], then changes in free tropospheric water vapor become a primary cause of changes in the occurrence and organization

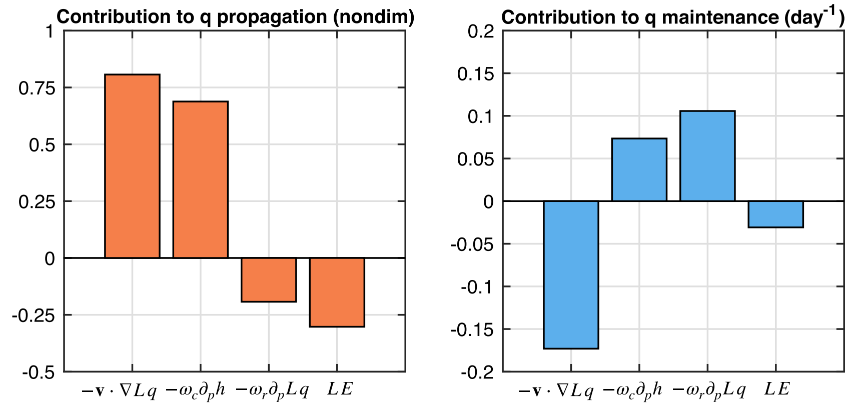

Fig. 3 Normalized contribution of the column-integrated right-hand side terms in Eq. 3 to the (left) propagation and (right) maintenance of the MJO in ERA-Interim data. The vertical MSE advection by convection was calculated as a residual from Eq. 3. The plot is obtained following the method outlined by Andersen and Kuang [95] and averaged over 20°N/S and 60–210° of longitude

of deep convection. This feature results in the existence of waves known as moisture modes.

Moisture Mode Theory of the MJO

The term moisture mode was originally coined in the theoretical work of Yu and Neelin [79] to a group of wave solutions they obtained in which water vapor played a dominant role in their dynamics. In these waves, enhanced precipitation is spatially colocated with positive column-integrated moisture anomalies, and the evolution of the moisture field governs the evolution of the wave. The moisture modes documented by Yu and Neelin were synoptic scale waves (∼1000 km across) that were not associated with the MJO. However, the observed MJO exhibits many of the features of moisture modes. It exhibits a strong signature in column-integrated water vapor [80, 81] that is nearly in phase with the intraseasonal precipitation anomalies [26]. This coherence between water vapor and precipitation is observed in other convectively coupled waves, but it is largest at the intraseasonal timescale [82, 83]. Furthermore, a toy model in which convection was made highly sensitive to water vapor exhibited variability reminiscent to the MJO [14]. Sensitivity of convection to free tropospheric water vapor was not a feature in most of the convective parameterizations included in GCMs at the time, and these models were largely unable to simulate a realistic MJO [11, 84]. All these observational, modeling, and theoretical studies suggested that water vapor was central to the evolution of the MJO, forming the foundations of the modern moisture mode theory [17, 18].

In moisture mode theory, the processes that lead to the maintenance and propagation of the intraseasonal precipitation anomalies can be understood by invoking the moisture budget. Averaged over a horizontal domain of roughly $1° \times 1°$, the budget can be written in isobaric coordinates as:

$$\frac{\partial \overline{q}}{\partial t} = -\overline{\mathbf{v}} \cdot \nabla \overline{q} - \overline{\omega} \frac{\partial \overline{q}}{\partial p} - \frac{Q_2}{L} \quad (2)$$

where the overline denotes a horizontal average, q is the specific humidity, $\mathbf{v}$ is the horizontal wind vector, ω is the pressure velocity, and Q_2 is the apparent moisture sink [85]. The processes on the right-hand side are the horizontal advection of moisture, vertical advection of moisture, and the sources and sinks of moisture (Q_2). The term Q_2 includes moistening/drying from subgrid-scale eddies and microphysical processes such as condensation, evaporation, deposition, and sublimation, mathematically expressed as $Q_2 = L\partial_p\overline{\omega' q'} + L(c - e + d - s)$. The variable Q_2 was first defined by Yanai et al. [85] and the notation has been in widespread use since. Equation (2) is commonly used since the horizontal domain can correspond to a GCM grid point, and parameterized processes such as cloud microphysics and deep convection are incorporated into Q_2.

In precipitating regions, the last two terms on the right-hand side of Eq. 2 are nearly an order of magnitude larger than the others [86, 87]. Furthermore, these two terms are physically related and roughly cancel one another: vertical moisture advection is dominated by the vertical transport of moisture in convection and Q_2 is dominated by the condensation of water vapor in convective clouds. Additionally, the contribution of radiative heating to the evolution of moisture is implicit and difficult to quantify in Eq. 2. The application of the WTG approximation can be used to replace the last two terms in Eq. 2 by a series of terms that summarize the impact that thermodynamic processes have in the evolution of moisture [88]. This substitution is done by first defining the diabatic heating rate Q as the sum of latent heat release $[L(c - e + d - s)]$, radiative heating (Q_R), and the turbulent flux convergence of sensible heat by subgrid-scale eddies ($\partial_p\overline{\omega' s'}$). We then apply the WTG approximation (1) by defining a vertical velocity that balances the latent heat release (ω_c) and the radiative heating (ω_r). With these definitions, Eq. 2 can be rewritten as:

$$\frac{\partial Lq}{\partial t} = -\mathbf{v} \cdot \nabla Lq - \omega_c \frac{\partial h}{\partial p} - \omega_r \frac{\partial Lq}{\partial p} - \frac{\partial \overline{\omega' h'}}{\partial p} \qquad (3)$$

where h is the MSE (the sum of enthalpy, potential energy, and latent energy), and we have dropped the overlines from all the terms except the eddy covariance term. The terms in Eq. 3 that are not in Eq. 2 are the vertical advection of MSE by convection—the residual between the loss of water vapor due to latent heating and the gain of moisture from vertical moisture advection driven by convective heating—vertical moisture advection by radiative heating and the vertical eddy flux divergence of MSE. The application of the WTG approximation replaces the last two terms in Eq. 2, which are large and tend to cancel, with terms that are comparable in magnitude to the moisture tendency [89]. It also provides a more in-depth explanation of the processes that lead to the evolution of water vapor. For example, it shows that radiative heating can moisten the free troposphere through vertical moisture advection. It also describes the impact of convection in a single term. Equation (3) can also be modified to include the role of dry adiabatic lifting by using a "relaxed" WTG approximation instead of the conventional definition in Eq. 1 [89].

Equation 3 is reminiscent of the MSE budget, which is also often employed to study the MJO [22, 90, 91]. Unlike MSE budgets, which are easiest to understand when column-integrated, Eq. 3 can provide a lucid picture of the processes that lead to the evolution of moisture without resorting to column integration [88, 92–94].

Application of Eq. 3 and the MSE budget to observed and simulated MJO events have revealed the importance of anomalous cloud-radiative heating in the maintenance of the intraseasonal precipitation anomalies (Fig. 3). Mechanism-denial experiments show that when cloud-radiative heating is turned off, MJO-like activity is weakened [25, 95–99]. In addition to radiative heating, surface latent heat fluxes also play a role in MJO maintenance, although this contribution depends on the phase of the MJO [20, 91, 100]. During the early stages of MJO formation, anomalous easterlies over the Indian Ocean weaken the surface westerlies, suppressing surface latent heat fluxes. As the MJO amplifies over the Indian Ocean, anomalous surface westerlies develop near the convectively active region, which increase the surface latent heat fluxes [101].

When considering the processes that govern the eastward propagation of the MJO, observations and modeling studies suggest that horizontal moisture advection is of primary importance (Fig. 3) [20, 22, 88, 91, 92]. Vertical advection of moisture driven by convection is also important (Fig. 3). GCM studies show that enhancing the magnitude of horizontal moisture advection results in more robust MJO eastward propagation [23, 102]. Vertical moisture advection is particularly important for the propagation of the MJO from the Maritime Continent to the Western Pacific [87, 103].

The strength of both horizontal and vertical moisture advection is dependent on the magnitude of the moisture gradients, which is controlled by the background concentration of water vapor in the warm pool. Analysis of different GCMs shows that the models that exhibit the strongest MJO activity tend to exhibit more humid mean states [104–106]. Similarly, forecast models exhibit weakening MJO activity after initialization partly because the models tend to excessively dry the troposphere after they are initialized [31, 107–109]. Models with active MJOs may also feed back onto the mean moisture distribution, and so further model sensitivity tests are needed to better constrain the nature of such interactions.

During boreal winter, the eastward propagation of the MJO is interrupted by the islands of the Maritime Continent. This interruption can lead to the termination of roughly half of MJO events, which has become known as the "Maritime Continent barrier effect" [110]. MJO events that reach the west Pacific tend to "detour" to the south of the Maritime Continent, propagating to the south of Indonesia and through the Timor Sea [111]. Recent studies have shown that the climatological-mean moisture gradients in the Maritime Continent are critical to the propagation past these islands [29, 105].

Multiple studies have shown that the amplitude and propagation characteristics of the MJO improve when GCMs include ocean coupled processes [112]. While the physical pathway for the improved simulation remains a topic of active research, a recent study suggests that coupled models exhibit mean states with steeper horizontal moisture gradients that favor enhanced MJO propagation [106], consistent with moisture mode theory.

When the South Asian monsoon is active during boreal summer, the intraseasonal precipitation anomalies tend to propagate northeast towards the Bay of Bengal [113, 114]. This behavior is sufficiently different from the boreal winter MJO that numerous studies refer to this phenomenon as the boreal summer intraseasonal oscillation (BSISO) [115]. Moisture mode theory has been applied to understand the BSISO's propagation and has found that the monsoonal mean state is of critical importance. When the monsoon is active, the largest concentration of moisture is centered over the Bay of Bengal, resulting in a northeastward moisture gradient over much of the Indian Ocean. This distribution of water vapor causes the BSISO-related horizontal winds to advect moisture in a way that northeast propagation of the anomalous convection occurs [116, 117]. The northeast propagation is enhanced by the advection of BSISO-related moisture by the monsoon low-level westerly jet [118, 119]. During boreal summer, the eastward-propagating MJO also produces a secondary convective center in the tropical northeast Pacific Ocean due to remote teleconnections through the Pacific equatorial waveguide [120].

Another important quantity used in the study of moisture modes is the so-called normalized gross moist stability (NGMS) [121, 122]. The name NGMS is a misnomer. It is not a lapse rate as the conventional definitions of stability, but a measure of the amount of column-integrated MSE exported by a region of convection [10]. Thus, the NGMS is not a true measure of stability, but a diagnostic quantity of the impact convection has on the thermodynamic environment. Another quantity, called the effective NGMS, includes the impact of radiative heating and surface fluxes in the export of MSE. Both the NGMS and effective NGMS are useful in analytical models of tropical motion systems since they act as proxies of the column-averaged moist static stability [18, 33]. Theoretical studies have shown that moisture modes grow when the effective NGMS is negative, i.e., when there is a net import of MSE into precipitating regions [17, 18, 71, 123].

In observations and reanalysis, the conventional NGMS tends to be slightly positive when the MJO is active [91, 124–126]. The effective NGMS, however, tends to be near zero or negative in observations and in models that exhibit strong MJO activity [126–131]. That the effective NGMS is negative while the conventional one is positive is due to cloud-radiative heating. Trapping of outgoing longwave radiation by upper tropospheric clouds causes anomalous heating throughout the troposphere that exceeds the reduction in shortwave radiative heating. This net cloud-radiative heating reduces the net export of MSE in the convective region and supports the convection by maintaining the troposphere humid, as indicated by Eq. 3.

Moisture mode theory has also been applied to understand the MJO's planetary scale. Different views exist on the key mechanism. One view suggests that cloud-radiative feedbacks are strongest at the planetary scale, leading to planetary-scale moisture modes [71]. Another view posits that the NGMS is smallest at the planetary scale [132]. Other views suggest that an instability exists between the large-scale circulation and wind-induced surface heat exchange [133], or frictional convergence [134], leading to preferential growth at the planetary scale. There is yet another view that suggests the MJO's scale is planetary because moisture is diffused more easily at smaller scales [18, 135]. While these physical mechanisms are different, they agree in that interactions between water vapor and convection play a key role in the planetary-scale selection of the MJO.

Moisture mode theory has also been used to understand the response of the MJO to climate change (see Maloney et al. [34] for a thorough discussion). An increased vertical moisture gradient with warming, partially counteracted by weaker radiative feedbacks and decreased vertical velocity per unit diabatic heating, makes vertical moisture advection more efficient and leads to increased MJO precipitation amplitude with warming in most models [136]. Stronger vertical and horizontal advective moistening to the east of MJO convection with warming have been cited as possible reasons for faster model MJO propagation speed [100, 137]. Finally, moisture mode theory, particularly the assumption of WTG underlying it, predicts that the MJO-related circulation will amplify more slowly than the the precipitation anomalies, and possibly even weaken with warming [138], which already has some support in the observed record [139].

A warming climate is also expected to produce potentially complex changes to the strength of MJO circulations and North Pacific basic state that lend uncertainty to how the MJO teleconnection may change in the future [136]. Recent modeling evidence suggests possible increasing impacts of MJO teleconnections on the U.S. West Coast associated with an eastward extension of the subtropical jet and MJO teleconnection [140].

Differences Between Moisture Modes and Other Convectively Coupled Waves

Up to this moment, we have discussed the moisture mode framework and its application to the MJO. But why do moisture modes exist? How are these motion systems different from other equatorial waves? The answer to these questions reveals important details about convective coupling in the tropics and the mechanisms that lead to a diversity of convectively coupled tropical motion systems.

Simplified models of tropical rainfall indicate that there are two processes that occur in response to the onset of deep convection. One is the gravity wave response to the latent heating/cooling, which adjusts the troposphere towards WTG balance (Fig. 2). The other is the drying of the troposphere through condensation and rainfall. Simple models of tropical motion systems reveal that the timescale in which convection dries the tropospheric column (τ_D) is inversely proportional to the absolute value of the effective NGMS. As mentioned in the previous section, in simple models, the NGMS can be thought of as an effective static stability, or as an "equivalent" shallow water depth. The two adjustment processes, one driven by convective adjustment (τ_D) and another by its gravity wave response (τ_{WTG}), may explain much of the diversity in convectively coupled equatorial waves and other tropical motions systems.

Analysis of moist shallow water basic equations in the equatorial belt reveals two regimes of equatorially trapped waves that are defined by τ_D and τ_{WTG} [32, 33] (Fig. 4). If $\tau_D \ll \tau_{WTG}$, convection dries the troposphere before gravity waves are able to redistribute the energy from the convection, failing to completely homogenize the horizontal distribution of temperature (i.e., the process shown in Fig. 2 is not completed). Decoupled from convection, the gravity waves can now propagate freely, and the temperature anomalies associated with these waves can induce convection by modulating the CAPE and CIN of the region they propagate into. These convectively coupled gravity waves could have significant moisture anomalies, but they are much smaller than those observed in moisture modes [33]. These waves may grow from a "stratiform instability" that results from feedbacks between the temperature anomalies and convection [141]. An analogous instability that also involves water vapor fluctuations, known as moisture-stratiform instability, may also explain the growth of these waves [142].

If $\tau_D \gg \tau_{WTG}$, the temperature field is smoothed and the thermodynamics of waves in this regime are governed by moisture, i.e., the resulting waves are moisture modes. At the planetary scale, the existence of moisture modes is contingent on an effective NGMS that is close to 0 [33]. That studies have found that the effective NGMS close to 0 or slightly negative during the MJO cycle does not definitively mean that the MJO is a moisture mode, but it does indicate that moisture mode theory may at least explain some of its features.

In addition to the effective NGMS, the ratio τ_{WTG}/τ_D is also determined by the wave's horizontal scale, with larger scale waves more likely to be gravity waves than moisture modes. It is also dependent on the vertical profile of vertical velocity in these systems, since the phase speed of free gravity waves (c) decreases as the vertical wavenumber of vertical velocity increases, i.e., c is smaller for shallow and stratiform profiles of ascent than in deep convective ones [2]. While observations currently do not support the notion that larger scale waves are more likely to be gravity waves, there is some evidence supporting the role of the vertical profile of ascent. Shallow and stratiform ascent appears to play an important role in the tilted structure of ascent of inertio-gravity, Kelvin and mixed Rossby-gravity waves [82, 126]. Vertical velocities in the MJO and equatorial Rossby waves are predominantly explained by a single profile of vertical velocity that is slightly more elevated from that of deep convective ascent, which also favors a reduced NGMS from enhanced cloud-radiative heating [126].

A recent study by Benedict et al. [99] showed some evidence of the moisture mode and gravity wave regimes in the Community Earth System Model. When cloud-radiative feedbacks were turned off in the model, they found a reduction in the spectral amplitude of the MJO, while Kelvin and inertio-gravity waves exhibited an increase in amplitude. The elimination of cloud-radiative feedbacks eliminated the import of moisture that results from said process (3), resulting in a larger effective NGMS. In the absence of moistening from cloud-radiative heating, the drying timescale τ_D becomes shorter, favoring the existence of gravity waves and suppressing the existence of moisture modes.

Synthesis and Future Research Directions

The results of multiple modeling, observational, and theoretical studies have led to an emerging consensus

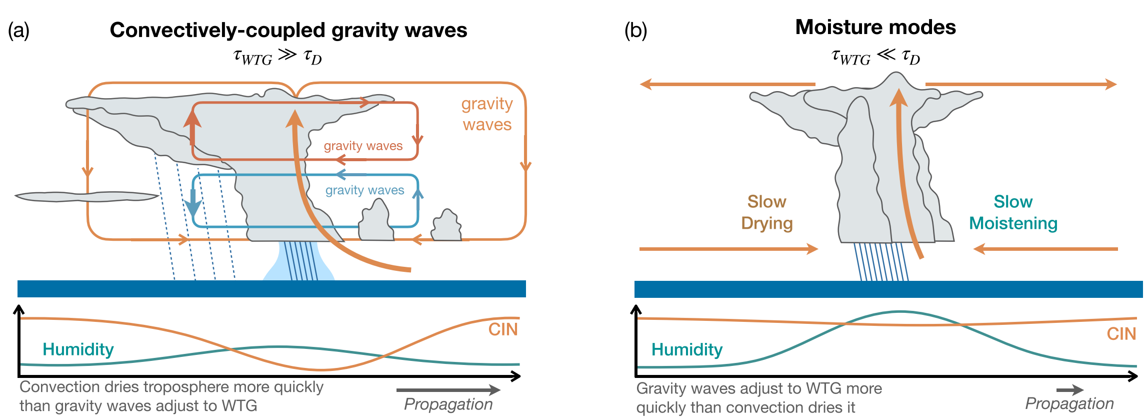

Fig. 4 Schematic description of how the WTG and QE adjustment processes can lead to diversity in convectively coupled waves. (a) If the WTG adjustment timescale (τ_{WTG}) is much longer than the QE adjustment timescale (τ_D), convection shuts down before the temperature anomalies are fully eliminated by gravity waves. The gravity waves can then propagate and modulate the temperature of the troposphere via adiabatic lifting. Such lifting can reduce convective inhibition (CIN) and induce subsequent convection. (b) If $\tau_{WTG} \ll \tau_D$, the temperature anomalies are completely eliminated and the evolution of the convection in the resulting wave is determined by the distribution of water vapor. These waves are referred to as moisture modes

that the MJO exhibits properties of a moisture mode. In spite of its success in explaining the MJO's features, some unanswered questions remain, and the theory has not been extended to explain other tropical motion systems. Furthermore, other competing views of the MJO also exist. We conclude this article by highlighting the unresolved questions and competing views, and offering future research directions.

Moisture Modes as an Integral Part of the Spectrum of Convectively Coupled Waves

The discussion in the previous section focused on two limits: one which leads to moisture modes and one which leads to gravity waves. When $\tau_{WTG} \sim \tau_D$, waves with an intermediate behavior between Matsuno's equatorial wave solutions and moisture modes are possible [32, 33]. The existence of these "mixed" systems would complete a spectrum of waves that can be observed in the tropics.

The idea that waves exist in a spectrum in the tropics is not new. Roundy [144–147] suggested that the MJO and convectively coupled Kelvin waves are not distinct phenomena. Instead, he suggested that they comprise the edges of a continuum, with waves with an intermediate structure existing between the spectral peaks of the MJO and Kelvin waves [144, 146]. When considered as a spectrum, the amplitude of the water vapor anomalies in these waves increases as their phase speed decreases [146], consistent with the moisture mode–gravity wave spectrum hypothesized by Adames et al. [32]. The continuum in which gravity waves and moisture modes exist is described in Fig. 5. Dry gravity waves and moisture modes are the waves that are found in the top-left and bottom-right vertices, with waves that exhibit intermediate characteristics—"mixed moisture-gravity waves"—existing in between.

While a spectrum connecting moisture modes and gravity waves has been suggested, it would still not fully explain the observed diversity of tropical motion systems. Equatorial Rossby waves are part of the same family of waves as inertio-gravity waves and mixed Rossby gravity waves, but the former evolve more slowly than the latter. Theoretical considerations of slowly evolving waves suggest that moisture modes and dry Rossby waves also exist in a continuum, forming the bottom of the triangle in Fig. 5 [33, 143]. Moisture modes are observed in a humid atmosphere where the effective NGMS is small, and hence τ_D is large. While the ratio τ_{WTG}/τ_{WTG} does not depend on the frequency of the wave, another number that can also describe the moisture mode-gravity wave spectrum shows that moisture modes are inherently low-frequency phenomena, as in Rossby waves [32]. Indeed, dry gravity waves are the fastest waves that can be observed in the tropics, and hence why Fig. 5 is shaped as a triangle.

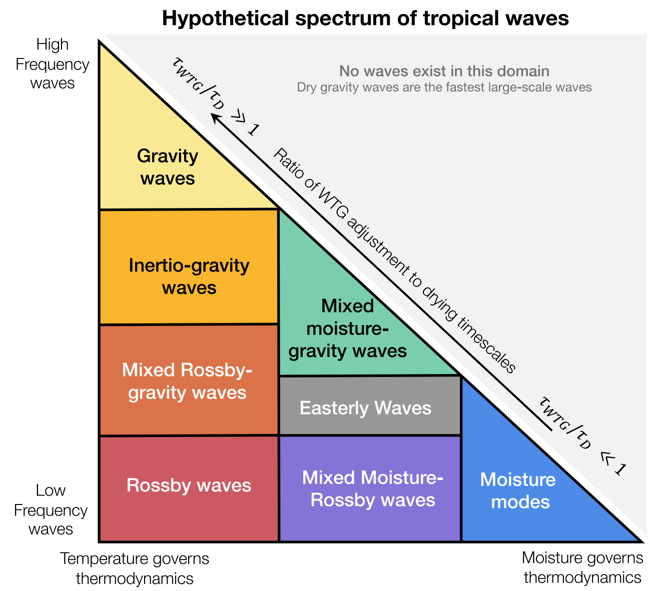

Fig. 5 Schematic description of the hypothetical spectrum of tropical motion systems obtained by synthesizing recent theoretical work on convectively coupled tropical waves [32, 33, 143]. At the vertices of the pyramid are the gravity waves, Rossby waves, and moisture modes. Between the vertices are modes which exhibit mixed behavior. Dry waves are in the left of the triangle, and waves become increasingly more humid from left to right The characteristics of each wave can be explained by their frequency and by the relative magnitude of the gravity wave adjustment timescale to the drying timescale (the latter is also inversely proportional to the effective NGMS). The triangle shape is due to dry gravity waves being the highest frequency large-scale waves possible. All moist waves are considerably slower than dry gravity waves

Moist waves with structures reminiscent of Rossby waves are also observed in the tropics, and it is possible that the evolution of water vapor plays a key role in these systems. Recent studies have hypothesized that monsoon low pressure systems may grow from an interaction between water vapor and circulation known as "moisture-vortex instability" [143, 148], or a mechanism known as "moist batropic instability" [149]. Recent work also suggests that African easterly waves may grow through a mechanism referred to as "rotational stratiform instability" [150]. These instabilities are rooted in the evolution of water vapor and convection in these systems, and they would not exist if water vapor were not a prognostic variable. Recent work shows that including prognostic moisture into a model that qualitatively represents the South Asian and West African monsoons causes the aforementioned instabilities to be the primary mechanism of growth, while weakening baroclinic instability, a process in which prognostic moisture is not necessary [89]. Thus, easterly waves and monsoon low pressure systems may be disturbances that exhibit an intermediate behavior between moisture modes and Rossby and Rossby-gravity waves. East Pacific easterly waves and some moist equatorial Rossby waves may also be mixed modes, since moisture explains the majority of their variance in rainfall [151–153]. These studies provide hints that moisture mode theory can be applied or be combined with other ideas to explain tropical phenomena.

Unanswered Questions and Other Views

There are numerous questions about the MJO that moisture mode theory has been unable to explain, or has yet to be applied. Among the most salient is the relationship between the MJO and the QBO [154]. Questions also remain on the processes that lead to MJO initiation and Maritime Continent transit, as well as planetary-scale selection [10, 15]. The precise balance of processes typically associated with MJO propagation (e.g., horizontal vs. vertical advection) has been shown to vary across models and different observational datasets, providing a challenge to the robustness of some of the findings of moisture mode theory [20, 155–157]. The role of surface flux feedbacks to MJO maintenance is also unclear, and may be location-dependent. Models and reanalyses even differ on the sign of the flux feedback (e.g., Figure 3, [157, 158]). How the MJO will change in a future warmer climate is also uncertain among models. A subset of climate models indicate weaker MJO precipitation variability in a warmer climate, even in the presence of a moister tropical mean lower tropospheric basic state that would predict MJO amplification through moisture mode theory [15, 34]. The pattern of SST change appears to be an important regulator of future MJO variability in such models [159]. Moisture mode theory might still explain this result, although in a different way than through simple arguments about the lower tropospheric moisture gradient.

It is important to note that moisture mode theory is not universally accepted. Several other views exist [10, 15]. Existing MJO theories can be categorized into two groups. One is a group posits that water vapor is prognostic and plays a prominent role in the MJO. This group includes different variants of moisture mode theory, which differ on the prominence that different moist processes play in the MJO [71, 133]. There are other views within this group that are not variants of moisture mode theory, but contain elements of the theory [98, 134, 135]. They also include prognostic water vapor, but emphasize other processes such as multiscale interactions [160]. A second group of theories exists where the role of water vapor is either secondary or nonexistent. This group includes two theories that are rooted in dry dynamics: one based on nonlinear Rossby wave dynamics [161], and one based on a linear Kelvin wave with momentum damping [162]. Another framework posits that the MJO is an interference pattern between eastward and westward propagating inertia-gravity waves [163].

The current diversity in MJO theories is a sign that more work is needed to understand its underlying mechanisms. Recent review papers provide several recommendations to evaluate these theories [10], and provide clues on how to elaborate on the theories based on recent observations and modeling results [15]. It is possible that an accepted theory of the MJO will have a combination of elements from moisture mode theory and other views.

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Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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