The Madden-Julian Oscillation

Introduction

The Madden-Julian Oscillation, named after the scientists who first detailed it in the early 1970s, represents the leading mode of intraseasonal (a week to a season in length) variability in the tropics. This lecture begins with a qualitative description of the MJO's characteristics and structure. It then briefly introduces the MJO's impacts to selected tropical and higher-latitude weather patterns. Four leading theories for the MJO are then introduced, after which the lecture ends with a discussion of how the MJO is monitored with real-time data.

Key Questions

- What are the Madden-Julian Oscillation's temporal evolution, horizontal structure, and seasonal variability?

- How do shifts in diabatic-warming maxima associated with the Madden-Julian Oscillation lead to impacts to tropical and higher-latitude weather patterns?

- What are the fundamental characteristics that Madden-Julian Oscillation theories must represent? What are the characteristics that these theories would ideally represent even though they are not all unique to the Madden-Julian Oscillation?

- How do the skeleton, moisture-mode, gravity-wave, and trio-interaction theories for the Madden-Julian Oscillation differ from each other, particularly with respect to how they explain the Madden-Julian Oscillation's planetary scale and eastward propagation?

- What are the two leading modes of variability in 850 hPa zonal wind, 200 hPa zonal wind, and outgoing longwave radiation data in the equatorial region, and how is this information used to monitor the Madden-Julian Oscillation?

Background

The Madden-Julian Oscillation (MJO) was first detailed in 1971 and affects phenomena on multiple scales from the convective to the planetary-scale. Contemporary reviews of the MJO include Zhang (2005), Jiang et al. (2020), and Zhang et al. (2020).

An MJO event typically lasts between 30-60 days and is manifest by a coherent cycle in sea-level pressure, horizontal and vertical motions, and precipitation. In this sense, the MJO can be viewed as short-lived local variability in the Walker circulation. MJO events often initiate in the equatorial Indian Ocean, from which they propagate eastward at ~5 m s^{-1}. MJO events are typically strongest in the equatorial Indian Ocean, with decreasing amplitude to the east particularly as they cross the Maritime Continent. In fact, about half of all MJO events terminate over the Maritime Continent (the so-called *barrier effect*, the physical reasoning for which is uncertain; Zhang and Ling 2017, Section 3.6 of Jiang et al. 2020). Conversely, some MJO events can traverse the globe within the event's 30–60-day lifecycle. An MJO event's ability to propagate eastward through the equatorial Pacific Ocean (if it successfully propagates across the Maritime Continent) is greater during El Niño events because of the anomalously warm central to eastern equatorial Pacific Ocean upper-ocean temperatures that accompany El Niño events (Jiang et al. 2020).

The MJO's lower-tropospheric structure is characterized by anomalously strong easterly trade winds known as the MJO's "easterly" phase preceding tropospheric-deep ascent and above-normal thunderstorm activity. This is then followed by anomalous westerly trade winds known as the MJO's "westerly phase" preceding tropospheric-deep descent and below-normal thunderstorm activity. In the annual mean, these features are centered along the Equator, with a pair of anticyclonically rotating vortices on either side of the Equator to the east and a pair of cyclonically rotating vortices on either side of the Equator to the west of the region of tropospheric-deep ascent. These structures result from the superposition of an $n = 1$ equatorial Rossby wave and a Kelvin wave, although there is some disagreement as to whether this structure is essential to the MJO. The MJO's upper-tropospheric structure is the opposite of its lower-tropospheric structure.

The MJO is strongest during the Southern Hemisphere summer in association with the Australian monsoon (Zhang 2005), at which time its latitudinal axis is located just south of the Equator. It has a secondary peak in intensity during the Northern Hemisphere summer in association with the Indian monsoon (Zhang 2005), at which time its latitudinal axis is located north of the Equator. Seasonal variability in the MJO's intensity and latitude is reduced in the Western Hemisphere, where the MJO is typically weaker and more variable.

Impacts of the MJO on Tropical and Midlatitude Weather Patterns

The MJO is associated with subseasonal to interannual variability in tropical weather patterns. For example, MJO forcing can influence when the Asian/Indian, African, and Australian monsoons begin, terminate, and transition from active to break periods while the monsoon itself remains present. The MJO's thunderstorm-active phase is typically associated with increased tropical-cyclone development potential when and where it is located due to the large-scale moistening, ascent, and (on its trailing side) increased lower-tropospheric cyclonic rotation that accompany this MJO phase. On longer timescales, El Niño events are often preceded by strong MJO events and their trailing westerly near-surface winds 6-12 months ahead of time. Given that this 6–12-month period typically occurs during the Northern Hemisphere spring, the intrinsic difficulties in predicting the MJO could be a contributor to ENSO's well-known spring predictability barrier. Finally, the MJO can also influence upper-ocean transport within and between the Indian and Pacific Oceans, including the ENSO-like Indian Ocean dipole circulation in the Indian Ocean. Further details on these impacts can be found in Zhang (2013).

The MJO has also been shown to be associated with subseasonal variability in midlatitude and polar weather patterns in the Northern and Southern Hemispheres, including:

- Precipitation, whether globally, in North and South America (particularly along their west coasts), or in Australia and New Zealand.
- Surface temperatures, particularly in North and South America and in the Arctic.
- Large-scale circulation patterns, often contextualized by what are known as teleconnection indices.

Further details on these impacts are provided by Jiang et al. (2020) in their Section 3.7.1. An exhaustive list of these and other impacts are provided by Zhang (2013).

These impacts to higher-latitude weather patterns are tied to the atmospheric response to diabatic warming. Tropospheric diabatic warming results from ascent over a deep vertical layer, with convergence in the lower tropospheric giving way to divergence in the upper troposphere. Rossby-wave initiation is favored in areas where the upper-tropospheric divergence (evacuating both mass and warmth) impinges upon the subtropical jet. These Rossby waves are large-scale perturbations on the jet and propagate along the jet's waveguide (a structure that guides waves). Their influences reach to higher latitudes where the subtropical and polar jets superimpose, such as when the subtropical jet reaches further poleward than normal or the polar jet reaches further equatorward than normal. Cyclones triggered downstream by the MJO-triggered Rossby waves can themselves also impact larger-scale higher-latitude weather patterns, thus continuing (in an indirect fashion) the MJO's influence on higher-latitude weather patterns well removed from its thunderstorm-active region. These influences typically dampen, however, with further eastward extent from an MJO event, particularly in the midlatitude jet's climatological exit regions over the eastern Pacific and Atlantic Oceans.

MJO Theories

There are four leading MJO theories (Zhang et al. 2020):

- *Skeleton theory*, in which the MJO is characterized by a planetary-scale envelope (or skeleton) of organized convective systems on the meso- to synoptic-scales.
- *Moisture-mode theory*, in which the large-scale convective envelope associated with the MJO is facilitated by a feedback between clouds and radiation that allows tropospheric water-vapor content to remain high despite losses due to condensation and subsequent precipitation.
- *Gravity-wave theory*, in which the MJO is characterized by a large-scale envelope of short-lived synoptic-scale inertia-gravity waves.
- *Trio-interaction theory*, in which friction-induced convergence in the atmospheric boundary layer couples thunderstorms, equatorial waves, and moisture within a planetary-scale envelope.

These theories are distinguished from MJO hypotheses by the former's connection to the so-called primitive equations, specifically simplified forms of the Navier-Stokes equations describing atmospheric motions.

There are three MJO characteristics essential to all theories: propagation speed (slower than all equatorial-wave modes), propagation direction (eastward), and spatiotemporal scale (planetary in space, intraseasonal in time). There are an additional seven MJO characteristics that we desire each theory to represent, although with the caveat that these are not necessarily unique to the MJO (unlike the essential MJO characteristics): its three-dimensional kinematic structure, including Kelvin and $n = 1$ equatorial Rossby waves; its seasonal cycle; its irregular duration, recurrence, and termination properties; its multiscale structure, which includes thunderstorms organized on multiple spatial and temporal scales; its modulation by other modes of tropical variability such as ENSO; the role of air-sea interaction, particularly in terms of the MJO's impacts to ocean conditions; and an explanation and/or remedy for the MJO's limited predictability.

Despite the MJO being associated with Kelvin and $n = 1$ equatorial Rossby waves, the MJO is not a solution of the shallow-water equations in the equatorial region when no forcing (e.g., diabatic warming) is applied. This contrasts with equatorial waves, which are solutions to the shallow-water equations with or without a specified forcing. This has two implications: the MJO is not simply an equatorial-wave mode, and the MJO requires some sort of forcing (whether external to the MJO system or contained within it) to initiate. Of the four leading MJO theories, three (the skeleton, moisture-mode, and trio-interaction theories) are associated with external forcing whereas on (the gravity-wave theory) is internally or self-forced.

Skeleton Theory

In the skeleton theory, the MJO is conceptualized as a planetary-scale envelope of organized convective (or thunderstorm) systems on the meso- to synoptic-scales. It can be characterized by a predator-prey model in which positive lower-tropospheric moisture anomalies develop *in advance of* thunderstorms that ultimately consume them. This separation between where lower-tropospheric water-vapor content is largest and where thunderstorms are found is unique to the skeleton theory; the other leading MJO theories assume that there is no separation between these fields. Since positive lower-tropospheric moisture anomalies are found *east* of the MJO's thunderstorm envelope, this separation is responsible for the MJO's eastward propagation.

In this theory, thunderstorms initiate once conditional instability is realized. The planetary-scale envelope of thunderstorms is sustained by positive lower-tropospheric moisture anomalies; this envelope's amplitude grows so long as these anomalies remain positive and begins to decay once they become negative (resulting from tropospheric moisture reductions caused by precipitation formation and fallout). The positive moisture anomaly is formed and maintained *at the ground* primarily by surface evaporation. Immediately above the ground, however, the positive moisture anomaly is formed and maintained primarily by the upward mixing of moisture from nearer to the surface. This upward mixing results from horizontal convergence associated with the Kelvin and n =1 equatorial Rossby waves driven by the planetary-scale thunderstorm envelope.

Moisture-Mode Theory

Moisture-mode theory is predicated on cloud-radiation feedbacks. Without these feedbacks, thunderstorms are short-lived as they consume instability and dry the tropospheric column. With these feedbacks, however, thunderstorms become longer-lived and cover a greater zonal extent. These feedbacks are characterized as:

- Upper-tropospheric winds cause a thunderstorm's anvil to spread over a large area relative to that of the thunderstorm itself. The anvil's cirrus canopy traps outgoing longwave radiation, causing the troposphere below the anvil to warm.
- This diabatic warming initiates larger-scale thermally direct circulations in the form of Kelvin and n = 1 equatorial Rossby waves. The lower-tropospheric horizontal convergence between these waves imports moisture into the MJO's thunderstorm envelope from the east. Surface evaporation helps to increase the near-surface moisture content along the converging air.
- To maintain the weak horizontal temperature gradients that characterize the tropics against this diabatic warming, adiabatic cooling driven by ascent occurs where the anvil-induced diabatic warming takes place. This ascent spreads the imported moisture throughout the troposphere.
- Together, these processes result in tropospheric moisture import exceeding moisture loss (to condensation and precipitation), thus allowing thunderstorms to persist.

In other words, *thunderstorms result in a cloud-radiation-dynamics feedback that supports thunderstorms' continued maintenance*!

In this theory, the MJO's planetary scale is governed by thunderstorm anvils' lateral extent, as their expanse facilitates thunderstorm formation and maintenance on a large horizontal scale. The MJO's eastward motion is driven by positive lower-tropospheric horizontal moisture advection being maximized east of the MJO's thunderstorm center (Ádames and Kim 2016).

Gravity-Wave Theory

In the gravity-wave theory, the MJO is conceptualized as a planetary-scale envelope of short-lived synoptic-scale inertia-gravity waves that are triggered by and interact with thunderstorms. The characteristic Kelvin and $n = 1$ equatorial Rossby waves are not produced or assumed by this theory.

In this theory, thunderstorms initiate where tropospheric thickness falls below a specified threshold. These thunderstorms generate both westward- and eastward-moving inertia-gravity waves. The magnitude of the latter's phase speed slightly exceeds that of the former, with this asymmetry causing the entire envelope of thunderstorms and gravity waves characterizing the MJO to propagate eastward.

Consider the general dispersion relation for equatorial waves (with no assumptions) from an earlier lecture:

$$\frac{\sqrt{g'H}}{\beta}\left(\frac{\omega^2}{g'H} - k^2 - \frac{\beta k}{\omega}\right) = 2n + 1$$

This equation is cubic for the frequency ω. Two of its roots correspond to westward- and eastward-moving inertia-gravity waves. The root that corresponds to eastward-moving inertia-gravity waves includes a factor of $+\beta$, whereas the root that corresponds to westward-moving inertia-gravity waves includes a factor of $-\beta$. Because β is positive-definite, the eastward-moving inertia-gravity wave phase speed's magnitude exceeds that of the westward-moving inertia-gravity wave.

As the inertia-gravity waves propagate away from where they are generated, they trigger new thunderstorms where sufficient conditional instability exists. This occurs within a coherent planetary-scale envelope owing to tropical thunderstorms' propensity to *self-aggregate*:

- Although a single thunderstorm reduces tropospheric water-vapor content through precipitation, it also moistens its immediate surroundings through *detrainment* (characterized by the outward mixing and subsequent evaporation of saturated air from a thunderstorm).
- Furthermore, diabatic warming within thunderstorms facilitates increased column thickness, reduced surface pressure, and lower-tropospheric convergence. The associated increase in surface wind speeds increases surface sensible and latent heat fluxes, maintaining lower-tropospheric warmth and moisture even in the presence of precipitation.

Together, these processes favor subsequent thunderstorms forming near where they originated. Over time, individual thunderstorms merge into larger-scale thunderstorm clusters as their outflow boundaries collide, resulting in self-aggregation. In the gravity-wave theory, these subsequent thunderstorms result from ascent fostered by the leading crest of an inertia-gravity wave triggered by another thunderstorm.

The MJO's horizontal scale is determined by the average distance an inertia-gravity wave can travel before intercepting an existing thunderstorm. Faster waves and/or greater distance between thunderstorms results in a faster MJO whereas slower waves and/or less distance between thunderstorms results in a slower MJO.

Trio-Interaction Theory

The trio-interaction theory is named because of its theorized interactions between thunderstorms, dynamics, and moisture. In specific, the dynamics – here characterized by boundary-layer convergence – is responsible for driving the thunderstorms and moisture, which feed back to the dynamics. The requisite boundary-layer convergence results from the surface low-pressure anomaly associated with the leading half-wavelength of a Kelvin wave; friction reduces surface wind speeds and thus the Coriolis force, causing near-surface air to be directed across isobars toward areas of lower pressure. This has three effects:

- Triggers a moisture-mode–like instability that increases boundary-layer moisture and conditional instability east of the larger-scale lower-tropospheric convergence maximum between the Kelvin and $n = 1$ equatorial Rossby waves. This results in the MJO's eastward propagation.
- Reduces the coupling between diabatic warming and the zonal overturning circulation (as diabatic warming becomes confined over a broader zonal extent rather than concentrated in a single area). The more-expansive diabatic warming increases the larger-scale energy growth rates and results in the MJO having a broader, planetary-scale (rather than confined) horizontal structure.
- Through the continual eastward progression of where diabatic warming is occurring, helps to hold the Kelvin and $n = 1$ equatorial Rossby wave structures together (in contrast to their propensity to propagate in opposing directions after being triggered by a spatially fixed diabatic warming).

MJO Monitoring

As with equatorial waves, the MJO can be monitored by filtering relevant data (such as outgoing longwave radiation or zonal winds) by their frequency (return period/propagation speed), wavelength (spatial scale), and propagation direction. Traditionally, this filtering is accomplished after first removing larger-scale and longer-period modes of variability such as the seasonal, annual, and interannual cycles so as to more reliably isolate signals within the data associated with smaller-scale and shorter-period modes of variability.

Unlike equatorial waves, which are associated with small perturbations and thus require advanced filtering techniques (such as the Fourier-based filtering described previously) to identify in observed data, the MJO can more readily be identified using other statistical filtering techniques like empirical orthogonal function (EOF) analysis (Wheeler and Hendon 2004). Empirical orthogonal function analysis is a mathematical tool that identifies modes of variability within time-series data. The leading modes of the EOF analysis represent the greatest variability in the data subject to the limitations of the chosen EOF analysis method. However, an EOF analysis is intrinsically statistical; while it often does highlight physically explainable signals, there is no guarantee that each signal (even the leading ones) are truly physical.

There have been several applications of EOF analysis to MJO identification, the first of which was Wheeler and Hendon (2004). In their study, an EOF analysis was applied to outgoing longwave radiation, 850 hPa zonal wind, and 200 hPa zonal wind data averaged between 5°S-5°N at all longitudes, from which the first two leading modes were retained. These two leading modes explain 25% of the total variance in these fields, with 60% of the variance explained by these two leading modes occurring in the MJO's 30–60-day temporal range. Thus, the MJO can be monitored without first filtering out variability on other spatiotemporal scales!

The two leading modes from the EOF analysis, referred to as EOF1 and EOF2, characterize zonal variation in outgoing longwave radiation, 850 hPa zonal wind, and 200 hPa zonal wind in the tropics associated with the MJO. EOF1 is characterized by lower-tropospheric convergence that causes reduced outgoing longwave radiation (associated with thunderstorms) over the Maritime Continent. The convergence is associated with lower-tropospheric westerly zonal wind anomalies in the equatorial Indian Ocean and easterly zonal wind anomalies across the equatorial western Pacific Ocean. Upper-tropospheric flow anomalies mirror those in the lower troposphere. EOF2 has a similar structure except shifted eastward to the equatorial Pacific Ocean.

The two EOFs are well-correlated to each other with a lag of about nine days, such that a cycle through the observed structures associated with each EOF completes over a 35–40-day period.

Real-time MJO monitoring is accomplished by projecting outgoing longwave radiation and zonal wind data (specifically, anomalies in these data) onto the two leading modes of variability from the EOF analysis. In a basic sense, *projecting* refers to identifying how well the observed data match with EOF1's and EOF2's structures. The projection is positive if the observed anomalies vary in the same way as does an EOF but is negative if the observed anomalies vary in the opposite way as does an EOF. Higher projection magnitudes result when the observed anomalies closely resemble an EOF and have large magnitudes of their own. For the MJO, these projection values are referred to as RMM1 and RMM2 for EOF1 and EOF2, respectively. Combinations of RMM1 and RMM2 define eight MJO phases, each describing a unique spatial structure of anomalous zonal wind and thunderstorm activity associated with the MJO, with phase 1 (negative RMM1 and RMM2) associated with enhanced thunderstorm activity near the African east coast cycling eastward around the globe to phase 8 (negative RMM1 and positive RMM2) associated with enhanced thunderstorm activity in the Western Hemisphere.

The Wheeler and Hendon (2004) MJO index is not the only such index that is used to identify and track the MJO. Other MJO monitoring indices include the OLR MJO index and its variants (Kiladis et al. 2014) and velocity-potential MJO index (Ventrice et al. 2013). The former is similar to Wheeler and Hendon (2004), except using only outgoing longwave radiation data. The latter uses upper-tropospheric velocity potential, which is a measure of the divergent component of the horizontal wind, to monitor the MJO. Altogether, the various MJO monitoring indices typically provide similar results given the dynamical relationships linking zonal winds, divergence, ascent, and thunderstorm activity. Subtle differences between indices result from differences in whether or not the input data are filtered before the analysis.

For Further Reading

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