Monsoons

Introduction

The tropical circulations that we have considered thus far are all driven by diabatic warming. However, we have been a bit loose with this terminology. While it is true that tropical circulations are driven by diabatic warming, it is more accurate to say that they are driven by *spatial variations in diabatic warming*. Although this may seem like a small nit to pick with our definition, it is vitally important for tropical circulations that are asymmetric across the Equator. In this lecture, we introduce the leading meridionally asymmetric, large-scale tropical circulation, the *monsoon*, and analyze how meridional diabatic-warming differences result in its characteristic three-dimensional circulation. We also introduce the world's most-noteworthy monsoons and describe how intraseasonal to interannual modes of tropical variability can influence these monsoons.

Key Questions

- What is the characteristic three-dimensional structure of the monsoon circulation?
- What causes the meridional differences in diabatic warming that drive the monsoon? How do monsoon-induced atmospheric and oceanic transports counteract these differences?
- What are the world's predominant monsoon circulations? How are they similar to each other? How do they differ from each other?
- How do other modes of tropical variability impact the monsoon, particularly its rainfall characteristics?

Introduction to Monsoons

To first order, the term *monsoon* refers to the seasonal reversal of the prevailing surface winds over southern Asia and the Indian Ocean. This reversal is driven by the seasonal development of a meridional temperature gradient between comparatively warm lands and comparatively cool oceans that results in reduced sea-level pressure, convergent onshore flow, and enhanced precipitation over land during the local summer months. This circulation reverses in winter, such that increased sea-level pressure and reduced precipitation are seen over these same landmasses during the local winter months. Although the term *monsoon* formally refers to this circulation over Asia and the Indian subcontinent, monsoons are not exclusive to this region; they also occur in some form over Australia and the Maritime Continent, Africa, and North and South America.

All monsoons are characterized by convergent cyclonic lower-tropospheric flow and divergent anticyclonic upper-tropospheric flow in the summer hemisphere. The lower-tropospheric flow crosses the Equator from the winter to the summer hemisphere and the upper-tropospheric flow crosses the Equator from the summer to the winter hemisphere. Ascent and seasonally enhanced rainfall are promoted in the summer hemisphere whereas descent and seasonally reduced rainfall are promoted in the winter hemisphere. On seasonal scales, this is manifest through seasonal variations in the Hadley cell's ascending branch On climatological scales, this is manifest through the Am *monsoon* climate classification.

The characteristic meridional temperature gradient between land and water that drives the monsoon is, just as with many other tropical phenomena, driven by spatial variations in diabatic heating. We now return to the shallow-water equations to discuss how spatially variable diabatic warming – here displaced off of the Equator rather than centered along it – gives rise to the monsoon.

Monsoon Structure

Surface sensible warming in the subtropics is maximized during the local summer when insolation is at its annual maximum. Because land has a low specific heat capacity (energy required to change temperature by a fixed amount, usually 1°C), subtropical landmasses warm rapidly as the local summer months approach. This causes subtropical landmasses to be substantially warmer than the subtropical oceans and especially landmasses in the winter hemisphere, resulting in a large meridional temperature gradient between summer and winter hemispheres. These spatial variations in surface sensible heating – warm in either the Northern or the Southern Hemisphere, cold in the other hemisphere – drive the monsoon.

As with the Walker circulation, we can use the shallow-water equations to describe how the monsoon arises from meridional differences in diabatic warming. However, whereas diabatic warming is symmetric along the Equator for the Walker circulation, it is asymmetric across the Equator for the monsoons. Consequently, the shallow-water equations provide a different solution with the monsoon than with the Walker circulation. Proceeding from a Northern Hemisphere-centric perspective, with warming prescribed over a limited zonal extent north of the Equator, this solution is characterized by the superposition of two equatorial waves:

- A mixed Rossby-gravity wave.
- An $n = 2$ equatorial Rossby wave.

We have not yet introduced the second of these waves. It has similar lower-tropospheric pressure anomalies to the mixed Rossby-gravity wave and a similar horizontal-flow structure to $n = 1$ equatorial Rossby waves. The $n = 1$ and $n = 2$ equatorial Rossby waves are both allowable solutions to the shallow-water equations, differing only in the value of the generic wavenumber n that is considered.

The lower-tropospheric superposition of the mixed Rossby-gravity wave and $n = 2$ equatorial Rossby wave is characterized by low pressure north of the Equator and high pressure south of the Equator. Ascent is maximized southeast of the low near the prescribed warming whereas descent is maximized northeast of the high. Zonally integrating this solution provides a depiction of the monsoon's meridional structure, with strong ascent, lower-tropospheric westerlies, and upper-tropospheric easterlies in the Northern Hemisphere and the opposite vertical and horizontal motions in the Southern Hemisphere. Meridional transport in both hemispheres is cross-equatorial, from the Southern to the Northern Hemisphere at low levels and from the Northern to the Southern Hemisphere at upper levels, and exports heat from where it is warmer to where it is cooler. The solution is identical for the Southern Hemisphere summer monsoon except for being mirrored or flipped across the Equator. The net picture is of a Hadley-like circulation displaced northward off of the Equator toward the warming source that is much stronger than the Hadley-like circulation that results from warming prescribed along the Equator.

Finally, it is also possible to use the shallow-water equations to identify the circulation resulting from both symmetric and asymmetric warming, the combination of which more-accurately characterizes summertime conditions. This solution is characterized by the superposition of the four equatorial waves – a Kelvin wave, $n = 1$ and $n = 2$ equatorial Rossby waves, and a mixed Rossby-gravity wave – that comprise the symmetric-only and asymmetric-only solutions. This superposition is constructive in the hemisphere in which warming is applied and destructive in the opposite hemisphere; thus, the lower-tropospheric monsoon low is stronger than the monsoon high. The combined solution depicts the monsoon's characteristic curved cross-equatorial flow and strong ascent through the combined warming source. Zonally integrating this solution results in a realistic Hadley-like circulation whereas meridionally integrating this solution results in a realistic Walker-like circulation.

Monsoons of the World

Asian/Indian Monsoon

The Asian or Indian monsoon is the best-known, largest-scale, and highest-impact of the world's monsoons. Its structure consists of:

1. A positive lower-tropospheric meridional temperature gradient between the strongly sensibly warmed Tibetan Plateau in the Northern Hemisphere and comparatively cool South Indian Ocean.

2. From #1, a lower-tropospheric monsoon low over India and southeast Asia and the lower-tropospheric Mascarene high in the southwestern Indian Ocean.

3. Onshore, cross-equatorial flow that spirals inward toward the monsoon low and facilitates thunderstorm development. The cross-equatorial flow is the result of friction causing lower-tropospheric air to diverge from the Mascarene high and converge into the monsoon low.

4. The lower-tropospheric Somali jet, which results from channeling of the cross-equatorial flow by the high mountains of east Africa.

5. From mass continuity, an upper-tropospheric anticyclone atop the monsoon low.

6. The upper-tropospheric tropical easterly jet immediately south of the upper-tropospheric anticyclone in #5.

The monsoon's arrival or onset is characterized by the onset of persistent rainfall. This happens first in the Bay of Bengal in late April and progresses steadily northward through the Indian subcontinent, east Asia, and the western North Pacific Ocean through summer. The monsoon's eastward extension into the western North Pacific Ocean is sometimes referred to as the East Asian and/or Western North Pacific monsoon. The monsoon ends or retreats with the seasonal cycle in fall. Enhanced precipitation driven by the monsoon is favored over strongly warmed land masses such as Indonesia and India and over the warm eastern equatorial Indian Ocean.

The monsoon circulation's intensity is directly proportional to the magnitude of the horizontal temperature gradient. The monsoon is strongest in India and southeast Asia where this temperature gradient is large and primarily meridional between the warm Tibetan Plateau and cool South Indian Ocean. Its eastern extension into the western North Pacific Ocean is somewhat weaker since the large meridional temperature gradient between the warm western North Pacific Ocean and cool Australia is somewhat offset by a zonal gradient of opposite sign between the even-warmer Asian landmass and not-as-warm western North Pacific Ocean.

As previously noted, monsoon evolution is significantly modulated by the seasonal cycle. It is also regulated by cross-equatorial oceanic transport. Recall that upper-ocean transport is influenced by the Coriolis force, such that it is directed 90° to the right of the mean surface wind in the Northern Hemisphere and 90° to the left of the mean surface wind in the Southern Hemisphere. As a result, the monsoon's cross-equatorial flow results in Ekman transport of oceanic warmth – southeastward in the Northern Hemisphere, southwestward in the Southern Hemisphere – that weakens the meridional temperature gradient and the monsoon itself.

The Asian monsoon's eastward extension is characterized by two semi-permanent meso- to synoptic-scale phenomena, the *Mei-yu/Baiu front* and the *monsoon trough*:

- The *Mei-yu/Baiu front* is a summertime semi-permanent, quasi-stationary weak front that extends from eastern China near 25°N east-northeastward into the North Pacific Ocean. This front becomes established in mid-May and shifts northward through early to mid-summer before weakening. The front is the focal point for persistent heavy precipitation produced by episodic mesoscale convective systems (MCSs) that form over eastern China. Such MCSs preferentially form in this location given the presence of a lower-tropospheric jet that brings warm, moist air northward to the region from the South China Sea and Bay of Bengal. Lower-tropospheric air that approaches this front is forced to ascend, resulting in thunderstorm formation and organization in the moist, conditionally unstable environment in which the Mei-yu/Baiu front is found.
- The *monsoon trough* is oriented along a west-northwest to east-southeast axis from the Philippines to north of the Maritime Continent. It results from the zonal change in the lower-tropospheric winds from westerly to the west (driven by the Asian monsoon) to easterly to the east (associated with the oceanic subtropical anticyclone and tropical easterly trade winds). As a result, the monsoon trough is a locus of convergent, cyclonically rotating lower-tropospheric flow. This cyclonic-rotation-rich environment is a prime breeding ground for tropical cyclones during the local summer months.

Australian/Maritime Continent Monsoon

In many respects, the Australian or Maritime Continent monsoon mirrors the Asian or Indian monsoon. Its onset occurs over Malaysia in late winter and progresses southeast toward northern Australia through spring and summer.

Like the Asian monsoon, the Australian monsoon is driven by a meridional temperature gradient, here being a negative gradient between strong warming over the Maritime Continent and deserts of northern Australia and comparatively cool conditions over Asia and the western North Pacific Ocean. This contrast results in the monsoon's characteristic cross-equatorial flow, here from the Northern to the Southern Hemisphere. As with the Asian monsoon, Ekman transport associated with the cross-equatorial flow helps to counteract the negative meridional temperature gradient, gradually weakening the monsoon circulation as summer begins to give way to fall (also weakening the monsoon circulation).

West African Monsoon

The West African monsoon (WAM) is characterized by rainy periods in interior Africa in both the Northern and Southern Hemisphere. However, the WAM and its accompanying cross-equatorial flow is not as well-defined as that of other monsoons given its proximity to the strong, larger-scale Asian/Indian and Australian monsoons. The WAM causes increased rainfall across interior northern Africa during Northern Hemisphere summer and across south-central Africa during Southern Hemisphere summer. The former is characterized by the poleward transport of warm, moist air from the tropical South Atlantic Ocean northward toward the hot, dry Sahara Desert.

North and South American Monsoons

Weak monsoons exist in both North and South America. The North American monsoon (NAM) is driven by strong surface sensible warming of the deserts of western Mexico and the southwest United States. This increases lower-tropospheric thickness, in turn reducing sea-level pressure and establishing what is known as a surface “heat low.” Lower-tropospheric convergent flow into this heat low transports warm, moist air from the Gulf of California and eastern North Pacific Ocean into western North America. The NAM’s onset is typically between mid-June and mid-July, with the monsoon subsequently lasting for two to three months until September. Likewise, the South American monsoon is also driven by strong surface sensible warming – except in this case, of the warm, moist Amazon River basin in South America. Precipitation is enhanced in northern South America as warm, moist air is imported from the equatorial Atlantic Ocean and Amazon River basin by the SAM’s circulation. The SAM’s onset is unique in that it occurs early in the local spring months (September-October) and persists through local summer (December-February).

Monsoon Variability

Monsoon rainfall varies on the intraseasonal scales with the MJO and on interannual scales with ENSO and other tropical modes of variability.

Intraseasonal variability is manifest as “active” and “break” monsoon periods. Active periods are associated with a strengthened monsoon circulation and above-normal rainfall over land. Break periods are associated with a weakened monsoon circulation and below-normal rainfall over land. The MJO is the primary cause of intraseasonal monsoon variability, with particularly significant impacts in the Eastern Hemisphere where the MJO is climatologically strongest. An active MJO phase can facilitate the onset of the Asian monsoon or an active monsoon period whereas an inactive MJO phase can facilitate the monsoon’s retreat or a break monsoon period. This impact is strongest with stronger MJO events. Further, given that the MJO is typically stronger in the Southern Hemisphere summer (as compared to Northern Hemisphere summer), its influence on the Australian monsoon is typically somewhat greater than its influence on the Asian or Indian monsoon.

Annual variability in the Asian and Australian monsoons results from upper-ocean temperature variability in the Indian Ocean known as the Indian Ocean Dipole (IOD). The IOD is characterized by an east-to-west dipole of upper-ocean water temperatures between the eastern and western equatorial Indian Ocean. Heavy monsoon rainfall follows with the portion of the Indian Ocean where it is comparatively warm: east Africa toward India when the western Indian Ocean is comparatively warm and southeast Asia and Indonesia when the eastern Indian Ocean is comparatively warm.

Annual variability in the WAM is related to the magnitude of the meridional temperature gradient between the Gulf of Guinea (in the equatorial Atlantic Ocean) and the sensibly warmed northern African landmass. Warmer ocean temperatures in the Gulf of Guinea reduce this meridional temperature gradient’s magnitude, in turn reducing the meridional sea-level pressure gradient’s magnitude, weakening onshore flow into and subsequent precipitation in western Africa. Conversely, colder ocean temperatures in the Gulf of Guinea increase this meridional temperature gradient, in turn increasing the meridional sea-level pressure gradient’s magnitude, strengthening onshore flow into and subsequent precipitation across west Africa.

Finally, ENSO is the leading cause of interannual variability, particularly in the Asian/Indian and Australian monsoons. The eastward shift of the Walker circulation's ascending branch to the central equatorial Pacific Ocean during El Niño events reduces rainfall in association with these monsoons, whereas the strengthening of the Walker circulation's ascending branch in the western equatorial Pacific Ocean during La Niña results in increased rainfall in association with the monsoons.

It should be emphasized that the relationships detailed in this section are *climatological* outcomes. There is substantial variability between individual MJO, IOD, and ENSO events. Further, the MJO, IOD, and ENSO never occur in isolation from other forms of variability; rather, the atmosphere-ocean system is comprised of variability across a wide range of scales. Consequently, it is not difficult to find times when and locations where these relationships do not precisely hold.

For Further Reading

- Chapter 3, *An Introduction to Tropical Meteorology, 2nd Edition*, A. Laing and J.-L. Evans, 2016.
- Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447-462.
- Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43.