TROPICAL SYNOPTIC METEOROLOGY

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Summary

The tropics, loosely defined as the latitude belt located equatorward of 30° latitude in either hemisphere, are characterized by a net input of heat, angular momentum, and water vapor (latent heat energy) to the atmosphere. The action of synoptic-scale eddies can transport tropical air masses to higher latitudes, resulting in abundant condensation and precipitation in areas where the moist air rises. Thus, tropical latent heat input and subsequent poleward transport represents an important component of the Earth's energy budget.

Early views of the tropical atmospheric circulation emphasized thermally direct convection currents, with rising air near the equator and sinking air near 30° latitude in either hemisphere. Over time, observations have demonstrated that this "Hadley cell view" of the tropical circulation as a steady, thermally direct latitudinal circulation is grossly oversimplified. Observations reveal a complex spectrum of wavelike disturbances, strong longitudinal circulations, and thermally driven monsoon flows. Wavelike disturbances are found in the Intertropical Convergence Zone (ITCZ), as well

as embedded in monsoon and trade wind circulations. In some circumstances, westward traveling wave disturbances can develop into warm-core tropical cyclones, the most violent form of tropical weather system. Interannual oscillations such as El Niño-Southern Oscillation (ENSO) exert important influences on tropical weather that can also extend poleward beyond the tropics.

Critical elements in the dynamics of the tropical circulation include the aforementioned wave disturbances, ocean-atmosphere coupling, and the role of convection. Global circulation models, such as those used in climate prediction, are challenged to accurately reproduce the ITCZ and corresponding wave phenomena. This is not surprising, given the complex interactions between small-scale convective processes and larger-scale wave disturbances in regions with limited in-situ observational data. However, the far-field influence of tropical circulations, including re-curving tropical cyclones, can exert important influences on the mid-latitude atmosphere. This in turn has important implications for climate change prediction and impacts.

1. Introduction

Synoptic scale weather systems are typically defined by temporal scales on the order of several days and spatial scales of approximately 1000 km. Dominant physical processes on the synoptic scale in the *extratropics* are strongly influenced by the Earth's rotation, as the Coriolis force has sufficient time to establish a balance between the mass and wind fields on these scales. Further, strong horizontal temperature contrasts, in conjunction with the Earth's rotation, lead to westerly jet streams that peak in strength in the mid-latitude upper troposphere, at approximately 10 km altitude. These jet streams exert a dominant influence on day-to-day weather, and are associated with the formation and movement of high and low pressure systems in the polar front belt of either hemisphere.

In contrast, tropical regions, defined here as those regions equatorward of 30° latitude, are characterized by relatively weak Coriolis deflection; the horizontal component of the Coriolis force approaches zero exactly at the equator. Thus, the fundamental dynamics of synoptic-scale systems in the tropics differ from those of the mid-latitudes. Rather than a balance of pressure gradient and Coriolis forces, the tropics feature weather systems driven by heating differences between land and water, and by condensational latent heat release. With relatively weak horizontal temperature contrasts and warm temperatures, the capacity for atmospheric water vapor is much greater than at higher latitudes, and a large amount of latent energy is transferred from the Earth's surface to the atmosphere. This latent heat energy is released in regions of rising air motion; in the tropics, such regions are found in monsoon circulations, wave disturbances, the Intertropical Convergence Zone (ITCZ), and in tropical cyclones. The weak influence of the Earth's rotation and strong latent heating result in tropical circulation systems that are complex, and the relatively straightforward theories of balanced mid-latitude dynamics do not apply.

The tropical atmosphere features wavelike systems that both organize convective storms and are driven by latent heat release within convective storms. Tropical wave motions are thus linked with cumulus convection, and these systems are in turn coupled to the ocean surface. Tropical weather systems are important for their role in the larger-scale climate system, and the occurrence of tropical cyclones can exert a strong effect on tropical and mid-latitude locations alike during active seasons. Tropical oscillations and wave systems can also have important mid-latitude impacts, for example, the El Niño-Southern Oscillation (ENSO) phenomenon.

1.1. Radiation and Momentum

The tropics are characterized by a surplus of incoming radiant energy. In other words, the net surface input of solar energy in the tropics exceeds that lost to space through infrared thermal radiation. Thus, to maintain steady state energy balance, there must be a net export of energy from this region toward the poles, where a net deficit of radiant energy is observed. This transport is accomplished both by ocean currents and atmospheric circulation systems acting on a variety of spatial and temporal scales. There is also a net gain of angular momentum by the atmosphere in the tropical belt, as evident from the predominance of easterly surface wind flow in this zone. The presence of predominant easterly flow means that the atmosphere is, on average, rotating more slowly than the earth in this latitude belt. Thus, a net export of angular momentum from the tropics toward the poles also takes place.

1.2. Heat and Water Vapor

The tropics are the most important source region for global atmospheric water vapor, and the transport of water vapor from the tropics to higher latitudes constitutes an important component of the Earth’s energy budget. The maximum water vapor content is a function of only of temperature. The presence of large, warm oceans, vast expanses of trade winds, and strong solar heating all allow for optimal extraction of latent heat energy over the tropical oceans via surface evaporation. Steady winds are important due to the turbulence that is generated in the lowest 1-2 km of the atmosphere, which serves to mix heat and moisture acquired from the surface into the lower atmosphere. When moist tropical air masses are transported to higher latitudes, strong condensation and heavy precipitation can result where rising air motions occur, releasing latent heat. Owing to the fact that vapor capacity is proportional to temperature, which decreases with height in the lowest 10 km of the atmosphere, the largest vapor content is almost always found in the lowest 1-2 km of the tropical atmosphere. The transport of water vapor from the tropics to midlatitude locations takes place at low altitudes within cyclone-scale disturbances. For instance, in extratropical cyclones, it is common to observe low-level jets of vapor-rich tropical air directed poleward. Seasonal monsoon circulations, to be discussed in greater detail in section 2, are organized circulations capable of transporting and releasing large quantities of latent heat energy.

1.3. Mean Circulation

Early theories of the tropical circulation described semi-permanent, thermally direct Hadley-cell circulations in either hemisphere, with a region of ascending air, clouds, and showers near the equator that shifts with the seasons, and descending branches corresponding to arid regions located near 30°latitude in either hemisphere. The sinking branches of the equatorial Hadley circulations correspond to the locations of major desert regions, such as the Sahara, and over oceanic regions, to the location of the subtropical high pressure systems. However, this simplified view of the tropical circulation is far from complete, even if it does explain some important features of the tropical circulation in time-averaged data.

The rising branch of the Hadley circulation takes the form of a narrow, discontinuous, and intermittent band of intense convection known as the ITCZ (Fig. 1). Vapor condensation in the rising convective towers releases tremendous amounts of latent heat energy, which warms the air column, giving rise to high pressure and diverging winds aloft and sustaining lower pressure and converging winds near the surface. This converging flow imports vapor-rich air to the ITCZ and sustains the circulation. Additional complexities include the presence of land masses and monsoonal circulations, which shift and distort this basic circulation considerably.

The ITCZ is also characterized by the presence of organized convective clusters and wavelike disturbances that typically migrate westward in the equatorial region. Thus, the Hadley circulation is not a steady feature, but is most strongly evident in data which have been averaged in the zonal (east-west) direction and over time. The presence of dual Hadley cells in either hemisphere is rare, as usually the cell in the winter hemisphere is dominant.

1.4. Importance

A complete description of tropical dynamics requires understanding of the aforementioned wave disturbances, ocean-atmosphere coupling, and the role of convection. Global circulation models, such as those used in climate prediction, are challenged to accurately reproduce the ITCZ and corresponding wave phenomena. This is not surprising, given the complex interactions that are observed to take place between small-scale convective processes and larger-scale wave disturbances, often in regions with limited in-situ observational data. However, the extension of tropical circulation influences to the mid-latitudes can exert important weather and climate signals there, which has important implications for global climate change.

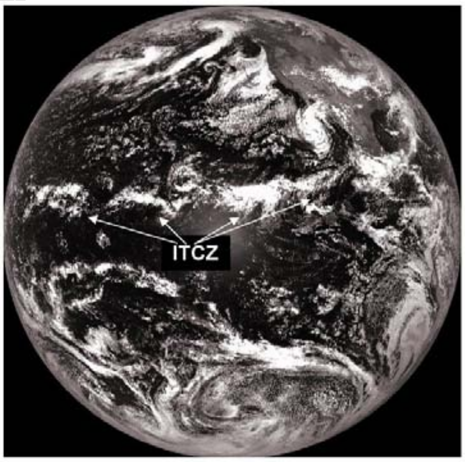

Figure 1. Geostationary visible satellite image depicting the Intertropical Convergence

Zone (ITCZ). Image source: NASA.
http://daac.gsfc.nasa.gov/oceancolor/scifocus/oceanColor/convergence.shtml

The remainder of this chapter is organized as follows: Section 2 includes a brief summary of the vertical structure of the tropical atmosphere, followed by an account of tropical wave systems, cyclonic systems including tropical cyclones, monsoon circulations, and large-scale oscillations. The final section provides an overview of tropical synoptic weather systems, and places their importance into a broader context.

2. The Tropical Atmosphere

2.1. Vertical Structure

Relative to extratropical locations, the strong input of solar energy at the surface, in conjunction with evaporation from the ocean surface and vegetation, yields the tropical atmosphere much less stable to buoyant vertical motions (convection). This is especially true near the rising branches of regions characterized by active Hadley circulations, tropical waves, and monsoon systems. The convergent flow into the ITCZ region takes the form of *trade winds*, which are found equatorward of subtropical high pressure systems in either hemisphere. Within the trade wind regime, there is typically a lower region of 1-2 km depth that is moist and neutrally stable to vertical air motions. A stable layer, known as the *trade wind inversion*, is located above the moist lower layer, and often separates drier air aloft. The lower moist layer tends to be deeper near the ITCZ and shallower at higher latitudes corresponding to the sinking branches of the Hadley circulation, although this is variable with time and location.
The depth of the troposphere in the tropics is generally greater than in the mid-latitudes. The troposphere is characterized by decreasing temperature with increasing altitude, and is generally recognized as the layer of the atmosphere that contains the most important weather-producing systems. The layer separating the troposphere from the stable stratosphere above is known as the tropopause. In the stratosphere, temperature begins increasing with height, and thus one can define the tropopause based on the *lapse rate*, which is the rate of temperature decrease with height. The altitude of the tropical tropopause can be defined by different measures, and the determined height is sensitive to this methodology. Convective systems in the tropics can penetrate to 12 km altitude, but the altitude of the tropical tropopause defined by lapse rate is higher, approximately 16 km on average, with some variation with longitude. In the remainder of this chapter, we will restrict our focus to tropospheric weather systems.

Prevailing surface winds in the tropical belt blow from east to west near the surface, but winds aloft can fluctuate between easterly and westerly, depending on the location and time of year. High-altitude subtropical tropospheric jet streams, usually characterized by southwesterly (northwesterly) flow in the Northern (Southern) Hemisphere, extend into mid-latitude regions and can play an important role in the dynamics of mid-latitude weather systems. There are regions of strong lower-tropospheric jet streams, including the Somali jet east of Africa, and an easterly low-level jet that develops over western Africa, to name a few.

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Bibliography

Holton, J. R., (2004) *An Introduction to Dynamic Meteorology*, 4th ed. Elsevier Academic Press: [Chapter 11 of this text, entitled "Tropical Dynamics", was drawn heavily upon in the current work.]

Palmen, E. and C. W. Newton, (1969) *Atmospheric Circulation Systems*. Academic Press. [In this text, Chapter 14, entitled "Circulation and Disturbances of the Tropics", provides a useful description of the processes and conditions in the tropical atmosphere.]

Biographical Sketch

Dr. Gary Lackmann is a native of Seattle, Washington (USA) and holds bachelor's and master's degrees in atmospheric science from the University of Washington (1986, 1989, respectively). He earned his Ph.D. at the University at Albany, State University of New York in 1995. He has worked as a research meteorologist for government laboratories, the military, as a private sector consultant, and as a professor at two academic institutions. His current position is professor of meteorology in the department of Marine, Earth, and Atmospheric Sciences at NC State University. Areas of research focus include improving understanding and prediction of high-impact weather events such as hurricanes, severe thunderstorms, and mid-latitude winter storms. He has a long-standing interest in climate change issues, and especially the question of whether climate change could impact the frequency or intensity of storms. Dr. Lackmann is a member of the AMS, NWA, and Sigma Xi.