Tropical Cyclone Climatology

Introduction

In this section, we open our study of tropical cyclones, one of the most recognizable (and impactful) weather features of the tropics. We begin with an overview of what tropical cyclones are by presenting the most basic of definitions for a tropical cyclone. Subsequently, the locations in which tropical cyclones form, the paths they take, and the large-scale factors that influence their formation are discussed. This overview will motivate future lectures on tropical cyclone formation and intensity change, enabling us to better understand the physics and dynamics behind *why* and *how* tropical cyclones form.

Key Questions

- What is a tropical cyclone?
- Where do tropical cyclones typically form and in which direction(s) do they typically travel?
- What is unique about tropical cyclone development in the North Atlantic basin?
- What are the large-scale conditions thought to be necessary for tropical cyclone formation?

Tropical Cyclone Definitions

A tropical cyclone is a non-frontal, synoptic-scale, low-pressure system over tropical or subtropical waters with persistent, organized convection and a closed cyclonic circulation (Holland 1993). Tropical cyclones are typically classified by their intensity, with the maximum sustained surface (10-m) wind speed being the most commonly used intensity measure. Tropical cyclone classifications include:

- A *tropical depression* is a tropical cyclone with maximum sustained surface winds less than 17.5 m s^{-1} (34 kt).
- A *tropical storm* is a tropical cyclone with maximum sustained surface wind speeds 17.5-33 m s^{-1} (34-64 kt). Near Australia and in the Indian Ocean, tropical storms are generically referred to as "*tropical cyclones*."
- A *hurricane* is a tropical cyclone with maximum sustained surface winds in excess of 33 m s^{-1} (64 kt). In the Western North Pacific, hurricanes are known as "*typhoons*." Near Australia and in the Indian Ocean, hurricanes are known as "*severe tropical cyclones*."

The maximum sustained surface wind speed reflects the average wind speed over a specified time interval: 1-min by Western Hemisphere warning centers and 10-min by Eastern Hemisphere warning centers. The former is approximately 1.15 times larger than the latter; i.e., a 1-min maximum sustained surface wind of 50 m s^{-1} typically equates to a 10-min maximum sustained surface wind of 43.48 m s^{-1}.

Within the Atlantic and Eastern North Pacific basins, the Saffir-Simpson Hurricane Wind Scale (National Hurricane Center 2021) is used to further classify hurricanes as a function of wind speed and, subsequently, the damage that such winds can inflict. The categories of the Saffir-Simpson Hurricane Wind Scale include:

Saffir-Simpson Hurricane Wind Scale Category	Maximum Sustained Wind Speeds
Category 1	64-82 kt
Category 2	83-95 kt
Category 3	96-112 kt
Category 4	113-136 kt
Category 5	>136 kt

Category 3+ hurricanes are often referred to as "major hurricanes." In the Western North Pacific, the Joint Typhoon Warning Center refers to typhoons with maximum sustained wind speeds in excess of 130 kt as "super typhoons." The Australian Bureau of Meteorology uses a separate five-category scale to express the intensity and expected impacts of tropical cyclones of tropical storm intensity or higher.

Tropical Cyclone Climatology

On average, approximately 84 tropical cyclones of tropical storm intensity or greater form annually across the globe. Approximately 45, or 54%, of these reach hurricane intensity at some point during their existence. The Western North Pacific is the most active of the world's ocean basins on average, home to approximately 26 tropical cyclones and 16 typhoons each year. The Eastern North Pacific is the second-most active basin on average, home to approximately 17 tropical cyclones and 9 hurricanes each year. Approximately 10 tropical cyclones occur annually in each of the North Atlantic, Southwest Indian, and Southwest Pacific basins. Slightly more of these tropical cyclones reach hurricane intensity in the North Atlantic as compared to the Southwest Indian and Southwest Pacific. The Southeast Indian basin experiences approximately 7 tropical cyclones and 3 hurricanes per year. The North Indian basin experiences approximately 5 tropical cyclones and 2.5 hurricanes per year. Tropical cyclone activity is rare, though not unprecedented, in the Eastern South Pacific and South Atlantic basins.

Tropical cyclones are primarily seasonal phenomena. Most basins have their peak tropical cyclone activity in the late summer and early fall months. Tropical cyclone formation occurs at lower latitudes early in the tropical season, spreads northward through the season's peak, and returns only to lower latitudes at season's end. Tropical cyclones are possible all year if the conditions which promote their development are present; however, this is generally only true in the Western North Pacific.

Tropical cyclones typically form in the tropics between 5-20° latitude and decay at higher latitudes. To first order, tropical cyclones move in a direction and at a rate of speed approximated by the mean wind over a vertical layer that varies with cyclone intensity. Put more simply, tropical cyclones are typically steered by the flow associated with subtropical anticyclones and midlatitude troughs. Thus, tropical cyclones generally move slightly poleward of due west at low latitudes at a rate of speed of approximately 10-15 kt (5-7.5 m s^{-1}). Thereafter, as they reach the periphery of the steering subtropical anticyclone, tropical cyclones acquire a significant poleward component of motion, where they accelerate and recurve poleward and eastward into the midlatitudes. Exceptions occur with tropical cyclones that make landfall or, in the Eastern North Pacific basin, with tropical cyclones that dissipate over cool subtropical waters. Significant intraseasonal variability in tropical cyclone tracks is largely a function of intraseasonal variability in the large-scale weather pattern across the subtropics and midlatitudes.

Eastern North Pacific

Most Eastern North Pacific tropical cyclones form within a localized region to the west of Central America, where sea-surface temperatures are typically well above 29°C during the tropical season. Tropical cyclone formation is increasingly less likely moving west toward the Central North Pacific, where tropical cyclone formation rare outside of El Niño years. Tropical cyclone season lasts from late May to October, concurrent with the seasonal northward shift in sufficiently warm sea-surface temperatures. Tropical cyclone activity peaks in late August.

Western North Pacific

Tropical cyclones form over a large area (in terms of both latitudinal and longitudinal extent) across the Western North Pacific. Although tropical cyclones can form year-round in this basin, they are most common between June and November and least common during February and March. During local summer, tropical cyclone activity is characterized by successive relatively active and relatively inactive periods with a period of ~30-45 days, consistent with the MJO. The Western North Pacific is noted for a relatively high frequency of intense tropical cyclones, largely due to a large extent of very warm (~30°C) sea-surface temperatures during the tropical season's peak.

North Indian Ocean

Tropical cyclones in this basin are much more common in the Bay of Bengal than in the Arabian Sea since the Arabian Sea generally lacks the precursor tropical disturbances needed for tropical-cyclone formation and is associated with dry midtropospheric conditions fostered by large-scale dry flow from Middle Eastern deserts. They generally form during April-June and October-December when sea-surface temperatures are sufficiently high and the monsoon circulation is not present. Vertical wind shear is relatively large during monsoon season, inhibiting tropical-cyclone formation during these months.

Southwest Indian Ocean

Tropical cyclones in this basin primarily form in two distinct geographic locations: over the open waters of the Indian Ocean between 8-12°S latitude and near Madagascar (15-20°S) in the far western portion of the basin. Tropical cyclones are most common between November and April, with maxima in mid-late January and mid-late February.

Southeast Indian and Southwest Pacific Ocean Basins

Tropical cyclone activity in these basins preferentially occurs near the northern coast of Australia, the Gulf of Carpenteria, and the Coral Sea northeast of Australia. Most tropical cyclones in these basins form from disturbances in the monsoon trough, though some over the eastern reaches of the Southwest Pacific Ocean form from disturbances in the South Pacific Convergence Zone or from persistent equatorial-wave forcing. Tropical cyclone season lasts from December through April, with a relative maximum in mid-late February. Tropical cyclone activity is suppressed on intraseasonal scales during active monsoon periods.

Other Ocean Basins

Tropical cyclones are rare in the Eastern South Pacific and South Atlantic basins. Although sea-surface temperatures are occasionally supportive of tropical cyclones in these basins, strong vertical wind shear and the lack of coherent seedling disturbances from which tropical cyclones can form inhibit their formation.

Tropical Cyclone Development in the North Atlantic Basin

The North Atlantic tropical cyclone season lasts from June through November, peaking in mid-September with a lesser peak in mid-October. Tropical cyclone development is favored in the western Caribbean Sea, Gulf of Mexico, and midlatitude North Atlantic Ocean at the season's start and end, expanding eastward as the season progresses through to its peak.

Owing to the large range of latitudes at which tropical cyclones form in the North Atlantic basin, there are multiple types of precursor disturbances that can facilitate tropical-cyclone development. The leading such precursor disturbances are African easterly waves. However, a significant fraction of tropical cyclones form from non-African easterly wave disturbances (McTaggart-Cowan et al. 2008, 2013). Based on the extent to which the large-scale environment where tropical-cyclone formation occurs is baroclinic (representative of midlatitude forcing), McTaggart-Cowan et al. (2008) identified six tropical-cyclone formation pathways for the North Atlantic basin. These pathways include:

- *Non-baroclinic* (40%). These are the "traditional" tropical cyclones, forming most often in the deep tropics from African easterly waves. It is this pathway to genesis that we will examine most closely in subsequent lectures.

- *Low-level baroclinic* (13%). These tropical cyclones preferentially occur at low latitudes near the African west coast and in the western Caribbean Sea, both locations where substantial lower tropospheric temperature gradients exist. These are associated with the African easterly jet and Saharan air layer near Africa and with land-sea temperature contrasts in the western Caribbean.

- *Transient trough interaction* (16%). These tropical cyclones preferentially occur early in the season, when transient midlatitude troughs impinge upon sufficiently warm oceans. Most of these developments occur in the Gulf of Mexico or central tropical North Atlantic.

- *Trough-induced* (3%). These tropical cyclones preferentially occur in the Gulf of Mexico or off of the east coast of Florida during the season's peak, when lower-tropospheric temperature gradients are weak but the large-scale forcing for ascent can be strong in the presence of a midlatitude trough.

- *Weak tropical transition* (13%). These tropical cyclones occur in environments of strong large-scale forcing for ascent and medium-to-large lower-tropospheric temperature gradients, such as are commonly found along stationary or decaying fronts. These conditions are most commonly found across the Gulf of Mexico and east of Florida throughout the season, although a relative maximum in such events is noted during June.

- *Strong tropical transition* (15%). These tropical cyclones most commonly occur late in the season at higher latitudes (at or above 30°N) in the western and central North Atlantic. These tropical cyclones are most sensitive to the relatively cool temperatures of the outflow layer in the upper troposphere, which can permit tropical-cyclone development over relatively cool oceans.

The McTaggart-Cowan et al. (2013) global climatology eliminated the transient trough interaction pathway. Cases comprising this classification in McTaggart-Cowan et al. (2008) are instead classified in the trough-induced, weak tropical transition, or strong tropical transition classifications in McTaggart-Cowan et al. (2013), with most cases classified as either of the two tropical transition categories.

In addition to the geographic and seasonal distributions referenced above, there exists substantial variability in the peak intensity of tropical cyclones forming along each of these pathways. Trough-induced, weak tropical transition, and strong tropical transition events tend to have higher numbers of weaker tropical cyclones and smaller numbers of stronger tropical cyclones as compared to the set of all tropical cyclone formation events. Strong tropical cyclones are generally of non-baroclinic or low-level baroclinic origin.

Large-Scale Conditions Necessary for Tropical Cyclone Formation

Gray (1968) highlighted six necessary large-scale conditions for tropical cyclone formation:

- Large cyclonic vertical vorticity in the lower troposphere, such as is often associated with an African easterly wave, the monsoon trough, or a decaying midlatitude frontal boundary.

- A distance of at least several degrees latitude poleward of the equator, such that sufficiently large planetary vorticity is present.

- Weak vertical wind shear magnitude (typically less than ~10 m s^{-1}), to promote the development of an upright vortex that is resilient to the infiltration of cool, dry air from the external environment.

- Sea-surface temperatures exceeding 26°C, preferably over a relatively large depth, to provide the necessary heat energy for tropical cyclone development to occur.

- Conditional instability through a deep tropospheric layer, so as to promote the development of deep, moist convection in the vicinity of a tropical disturbance.

- Large relative humidity in the lower to middle troposphere, so as to negate the destructive potential of convectively generated downdrafts on a disturbance’s lower-tropospheric circulation.

The first three are dynamic parameters and the last three are thermodynamic parameters. Each are necessary conditions; *all* must be present for a tropical cyclone to be able to form. The dynamic parameters are rapidly varying, such that tropical cyclone activity generally occurs only when these parameters are more favorable than their climatological-mean values. Conversely, the thermodynamic parameters vary slowly and are all generally favorable for development throughout the season’s peak months (with localized exceptions).

Some of these parameters are not independent of one another. For instance, high sea-surface temperatures are typically also associated with the presence of conditional instability. From this, Frank (1987) proposed removing the fifth criterion from the Gray (1968) list. Furthermore, the two vorticity-related factors can be combined into a single absolute vorticity criterion. Finally, mean upward vertical motion can be added to the relative-humidity criterion to emphasize the connection between moisture and ascent that is manifest in persistent thunderstorms during the formation process. Thus, we can express four necessary conditions for tropical-cyclone formation (Frank 1987):

- Large cyclonic *absolute* vorticity in the lower troposphere, such as is often found in association with an African easterly wave, the monsoon trough, or a decaying midlatitude front. This provides a locus around or along which thunderstorm activity can form and coalesce.

- Weak tropospheric-deep vertical wind shear magnitude (typically less than ~10 m s^{-1}). This allows the developing cyclone to remain nearly upright vertically (such that its relative warmth is spread over a radially confined area, allowing for the cyclone's winds to become stronger). It also mitigates the infiltration of cool, dry environmental air into the cyclone's warm, moist interior, whereupon it could facilitate evaporatively cooled downdrafts that reduce the cyclone's relative warmth and disrupt its lower-tropospheric convergent cyclonic circulation.

- Sea-surface temperatures exceeding 26°C. These are tropical cyclones' fuel source, in the form of surface enthalpy (heat and moisture) transports from the underlying ocean.

- Large relative humidity in the lower and middle troposphere in association with mean ascent, reflecting the ability for thunderstorms to form and persist. Persistent thunderstorms are necessary to spread the enthalpy gained from the underlying ocean over a deep vertical column to fuel a cyclone's winds.

The following characteristics have been shown by observational studies to also be necessary but insufficient to the tropical cyclone formation process, some of which are closely related to the necessary conditions:

- The transformation of the disturbance's initially cold-core thermal structure into that of a tropospheric-deep, warm-core thermal structure.

- Increasing synoptic-scale, lower-tropospheric cyclonic relative vorticity with the disturbance.

- The development of curved banding features associated with active convection, often a signature of intensifying rotation found in association with the disturbance.

- The presence of synoptic-scale, upper-tropospheric divergence, to promote lower-tropospheric convergence and tropospheric-deep ascent in the environment of the disturbance.

References

- Elsberry, R. L., 1995: "Tropical cyclone motion." *Global Perspectives on Tropical Cyclones*, R. L. Elsberry (ed.). World Meteorological Organization, Geneva, Switzerland, Report No. TCP-38.

- Frank, W. M., 1987: "Tropical cyclone formation." Chapter 3, *A Global View of Tropical Cyclones*. Office of Naval Research, Arlington, Virginia, 53-90.

- Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700.

- Holland, G. J., 1993: "Ready Reckoner." Chapter 9, *Global Guide to Tropical Cyclone Forecasting*, WMO/TC-No. 560.

- McBride, J. L., 1995: “Tropical cyclone formation.” *Global Perspectives on Tropical Cyclones*, R. L. Elsberry (ed.). World Meteorological Organization, Geneva, Switzerland, Report No. TCP-38.

- McTaggart-Cowan, R., G. D. Deane, L. F. Bosart, C. A. Davis, and T. J. Galarneau, Jr., 2008: Climatology of tropical cyclogenesis in the North Atlantic (1948-2004). *Mon. Wea. Rev.*, **136**, 1284-1304.

- McTaggart-Cowan, R., T. J. Galarneau, Jr., L. F. Bosart, R. W. Moore, and O. Martius, 2013: A global climatology of baroclinically influenced tropical cyclogenesis. *Mon. Wea. Rev.*, **141**, 1963-1989.

- National Hurricane Center, 2021: The Saffir-Simpson hurricane wind scale. [Available online at https://www.nhc.noaa.gov/pdf/sshws.pdf].