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 Concepts

- 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 important large-scale conditions thought to be necessary for tropical cyclone formation?

Tropical Cyclone Definitions

As defined by Holland (1993), 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. Tropical cyclones are typically classified by their intensities, with the maximum sustained surface (10-m) wind speed being the most common measure of tropical cyclone intensity. 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*."

In products issued by the National Hurricane Center, Central Pacific Hurricane Center, and Joint Typhoon Warning Center (e.g., United States-based agencies), the maximum sustained surface wind speed is expressed as the 1-min average wind speed. In products issued by all other agencies, the maximum sustained surface wind speed is expressed as the 10-min average wind speed. The former value is approximately 1.15 times larger than the latter. Thus, care must be taken when comparing tropical cyclone intensities between individual basins.

Within the hurricane classification, there exist several sub-classifications that vary between individual ocean basins. Within the Atlantic and Eastern North Pacific basins, the Saffir-Simpson Hurricane Wind Scale (Schott et al. 2012) is used to 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

Note that category 3 and higher 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. More details on this classification system may be found on the Bureau of Meteorology's website at http://www.bom.gov.au/cyclone/about/intensity.shtml.

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 seasonal phenomena. Most basins experience peak tropical cyclone activity during the late summer and early fall months. In the Southern Hemisphere, this corresponds to January through March. In the Northern Hemisphere, this corresponds to July through September. Tropical cyclone formation occurs at lower latitudes early in the tropical season, spreads northward thereafter, and returns only to lower latitudes at the very end of the season. Tropical cyclone activity is possible year-round if the conditions which promote tropical cyclone development are present; however, this is most commonly true only in the Western North Pacific basin. The seasonal distribution of tropical cyclone activity is strongly influenced by the seasonal evolutions of sea surface temperatures and the location/presence of the phenomena that give rise to tropical cyclones.

Tropical cyclones typically form within the deep tropics between 5-20° latitude. 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 mid-latitude troughs. As a result, in the majority of the world's ocean basins, tropical cyclones move slightly poleward of due west in the deep tropics 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. They subsequently accelerate and recurve poleward and eastward into the mid-latitudes. Exceptions occur with tropical cyclones that make landfall or, in the Eastern North Pacific basin, with tropical cyclones that dissipate over the cool waters of the subtropical Eastern North Pacific Ocean. Significant intraseasonal variability in tropical cyclone tracks is largely a function of intraseasonal variability in the large-scale weather pattern across the subtropics and mid-latitudes.

In the following, we consider unique characteristics associated with the climatology of tropical cyclones within each of the ocean basins in which tropical cyclones occur. The exception to this is the North Atlantic basin, which is covered separately within its own section.

Eastern North Pacific

The majority of tropical cyclones in the Eastern North Pacific basin form within a fairly localized region to the west of Central America, where sea surface temperatures are typically well in excess of 29°C during the tropical season. It is in this narrow region where the world's highest frequency of tropical cyclone genesis per unit area occurs. Tropical cyclone formation becomes progressively less likely with westward extent into the Central North Pacific, where tropical cyclone formation is most common during El Niño years and is rare during neutral ENSO and La Niña years. Tropical cyclone season lasts from June to October, concurrent with the northward shift in sea surface temperatures and ITCZ associated with Northern Hemisphere summer. Tropical cyclone activity peaks in late August. Many tropical cyclones that form in the Eastern North Pacific owe their origins to African easterly waves that did not spawn tropical cyclones in the North Atlantic basin.

Western North Pacific

As compared to the Eastern North Pacific basin, tropical cyclones form over a large area (in terms of both latitudinal and longitudinal extent) across the Western North Pacific. As noted above, tropical cyclones can form throughout the year in the Western North Pacific. However, tropical cyclone activity is maximized between June and November and minimized during February and March. Within the tropical cyclone season, tropical cyclone activity is characterized by successive relatively active and relatively inactive periods with a period of approximately 30-45 days, consistent with a control on tropical cyclone activity by the MJO. The Western North Pacific is particularly noted for the relatively high frequency of very large and very intense tropical cyclones. The former has origins in the size and characteristics of the disturbances (particularly the monsoon trough) which spawn tropical cyclones in the Western North Pacific; the latter has origins in the relatively large extent of very warm (~30°C) sea surface temperatures during the peak of the tropical season.

North Indian Ocean

Although less than 10% of the global tropical cyclones occur in the North Indian Ocean, they are the most deadly. This is because of a number of factors: the shallow waters of the Bay of Bengal promote the development and propagation of large trapped-fetch waves; low, flat coastal terrain promotes the inland spread of waves as they reach the coast; the funneling shape of the coastline promotes the amplification of wave heights over a narrow, focused area; and the presence of a large number of people in a relatively small, third world area. Within the North Indian Ocean, tropical cyclone activity is much more common in the Bay of Bengal than in the Arabian Sea, largely because of the lack of seedling disturbances and the relatively dry middle tropospheric environment found in the Arabian Sea fostered by flow off of the deserts of the Arabian Peninsula and Middle East. Tropical cyclones most commonly form between April and June and October through December when the sea surface temperatures are warm enough to support their formation and while the monsoon is relatively weak. During monsoon season, monsoon depressions (or weak, very large tropical cyclone-like disturbances with no inner core structure) are the preferred mode of cyclone development across the basin.

Southwest Indian Ocean

Tropical cyclone activity is most prevalent in the Southwest Indian Ocean between November and April with maxima in mid-late January and mid-late February. 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. Apart from the seasonal variability in sea surface temperatures, activity in this basin – and particularly near Madagascar – is controlled by seasonal variability in the surface trades. During tropical cyclone season, the typical southeasterly surface trades reverse and acquire a northerly component. This reversal appears to be crucial to tropical cyclone development near Madagascar, although why is not entirely clear.

Southeast Indian and Southwest Pacific Ocean Basins

Tropical cyclone activity in these basins preferentially occurs near the northern coast of Australia. More specifically, three regions near the northern Australian coast are favored for tropical cyclone development: the northwest coastline, the Gulf of Carpenteria, and the Coral Sea to the northeast of Australia. Of these regions, weaker tropical cyclones occur most commonly in the small Gulf of Carpenteria whereas stronger tropical cyclones occur most commonly off of the northwest coast 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 equatorial wave forcing. Tropical cyclone season in both basins lasts from December through mid-April with a relative maximum in mid-late February. Tropical cyclone activity is suppressed during the midst of the season while the monsoon is over land. Thus, compared to the North Indian Ocean, tropical cyclones and the monsoon typically co-exist with one another in the Southeast Indian and Southwest Pacific basins.

Other Ocean Basins

As noted above, tropical cyclone activity is rare, though not altogether impossible, in the Eastern South Pacific and South Atlantic basins. Though sea surface temperatures are occasionally supportive of tropical cyclone activity within these basins, strong vertical wind shear and the lack of coherent lower tropospheric disturbances from which tropical cyclones can form inhibit such activity. That said, in a subsequent lecture on the tropical transition process, we will examine the physics and dynamics of a tropical cyclone formation event that occurred within the South Atlantic basin in 2004.

Tropical Cyclone Development in the North Atlantic Basin

Though it was previously thought that the North Atlantic was the only one of the world's tropical cyclone-supporting ocean basins to not have a monsoon trough, more recent studies have highlighted the presence of a monsoon trough along the western coast of Africa associated with the West African monsoon and, on occasion, near Central America. That said, though these monsoon troughs acts as loci of cyclonic vertical vorticity and deep-layer moisture, tropical cyclone development in the tropical North Atlantic most often results from AEWs. Note also that while the North Atlantic basin is unique amongst the world's tropical cyclone-supporting ocean basins to have a seasonal mean westerly vertical wind shear, such shear typically reverses in direction prior to individual tropical cyclone developments.

Tropical cyclone season in the Atlantic lasts from June through November, peaking in mid-September. Minor relative peaks occur in mid-October and, to a lesser extent, late June. Tropical cyclone development is typically confined to tropical latitudes early and late in the season while it expands north and eastward during the middle of the season as sea surface temperatures warm and vertical wind shear magnitudes lessen. Owing to the relatively large range of latitudes at which tropical cyclones form in the North Atlantic (as well as the Western North Pacific) basin(s), there exist multiple types of disturbances that spawn tropical cyclone development. As noted above, many developments in the tropical North Atlantic occur in conjunction with AEWs. Such tropical cyclones form to the south of the AEJ and at the southern boundary of the SAL. A small fraction of tropical cyclones arise from non-easterly wave disturbances in the ITCZ or, in rare instances, the West African monsoon trough. Still yet other disturbances have origins, whether direct or indirect, with baroclinic systems.

The wide variety of incipient disturbances for tropical cyclone formation in the North Atlantic is captured by the climatologies of McTaggart-Cowan et al. (2008, 2013). Based off of the evolutions of large-scale forcing for ascent and lower tropospheric thickness prior to tropical cyclone formation, McTaggart-Cowan et al. (2008) developed six unique pathways for tropical cyclone formation in the North Atlantic basin. These pathways include:

- Non-baroclinic, accounting for 40% of all tropical cyclone formation events. 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, accounting for 13% of all tropical cyclone formation events. These tropical cyclone formation events preferentially occur at low latitudes near the west coast of Africa and in the western Caribbean, both locations where substantial lower tropospheric temperature gradients exist. Near Africa, these are associated with the African easterly jet and Saharan air layer; in the western Caribbean, these are associated with land-sea temperature contrasts.

- Transient trough interaction, accounting for 16% of all tropical cyclone formation events. These tropical cyclone formation events preferentially occur early in the tropical cyclone season, when transient mid-latitude troughs impinge upon the still relatively cool sea surface temperatures of the tropics. Most of these developments occur in the Gulf of Mexico or central tropical North Atlantic.

- Trough-induced, accounting for only 3% of all tropical cyclone formation events. These tropical cyclone formation events preferentially occur in the Gulf of Mexico or off of the east coast of Florida during the peak of hurricane season. At this time, lower tropospheric temperature gradients are weak but large-scale forcing for ascent can be strong in the presence of a mid-latitude trough.

- Weak tropical transition, accounting for 13% of all tropical cyclone events. These tropical cyclone formation events occur in environments of strong large-scale forcing for ascent and medium to large lower tropospheric temperature gradients. Such conditions are most commonly found across the Gulf of Mexico and off of the east coast of Florida throughout the tropical cyclone season, although a relative maximum in such events is noted during June.

- Strong tropical transition, accounting for 15% of all tropical cyclone events. Such tropical cyclone formation events most commonly occur late in the season at higher latitudes (at or above 30°N) in the western and central North Atlantic basin. These tropical cyclones are most sensitive not to sea surface temperatures but to the relatively cool temperature of the outflow layer of the cyclone in the upper troposphere. How and why this is the case will be discussed in a subsequent lecture on tropical cyclone intensity change.

The McTaggart-Cowan et al. (2013) global climatology of tropical cyclone formation condensed the six pathways of McTaggart-Cowan et al. (2008) to five, eliminating the transient trough interaction classification. Cases that comprised this classification in McTaggart-Cowan et al. (2008) are classified in the trough-induced, weak tropical transition, or strong tropical transition classifications in McTaggart-Cowan et al. (2013), with most transient trough interaction cases classified as tropical transition.

In addition to the geographic and seasonal distributions referenced above for the six tropical cyclone development pathways, 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 tropical cyclone formations tend to have greater numbers of weaker tropical cyclones and fewer numbers of stronger tropical cyclones as compared to the set of all tropical cyclone formation events. Most of the strongest tropical cyclones are of non-baroclinic or low-level baroclinic origin, although a non-insignificant number of tropical cyclones that develop along the transient trough interaction pathway do go on to become intense tropical cyclones.

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 the ITCZ, an African easterly wave, or the monsoon trough.

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

- Weak vertical wind shear of the horizontal winds (typically less than ~10 m s^{-1}), so as 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 values of relative humidity in the lower and middle troposphere, so as to negate the destructive potential of convectively-generated downdrafts upon the lower tropospheric circulation of a tropical disturbance.

Of these factors, the first three are said to be dynamic parameters whereas the last three are said to be thermodynamic parameters. Each factor is multiplicative, meaning that *all* must be present in order for tropical cyclone formation to occur. The thermodynamic parameters are slowly varying; indeed, with localized exceptions, the three thermodynamic parameters are all generally favorable for development over a large area throughout the peak of the tropical cyclone season. The same cannot be said for the dynamic parameters, however, and Gray (1968) thus hypothesized that tropical cyclone activity occurs only during periods in which the dynamic parameters are perturbed to more favorable values above their local climatological means.

Frank (1987) noted that some of Gray (1968)'s six environmental parameters are not independent of one another. In the tropics, where horizontal temperature gradients are typically weak, regions of 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. Frank (1987) also suggested that the two vorticity-related factors could be combined into a single, more general absolute vorticity criterion and that mean upward vertical motion could be added to the relative humidity criterion so as to better reflect the necessity of deep, moist convective activity to the tropical cyclone formation process. Thus, in the context of Frank (1987), the following four criteria are said to be the necessary conditions for tropical cyclone formation:

- Large cyclonic absolute vorticity in the lower troposphere, such as is often found away from the equator in association with the ITCZ, an African easterly wave, or the monsoon trough.

- Weak vertical wind shear of the horizontal winds (typically less than ~10 m s^{-1}), so as 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.

- Large values of relative humidity in the lower and middle troposphere in association with mean ascent, so as to negate the destructive potential of convectively-generated downdrafts upon the lower tropospheric circulation of a tropical disturbance

In addition to the aforementioned requisite factors for tropical cyclone formation, the following characteristics have been shown by observational studies to be important to the tropical cyclone formation process:

- The presence of a pre-existing, convectively-active disturbance, such as an African easterly wave, monsoon trough, or other similar disturbance.

- The transformation of the disturbance's initially cold-core thermal structure into that of a tropospheric-deep warm-core thermal structure. Precisely how this occurs is detailed in a subsequent section on tropical cyclone formation.

- The accumulation (increase, spin-up, etc.) of lower tropospheric cyclonic relative vorticity on the synoptic-scale in the presence of the disturbance.

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

- 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, so as to promote lower tropospheric convergence and tropospheric-deep ascent in the environment of the disturbance.

It should be noted that, as with the Gray (1968) and Frank (1987) conditions, these are all necessary but insufficient conditions for tropical cyclone development. Furthermore, missing from the above discussion are considerations of precisely how the tropical cyclone vortex develops, the role that deep, moist convection and its organization play in the tropical cyclone formation process, and the precise energetics of the tropical cyclone. The physics and dynamics of these processes are discussed in subsequent lectures on tropical cyclone formation.

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