Tropical Cyclones: Meteorological Aspects

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Every year, TCs claim many lives—occasionally exceeding 100,000. Some of the world’s greatest natural disasters have been associated with TCs. For example, Tropical Cyclone 02B was the deadliest and most destructive natural disaster on earth in 1991. The associated extreme storm surge along the coast of Bangladesh was the primary reason for the loss of 138,000 lives (Joint Typhoon Warning Center, 1991). It occurred 19 years after the loss of ≈300,000 lives in Bangladesh by a similar TC striking the low-lying Ganges River region in April 1970. In a more recent example, flooding caused by Hurricane Mitch killed 10,000+ people in Central America in Fall 1998. Nearly all tropical islands—the islands of the Caribbean, Hawaii, French Polynesia, Micronesia, Fiji, Samoa, Mauritius, La Reunion, Madagascar, and many others—are vulnerable to direct strikes by intense TCs. Devastating TCs often make landfall in Japan, India,
China, Vietnam, the United States, Mexico, and other nations. With their natural tendency to move out of the tropics, TCs (in their later stage of extratropical transition) are also a tangible threat to higher latitude regions such as New England and the Maritime Provinces of Canada.

This paper provides a brief description of the structure, physics and motion of TCs. This is followed by an overview of the hazards associated with TCs and a discussion of some of the proposed changes to TC climate as a result of an anticipated greenhouse gas-induced rise in air and sea-surface temperatures.

Note that tropical cyclone advisories, TC empirical relationships, and TC wind-damage scales are still widely based on units of millibars (mb) for pressure, nautical miles (n mi) for distance, and knots (kt) for the wind speed. Wherever these units appear in the text, the equivalent measurement in SI units is given in parentheses. 1 mb = 1 hPa; 1 n mi = 1.85 km; and, 1 kt = 0.5144 m·s⁻¹.

TROPICAL CYCLONE STRUCTURE

Tropical cyclone structure includes the wind-, thermal- and moisture-fields, the characteristic banded distribution of cloud and rainfall, and the central calm or eye. Three common measures of TC wind-field include intensity, strength and size.

The intensity of a TC is defined as the maximum sustained wind speed near the low-level circulation center. The minimum sea-level pressure within the eye has also been used as a measure of intensity. The maximum wind and minimum sea-level pressure of TCs are loosely related, and TC wind-pressure relationships are often used when the measure of one parameter (usually the maximum sustained wind) is uncertain. A TC wind-pressure relationship developed by Atkinson and Holliday (1977) is used operationally in the western North Pacific. This wind-pressure relationship was especially useful in the daily aircraft reconnaissance, when the central sea-level pressure of the TC was estimated by techniques considered far more reliable than those used to estimate the maximum surface-wind-speed. In official advisories and warnings issued to the public, the winds given for a TC are the expected sustained wind and peak gust. A sustained wind is the highest value of the wind speed averaged over a specific time interval. In the United States, the averaging interval used to derive the sustained wind is 1 min. In other countries, an averaging interval of 10 min is usually used to derive the sustained wind. The peak gust is another common parameter used to describe the wind in TCs. When a 1-min averaging interval is used to derive the maximum sustained wind, the peak gust over-water is 112% higher than the maximum sustained wind (Krayer and Marshall, 1992). Over land, the gust factor increases. Over flat open terrain with small trees and shrubs, the ratio of the peak gust to the maximum sustained 1-min wind increases to 1.5.

As the maximum wind speed of a TC increases, it changes from tropical depression to tropical storm to hurricane/typhoon. By U.S. standards (Office of the Federal Coordinator for Meteorology, 1999), a tropical depression is any TC possessing maximum-sustained over-water winds of 33 kt (17 m·s⁻¹) or less. A reference height of 10 m is used for these measurements. A TC becomes a tropical storm when its wind increases to 34–63 kt (18–32 m·s⁻¹), a hurricane or typhoon when the sustained wind speed increases to 64 kt (33 m·s⁻¹) or more. In the western North Pacific, a typhoon becomes a super typhoon when the maximum wind pressure decreases to 12 n mi (22 km) when observed by a U.S. Air Force weather reconnaissance aircraft on 11 Oct. 1979 (JTWC, 1979).

Certain TCs, especially the more intense, develop two eyewalls that are concentric and separated by a relatively cloud-free moat. In such cases, the outer eyewall typically contracts while the inner eyewall collapses in a process known as eyewall replacement. The phenomenon of eyewall replacement has been discussed at length by Willoughby et al. (1982) and Willoughby (1990). These authors note that TC eyes almost invariably contract during intensification so that small eyes and extreme intensity tend to be correlated. The most intense TC ever observed—Super Typhoon Tip—had an intensity of 165 kt (85 m·s⁻¹), a minimum sea-level pressure of 870 hPa, and an eye diameter of 12 n mi (22 km) when observed by a U.S. Air Force weather reconnaissance aircraft on 11 Oct. 1979 (JTWC, 1979).

TROPICAL CYCLONE PHYSICS

Although tropical disturbances and tropical depressions can form over land, TCs intensify to hurricanes and typhoons only over the ocean, and usually weaken rapidly upon landfall. This fundamental property of TC distribution hints at the mechanisms governing their development. Friction is an obvious factor acting to oppose the spin-up of an intense atmospheric vortex, and is obviously greater over land than over water. But what initiates the spin-up in the first place? What energy reservoir is tapped for conversion to the kinetic energy of the TC wind-field?

Despite decades of scientific research, many aspects of TCs remain enigmatic, and controversy about their physics persists. Early theories proposed that the cumulus clouds organized in clumps, rather than random, spaced, could act to tap the potential energy reservoir existing between the lower and upper levels of the tropical atmosphere. Tropical cyclones were widely believed to be caused by the release of the latent heat of condensation of water vapor in cumulus clouds. Such an energetically driven mechanism seems to have been the right thinking; however, it is now thought to reside in the thermodynamic disequilibrium between the
atmosphere and the underlying ocean (Emanuel, 1988). This is reflected in the fact that air immediately above the ocean is subsaturated, yielding a potential for transfer of latent and sensible heat from sea to air, even though the temperatures of the two media are usually about equal. The mature TC can be regarded as an elegant example of a natural Carnot heat engine (an idealized, reversible thermodynamic cycle that converts heat to mechanical energy).

The ability of a TC to extract energy from the sea is enabled by its lowered sea-level pressure and high surface wind. How then does a TC form if it depends on its own existence to enable the air-sea energy exchanges? The formation, or genesis, of TCs is one of the most poorly understood portion of their life cycle. By examining the climatology of TC genesis in relation to large-scale variables, some of the important physical characteristics associated with their formation can be inferred. The most extensive climatology of TC genesis was performed by Gray (1979), who found that the climatological frequency of TC formation was related to six factors: a) above-average low-level vorticity (a measure of the local spin of the air); b) above-average moisture in the middle levels of the atmosphere (1500–6000 m); c) conditional instability through a deep layer (i.e., free ascent of the air would occur if its water vapor began to condense); d) a warm and deep oceanic mixed layer; e) weak vertical shear of the horizontal wind; and, f) a location at least a few degrees poleward of the equator (i.e., a sufficient value of planetary vorticity). The intrinsic spin of the earth’s surface with respect to the local vertical governs the sense of rotation of the wind in a TC. This is counterclockwise in the Northern Hemisphere, zero on the equator, and clockwise in the Southern Hemisphere.

These general climatological conditions exist over many regions of the tropics for extended periods of time, and yet TCs rarely form. Gray (1975) hypothesized that TCs would form only when these conditions were perturbed and reached values above their normal climatological range. Attempts to apply these criteria to daily forecasting of TC genesis have had little success. Forecasters have long recognized that a required precursor to TC formation is a preexisting tropical disturbance containing abundant deep convection (i.e., large cumulonimbus clouds of great vertical depth) (e.g., McBride and Gray, 1980; McBride and Zehr, 1981). So, in addition to the special atmospheric conditions that are conducive to them, TCs clearly derive from the influence of these conditions on preexisting tropical disturbances. At any given time, however, there are many tropical disturbances, and the reasons why a select few become TCs is still largely unknown. To date, there has been little progress in the ability to predict TC formation or of changes to the intensity of existing TCs. Substantial departures of TC intensity change from average rates, such as rapid deepening (Holliday and Thompson, 1979) and explosive deepening (Dunnavan, 1981) are rarely successfully anticipated.

**TROPICAL CYCLONE MOTION**

To a first order, TCs originate in the tropics and track westward to terminate over land within the tropics, or they move into higher latitudes on roughly “C”- or “s”-shaped tracks, where they die over land or open ocean. A TC moving westward in the tropics that slows, turns poleward, and lastly accelerates as it moves eastward in the mid-latitudes is said to have “recurved.” While some actual TCs travel on smooth tracks, most tend to meander about a mean path in a more or less complex combination of loops, stalls, abrupt turns, and other prominent excursions (Holland and Lander, 1993) (Fig. 2).

As a crude approximation, TC motion may be conceptualized as the drift of a cork in a stream. In this framework, the TC is simply carried along by the earth’s large-scale wind systems (e.g., the tradewind easterlies, the subtropical anticyclones, and the mid-latitude westerlies). Consider a typical North Atlantic hurricane. Born near the African coast, it drifts westward in the tropical easterlies for several days. When it reaches the western side of the basin, it begins a turn to the north as it rides around the periphery of the large clockwise flow of the subtropical high that is often centered near Bermuda. When the hurricane reaches the mid-latitudes, say east of Cape Hatteras, it enters the mid-latitude westerlies and—as it dies—races back across the Atlantic towards Europe. All along its journey, it has roughly followed the course of the large-scale wind patterns, like a cork in a stream.

Real TC motion, however, is more complicated than the analogy of a cork passively following the exact path dictated by the runs and eddies of a stream. Tropical cyclones are not passive atmospheric entities. They can alter the large-scale currents that steer them—an ideal case of the tail wagging the dog. For example, the common trait of most TCs to gain latitude can be partly attributed to the effects of the TC itself operating on its environment. To illustrate this, consider a symmetrical TC embedded in an environment with zero initial flow. Despite the initial absence of a steering current, the TC nevertheless would begin to drift westward and poleward as it induces large-scale flow patterns in the environment (Chan and Williams, 1987; Holland, 1983). The meridional gradient of the intrinsic spin of the earth along a local vertical axis is an essential factor for this self-induced drift of a TC. The path taken by a TC is the final product of the large-scale flow, alterations to the large-scale flow induced by the TC, and interactions of the TC with other weather systems in its environment, such as other TCs, monsoon surges, and mid-latitude highs and lows (Carr and Elsberry, 1994a, 1994b).

Forecasts of TC motion have steadily improved over the past three decades. Official forecasts and guidance from numerical models show substantial improvements over standard benchmark measures of skill such as CLIPER (a simple statistical forecast based on CLImatology and PEr sistence). Typical forecast position errors of official TC advisories and numerical guidance are on the order of 150, 300, and 450 km at 24, 48, and 72 h, respectively (e.g., JTWC, 1996; United Kingdom Meteorological Office, 1999). Studies of intrinsic limits on forecasts of TC motion (e.g., Leslie and Abbey, personal communication) indicate that there is yet room for improvement. Future improvements, however, are likely to be incremental. As it now stands, the accuracy of TC motion forecasts is, on the whole, a success story.

**TROPICAL CYCLONE HAZARDS**

There are several hazards associated with TCs. Three primary hazards affect a substantial portion of any populated area, and can cause widespread and immediate damage. These are destructive winds, storm surge and high waves, and flooding. There are additional hazards that are dangerous and costly, but they generally are of less concern or affect fewer people. Emergency managers should have a good understanding of the hazards associated with TCs and understand their potential impacts. The primary and additional hazards include: a) destructive winds and windblown debris; b) storm surge, high surf, and inundation; c) torrential rains and flooding; d) wind shear and mechanical turbulence; e) phenonema seas; e) tornados; f) sea salt deposition; g) erosion and pollution; and h) slope failures.

Public TC advisories typically focus on the intensity of the TC, and secondarily on the expected storm surge, heavy rain, and possibility of embedded tornadoes. Most people have difficulty relating an advertised TC intensity—a numerical value—to its potential for causing damage. Numerous questions come to mind. For example: What kind of damage would a 100-kt (51-m·s−1) hurricane cause? What kind of wave action would a 130-kt (67-m·s−1) hurricane produce in a bay or across a reef? At what wind speed would a tin roof blow off? At what wind speed would concrete power poles sustain damage or blow down? At what wind speed would a significant fraction of mature healthy deciduous trees be uprooted? For the Atlantic and Gulf Coast regions of the United States the Saffir-Simpson Hurricane Scale (SSHS) (Saffir, 1972, 1975; Simpson, 1974) is widely used to relate hurricane wind speed to potential damage. In these regions, the SSHS has taken on the importance for hurricanes that the Richter Scale has taken on for earthquakes in earthquake-prone areas. The innovative SSHS, which ranks hurricanes in categories of destructive potential from Category 1 (weak hurricane) through Category 5 (devastating hurricane), was devised in 1971 by Mr. Herb Saffir, a Miami, Fla.,-based engineer, who developed the scale for the United Nations. He later gave the scale to the National Hurricane Center (NHC) in Miami. Dr. Robert Simpson, then the director of the NHC, added storm surge information to the SSHS. While the SSHS has been used very successfully in the United States,
it has not been applicable to the tropical Pacific (Office of the Federal Coordinator for Meteorology, 1995; Saffir, 1993).

A scale relating TC wind speed to potential damage for the tropical Pacific Ocean region was developed by Guard and Lander (1999). After assessing many available wind-damage scales (e.g., Amadore, 1982; Fujita, 1971), Guard and Lander (1999) adapted the parameters of the SSHS for use in tropical island environments. This new TC wind-damage scale has been coined the Saffir-Simpson Tropical Cyclone Scale (STCS) as recommended by Mr. Herbert Saffir. This STCS ("sticks") scale is specifically adapted for the tropics, and considers the construction and building practices that are common there. It incorporates the harshness of the tropical environment by considering the weakening effects of termite infestation, wood rot, and the corrosion due to salt water inundation and airborne sea-salt. It also identifies the wind and sea-salt damage to tropical trees. Finally, STCS accounts for the unique effects of coral reefs on coastal wave action, storm surge, and wave setup.

Trees are excellent indicators of TC wind speed. Guard and Lander (1999) divide tropical trees into 12 specific types based on their characteristic responses to strong winds. These types were based to a large extent on other studies describing TC damage to tropical trees (e.g., Cameron et al., 1983; Raulerson and Rinehart, 1991). The following is excerpted from Guard and Lander (1999) for Type 1 and Type 8 trees:

"(Type 1)—Palm trees—Plants with tall woody trunks and a crown of radiating (palm) fronds. Palm fronds begin to crimp, often back through the crown, when winds reach 65 kt [33 m·s⁻¹] (weak TY CAT 1) intensity; crowns begin to break from the top of the trunk (decapitate) when winds reach 100 kt [51 m·s⁻¹] (weak-medium TY CAT 3); falls are around 10% when wind speeds reach around 105 kt [54 m·s⁻¹]. Coconut palm [Cocos nucifera L.] trunks can also snap at these wind speeds, but falling is more common."

"(Type 8)—Plumeria/Acacia/Albizia/African Tulip/Yoga/Ifil/Orchid/Coral/Cebera/Talisai—Small to large trees that readily shed limbs but generally resist defoliation in strong winds. Trees that survive TY CAT 3 or stronger winds tend to shed large branches and develop stocky, typhoon resistant trunks . . . Despite damage, these trees tend to recover rapidly."

Some of the tree types described by Guard and Lander may share the same characteristics of adjacent types. This is especially the case with Type 8 trees. For example, the African tulip tree (Spathodea campanulata Pal.) has some characteristics of Type 9 trees (heavy defoliation) and the Yoga tree (Elaeocarpus joga E.D. Merrill.) has some characteristics of both a Type 7 tree (strong trunk) and a Type 6 tree (resistance to uprooting).

The primary use of STCS is straightforward. When a TC is threatening a specific tropical location, and warnings are issued reflecting the expected intensity, decision-makers can match the intensity to the appropriate TC Category to determine the potential wind damage and coastal wave action. In practice, disaster management officials frequently prepare a population for the destructive effects of winds one-half to one category higher than those predicted. This is to help compensate for TC intensity prediction errors that can, at times, be large.

Another use of STCS is poststorm assessment of TC intensity from observed damage to structures, infrastructure, and trees, and from observed coastal wave action. This type of analysis is difficult; an accurate assessment requires considerable experience.

**TROPICAL CYCLONES AND CLIMATE CHANGE**

Among the more problematic consequences of climate change is the possible change in the distribution and severity of TCs. The issue of TCs and climate change was the subject of an international symposium in Mexico in 1993, organized by J. Lighthill and reported on by Lighthill et al. (1994). An updated assessment of this issue is found in Henderson-Sellers et al. (1998). The following alterations to the present-day distribution and severity of TCs as a product of anticipated greenhouse gas-induced warming are cited in Lighthill et al. (1994): 1) an increase in the global annual number of TCs; 2) an increase in the number of intense TCs; 3) an increase in the maximum possible intensity attainable by TCs; 4) an increase in the range where TCs may occur.
form; and 5) an increase in the range where TCs retain their intensity and mature stage. Hypotheses of systematic changes to the global distribution of TCs can be addressed through investigation of the historical record, consideration of changes to the mechanisms now thought to influence TC distribution and structure, and analyses of the output of general circulation model (GCM) simulations.

The very limited record makes extensive analysis of the natural variability of global TC activity difficult in most of the TC basins. However, in the two regions where reasonably reliable records exist (the North Atlantic and the western North Pacific), substantial multidecadal variability (particularly for intense Atlantic hurricanes) is found, but no clear evidence of long-term trends. The realism and hence predictive skill of GCM simulations is greatly limited by the coarse resolution of current GCMs and the failure to capture environmental factors that govern TC intensity. Based on these lines of reasoning, Lighthill et al. (1994) and Henderson-Sellers et al. (1998) concluded that greenhouse gas-induced warming probably will not significantly affect the distribution and severity of TCs, and that at least for the next 60–70 years any effects will be quite small compared with natural variability. The broad geographic regions of TC formation, and, therefore, also the regions affected by TCs, are not expected to change significantly. However, regional and local frequencies could change substantially in either direction, because of the dependence of TC formation and track on other phenomena (e.g., ENSO) that are not yet predictable. Theoretical studies of TC maximum potential intensity indicate that it will remain the same or undergo a modest increase of up to 10% to 20%. These predicted changes are small compared with the observed natural variations. Greatly improved skills from coupled global ocean-atmosphere models are required before improved predictions are possible.

Although the consensus reported in Lighthill et al. (1994) and Henderson-Sellers et al. (1998) was that possible changes to TC climate (list items 1–5 above) would probably be small compared with natural variability (which itself is poorly understood), one of the coauthors of these two papers warned that predictions of an increase in TC maximum potential intensity (list item 3) need to be taken seriously (Emmanuel, 1995). He concluded that increased thermodynamic disequilibrium between the tropical atmosphere and ocean (as is suggested by the current generation of climate models) would probably be accompanied by an increase in the limiting intensity of actual TCs. Several decades may be required before any sustained change to TC climate can be recognized and its cause determined.

**CONCLUDING REMARKS**

Each year, tropical cyclones and their many associated hazards cause much loss of life and enormous damage to property and natural resources. Some of the world’s greatest natural disasters have been associated with TCs. Forming in every tropical ocean basin, except the South Atlantic, TCs are a threat to much of the earth’s population. With more and more people residing and building on tropical islands and TC-prone coastlines of many nations, there is even more at risk to TC hazards. Disaster preparation and mitigation efforts must evolve to meet the increasing challenges—witness the largest mass evacuation in American history when more than 1 million people were evacuated from the east coast of Florida at the approach of the powerful Hurricane Floyd. Strategies for recovery after a TC must also be tailored to meet the growing risks and cascade of problems that may arise—witness the devastating floods in North Carolina caused by Hurricane Floyd, and the unanticipated health risks associated with the drowning of thousands of pigs, chickens, and other farm animals.

Like the human effort to withstand and recover from the TC disaster, the natural world appears to employ certain strategies to withstand and recover from TCs. These strategies vary among areas affected by TCs, and have differing degrees of success. A wind that would fall nearly every tree in the forests of New England would only fell a small fraction of a stand of coconut palms in a TC-prone location in the deep tropics. On my home island of Guam, two typhoons (Elise and Hunt) passed near, and three (Omar, Brian, and Gay) passed directly over the island during 1992. Wind gusts to 130 kt (67 m s$^{-1}$) in Typhoon Omar, and a mist of airborne sea salt in Typhoon Gay caused great destruction of the island’s vegetation. A major drought in 1993 followed this onslaught of TCs. Five years later, during Dec. 1997, an even more intense typhoon (Paka) raked the island with wind gusts reliably measured to 149 kt (77 m s$^{-1}$). The damage to residential and commercial infrastructure and to the island’s vegetation was extensive. After Paka in 1997, severe drought conditions ensued in 1998, and 1400 individual wildfires scorched 12% of the land area of the island. Now, 2 years later, the island has recovered remarkably well. One can stand in the cool shade of coconut groves along coral-sand beaches, watch small waves breaking along the reef margin, and wonder what the fuss over typhoons is all about.

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