Tropical Cyclones

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Abstract
This entry provides an overview on tropical cyclones. A tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has a closed low-level cyclonic circulation. The life cycle from genesis to mature, intense storms is discussed, the physical causes of their development are described, and their wind/cloud structure is presented. The causes of storm surge are described in detail, along with a storm surge scale based on intensity, bathymetry, storm size, and storm speed. The mechanisms that damage property and vegetation from tropical cyclone wind, storm surge, and flooding are explained in detail. The Saffir–Simpson wind damage scale and the Australian wind damage scale are contrasted. A global context is provided for tropical cyclone climatology, classifications, and terminology. A table is provided of classification schemes—from genesis to intense categories—for the seven ocean regions where tropical cyclones occur. The process for assigning tropical cyclone names in each ocean basin is presented. A brief overview on forecasting procedures is discussed.

INTRODUCTION USING A WESTERN HEMISPHERE PERSPECTIVE

A tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has a closed low-level cyclonic circulation. These systems form and intensify from ocean heat extraction through complex processes, with a warm upper-level centre which distinguishes it from other windy weather systems. Due to the earth's rotation, these storms spin counterclockwise in the Northern Hemisphere, and clockwise in the Southern Hemisphere. Both hemispheric spins are referred to as *cyclonic rotation* because the sense of spin about a local vertical axis is the same as the earth's rotation when viewed from above.

Classifications for tropical cyclones vary globally. In this initial discussion, we use Western Hemisphere terminology, which covers the North Atlantic, Northeast Pacific, and North Central Pacific basins. Classifications in the Eastern Hemisphere are different compared with the Western Hemisphere. Furthermore, classifications vary between the Northwest Pacific, the North Indian Ocean, the Southwest Indian Ocean, the Southeast Indian Ocean, and the Southwest Pacific Ocean. For example, the term *hurricane* in the Western Hemisphere is the equivalent to the term *typhoon* in the Northwest Pacific Ocean. Their origins are locally derived. Hurricane is derived from the Caribbean Indian word hurican meaning "evil spirit," who in turn translated it from the Mayan storm god Hurakan. Typhoon is derived probably from the Chinese words tung fung ("a terrible storm of east winds"), ta fung (a "great wind"), or t'ai fung (either "eminent wind" or "wind of Taiwan"). A Greek god is also called Typhon (a storm giant and father of all "monsters") but it is unknown if there is a connection to the word typhoon or China. The global classifications will be discussed in the last section.

Wind speed is the fundamental demarcation of tropical cyclone classifications. International units are in ms^{-1}, and most countries have adopted the metric standard. However, some regions, countries, and professions prefer other wind units. The Unites States uses mph, where $1\ ms^{-1} = 2.2$ mph. Other countries prefer kmh^{-1}, where $1\ ms^{-1} = 3.6\ kmh^{-1}$. Mariners prefer knots, where $1\ ms^{-1} = 1.9$ knots. This text uses the metric standard of ms^{-1} for wind speed. Because the fastest winds in tropical cyclones occur near the ground, a standard height of 10 m (33 ft) is used. Winds are also averaged by either 1 or 10 minutes (depending on global region), and referred to as *sustained winds*.

A tropical cyclone does not form instantaneously. Initially a tropical cyclone begins as a *tropical disturbance* when a mass of organized, oceanic thunderstorms persists for 24 hours. The tropical disturbance becomes a *tropical depression* when a closed circulation is first observed and all sustained winds are less than 17 ms^{-1}. When these sustained winds increase to 17 ms^{-1} somewhere in the circulation, it is then classified as a *tropical storm.* A tropical cyclone becomes a *hurricane* when sustained surface winds are 33 ms^{-1} or more somewhere in the storm.

To clarify the life cycle, this entry discusses tropical cyclone formation in phases. The first phase is the *genesis stage*, and includes tropical disturbances and tropical depressions. The second phase includes tropical storms and hurricanes, called the *mature stage.* These phases are separated because most disturbances and a few depressions

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never reach tropical storm intensity, eventually dissipating, whereas mature systems may intensify, remain steady-state, or weaken. About 25% of mature systems evolve into a non-tropical system as they move out of the tropics; these systems may even re-intensify, becoming a storm with sustained winds up to 38 ms^{-1} and impacting regions outside the tropics. The genesis and mature stages will now be described.

LIFE CYCLE

Tropical disturbances form where there is a net inflow of air at the surface, known as *convergence,* resulting in ascent to compensate. As air rises, it will often saturate and form a cloud base. Once the air is saturated, ascent may be enhanced where the atmosphere is in a state of *static instability*. In a *statically unstable* atmosphere, ascending saturated air is less dense than surrounding unsaturated air. As a result, it accelerates upwards because the air is buoyant relative to its environment, forming a broad spectrum of vertically growing cumulus clouds.

However, thunderstorm formation is common in the tropics, and is only a prerequisite. Several conditions must simultaneously exist for a tropical disturbance to develop a closed circulation and become a tropical depression. First, the disturbance must be in a *trough*, defined as an elongated area of low *atmospheric pressure*. Atmospheric pressure is the weight of a column of air per area. All troughs away from the equator contain a weak, partial cyclonic rotation. These troughs can develop from a variety of mechanisms related to certain temperature and wind patterns beyond the scope of this article. Some disturbances undergo the transition to tropical depression directly inside troughs. However, others experience this transition as *tropical waves* (called inappropriately *easterly waves* in the Western Hemisphere), which form when a trough "breaks down" into a cyclonic wave-like pattern in the wind field and travels westward away from the source region. About 60% of the Atlantic tropical cyclones actually originate from tropical waves, which form over Africa and propagate into the Atlantic. Tropical waves are fairly persistent features, and can propagate long distances. In the Atlantic about 55–75 tropical waves are observed, but only 10–25% of these develop into a tropical depression or beyond.

The second condition required for genesis is a water temperature of generally at least 27°C (80°F). Heat and water vapour transferred from the ocean to the air generates and sustains static instability (and therefore thunderstorms) in the disturbance. The third genesis condition is minimal *vertical wind shear*, defined as the difference between wind speed and direction generally at 12-km (40,000-ft) aloft and near the surface. In other words, for genesis to occur, the wind must be roughly the same speed and from the same direction above the surface at all height levels in the atmosphere. This allows thunderstorms and the wind structure to grow unimpeded. The three conditions—warm water, surface trough, and weak vertical wind shear—are generally necessary but insufficient conditions to develop closed rotation (and, by definition, a tropical depression). Furthermore, a few exceptions exist with strong vertical wind shear or water temperature less than 27°C, but a depression still forms. Because of insufficient understanding on the genesis stage, much research is currently underway on this vexing forecast problem.

Once a tropical depression forms, the favourable conditions of wind shear, warm water, and complete cyclonic rotation provide the "ignition" process for further development. The ascending air, developing warm-core aloft, and decreasing surface pressure in the depression stimulates low-level inflow towards the centre. The cyclonic circulation of the disturbance increases. Typically, the genesis timeframe of both disturbance and depression lasts for several days or longer. However, under ideal conditions, they can evolve much quicker. When the cyclonic sustained winds increase to 17 ms^{-1} somewhere in the depression, the system is upgraded to a tropical storm. At this point, the mature stage begins.

For tropical storm intensification into a hurricane, the same conditions that allowed its initial development (warm water, moist air, and weak wind shear) must continue. However, a system with closed rotation develops faster compared with the genesis stage because the fluxes of heat and moisture from the ocean become more efficient at faster winds, and because a larger percentage of the heat is retained in the storm centre. The column of air begins to warm, which decreases atmospheric pressure. More air will flow towards the lower surface pressure, trying to redistribute the atmosphere's weight, resulting in faster winds. The faster cyclonic winds also enhance convergence. Both factors increase thunderstorm production and low-level inflow. A feedback mechanism now occurs in which faster cyclonic winds maintain thunderstorms by fluxes and convergence, dropping surface central surface pressure more, creating stronger inflow and faster cyclonic winds, and so on. When sustained winds reach 33 ms^{-1} somewhere in the storm, it is classified as a hurricane.

Water temperature is unquestionably linked to these storms' development. Tropical cyclones rarely form over water colder than 27°C. They also weaken dramatically if a mature system moves over water colder than 27°C, or if they make landfall, because their heat and moisture source has been removed. The warmer the water, the greater are the chances for genesis, the faster is the rate of development, and the stronger these storms can become. Because tropical cyclones mix the ocean column, it is also important the warm surface water is at least 60-m (200-ft) thick. Under conditions of prolonged weak shear and an ocean surface temperature greater than 29°C (85°F), sustained winds may reach 89 ms^{-1}.

Fortunately, few hurricanes reach their maximum potential because of some inhibiting factor. Conditions that stop intensification include wind shear, landfall, dry air intrusion, storm-induced ocean mixing or upwelling, and movement over colder water. Occurrence of any (or a combination) of these influences will stall development or cause weakening. Furthermore, even with no inhibiting factors, strong hurricanes rarely maintain their intensity. The internal physics of a hurricane preclude a strong steady-state storm for more than 1–2 days. Instead, strong wind conditions promote interior adjustments near the storm's centre, weakening it (see discussion in next section on concentric eyewalls).

Persistent occurrence of any or several inhibiting factors will cause disintegration of a tropical cyclone. Of these possibilities, most dissipating cases occur due to landfall or movement over colder water. Tropical cyclones making landfall rapidly decay. If the storm remains over land, its maximum sustained winds will decrease on average 20 ms^{-1}/day and the rate of dissipation is even faster for initially strong storms. Thirty-six hours after landfall, inland tropical cyclones rarely contain winds above tropical depression strength.

TROPICAL CYCLONE STRUCTURE

The structure of a tropical cyclone is one of the most fascinating features in meteorology (Fig. 1). Distinct cloud patterns exist for each stage of a tropical cyclone's life cycle. These distinct patterns allow meteorology centres worldwide to classify these systems as a depression, tropical storm, hurricane, or major hurricane based on cloud organization. During genesis, typically a mass of thunderstorms with a weak rotation is first observed. Usually these thunderstorms will temporarily dissipate or weaken, leaving a residual circulation. Often, no further development occurs. But should thunderstorms return (sometimes within 12 hours, but more often taking several days), and a closed circulation develops, a depression has formed. A dominant band of clouds gradually takes on more curvature around a cloud minimum centre. When the band curves at least one-half distance around the storm centre, typically tropical storm intensity has been achieved. A cloud shield extends further out with squall lines of thunderstorms of less vertical growth than near the storm centre. These thunderstorm bands are known as *spiral bands*. In between the bands is light-to-moderate rain or areas of sinking air (downdrafts).

As the tropical storm strengthens, the dominant cloud band continues coiling around the centre. When the band completely coils around the centre, hurricane intensity usually has been reached. At this point, a clear region devoid of clouds forms in the centre known as the *eye*, surrounded by a ring of thunderstorms known as the *eyewall*. The eyewall contains the fiercest winds and often the heaviest rainfall,

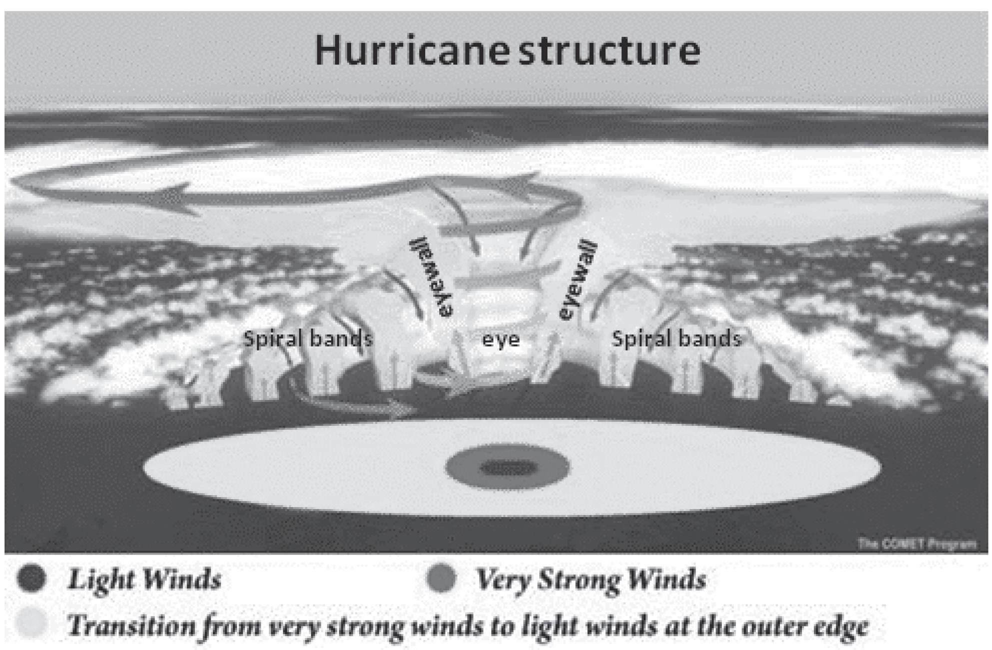


Fig. 1 Cross-section of a mature hurricane showing the eye in the centre surrounded by the eyewall and spiral bands circling its environment. Arrows depict a surface cyclonic airflow, air rising in the eyewall and spiral bands, air descending between the spiral bands in the eye, and anticyclonic outflow aloft. The circular colours depict the horizontal surface wind structure, in which winds are relatively calm in the eye, fastest in the eyewall, and decrease away from the storm centre. [The source of this material is the COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR), sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (DOC). © 1997–2013 University Corporation for Atmospheric Research. All Rights Reserved.]
Source: Adapted from COMET MetEd.[1]

making this feature the most dangerous part of a hurricane. The eyewall slants outwards with height giving the eye a "coliseum" appearance, as if one is in a giant football stadium made of clouds. In the eye, winds become weak, even calm! This transition from hurricane force winds to calm is rather sudden (often within minutes). The average eye size diameter is 32–64 km (20–40 miles). Typically an eye starts at about 56 km wide during the transition from tropical storm to hurricane. As the hurricane intensifies, the eye usually contracts. Small eyes correlate to intense hurricanes, with diameters as little as 14 km (9 miles). However, intense hurricanes with large eyes also occur, and there is considerable variance with these numbers.

Sometimes a second eyewall forms outside the original eyewall about 64–96 km (40–60 miles) from the centre. This outer eyewall "cuts-off" off the inflow to the inner eyewall, causing the inner one to weaken and dissipate. Because the eye is wider, temporary weakening occurs. The outer eyewall will begin to contract inwards to replace the inner eyewall, and approximately 12–24 hours later, intensification resumes. This internal adjustment process, known as the *concentric eyewall cycle*, is one reason strong hurricanes experience intensity fluctuations in otherwise favourable conditions.

Outside the eyewall, weaker spiral bands accompanying the hurricane typically affect a large area. The average width of a hurricane's cloud shield is 800 km (500 miles), but varies tremendously. However, cloud size is not an accurate indication of strong wind coverage. One criterion for size is the radial extent of tropical storm-force winds (17 ms^{-1}). Mariners and navy fleets typically avoid winds stronger than 17 ms^{-1}. Furthermore, many hurricane preparedness exercises require completion before tropical storm-force winds begin; for example, bridges are often closed if winds exceed 17 ms^{-1}, impeding last-minute evacuees.

DAMAGE FROM TROPICAL CYCLONES

Coastal communities devastated by strong hurricanes usually take years to recover. Many forces of nature contribute to the destruction. Obviously, tropical cyclone winds are a source of structural damage. As winds increase, stress against objects increases at a disproportionate rate. For example, a 22-ms^{-1} wind causes a stress of 36 kg m^{-2} (7.5 lb ft^{-2}). In 45-ms^{-1} winds, stress becomes 147 kg m^{-2} (30 lb ft^{-2}). Although sustained wind is used as a reference standard, the actual wind will be 20–30% faster or slower than the sustained wind at any instantaneous period. These gusts often initiate structure damage, typically beginning at the roof. The removal of roof coverings often occurs with wind gusts at 36 ms^{-1}, roof decks at 45 ms^{-1}, and roof structure at 54 ms^{-1}. Wind interacting with a building is deflected over and around it. Positive (inward) pressures are applied to the windward walls and try to "push" them down. Negative (outward) pressures are applied to the side and leeward walls. The resulting "suction" force can peel away any exterior covering (siding, shingles, and so on). Negative (uplift) pressures are applied to the roof, especially along windward eaves, roof corners, and leeward ridges, similar to the lifting aerodynamics on aircraft wings, and cause roof failure.

Building damage occurs in other ways. Wind damage begins with exterior items such as television antennas, satellite dishes, unanchored air conditioners, wooden fences, gutters, storage sheds, carports, and yard items. As the wind speed increases, cladding items on buildings become susceptible to wind damage including vinyl siding, gutters, roof coverings, windows, and doors. Debris is also propelled by strong winds, compounding the damage. The weak points to internal building exposure are usually through roof, window, door, or garage damage. Any cause which compromises the inside of a building usually results in extreme damage to that structure from rain and wind. Damage patterns tend to be uneven due to the streakiness of wind gusts; building construction quality; building age; wind interference, wind acceleration, or vortex shedding from other buildings; proximity to open fields, trees, or vegetation. In addition to structure damage, large tree branches will snap, trees will be uprooted, and power poles will be toppled (or power lines snapped), resulting in power outages which can last weeks.

Floods produced by the rainfall can also be quite destructive, and is a leading cause of tropical cyclone-related fatalities. A majority (57%) of the 600 U.S. tropical cyclone-related deaths between 1970 and 1999 were associated with inland flooding. Tropical cyclone rainfall averages 150–300 mm (6–12 in) at landfall regions, but varies tremendously. Heavy rainfall is not just confined to the coast. The remnants of tropical cyclones can bring heavy rain far inland, and is particularly dangerous in hills and mountains where acute concentrations of rain turn tranquil streams into raging rivers in a matter of minutes or cause mudslides. In addition, mountains "lift" air in tropical cyclones, increasing cloud formation and rainfall. Rainfall rates of 300–600 mm (1–2 ft) per day are not uncommon in mountainous regions when tropical cyclones pass through.

Although all these elements (wind, rain, floods, and mudslides) are dangerous, historically most people have been killed in the *storm surge*, defined as an abnormal rise of the sea along the shore associated with cyclonic wind storms such as tropical cyclones. Death tolls in coastal regions can be terrible for those who do not evacuate inundation zones. Most storm surge fatalities are associated with structural collapse or drowning. The worst natural disaster in the United States history occurred in 1900 when a hurricane-related 5-m (16-ft) storm surge inundated Galveston Island, TX, U.S.A., and claimed over 6000 lives. In 1893, nearly 2000 were killed in Louisiana and 1000 in South Carolina by two separate hurricanes. Camille in 1969 (181 fatalities), Katrina in 2005 (1836 fatalities), and Ike in 2008 (20–40 fatalities) are the latest U.S. examples.

However, these U.S. statistics pale compared with the lives taken globally. Regions around the North Indian Ocean, Japan, and China have experienced fatalities by storm surge ranging from 10,000 to 300,000 in the last few centuries, with the latest tragedy of 138,000 killed in Myanmar by Cyclone Nargis in 2008. In contrast, the 1900 Galveston hurricane ranks 16th globally in terms of storm surge fatalities based on the latest research.

Storm surge is caused by several factors. The main contribution to the storm surge results from the interaction of coastal water with wind-driven water at landfall known as the *wind stress effect*. In deep offshore water, a vertical ocean circulation occurs, which compensates surface water wind transport, and no storm surge from wind forcing exists. But as a tropical cyclone approaches the shoreline and begins to interact with the ocean floor and land boundaries, this circulation is disrupted and water levels must rise to compensate. As a tropical cyclone approaches a region, coastal waters begin to rise gradually from the wind stress effect, then quickly at landfall.

A current also develops parallel to the shoreline ahead of the tropical cyclone, causing water to rise in response to the earth's rotation, known as a *surge forerunner*. The forerunner effect is dangerous because it peaks before landfall, sometimes trapping residents before they complete evacuation. For example, many of the Hurricane Ike fatalities occurred when roads on the Bolivar Peninsula flooded one day before landfall, cutting off the only escape route.

The final factor to storm surge is a minor contribution associated with the low pressure of a hurricane, which causes a bulge of water known as the *inverse barometer effect*. For every 10-mb pressure drop, water rises 10 cm (3.9 in.). The contribution ranges from 0.3–1 m (1–3 ft) elevated water depending on intensity, peaking at landfall.

Other factors that determine a surge's height include coastal bathymetry, storm intensity, storm size, and storm translation speed (Fig. 2). All other factors being equal, the most intense tropical cyclones produce higher storm surge. However, for a given intensity, bathymetry causes tremendous variation in surge heights. A coastline with a shallow sloping ocean floor is prone to higher storm surge than a coastline with a steep ocean shelf nearby. For example, a Category 3 produces a surge of 1.5 m (5 ft) in very deep bathymetries but 6.7 m (22 ft) in very shallow, with most values in between for a given coastline. Low-lying regions adjacent to extended shallow seas, such as the Gulf of Mexico in the southern United States, and the Bay of Bengal bordering Bangladesh and India, are particularly vulnerable to the storm surge. In shallow bathymetries, large, slow-moving tropical cyclones produce more surge than average-sized, average speed hurricanes for the same intensity (Fig. 2). The storm surge is always highest on the side of the eye corresponding to onshore winds, which is usually the right side of the point of landfall in the Northern Hemisphere, called the *right front quadrant*.

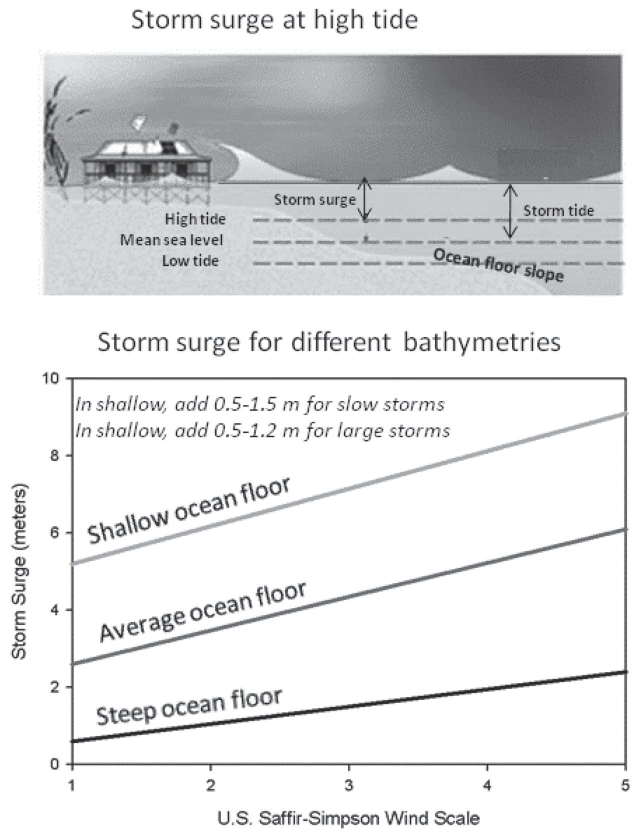


Fig. 2 (Top) Graphical portrayal of the storm surge at high tide impacting a structure along a shoreline. The definition of storm tide includes the storm surge plus water elevation departures from mean sea level due to the tide cycle. Waves are superimposed on the surge. (Bottom) Storm surge relationship to ocean floor slope and hurricane intensity using the U.S. wind scale. Note the large differences between shallow and steep bathymetry for a given intensity. Storm surge is 0.5–1.5 m higher for slow storms in shallow water, and is 0.5–1.2 m higher for large storms in shallow water. Storm size and speed only marginally modifies surge elevation in average and steep ocean floors, and is neglected.
Source: Top figure adapted from Australian Bureau of Meteorology.[2] Bottom figure adapted from Fitzpatrick et al.[3]

The total elevated water includes two additional components—the astronomical tide and ocean waves. The astronomical tide results from gravitational interactions between the earth, moon, and sun, producing high and low tides every 12–24 hours. Should the storm surge coincide with high tide, additional inundation occurs. The total water elevation due to surge and tides is known as the *storm tide* (Fig. 2), but in practice it is difficult to distinguish from storm surge during post-storm inspections. Waves are superimposed on top of the storm surge, running up past inundation boundaries, spilling over structures, sloshing against and inside structures, and enhancing damage. Waves may also contribute to inundation through a process called *wave setup* in which incoming waves exceed retreating waves, and is currently the subject of considerable research.

Water is very heavy, weighing 1025 kg m^{-3} (64 lb ft^{-3}), and dense. Therefore, waves possess much greater force than wind, and can undermine foundation and destroy support walls. Furthermore, if a wave is breaking, the force is 4–7 times greater than moving water. In addition, waves also cause an "uplift" force if the waves are under a horizontal structure, displacing the object and even toppling it, including bridge decks. Even without wave forces, water is very damaging. Buoyancy causes a lifting force on submerged wood buildings and beam foundations, damaging structures. Storm surge currents contain forces equal to or slightly greater than wind. Destruction can be thorough, leaving only slabs behind near the coast. Erosion of beaches and islands also is severe, and coastal highways can be devastated. Further inland where currents are weaker with little wave activity, inundation is still damaging. Most possessions, floors, and drywall that are submerged will be ruined, plus mould will grow on the items when the water retreats.

The United States has developed the *Saffir–Simpson hurricane wind scale*, which describes the expected level of wind damage for a given hurricane intensity. This scale classifies hurricanes into five categories according to maximum sustained wind and escalating potential property damage. Categories 1–5 correspond to a lower threshold of 33, 43, 50, 58, and 70 ms^{-1}, respectively. Although all categories are dangerous, categories 3, 4, and 5 are considered *major hurricanes*, with the potential for widespread devastation and loss of life. Whereas only 24% of U.S. landfalling tropical cyclones are major hurricanes, they historically account for 85% of the damage. However, while low-intensity hurricanes cause less physical devastation, preventative measures are still required during a landfall threat. Low-intensity hurricanes also disrupt regional economic activity for several days to several weeks through business interruption and evacuation costs. Additionally, freshwater flood threat is present for any tropical storm or hurricane regardless of intensity.

It should be noted that storm surge ranges used to be included in the Saffir–Simpson scale, but were removed in 2010 since surge depends not only on wind but bathymetry, storm size, and translation speed. Central pressure was also removed because it does not correspond to eyewall winds but instead correlates to wind structure. The wind scale also does not include damage from floods, and small-scale intense features such as imbedded tornadoes. Because damage is dependent on so many factors, preparations for a tropical cyclone impact should be thorough.

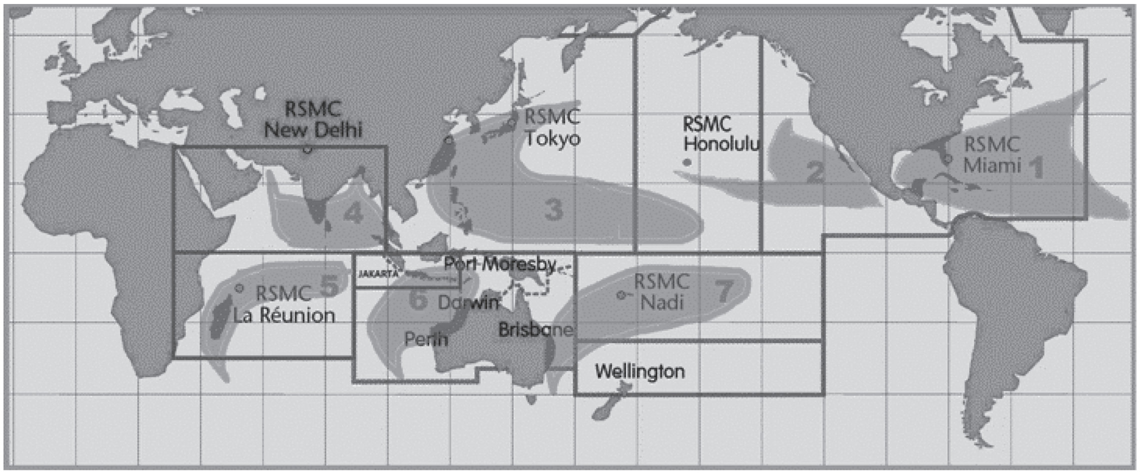
GLOBAL TROPICAL CYCLONE PREDICTION, CLIMATOLOGY, AND TERMINOLOGY

Different naming nomenclatures related to intensity classifications are used worldwide, and can be confusing. A global context of tropical cyclones will now be discussed. Tropical cyclones generally occur in every tropical ocean except the South Atlantic and eastern South Pacific (Fig. 3). Locations include the tropical North Atlantic Ocean (including the Caribbean Sea and Gulf of Mexico); the Northeast Pacific (off the west coast of Mexico); the Central North Pacific (near Hawaii); the Northwest Pacific (including the China Sea, Philippine Sea, and Sea of Japan); the North Indian Ocean (including the Bay of Bengal and the Arabian Sea); the Southwest Indian Ocean (off the coasts of Madagascar and extending almost to Australia); the Southeast Indian Ocean (off the northwest coast of Australia); and the Southwest Pacific Ocean (from the east coast of Australia to about 140°W). In addition, with improved satellite monitoring capabilities, several (mostly) weak, short-lived tropical cyclones in the South Atlantic Ocean have been unofficially identified the last two decades. Cyclone Catarina (2004) is the only official South Atlantic tropical cyclone with category 2 winds, named after the state in Brazil it made a landfall.

Regional Specialized Meteorological Centres (RSMCs) and Tropical Cyclone Warning Centres (TCWCs) monitor and forecast tropical cyclones used by each country, territory, and national meteorological service in their region (Fig. 3). RSMCs provide a spectrum of weather forecast products and responsibilities, which include hurricane forecasts, whereas TCWCs specialize in tropical cyclone services. Official warnings are the responsibility of each country/territory's national meteorological service. Monitoring is conducted with surface observations from land-based instruments; buoys and ships; upper-air balloon instruments, launched generally twice per day; satellite imagery; and satellite-derived diagnostics. Because these observations do not provide complete data coverage, the United States is the only nation to also use expensive reconnaissance aircraft.

Forecast agencies issue predictions for storm track, intensity, rainfall, storm surge, and other parameters. The priority is predicting tropical cyclone movement. To understand tropical cyclone motion, it is helpful to use the analogy of a wide river with a small eddy rotating in it. The river generally transports the eddy downstream, but the eddy will not move straight because the speed of the current varies horizontally, causing a slight left or right deviation, which also changes the eddy's speed of movement. Furthermore, this eddy's rotation may alter the current in its vicinity, which in turn will alter the motion of the eddy.

Likewise, one may think of a tropical cyclone as a vortex embedded in a river of air. The orientation and strength of large-scale pressure patterns generally dictates the storm's motion, except that the steering depends on both the horizontal and vertical distribution of the steering current. The tropical cyclone can also interact with steering currents, and even other nearby tropical cyclones, ultimately altering its own currents. Other factors impact track such as the earth's rotation and storm asymmetry, and are beyond the scope of this entry. This is a difficult forecast problem, especially in data-void regions such as the ocean.



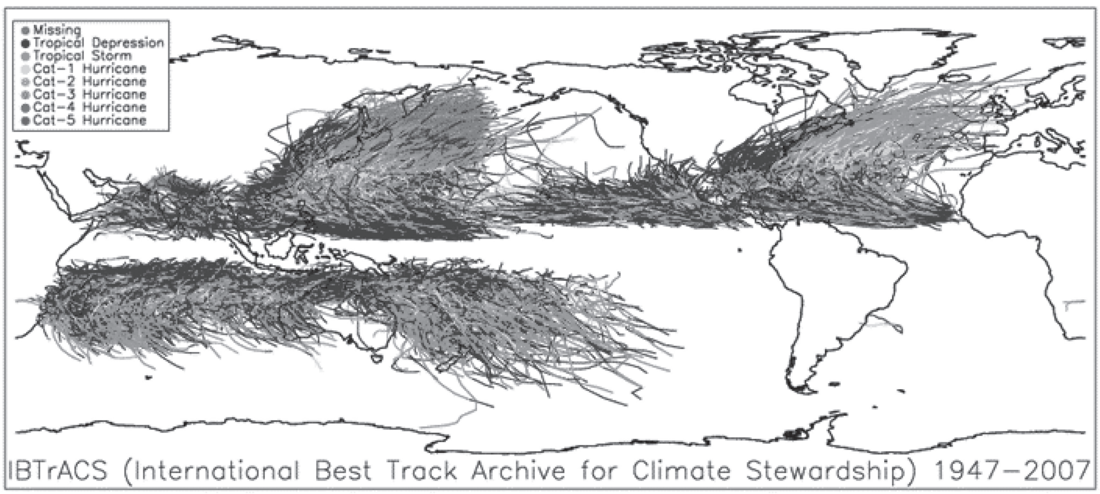


Fig. 3 (Top) Global genesis regions (in red), the Regional Specialized Meteorological Centres (RSMCs), and Tropical Cyclone Warning Centres (TCWCs; Wellington, Brisbane, Perth, Darwin, Port Moresby, and Jakarta). For example, the National Weather Service National Hurricane Center and the Japan Meteorological Agency Typhoon Center are RSMCs. (Bottom) Global tropical depression, tropical storm, and hurricane tracks by U.S. Saffir–Simpson wind categories for 1947–2007. "Missing" indicates a position was available but intensity data was missing.
Source: Top figure adapted from World Meteorological Organization.[4] Bottom figure Courtesy of Knapp et al. adapted from.[5] Bottom figure is © Copyright March 2010 AMS.

The complexity of track—as well as intensity and storm surge—predictions requires the use of computer models. Computer models ingest current weather observations and approximate solutions to complicated equations for future atmospheric values such as wind, temperature, and moisture. Forecast agencies use a suite of models that differ in their mathematical assumptions and complexities in describing atmospheric processes. The most complex models must be run on the fastest computers in the world, known as supercomputers.

Many U.S. residents perceive the North Atlantic Ocean basin as a proliferate producer of hurricanes due to the publicity these storms generate. In reality, several oceans produce more hurricanes annually than the North Atlantic. For example, the most active ocean basin in the world—the Northwest Pacific—averages 17 hurricanes per year. The second most active is the Northeast Pacific, which averages nine hurricanes. In contrast, the North Atlantic mean annual number of hurricanes is six. Table 1 summarizes each basin's average number of hurricanes and total tropical cyclones using U.S. definitions.

Tropical cyclone season is typically limited to the warm seasons. In the Atlantic, the official tropical cyclone season begins June 1 and ends November 30, although activity has been observed outside this timeframe. However, tropical cyclones are most numerous and strongest in late summer and early fall. Exceptions to this late-summer/early fall peak in tropical cyclone activity occur in certain parts of the world such as India since their monsoon trough moves inland during the summer. In addition, while activity does peak in late summer, the Northwest Pacific tropical cyclone season lasts all year.

Table 1 The mean number of total tropical cyclones (hurricanes and tropical storms), hurricanes, and major hurricanes per year in all tropical ocean basins using U.S. definitions

Tropical ocean basin	Mean annual tropical storms and hurricanes	Mean annual hurricanes	Mean major hurricanes
Northwest Pacific	26	17	8
Central North Pacific and Northeast Pacific	17	9	5
East Coast Australia and Southwest Pacific	10	5	2
West Coast Australia and Southeast Indian	8	4	1
North Atlantic	12	6	2
Southwest Indian	9	5	2
North Indian	5	2	Between 0 and 1
South Atlantic	0	0	0
Southeast Pacific	0	0	0
Global	86	47	20

Improved satellite monitoring capabilities have also unofficially identified several (mostly) weak, short-lived tropical cyclones in the South Atlantic Ocean the last two decades. Cyclone Catarina (2004) is the only official South Atlantic tropical cyclone with category 2 winds, named after the state in Brazil it made landfall. The official average is zero in the South Atlantic, but apparently a tropical cyclone forms every few year.

The classification schemes vary around the globe by assorted names, different time averaging for sustained winds, and diverse wind thresholds. Figure 4 summarizes global classifications. They all recognize classes from genesis to strong storms with consistent thresholds of 17 and 33 ms^{-1}, but use their own terms and wind thresholds for other delineations. For example, in the Northwest Pacific Ocean, the designation at 33 ms^{-1} is "typhoon," in India is "very severe cyclonic storm," and off Australia is "severe tropical cyclone." The rough equivalent term for major hurricanes in the North India Ocean is "super cyclonic storm," and in the Southwest Indian Ocean is "very intense tropical cyclone," although the wind thresholds are different. Finally, in the most active global region, the Northwest Pacific Ocean, storms with winds greater than 67 ms^{-1} are common enough that the Joint Typhoon Warning Center uses a special category exists for them—"supertyphoon."

Australia also uses a different wind damage scale than the United States (Fig. 4). Their category 1 begins at 17 ms^{-1} for minor damage, escalating to "some roof and structure damage" (Australian category 3), "significant damage" (Australian category 4), and "widespread damage" (Australian category 5). The U.S. Saffir–Simpson wind scale does not include tropical storms, the Australian wind scale of 3 is approximately the same as category 1 in America, Australian category 4 is approximately category 2–3 in America, and Australian category 5 is approximately category 4–5 in America.

When 17 ms^{-1} is reached, a name is assigned in most basins. However, the number of lists varies, as does whether a revolving cycle is used. For example, the Atlantic basin storms use a 6-year repeating list. However, the Northwest Pacific uses five lists, which do not rotate annually but simply goes to the next list when the last name is reached. Whenever a storm has had a major impact in terms of damage and/or fatalities, any country affected by the storm can request the name be "retired" by agreement of the World Meteorological Organization.

All names are determined at international meetings, and reflect the regional culture. For example, Northeast Pacific storms tend to have Hispanic names, whereas central North Pacific storms have Hawaiian names. In regions with multiple countries, names will vary reflecting the different cultures. Southwest Indian tropical cyclone names are based on French, Madagascar, and many African countries. Northwest Pacific uses Asian nomenclature that do not reflect personal names but instead natural objects (such as trees, flowers, rivers, or animals), "stormy" adjectives (such as swift, strong, sharp, fast), and gods or goddesses. In addition, the Philippines assigns local names to tropical cyclones in their region, even though it will also have an "official" international name, resulting in two names for the same storm. The two purposes for names are to facilitate easy regional communication of a storm between forecasters and the general public, and for historical context.

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Excellent background information and imbedded links on hurricanes is available at the following websites (accessed 2 September 2013):

1. The National Hurricane Center: http://www.nhc.noaa.gov
2. Australian Bureau of Meteorology: http://www.bom.gov.au/cyclone/
3. India Meteorological Department: http://www.imd.gov.in/section/nhac/dynamic/cyclone.htm

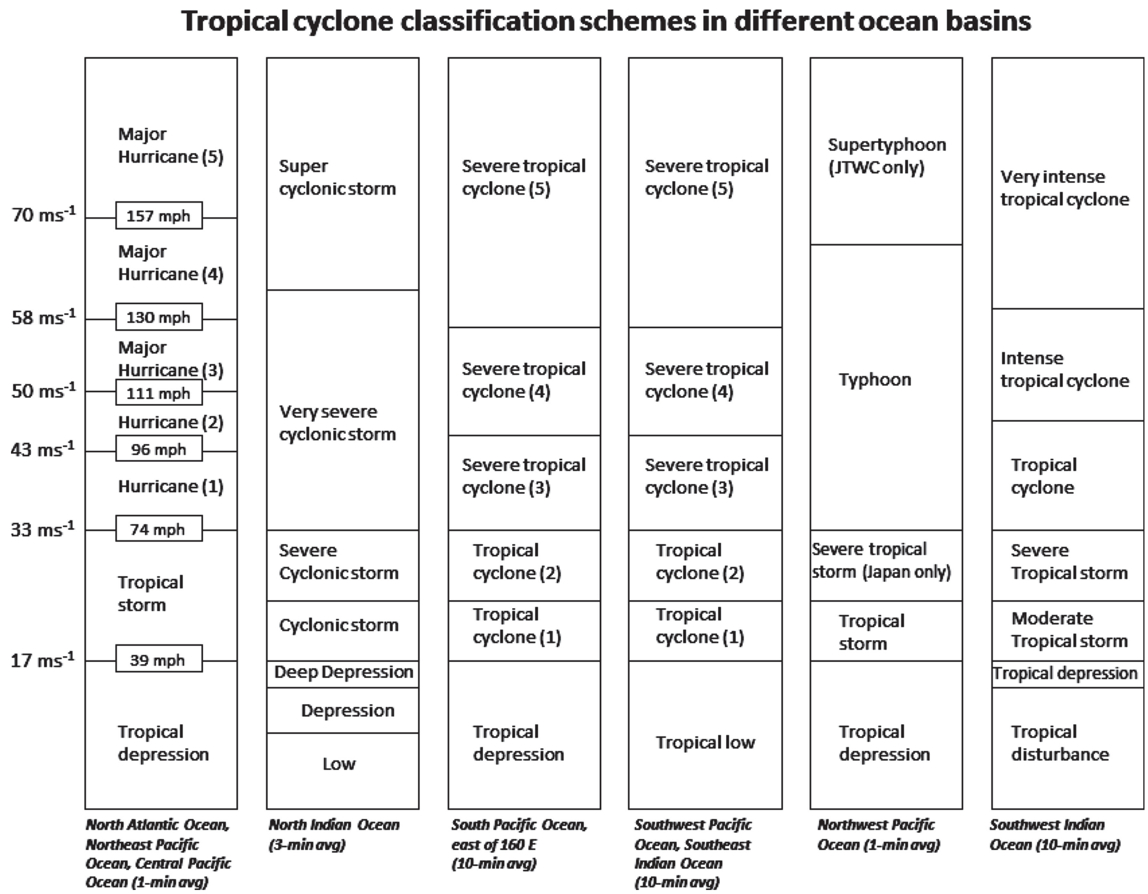

Fig. 4 Classification schemes for the six ocean regions where tropical cyclone terminology varies from genesis to intense categories. The U.S. definitions are used for reference in the leftmost column. Also shown are the wind damage scales used in the United States and in Australia. Wind averaging schemes are shown for each basin. One-minute averaging results in winds that are approximately 14% more than 10-minute average winds (1-minute winds = 1.14 times 10-minute winds). Wind units are provided in ms^{-1} and mph on the left side.

4. World Meteorological Organization Tropical Cyclone Programme: http://www.wmo.int/pages/prog/www/tcp/index_en.html
5. Frequently Asked Questions About Hurricanes: http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html
6. International Best Track Archive for Climate Stewardship: http://www.ncdc.noaa.gov/oa/ibtracs/index.php
7. Historical Hurricane Tracks: http://www.csc.noaa.gov/hurricanes/

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2. Australian Bureau of Meteorology. Storm surge preparedness and safety, 2013. Available at http://www.bom.gov.au/cyclone/about/stormsurge.shtml
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5. Knapp, K.R.; Kruk, M.C.; Levinson, D.H.; Diamond, H.J.; Neumann, C.J. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bull. American Meteor. Soc. **2010**, *91*, 363–376.