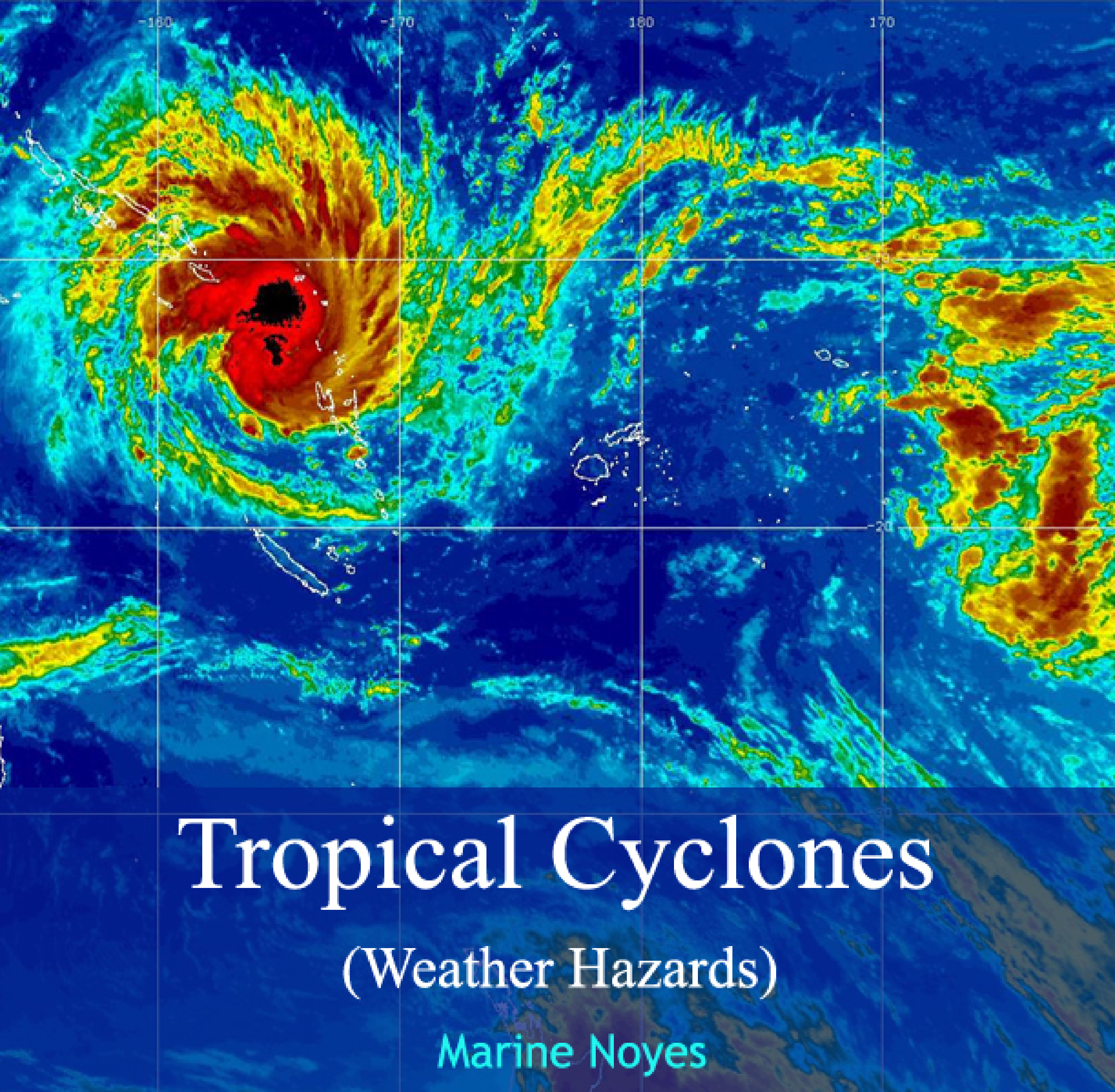

Tropical Cyclones

(Weather Hazards)

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Tropical Cyclone

Hurricane Isabel (2003) as seen from orbit during Expedition 7 of the International Space Station. The eye, eyewall and surrounding rainbands that are characteristics of tropical cyclones are clearly visible in this view from space.

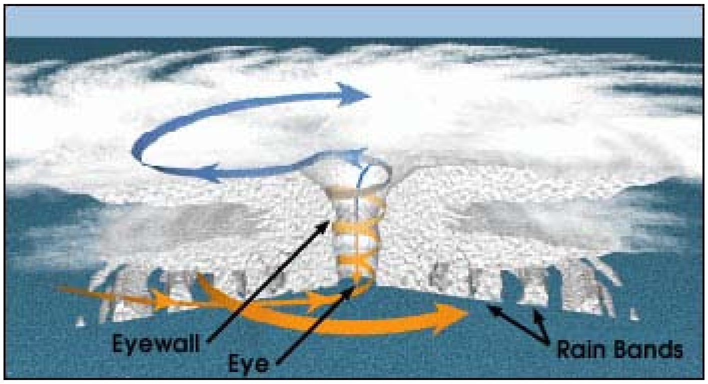
A **tropical cyclone** is a storm system characterized by a large low-pressure center and numerous thunderstorms that produce strong winds and heavy rain. Tropical cyclones strengthen when water evaporated from the ocean is released as the saturated air rises, resulting in condensation of water vapor contained in the moist air. They are fueled by a different heat mechanism than other cyclonic windstorms such as nor'easters, European windstorms, and polar lows. The characteristic that separates tropical cyclones from other cyclonic systems is that any height in the atmosphere, the center of a tropical cyclone will be warmer than its surrounds; a phenomenon called "warm core" storm systems.

The term "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in maritime tropical air masses. The term "cyclone" refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere. The opposite direction of spin is a result of the Coriolis force. Depending on its location and strength, a tropical cyclone is referred to by names such as **hurricane**, **typhoon**, **tropical storm**, **cyclonic storm**, **tropical depression**, and simply **cyclone**.

While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and damaging storm surge as well as spawning tornadoes. They develop over large bodies of warm water, and lose their strength if they move over land due to increased surface friction and loss of the warm ocean as an energy source. This is why coastal regions can receive significant damage from a tropical cyclone, while inland regions are relatively safe from receiving strong winds. Heavy rains, however, can produce significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 kilometres (25 mi) from the coastline. Although their effects on human populations can be devastating, tropical cyclones can also relieve drought conditions. They also carry heat and energy away from the tropics and transport it toward temperate latitudes, which makes them an important part of the global atmospheric circulation mechanism. As a result, tropical cyclones help to maintain equilibrium in the Earth's troposphere, and to maintain a relatively stable and warm temperature worldwide.

Many tropical cyclones develop when the atmospheric conditions around a weak disturbance in the atmosphere are favorable. The background environment is modulated by climatological cycles and patterns such as the Madden-Julian oscillation, El Niño-Southern Oscillation, and the Atlantic multidecadal oscillation. Others form when other types of cyclones acquire tropical characteristics. Tropical systems are then moved by steering winds in the troposphere; if the conditions remain favorable, the tropical disturbance intensifies, and can even develop an eye. On the other end of the spectrum, if the conditions around the system deteriorate or the tropical cyclone makes landfall, the system weakens and eventually dissipates. It is not possible to artificially induce the dissipation of these systems with current technology.

Physical structure



Structure of a tropical cyclone

All tropical cyclones are areas of low atmospheric pressure in the Earth's atmosphere. The pressures recorded at the centers of tropical cyclones are among the lowest that occur on Earth's surface at sea level. Tropical cyclones are characterized and driven by the release of large amounts of latent heat of condensation, which occurs when moist air is carried upwards and its water vapor condenses. This heat is distributed vertically around the center of the storm. Thus, at any given altitude (except close to the surface, where water temperature dictates air temperature) the environment inside the cyclone is warmer than its outer surroundings.

Eye and center

A strong tropical cyclone will harbor an area of sinking air at the center of circulation. If this area is strong enough, it can develop into a large "eye". Weather in the eye is normally calm and free of clouds, although the sea may be extremely violent. The eye is normally circular in shape, and may range in size from 3 kilometres (1.9 mi) to 370 kilometres (230 mi) in diameter. Intense, mature tropical cyclones can sometimes exhibit an outward curving of the eyewall's top, making it resemble a football stadium; this phenomenon is thus sometimes referred to as the *stadium effect*.

There are other features that either surround the eye, or cover it. The central dense overcast is the concentrated area of strong thunderstorm activity near the center of a tropical cyclone; in weaker tropical cyclones, the CDO may cover the center completely. The eyewall is a circle of strong thunderstorms that surrounds the eye; here is where the greatest wind speeds are found, where clouds reach the highest, and precipitation is the heaviest. The heaviest wind damage occurs where a tropical cyclone's eyewall passes over land. Eyewall replacement cycles occur naturally in intense tropical cyclones. When cyclones reach peak intensity they usually have an eyewall and radius of maximum winds that contract to a very small size, around 10 kilometres (6.2 mi) to 25 kilometres (16 mi). Outer rainbands can organize into an outer ring of thunderstorms that slowly moves inward and robs the inner eyewall of its needed moisture and angular momentum. When the inner eyewall weakens, the tropical cyclone weakens (in other words, the maximum sustained winds weaken and the central pressure rises.) The outer eyewall replaces the inner one completely at the end of the cycle. The storm can be of the same intensity as it was previously or even stronger after the eyewall replacement cycle finishes. The storm may strengthen again as it builds a new outer ring for the next eyewall replacement.

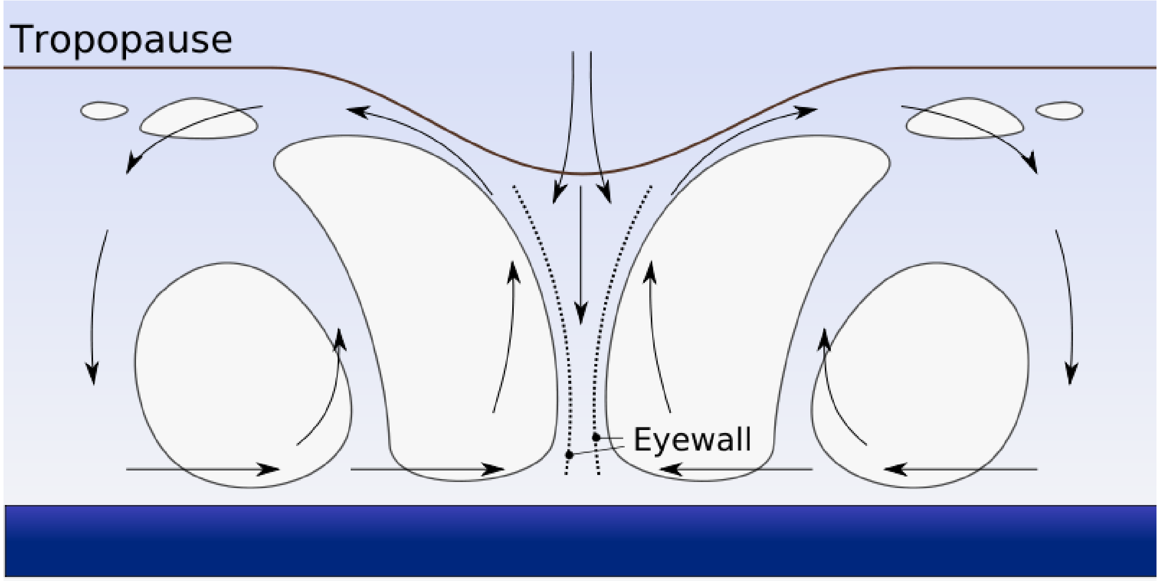
Size descriptions of tropical cyclones

ROCI	Type
Less than 2 degrees latitude	Very small/midget
2 to 3 degrees of latitude	Small
3 to 6 degrees of latitude	Medium/Average
6 to 8 degrees of latitude	Large anti-dwarf
Over 8 degrees of latitude	Very large

Size

One measure of the size of a tropical cyclone is determined by measuring the distance from its center of circulation to its outermost closed isobar, also known as its ROCI. If the radius is less than two degrees of latitude or 222 kilometres (138 mi), then the cyclone is "very small" or a "midget". A radius between 3 and 6 latitude degrees or 333 kilometres (207 mi) to 670 kilometres (420 mi) are considered "average-sized". "Very large" tropical cyclones have a radius of greater than 8 degrees or 888 kilometres (552 mi). Use of this measure has objectively determined that tropical cyclones in the northwest Pacific Ocean are the largest on earth on average, with Atlantic tropical cyclones roughly half their size. Other methods of determining a tropical cyclone's size include measuring the radius of gale force winds and measuring the radius at which its relative vorticity field decreases to 1×10^{-5} s^{-1} from its center.

Mechanics



Tropical cyclones form when the energy released by the condensation of moisture in rising air causes a positive feedback loop over warm ocean waters.

A tropical cyclone's primary energy source is the release of the heat of condensation from water vapor condensing, with solar heating being the initial source for evaporation. Therefore, a tropical cyclone can be visualized as a giant vertical heat engine supported by mechanics driven by physical forces such as the rotation and gravity of the Earth. In another way, tropical cyclones could be viewed as a special type of mesoscale convective complex, which continues to develop over a vast source of relative warmth and moisture. While an initial warm core system, such as an organized thunderstorm complex, is necessary for the formation of a tropical cyclone, a large flux of energy is needed to lower atmospheric pressure more than a few millibars (0.10 inch of mercury). The inflow of warmth and moisture from the underlying ocean surface is critical for tropical cyclone strengthening. A significant amount of the inflow in the cyclone is in the lowest 1 kilometre (3,300 ft) of the atmosphere.

Condensation leads to higher wind speeds, as a tiny fraction of the released energy is converted into mechanical energy; the faster winds and lower pressure associated with them in turn cause increased surface evaporation and thus even more condensation. Much of the released energy drives updrafts that increase the height of the storm clouds, speeding up condensation. This positive feedback loop, called the Wind-induced surface heat exchange, continues for as long as conditions are favorable for tropical cyclone development. Factors such as a continued lack of equilibrium in air mass distribution would also give supporting energy to the cyclone. The rotation of the Earth causes the system to spin, an effect known as the Coriolis effect, giving it a cyclonic characteristic and affecting the trajectory of the storm.

What primarily distinguishes tropical cyclones from other meteorological phenomena is deep convection as a driving force. Because convection is strongest in a tropical climate, it defines the initial domain of the tropical cyclone. By contrast, mid-latitude cyclones draw their energy mostly from pre-existing horizontal temperature gradients in the atmosphere. To continue to drive its heat engine, a tropical cyclone must remain over warm water, which provides the needed atmospheric moisture to keep the positive feedback loop running. When a tropical cyclone passes over land, it is cut off from its heat source and its strength diminishes rapidly.

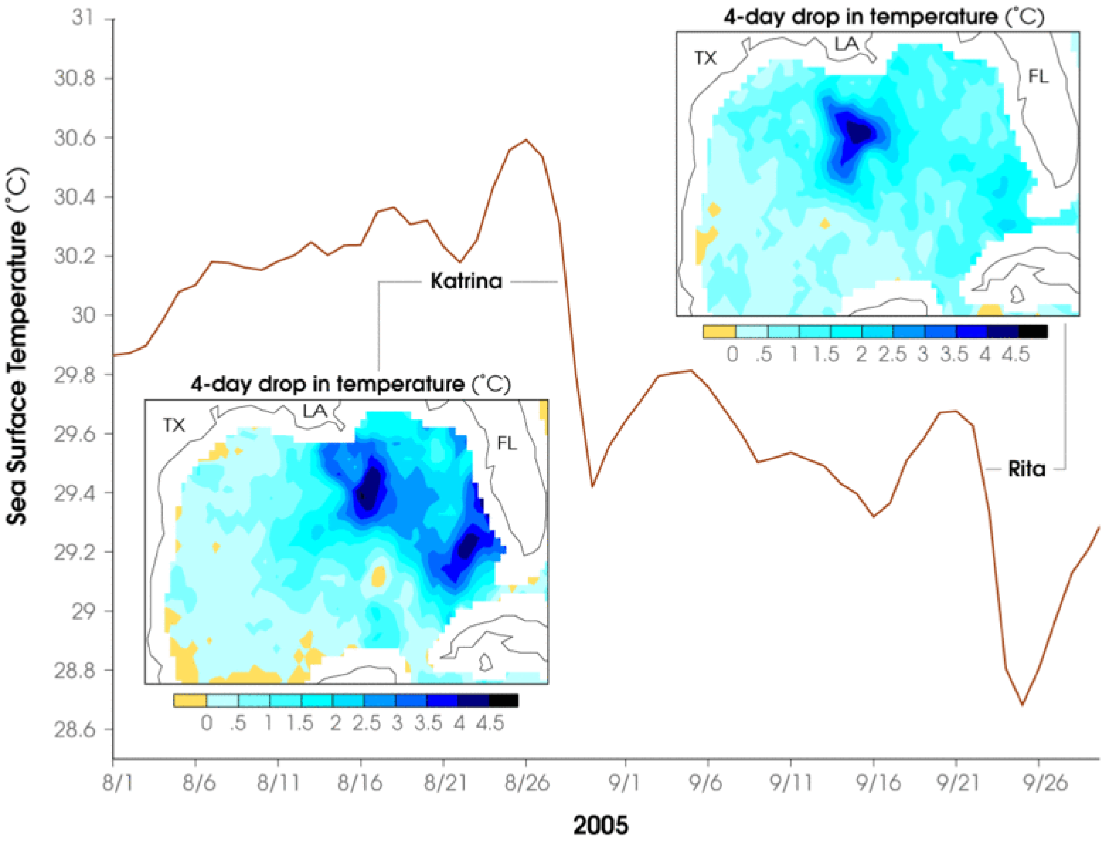


Chart displaying the drop in surface temperature in the Gulf of Mexico as Hurricanes Katrina and Rita passed over

The passage of a tropical cyclone over the ocean causes the upper layers of the ocean to cool substantially, which can influence subsequent cyclone development. This cooling is primarily caused by wind-driven mixing of cold water from deeper in the ocean and the warm surface waters. This effect results in a negative feedback process which can inhibit further development or lead to weakening. Additional cooling may come in the form of cold water from falling raindrops (this is because the atmosphere is cooler at higher altitudes). Cloud cover may also play a role in cooling the ocean, by shielding the ocean surface from direct sunlight before and slightly after the storm passage. All these effects can combine to produce a dramatic drop in sea surface temperature over a large area in just a few days.

Scientists estimate that a tropical cyclone releases heat energy at the rate of 50 to 200 exajoules (10^{18} J) per day, equivalent to about 1 PW (10^{15} watt). This rate of energy release is equivalent to 70 times the world energy consumption of humans and 200 times the worldwide electrical generating capacity, or to exploding a 10-megaton nuclear bomb every 20 minutes.

In the lower troposphere, the most obvious motion of clouds is toward the center. However tropical cyclones also develop an upper-level (high-altitude) outward flow of clouds. These originate from air that has released its moisture and is expelled at high altitude through the "chimney" of the storm engine. This outflow produces high, cirrus clouds that spiral away from the center. The clouds thin as they move outwards from the center of the system and are evaporated. They may be thin enough for the sun to be visible through them. These high cirrus clouds may be the first signs of an approaching tropical cyclone. As air parcels are lifted within the eye of the storm the vorticity is reduced, causing the outflow from a tropical cyclone to have anti-cyclonic motion.

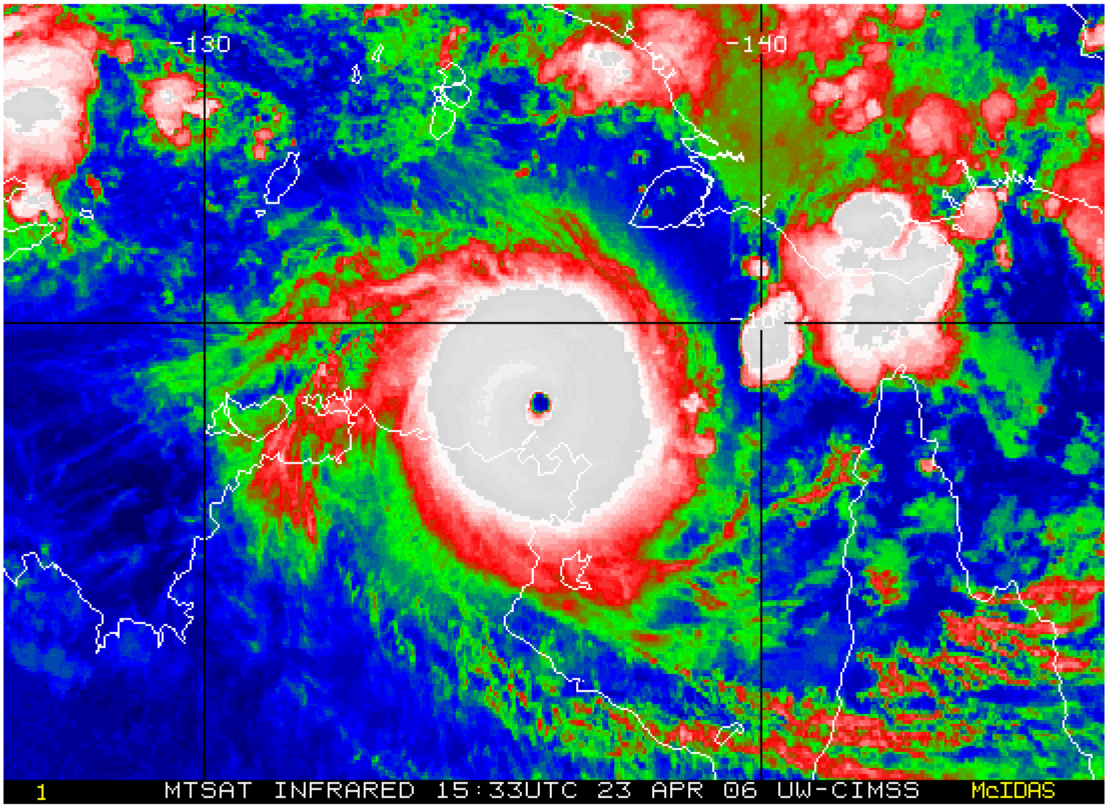
Movement and track

Steering winds

Although tropical cyclones are large systems generating enormous energy, their movements over the Earth's surface are controlled by large-scale winds—the streams in the Earth's atmosphere. The path of motion is referred to as a tropical cyclone's *track* and has been compared by Dr. Neil Frank, former director of the National Hurricane Center, to "leaves carried along by a stream".

Tropical systems, while generally located equatorward of the 20th parallel, are steered primarily westward by the east-to-west winds on the equatorward side of the subtropical ridge—a persistent high pressure area over the world's oceans. In the tropical North Atlantic and Northeast Pacific oceans, trade winds—another name for the westward-moving wind currents—steer tropical waves westward from the African coast and towards the Caribbean Sea, North America, and ultimately into the central Pacific ocean before the waves dampen out. These waves are the precursors to many tropical cyclones within this region. In the Indian Ocean and Western Pacific (both north and south of the equator), tropical cyclogenesis is strongly influenced by the seasonal movement of the Intertropical Convergence Zone and the monsoon trough, rather than by easterly waves. Tropical cyclones can also be steered by other systems, such as other low pressure systems, high pressure systems, warm fronts, and cold fronts.

Coriolis effect

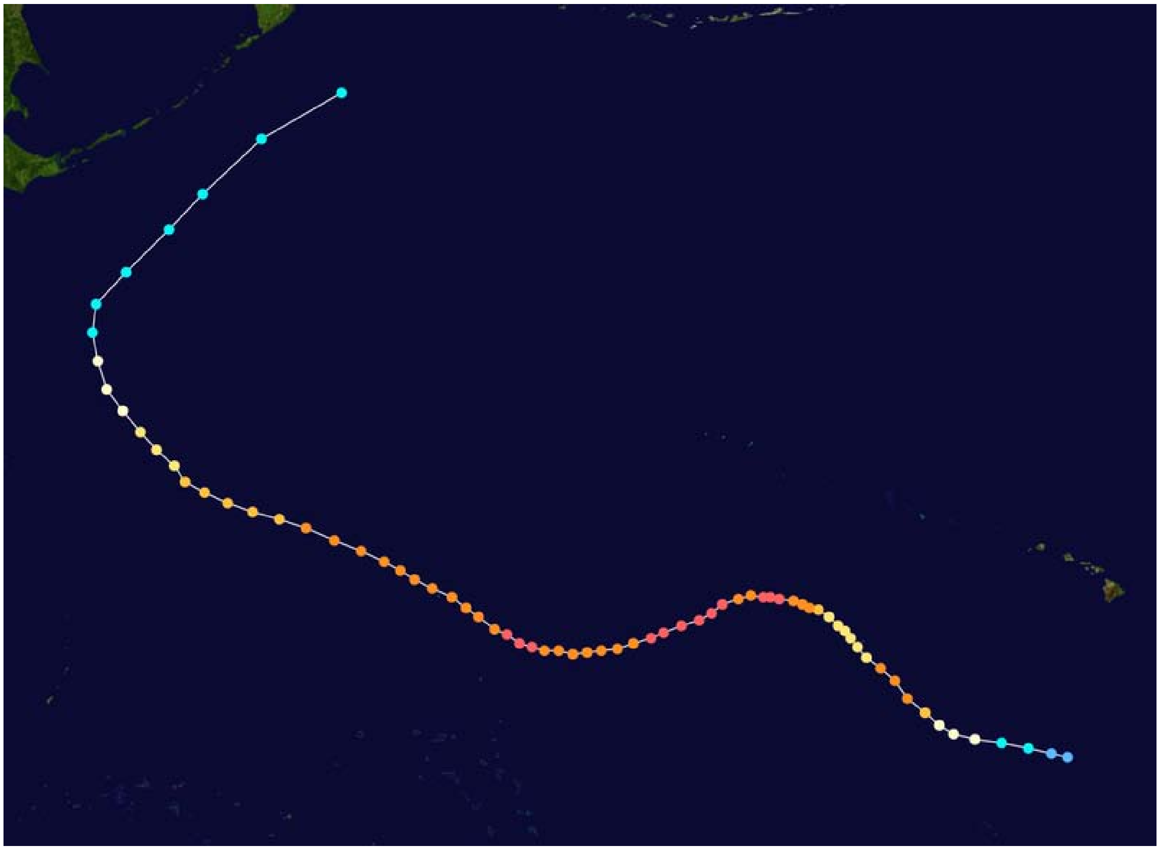


Infrared image of a powerful southern hemisphere cyclone, Monica, near peak intensity, showing clockwise rotation due to the Coriolis effect

The Earth's rotation imparts an acceleration known as the *Coriolis effect*, *Coriolis acceleration*, or colloquially, *Coriolis force*. This acceleration causes cyclonic systems to turn towards the poles in the absence of strong steering currents. The poleward portion of a tropical cyclone contains easterly winds, and the Coriolis effect pulls them slightly more poleward. The westerly winds on the equatorward portion of the cyclone pull slightly towards the equator, but, because the Coriolis effect weakens toward the equator, the net drag on the cyclone is poleward. Thus, tropical cyclones in the Northern Hemisphere usually turn north (before being blown east), and tropical cyclones in the Southern Hemisphere usually turn south (before being blown east) when no other effects counteract the Coriolis effect.

The Coriolis effect also initiates cyclonic rotation, but it is not the driving force that brings this rotation to high speeds – that force is the heat of condensation.

Interaction with the mid-latitude westerlies



Storm track of Typhoon Ioke, showing recurvature off the Japanese coast in 2006

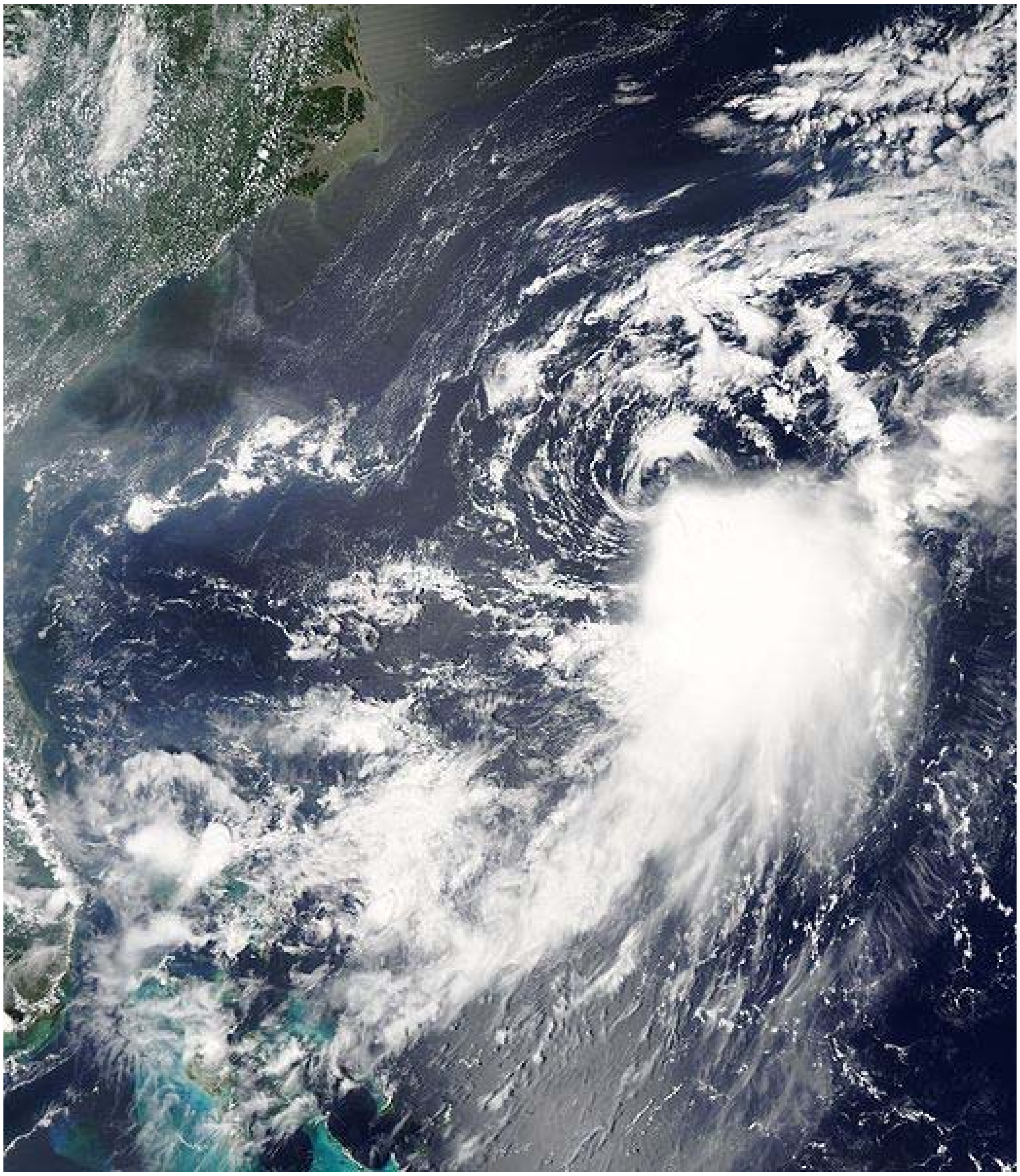
When a tropical cyclone crosses the subtropical ridge axis, its general track around the high-pressure area is deflected significantly by winds moving towards the general low-pressure area to its north. When the cyclone track becomes strongly poleward with an easterly component, the cyclone has begun *recurvature.* A typhoon moving through the Pacific Ocean towards Asia, for example, will recurve offshore of Japan to the north, and then to the northeast, if the typhoon encounters southwesterly winds (blowing northeastward) around a low-pressure system passing over China or Siberia. Many tropical cyclones are eventually forced toward the northeast by extratropical cyclones in this manner, which move from west to east to the north of the subtropical ridge. An example of a tropical cyclone in recurvature was Typhoon Ioke in 2006, which took a similar trajectory.

Landfall

Officially, *landfall* is when a storm's center (the center of its circulation, not its edge) crosses the coastline. Storm conditions may be experienced on the coast and inland hours before landfall; in fact, a tropical cyclone can launch its strongest winds over land, yet not make landfall; if this occurs, then it is said that the storm made a *direct hit* on the coast. As a result of the narrowness of this definition, the landfall area experiences half of a land-bound storm by the time the actual landfall occurs. For emergency preparedness, actions should be timed from when a certain wind speed or intensity of rainfall will reach land, not from when landfall will occur.

Dissipation

Factors



Tropical Storm Franklin, an example of a strongly sheared tropical cyclone in the Atlantic Basin during 2005

A tropical cyclone can cease to have tropical characteristics in several different ways. One such way is if it moves over land, thus depriving it of the warm water it needs to power itself, quickly losing strength. Most strong storms lose their strength very rapidly after landfall and become disorganized areas of low pressure within a day or two, or evolve into extratropical cyclones. There is a chance a tropical cyclone could regenerate if it managed to get back over open warm water, such as with Hurricane Ivan. If it remains over mountains for even a short time, weakening will accelerate. Many storm fatalities occur in mountainous terrain, as the dying storm unleashes torrential rainfall, leading to deadly floods and mudslides, similar to those that happened with Hurricane Mitch in 1998. Additionally, dissipation can occur if a storm remains in the same area of ocean for too long, mixing the upper 60 metres (200 ft) of water, dropping sea surface temperatures more than 5 °C (9 °F). Without warm surface water, the storm cannot survive.

A tropical cyclone can dissipate when it moves over waters significantly below 26.5 °C (79.7 °F). This will cause the storm to lose its tropical characteristics (i.e. thunderstorms near the center and warm core) and become a remnant low pressure area, which can persist for several days. This is the main dissipation mechanism in the Northeast Pacific ocean. Weakening or dissipation can occur if it experiences vertical wind shear, causing the convection and heat engine to move away from the center; this normally ceases development of a tropical cyclone. Additionally, its interaction with the main belt of the Westerlies, by means of merging with a nearby frontal zone, can cause tropical cyclones to evolve into extratropical cyclones. This transition can take 1–3 days. Even after a tropical cyclone is said to be extratropical or dissipated, it can still have tropical storm force (or occasionally hurricane/typhoon force) winds and drop several inches of rainfall. In the Pacific ocean and Atlantic ocean, such tropical-derived cyclones of higher latitudes can be violent and may occasionally remain at hurricane or typhoon-force wind speeds when they reach the west coast of North America. These phenomena can also affect Europe, where they are known as *European windstorms*; Hurricane Iris's extratropical remnants are an example of such a windstorm from 1995. Additionally, a cyclone can merge with another area of low pressure, becoming a larger area of low pressure. This can strengthen the resultant system, although it may no longer be a tropical cyclone. Studies in the 2000s have given rise to the hypothesis that large amounts of dust reduce the strength of tropical cyclones.

Artificial dissipation

In the 1960s and 1970s, the United States government attempted to weaken hurricanes through Project Stormfury by seeding selected storms with silver iodide. It was thought that the seeding would cause supercooled water in the outer rainbands to freeze, causing the inner eyewall to collapse and thus reducing the winds. The winds of Hurricane Debbie—a hurricane seeded in Project Stormfury—dropped as much as 31%, but Debbie regained its strength after each of two seeding forays. In an earlier episode in 1947, disaster struck when a hurricane east of Jacksonville, Florida promptly changed its course after being seeded, and smashed into Savannah, Georgia. Because there was so much uncertainty about the behavior of these storms, the federal government would not approve seeding operations unless the hurricane had a less than 10% chance of making landfall within 48 hours, greatly reducing the number of possible test storms. The project was dropped after it was discovered that eyewall replacement cycles occur naturally in strong hurricanes, casting doubt on the result of the earlier attempts. Today, it is known that silver iodide seeding is not likely to have an effect because the amount of supercooled water in the rainbands of a tropical cyclone is too low.

Other approaches have been suggested over time, including cooling the water under a tropical cyclone by towing icebergs into the tropical oceans. Other ideas range from covering the ocean in a substance that inhibits evaporation, dropping large quantities of ice into the eye at very early stages of development (so that the latent heat is absorbed by the ice, instead of being converted to kinetic energy that would feed the positive feedback loop), or blasting the cyclone apart with nuclear weapons. Project Cirrus even involved throwing dry ice on a cyclone. These approaches all suffer from one flaw above many others: tropical cyclones are simply too large and short-lived for any of the weakening techniques to be practical.

Observation and forecasting

Sunspot theory

A 2010 report correlates low sunspot activity with high cyclonic activity. Fewer sunspots appear to decrease temperature in the upper atmosphere, creating unstable conditions that help create cyclones. Analyzing historical data, there had been a 25% chance of at least one hurricane striking the continental US during a peak sunspot year; a 64% chance during a low sunspot year. In June 2010, the hurricanes predictors in the US were not using this information.

Classifications, terminology, and naming

Tropical depression

A **tropical depression** is an organized system of clouds and thunderstorms with a defined, closed surface circulation and maximum sustained winds of less than 17 metres per second (33 kn) or 38 miles per hour (61 km/h). It has no eye and does not typically have the organization or the spiral shape of more powerful storms. However, it is already a low-pressure system, hence the name "depression". The practice of the Philippines is to name tropical depressions from their own naming convention when the depressions are within the Philippines' area of responsibility.

Tropical storm

A **tropical storm** is an organized system of strong thunderstorms with a defined surface circulation and maximum sustained winds between 17 metres per second (33 kn) (39 miles per hour (63 km/h)) and 32 metres per second (62 kn) (73 miles per hour (117 km/h)). At this point, the distinctive cyclonic shape starts to develop, although an eye is not usually present. Government weather services, other than the Philippines, first assign names to systems that reach this intensity (thus the term *named storm*).

Hurricane or typhoon

A **hurricane** or **typhoon** (sometimes simply referred to as a tropical cyclone, as opposed to a depression or storm) is a system with sustained winds of at least 33 metres per second (64 kn) or 74 miles per hour (119 km/h). A cyclone of this intensity tends to develop an eye, an area of relative calm (and lowest atmospheric pressure) at the center of circulation. The eye is often visible in satellite images as a small, circular, cloud-free spot. Surrounding the eye is the eyewall, an area about 16 kilometres (9.9 mi) to 80 kilometres (50 mi) wide in which the strongest thunderstorms and winds circulate around the storm's center. Maximum sustained winds in the strongest tropical cyclones have been estimated at about 85 metres per second (165 kn) or 195 miles per hour (314 km/h).

Tropical Cyclone Classifications (all winds are 10-minute averages)

Beaufort scale	10-minute sustained winds (knots)	N Indian Ocean IMD	SW Indian Ocean MF	Australia BOM	SW Pacific FMS	NW Pacific JMA	NW Pacific JTWC	NE Pacific & N Atlantic NHC, CHC & CPHC
0–6	<28 knots (32 mph; 52 km/h)	Depression	Trop. Disturbance	Tropical Low	Tropical Depression	Tropical Depression	Tropical Depression	Tropical Depression
7	28–29 knots (32–33 mph; 52–54 km/h)	Deep Depression	Depression					
	30–33 knots (35–38 mph; 56–61 km/h)						Tropical Storm	Tropical Storm
8–9	34–47 knots (39–54 mph; 63–87 km/h)	Cyclonic Storm	Moderate Tropical Storm	Tropical Cyclone (1)	Tropical Cyclone (1)	Tropical Storm		
10	48–55 knots (55–63 mph; 89–102 km/h)	Severe Cyclonic Storm	Severe Tropical Storm	Tropical Cyclone (2)	Tropical Cyclone (2)	Severe Tropical Storm		
11	56–63 knots (64–72 mph; 104–117 km/h)						Typhoon	Hurricane (1)
12	64–72 knots (74–83 mph; 119–133 km/h)	Very Severe Cyclonic Storm	Tropical Cyclone	Severe Tropical Cyclone (3)	Severe Tropical Cyclone (3)	Typhoon		
	73–85 knots (84–98 mph; 135–157 km/h)							Hurricane (2)

	86–89 knots (99–102 mph; 159–165 km/h)			Severe Tropical Cyclone (4)	Severe Tropical Cyclone (4)			Major Hurricane (3)
	90–99 knots (100–114 mph; 170–183 km/h)		Intense Tropical Cyclone					
	100–106 knots (120–122 mph; 190–196 km/h)							Major Hurricane (4)
	107–114 knots (123–131 mph; 198–211 km/h)			Severe Tropical Cyclone (5)	Severe Tropical Cyclone (5)			
	115–119 knots (132–137 mph; 213–220 km/h)		Very Intense Tropical Cyclone				Super Typhoon	
	>120 knots (140 mph; 220 km/h)	Super Cyclonic Storm						Major Hurricane (5)

Origin of storm terms

Taipei 101 endures a typhoon in 2005

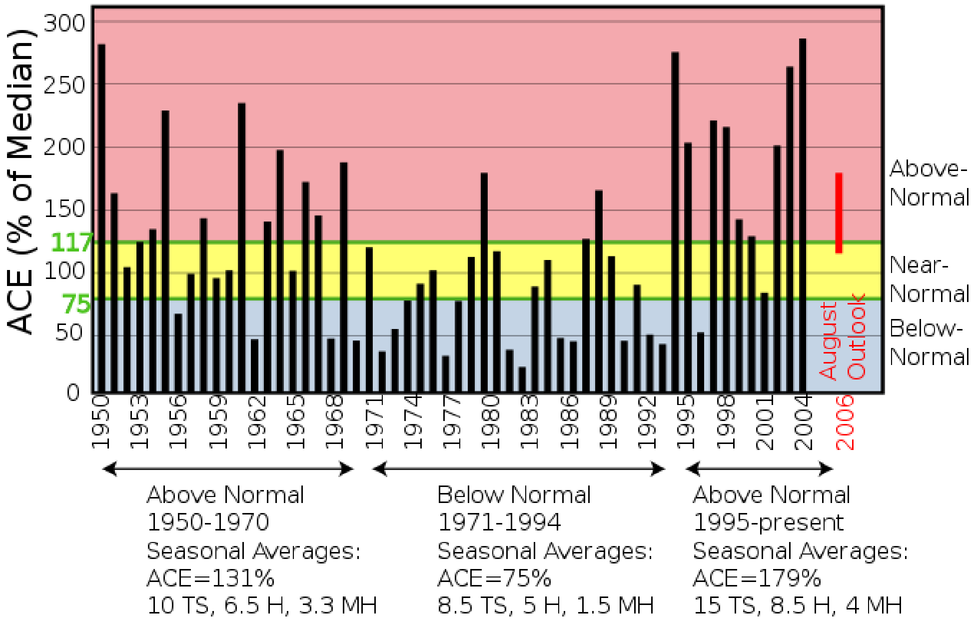
The word *typhoon*, which is used today in the Northwest Pacific, may be derived from Urdu, Persian and Arabic *ṭūfān* (طوفان), which in turn originates from Greek *Typhon* (Τυφῶν), a monster from Greek mythology associated with storms. The related Portuguese word *tufão*, used in Portuguese for typhoons, is also derived from *Typhon.* The word is also similar to Chinese "taifeng" ("toifung" in Cantonese) (颱風 – literally great winds), and also to the Japanese "taifu" (台風), which may explain why "typhoon" came to be used for East Asian cyclones.

The word *hurricane*, used in the North Atlantic and Northeast Pacific, is probably derived from the name of a Mayan storm god, Huracan, via the Spanish, *huracán*. Huracan is also the source of the word *Orcan*, another word for a European windstorm. Another possible source is Hyrrokkin, a Jotun or giantess in Norse mythology, called upon by the Aesir to launch the ship bearing the body of the god Balder, which was too heavy for even the gods to move.

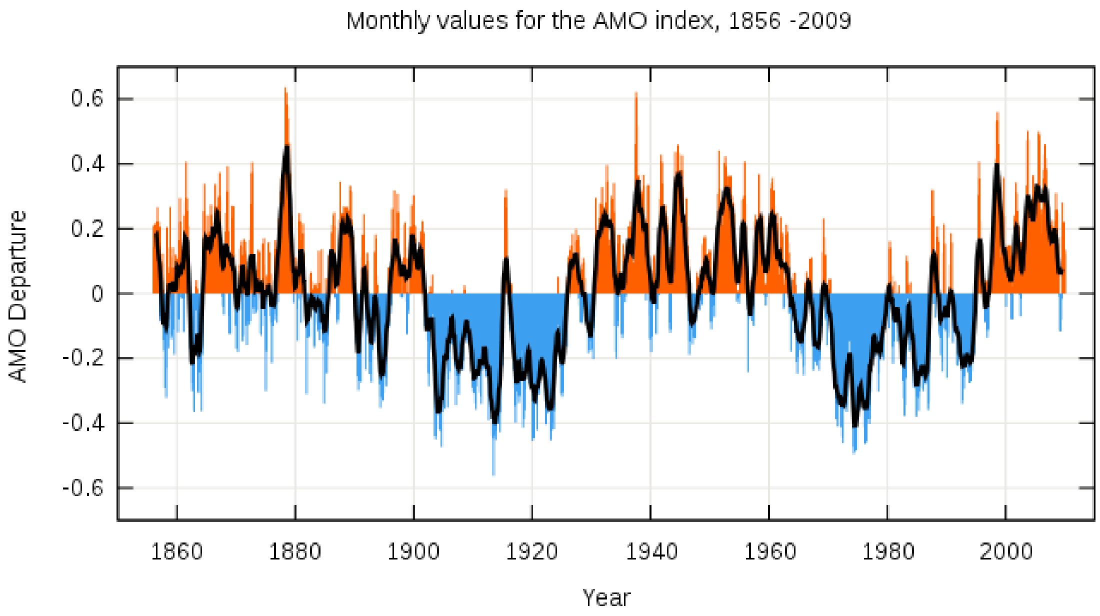
Changes due to El Niño-Southern Oscillation

Most tropical cyclones form on the side of the subtropical ridge closer to the equator, then move poleward past the ridge axis before recurving into the main belt of the Westerlies. When the subtropical ridge position shifts due to El Nino, so will the preferred tropical cyclone tracks. Areas west of Japan and Korea tend to experience much fewer September-November tropical cyclone impacts during El Niño and neutral years. During El Niño years, the break in the subtropical ridge tends to lie near 130°E which would favor the Japanese archipelago. During El Niño years, Guam's chance of a tropical cyclone impact is one-third of the long term average. The tropical Atlantic ocean experiences depressed activity due to increased vertical wind shear across the region during El Niño years. During La Niña years, the formation of tropical cyclones, along with the subtropical ridge position, shifts westward across the western Pacific ocean, which increases the landfall threat to China.

Long-term activity trends



Atlantic Multidecadal Cycle since 1950, using accumulated cyclone energy (ACE)



Atlantic Multidecadal Oscillation Timeseries, 1856–2009

While the number of storms in the Atlantic has increased since 1995, there is no obvious global trend; the annual number of tropical cyclones worldwide remains about 87 ± 10. However, the ability of climatologists to make long-term data analysis in certain basins is limited by the lack of reliable historical data in some basins, primarily in the Southern Hemisphere. In spite of that, there is some evidence that the intensity of hurricanes is increasing. Kerry Emanuel stated, "Records of hurricane activity worldwide show an upswing of both the maximum wind speed in and the duration of hurricanes. The energy released by the average hurricane (again considering all hurricanes worldwide) seems to have increased by around 70% in the past 30 years or so, corresponding to about a 15% increase in the maximum wind speed and a 60% increase in storm lifetime."

Atlantic storms are becoming more destructive financially, since five of the ten most expensive storms in United States history have occurred since 1990. According to the World Meteorological Organization, “recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions.” Pielke *et al.* (2008) normalized mainland U.S. hurricane damage from 1900–2005 to 2005 values and found no remaining trend of increasing absolute damage. The 1970s and 1980s were notable because of the extremely low amounts of damage compared to other decades. The decade 1996–2005 was the second most damaging among the past 11 decades, with only the decade 1926–1935 surpassing its costs. The most damaging single storm is the 1926 Miami hurricane, with $157 billion of normalized damage.

Often in part because of the threat of hurricanes, many coastal regions had sparse population between major ports until the advent of automobile tourism; therefore, the most severe portions of hurricanes striking the coast may have gone unmeasured in some instances. The combined effects of ship destruction and remote landfall severely limit the number of intense hurricanes in the official record before the era of hurricane reconnaissance aircraft and satellite meteorology. Although the record shows a distinct increase in the number and strength of intense hurricanes, therefore, experts regard the early data as suspect.

The number and strength of Atlantic hurricanes may undergo a 50–70 year cycle, also known as the Atlantic Multidecadal Oscillation. Nyberg *et al.* reconstructed Atlantic major hurricane activity back to the early 18th century and found five periods averaging 3–5 major hurricanes per year and lasting 40–60 years, and six other averaging 1.5–2.5 major hurricanes per year and lasting 10–20 years. These periods are associated with the Atlantic multidecadal oscillation. Throughout, a decadal oscillation related to solar irradiance was responsible for enhancing/dampening the number of major hurricanes by 1–2 per year.

Although more common since 1995, few above-normal hurricane seasons occurred during 1970–94. Destructive hurricanes struck frequently from 1926–60, including many major New England hurricanes. Twenty-one Atlantic tropical storms formed in 1933, a record only recently exceeded in 2005, which saw 28 storms. Tropical hurricanes occurred infrequently during the seasons of 1900–25; however, many intense storms formed during 1870–99. During the 1887 season, 19 tropical storms formed, of which a record 4 occurred after 1 November and 11 strengthened into hurricanes. Few hurricanes occurred in the 1840s to 1860s; however, many struck in the early 19th century, including a 1821 storm that made a direct hit on New York City. Some historical weather experts say these storms may have been as high as Category 4 in strength.

These active hurricane seasons predated satellite coverage of the Atlantic basin. Before the satellite era began in 1960, tropical storms or hurricanes went undetected unless a reconnaissance aircraft encountered one, a ship reported a voyage through the storm, or a storm hit land in a populated area. The official record, therefore, could miss storms in which no ship experienced gale-force winds, recognized it as a tropical storm (as opposed to a high-latitude extra-tropical cyclone, a tropical wave, or a brief squall), returned to port, and reported the experience.

Proxy records based on paleotempestological research have revealed that major hurricane activity along the Gulf of Mexico coast varies on timescales of centuries to millennia. Few major hurricanes struck the Gulf coast during 3000–1400 BC and again during the most recent millennium. These quiescent intervals were separated by a hyperactive period during 1400 BC and 1000 AD, when the Gulf coast was struck frequently by catastrophic hurricanes and their landfall probabilities increased by 3–5 times. This millennial-scale variability has been attributed to long-term shifts in the position of the Azores High, which may also be linked to changes in the strength of the North Atlantic Oscillation.

According to the Azores High hypothesis, an anti-phase pattern is expected to exist between the Gulf of Mexico coast and the Atlantic coast. During the quiescent periods, a more northeasterly position of the Azores High would result in more hurricanes being steered towards the Atlantic coast. During the hyperactive period, more hurricanes were steered towards the Gulf coast as the Azores High was shifted to a more southwesterly position near the Caribbean. Such a displacement of the Azores High is consistent with paleoclimatic evidence that shows an abrupt onset of a drier climate in Haiti around 3200 ^{14}C years BP, and a change towards more humid conditions in the Great Plains during the late-Holocene as more moisture was pumped up the Mississippi Valley through the Gulf coast. Preliminary data from the northern Atlantic coast seem to support the Azores High hypothesis. A 3000-year proxy record from a coastal lake in Cape Cod suggests that hurricane activity increased significantly during the past 500–1000 years, just as the Gulf coast was amid a quiescent period of the last millennium.

Global warming

The U.S. National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory performed a simulation to determine if there is a statistical trend in the frequency or strength of tropical cyclones over time. The simulation concluded "the strongest hurricanes in the present climate may be upstaged by even more intense hurricanes over the next century as the earth's climate is warmed by increasing levels of greenhouse gases in the atmosphere".

In an article in *Nature*, Kerry Emanuel stated that potential hurricane destructiveness, a measure combining hurricane strength, duration, and frequency, "is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals, including multidecadal oscillations in the North Atlantic and North Pacific, and global warming". Emanuel predicted "a substantial increase in hurricane-related losses in the twenty-first century". In more recent work published by Emanuel (in the March 2008 issue of the *Bulletin of the American Meteorological Society*), he states that new climate modeling data indicates “global warming should reduce the global frequency of hurricanes.” According to the Houston Chronicle, the new work suggests that, even in a dramatically warming world, hurricane frequency and intensity may not substantially rise during the next two centuries.

Similarly, P.J. Webster and others published an article in *Science* examining the "changes in tropical cyclone number, duration, and intensity" over the past 35 years, the period when satellite data has been available. Their main finding was although the number of cyclones decreased throughout the planet excluding the north Atlantic Ocean, there was a great increase in the number and proportion of very strong cyclones.

Costliest U.S. Atlantic hurricanes

Total estimated property damage, adjusted for wealth normalization

Rank	Hurricane	Season	Cost (2005 USD)
1	"Miami"	1926	$157 billion
2	"Galveston"	1900	$99.4 billion
3	Katrina	2005	$81.0 billion
4	"Galveston"	1915	$68.0 billion

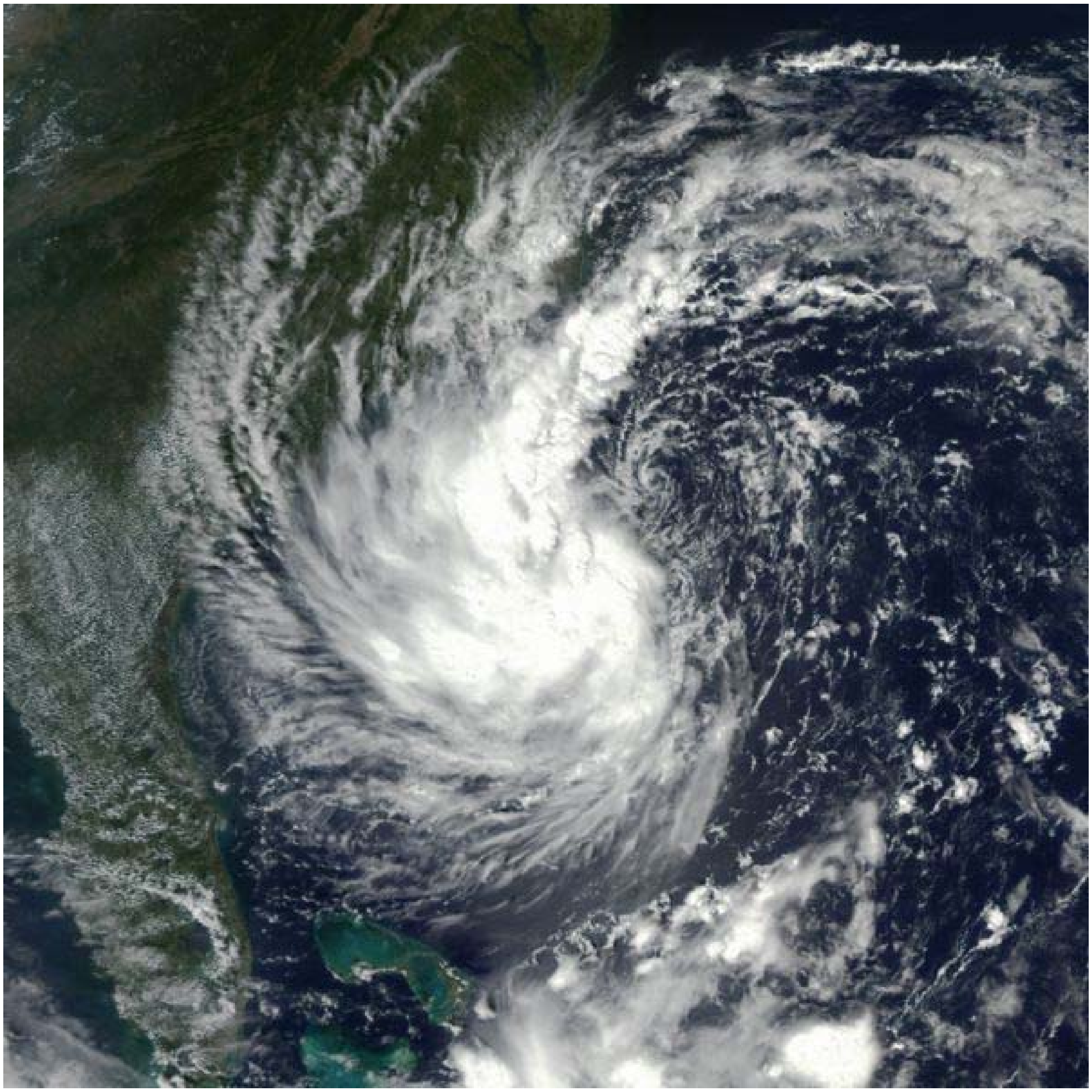
5	Andrew	1992	$55.8 billion
6	"New England"	1938	$39.2 billion
7	"Cuba–Florida"	1944	$38.7 billion
8	"Okeechobee"	1928	$33.6 billion
9	Donna	1960	$26.8 billion
10	Camille	1969	$21.2 billion

The strength of the reported effect is surprising in light of modeling studies that predict only a one half category increase in storm intensity as a result of a ~2 °C (3.6 °F) global warming. Such a response would have predicted only a ~10% increase in Emanuel's potential destructiveness index during the 20th century rather than the ~75–120% increase he reported. Secondly, after adjusting for changes in population and inflation, and despite a more than 100% increase in Emanuel's potential destructiveness index, no statistically significant increase in the monetary damages resulting from Atlantic hurricanes has been found.

Sufficiently warm sea surface temperatures are considered vital to the development of tropical cyclones. Although neither study can directly link hurricanes with global warming, the increase in sea surface temperatures is believed to be due to both global warming and natural variability, e.g. the hypothesized Atlantic Multidecadal Oscillation (AMO), although an exact attribution has not been defined. However, recent temperatures are the warmest ever observed for many ocean basins.

In February 2007, the United Nations Intergovernmental Panel on Climate Change released its fourth assessment report on climate change. The report noted many observed changes in the climate, including atmospheric composition, global average temperatures, ocean conditions, among others. The report concluded the observed increase in tropical cyclone intensity is larger than climate models predict. Additionally, the report considered that it is likely that storm intensity will continue to increase through the 21st century, and declared it more likely than not that there has been some human contribution to the increases in tropical cyclone intensity. However, there is no universal agreement about the magnitude of the effects anthropogenic global warming has on tropical cyclone formation, track, and intensity. For example, critics such as Chris Landsea assert that man-made effects would be "quite tiny compared to the observed large natural hurricane variability". A statement by the American Meteorological Society on 1 February 2007 stated that trends in tropical cyclone records offer "evidence both for and against the existence of a detectable anthropogenic signal" in tropical cyclogenesis. Although many aspects of a link between tropical cyclones and global warming are still being "hotly debated", a point of agreement is that no individual tropical cyclone or season can be attributed to global warming. Research reported in the 3 September 2008 issue of Nature found that the strongest tropical cyclones are getting stronger, particularly over the North Atlantic and Indian oceans. Wind speeds for the strongest tropical storms increased from an average of 140 miles per hour (230 km/h) in 1981 to 156 miles per hour (251 km/h) in 2006, while the ocean temperature, averaged globally over the all regions where tropical cyclones form, increased from 28.2 °C (82.8 °F) to 28.5 °C (83.3 °F) during this period.

Related cyclone types



Subtropical Storm Gustav in 2002

In addition to tropical cyclones, there are two other classes of cyclones within the spectrum of cyclone types. These kinds of cyclones, known as extratropical cyclones and subtropical cyclones, can be stages a tropical cyclone passes through during its formation or dissipation. An *extratropical cyclone* is a storm that derives energy from horizontal temperature differences, which are typical in higher latitudes. A tropical cyclone can become extratropical as it moves toward higher latitudes if its energy source changes from heat released by condensation to differences in temperature between air masses; additionally, although not as frequently, an extratropical cyclone can transform into a subtropical storm, and from there into a tropical cyclone. From space, extratropical storms have a characteristic "comma-shaped" cloud pattern. Extratropical cyclones can also be dangerous when their low-pressure centers cause powerful winds and high seas.

A *subtropical cyclone* is a weather system that has some characteristics of a tropical cyclone and some characteristics of an extratropical cyclone. They can form in a wide band of latitudes, from the equator to 50°. Although subtropical storms rarely have hurricane-force winds, they may become tropical in nature as their cores warm. From an operational standpoint, a tropical cyclone is usually not considered to become subtropical during its extratropical transition.

Chapter 2

Eye (Cyclone)

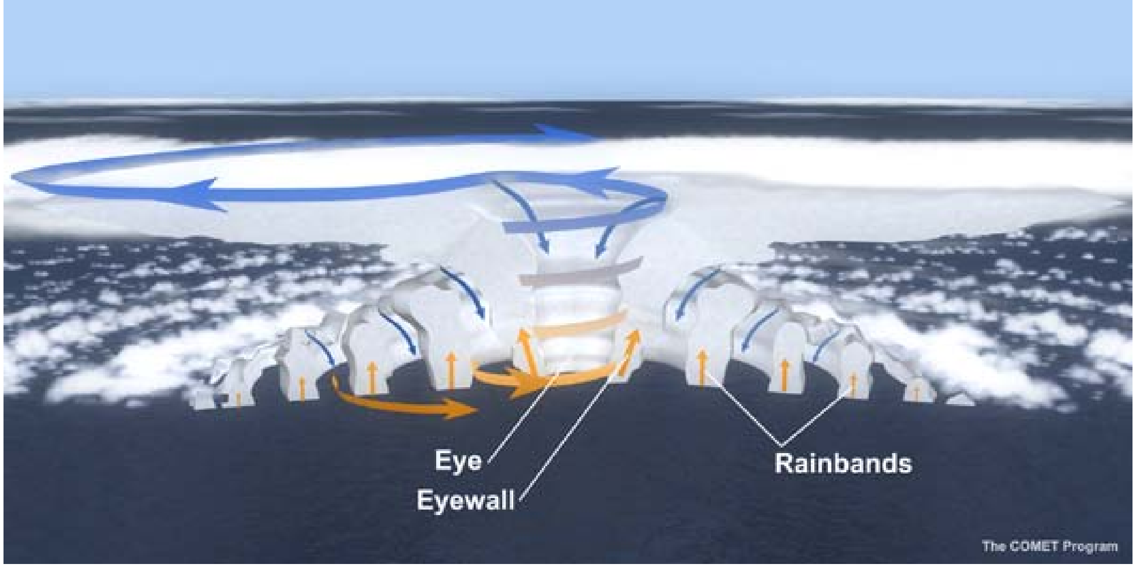
The **eye** is a region of mostly calm weather found at the center of strong tropical cyclones. The eye of a storm is a roughly circular area and typically 30–65 km (20–40 miles) in diameter. It is surrounded by the **eyewall**, a ring of towering thunderstorms where the most severe weather of a cyclone occurs. The cyclone's lowest barometric pressure occurs in the eye, and can be as much as 15% lower than the atmospheric pressure outside the storm.

In strong tropical cyclones, the eye is characterized by light winds and clear skies, surrounded on all sides by a towering, symmetric eyewall. In weaker tropical cyclones, the eye is less well-defined, and can be covered by the *central dense overcast*, which is an area of high, thick clouds that show up brightly on satellite imagery. Weaker or disorganized storms may also feature an eyewall that does not completely encircle the eye, or have an eye that features heavy rain. In all storms, however, the eye is the location of the storm's minimum barometric pressure: the area where the atmospheric pressure at sea level is the lowest.

Structure

A typical tropical cyclone will have an eye of approximately 30–65 km (20–40 mi) across, usually situated at the geometric center of the storm. The eye may be clear or have spotty low clouds (a *clear eye*), it may be filled with low- and mid-level clouds (a *filled eye*), or it may be obscured by the central dense overcast. There is, however, very little wind and rain, especially near the center. This is in stark contrast to conditions in the eyewall, which contains the storm's strongest winds. Due to the mechanics of a tropical cyclone, the eye and the air directly above it are warmer than their surroundings.

While normally quite symmetric, eyes can be oblong and irregular, especially in weakening storms. A large *ragged eye* is a non-circular eye which appears fragmented, and is an indicator of a weak or weakening tropical cyclone. An *open eye* is an eye which can be circular, but the eyewall does not completely encircle the eye, also indicating a weakening, moisture-deprived cyclone. Both of these observations are used to estimate the intensity of tropical cyclones via Dvorak analysis. Eyewalls are typically circular; however, distinctly polygonal shapes ranging from triangles to hexagons occasionally occur.



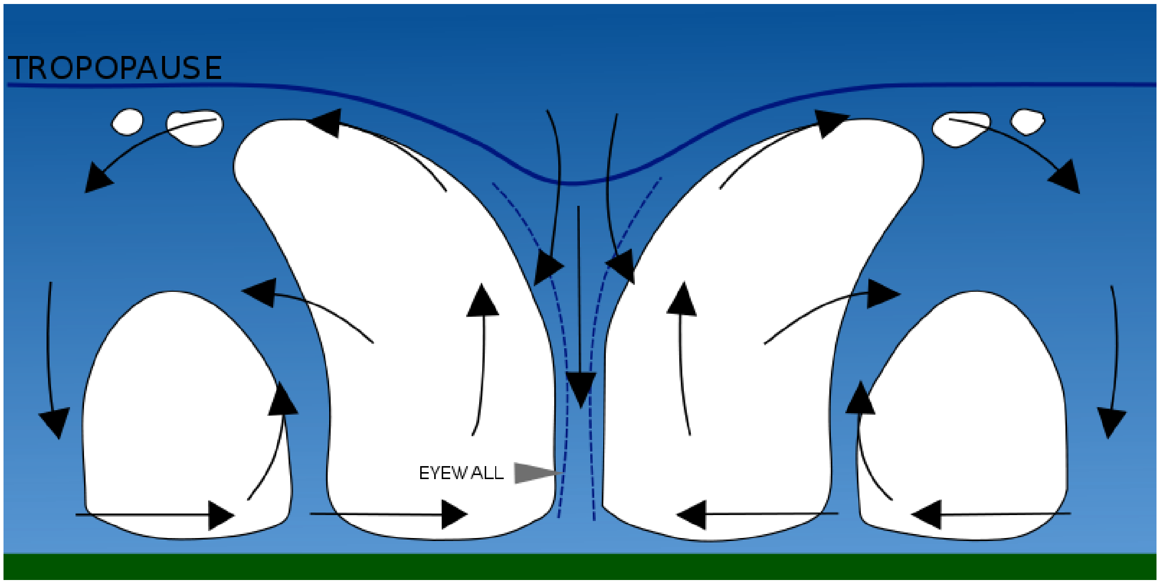
A cross section diagram of a mature tropical cyclone, with arrows indicating air flow in and around the eye

While typical mature storms have eyes that are a few dozen miles across, rapidly intensifying storms can develop an extremely small, clear, and circular eye, sometimes referred to as a *pinhole eye*. Storms with pinhole eyes are prone to large fluctuations in intensity, and provide difficulties and frustrations for forecasters.

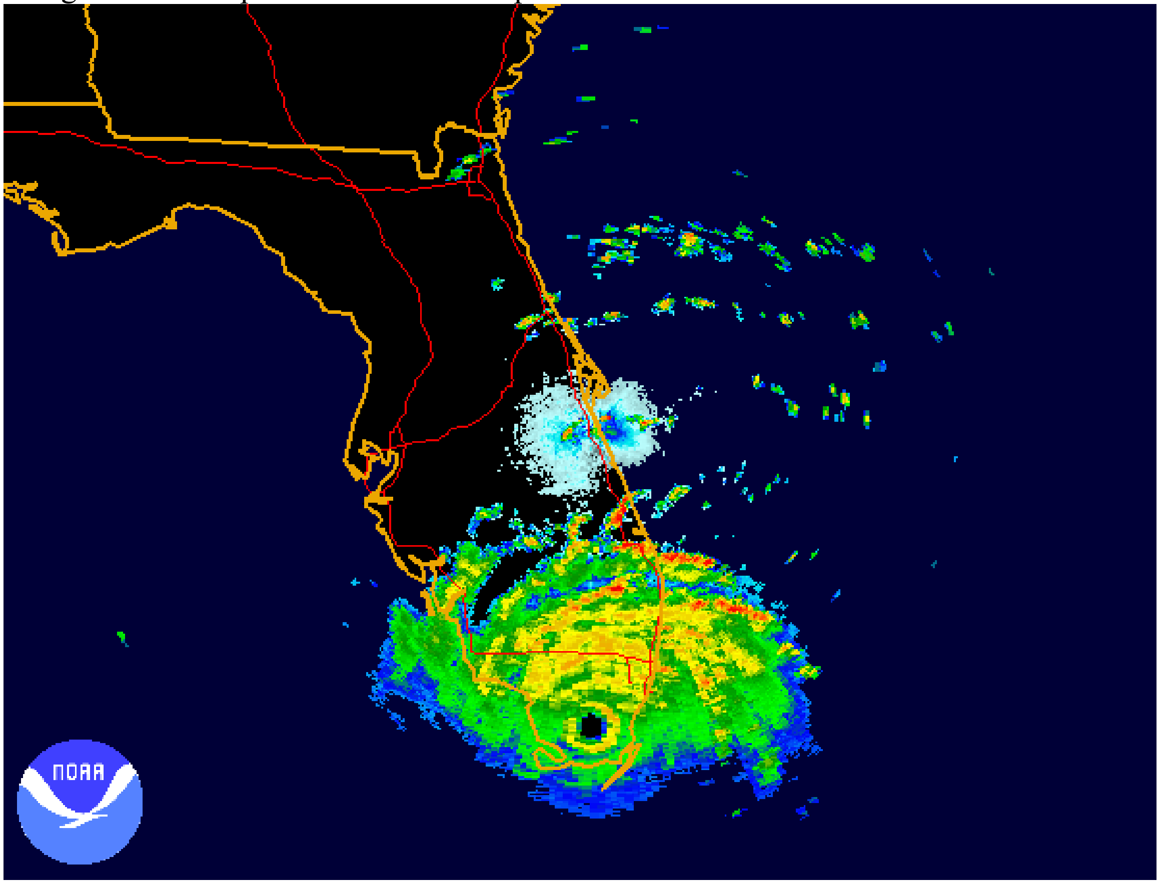
Small eyes—those less than 10 nmi (19 km, 12 mi) across—often trigger eyewall replacement cycles, where a new eyewall begins to form outside the original eyewall. This can take place anywhere from ten to a few hundred miles (fifteen to hundreds of kilometers) outside the inner eye. The storm then develops two *concentric eyewalls*, or an "eye within an eye". In most cases, the outer eyewall begins to contract soon after its formation, which chokes off the inner eye and leaves a much larger but more stable eye. While the replacement cycle tends to weaken storms as it occurs, the new eyewall can contract fairly quickly after the old eyewall dissipates, allowing the storm to re-strengthen. This may trigger another cycle of eyewall replacement.

Eyes can range in size from 320 km (200 miles) (Typhoon Carmen) to a mere 3 km (2 mi) (Hurricane Wilma) across. While it is uncommon for storms with large eyes to become very intense, it does occur, especially in annular hurricanes. Hurricane Isabel was the eleventh most powerful Atlantic hurricane in recorded history, and sustained a large, 65–80 km (40–50 mi)-wide eye for a period of several days.

Formation and detection



Tropical cyclones form when the energy released by the condensation of moisture in rising air causes a positive feedback loop over warm ocean waters.



Typically, eyes are easy to spot using weather radar. This radar image of Hurricane Andrew clearly shows the eye over southern Florida.

Tropical cyclones typically form from large, disorganized areas of disturbed weather in tropical regions. As more thunderstorms form and gather, the storm develops rainbands which start rotating around a common center. As the storm gains strength, a ring of stronger convection forms at a certain distance from the rotational center of the developing storm. Since stronger thunderstorms and heavier rain mark areas of stronger updrafts, the barometric pressure at the surface begins to drop, and air begins to build up in the upper levels of the cyclone. This results in the formation of an upper level anticyclone, or an area of high atmospheric pressure above the central dense overcast. Consequentially, most of this built up air flows outward anticyclonically above the tropical cyclone. Outside the forming eye, the anticyclone at the upper levels of the atmosphere enhances the flow towards the center of the cyclone, pushing air towards the eyewall and causing a positive feedback loop.

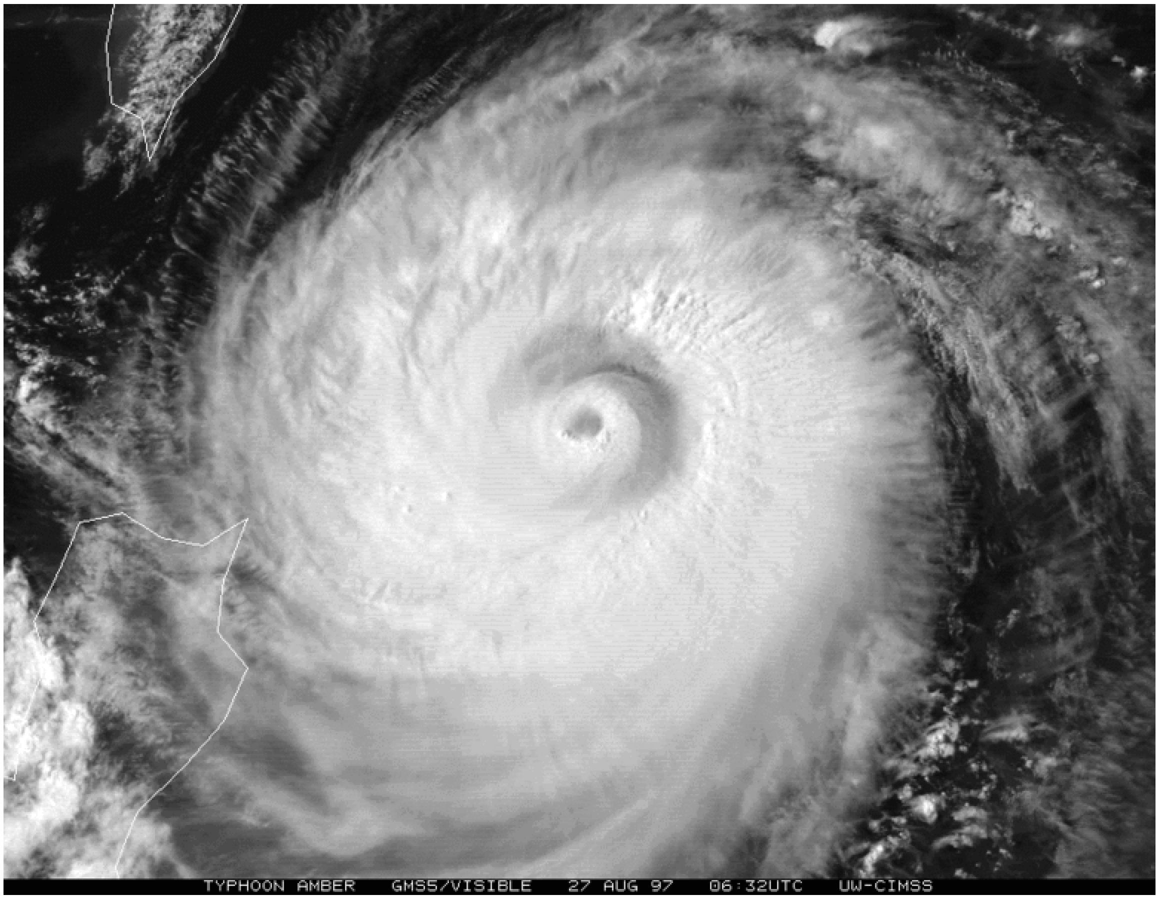
However, a small portion of the built-up air, instead of flowing outward, flows inward towards the center of the storm. This causes air pressure to build even further, to the point where the weight of the air counteracts the strength of the updrafts in the center of the storm. Air begins to descend in the center of the storm, creating a mostly rain-free area; a newly formed eye.

There are many aspects of this process which remain a mystery. Scientists do not know why a ring of convection forms around the center of circulation instead of on top of it, or why the upper-level anticyclone only ejects a portion of the excess air above the storm. Many theories exist as to the exact process by which the eye forms: all that is known for sure is that the eye is necessary for tropical cyclones to achieve high wind speeds.

The formation of an eye is almost always an indicator of increasing tropical cyclone organisation and strength. Because of this, forecasters watch developing storms closely for signs of eye formation.

For storms with a clear eye, detection of the eye is as simple as looking at pictures from a weather satellite. However, for storms with a filled eye, or an eye completely covered by the central dense overcast, other detection methods must be used. Observations from ships and Hurricane Hunters can pinpoint an eye visually, by looking for a drop in wind speed or lack of rainfall in the storm's center. In the United States, South Korea, and a few other countries, a network of NEXRAD Doppler weather radar stations can detect eyes near the coast. Weather satellites also carry equipment for measuring atmospheric water vapor and cloud temperatures, which can be used to spot a forming eye. In addition, scientists have recently discovered that the amount of ozone in the eye is much higher than the amount in the eyewall, due to air sinking from the ozone-rich stratosphere. Instruments sensitive to ozone perform measurements, which are used to observe rising and sinking columns of air, and provide indication of the formation of an eye, even before satellite imagery can determine its formation.

Associated phenomena



A satellite photo of Typhoon Amber of the 1997 Pacific typhoon season, exhibiting an outer and inner eyewall while undergoing an *eyewall replacement cycle*.

Eyewall replacement cycles

Eyewall replacement cycles, also called *concentric eyewall cycles*, naturally occur in intense tropical cyclones, generally with winds greater than 185 km/h (115 mph), or major hurricanes (Category 3 or above). When tropical cyclones reach this intensity, and the eyewall contracts or is already sufficiently small (see above), some of the outer rainbands may strengthen and organize into a ring of thunderstorms—an outer eyewall—that slowly moves inward and robs the inner eyewall of its needed moisture and angular momentum. Since the strongest winds are located in a cyclone's eyewall, the tropical cyclone usually weakens during this phase, as the inner wall is "choked" by the outer wall. Eventually the outer eyewall replaces the inner one completely, and the storm can re-intensify.

The discovery of this process was partially responsible for the end of the U.S. government's hurricane modification experiment Project Stormfury. This project set out to seed clouds outside the eyewall, causing a new eyewall to form and weakening the storm. When it was discovered that this was a natural process due to hurricane dynamics, the project was quickly abandoned.

Almost every intense hurricane undergoes at least one of these cycles during its existence. Hurricane Allen in 1980 went through repeated eyewall replacement cycles, fluctuating between Category 5 and Category 3 status on the Saffir-Simpson Scale several times. Hurricane Juliette was a rare documented case of triple eyewalls.

Moats

A *moat* in a tropical cyclone is a clear ring outside the eyewall, or between concentric eyewalls, characterized by slowly sinking air, little or no precipitation, and strain-dominated flow. The moat between eyewalls is just one example of a *rapid filamentation zone*, or an area in the storm where the rotational speed of the air changes greatly in proportion to the distance from the storm's center. Such strain-dominated regions can potentially be found near any vortex of sufficient strength, but are most pronounced in strong tropical cyclones.

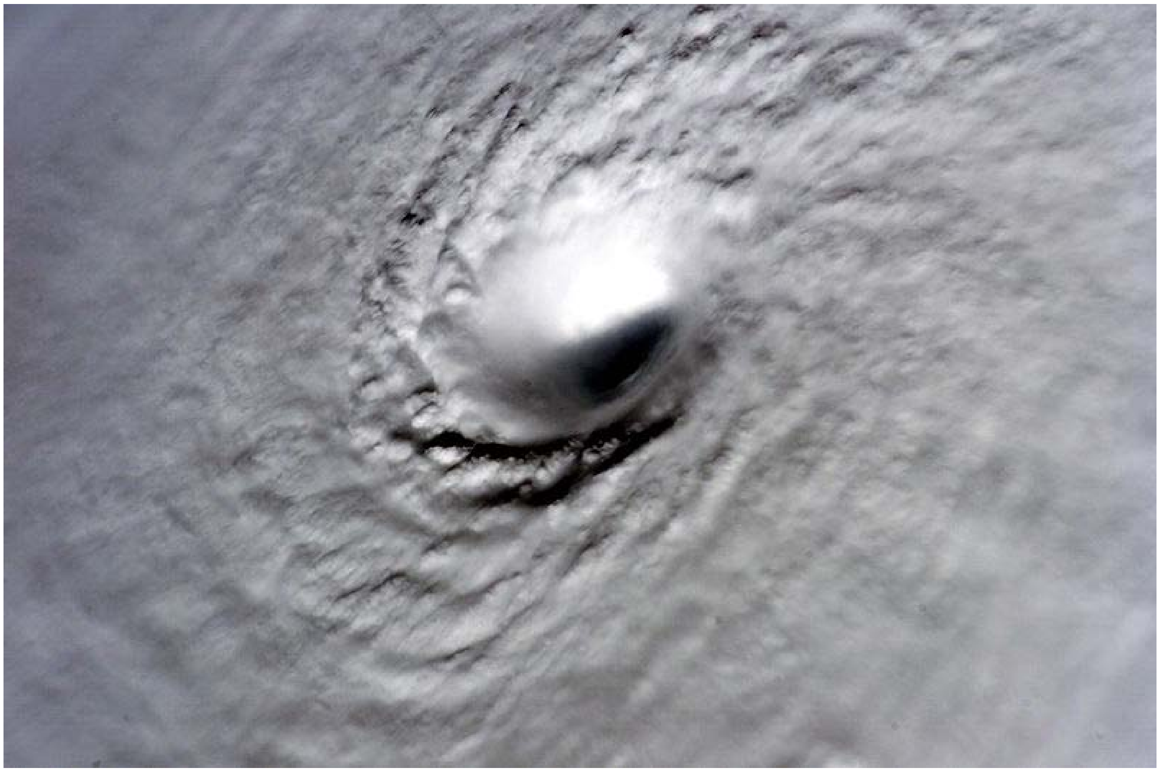
Eyewall mesovortices

Eyewall mesovortices are small scale rotational features found in the eyewalls of intense tropical cyclones. They are similar, in principle, to small "suction vortices" often observed in multiple-vortex tornadoes. In these vortices, wind speed can be up to 10% higher than in the rest of the eyewall. Eyewall mesovortices are most common during periods of intensification in tropical cyclones.

Eyewall mesovortices often exhibit unusual behavior in tropical cyclones. They usually rotate around the low pressure center, but sometimes they remain stationary. Eyewall mesovortices have even been documented to cross the eye of a storm. These phenomena have been documented observationally, experimentally, and theoretically.

Eyewall mesovortices are a significant factor in the formation of tornadoes after tropical cyclone landfall. Mesovortices can spawn rotation in individual thunderstorms (a mesocyclone), which leads to tornadic activity. At landfall, friction is generated between the circulation of the tropical cyclone and land. This can allow the mesovortices to descend to the surface, causing large outbreaks of tornadoes.

Stadium effect



A picture of Hurricane Wilma's eye taken at 08:22 CDT (13:22 UTC) October 19, 2005, by the crew aboard the International Space Station. Wilma was at peak intensity at the time, with a minimum central pressure of only 882 mbar (26.06 inHg), making it the strongest Atlantic hurricane in history. Not only is this a classic example of a *pinhole eye*, but also of the *stadium effect*, where the eyewall slopes out and up.

The *stadium effect* is a phenomenon observed in strong tropical cyclones. It is a fairly common event, where the clouds of the eyewall curve outward from the surface with height. This gives the eye an appearance resembling an open dome from the air, akin to a sports stadium. An eye is always larger at the top of the storm, and smallest at the bottom of the storm because the rising air in the eyewall follows isolines of equal angular momentum, which also slope outward with height. This phenomenon refers to the characteristics of tropical cyclones with very small eyes, where the sloping phenomenon is much more pronounced.

Eye-like features

An eye-like structure is often found in intensifying tropical cyclones. Similar to the eye seen in hurricanes or typhoons, it is a circular area at the circulation center of the storm in which convection is absent. These eye-like features are most normally found in intensifying tropical storms and hurricanes of Category 1 strength on the Saffir-Simpson Scale. For example, an eye-like feature was found in Hurricane Beta when the storm had maximum wind speeds of 50 mph. These eye-like features are typically not visible on visible wavelengths or infrared wavelengths from space, however, they are easily seen on microwave satellite imagery. The development of this feature at middle levels of the atmosphere is similar to the formation of the complete eye, but its position might be horizontally displaced due to vertical wind shear.

Hazards

Though the eye is by far the calmest part of the storm, with no wind at the center and typically clear skies, over the ocean it is possibly the most hazardous area. In the eyewall, wind-driven waves are all traveling in the same direction. In the center of the eye, however, waves from all directions converge, creating erratic crests which can build on each other, creating rogue waves. The maximum height of hurricane waves is unknown, but measurements of Hurricane Ivan, when it was a category four hurricane, estimated that waves near the eyewall were in excess of 40 meters (130 ft) from peak to trough.

A common mistake, especially in areas where hurricanes are uncommon, is for residents to wander outside to inspect the damage while the eye passes over, thinking the storm is over. They are then caught completely by surprise by the violent winds in the opposite eyewall. The National Weather Service strongly discourages leaving shelter while the eye passes over.

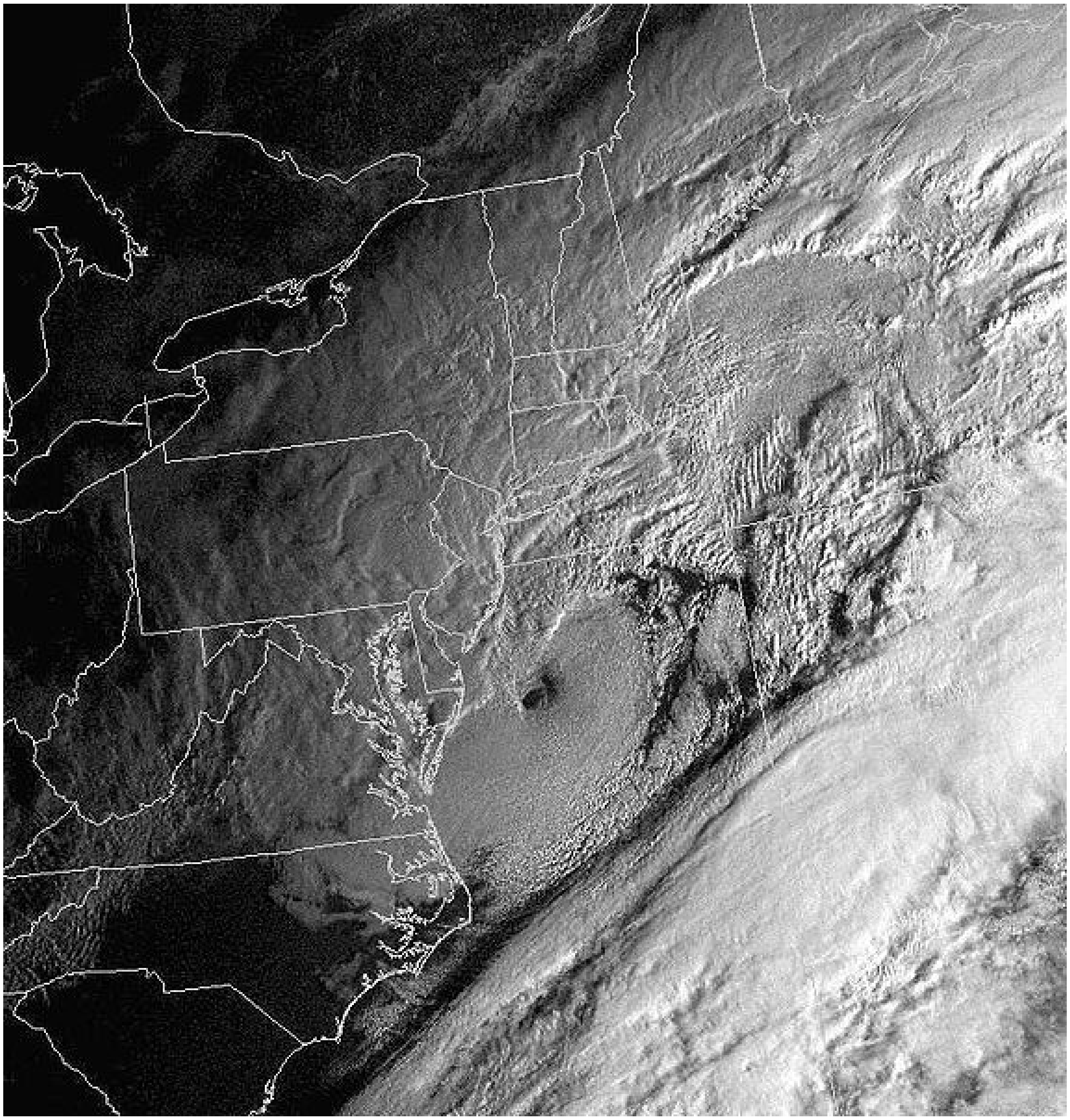
Other storms

Though only tropical cyclones have structures which are officially called "eyes", there are other storms which can exhibit eye-like structures:

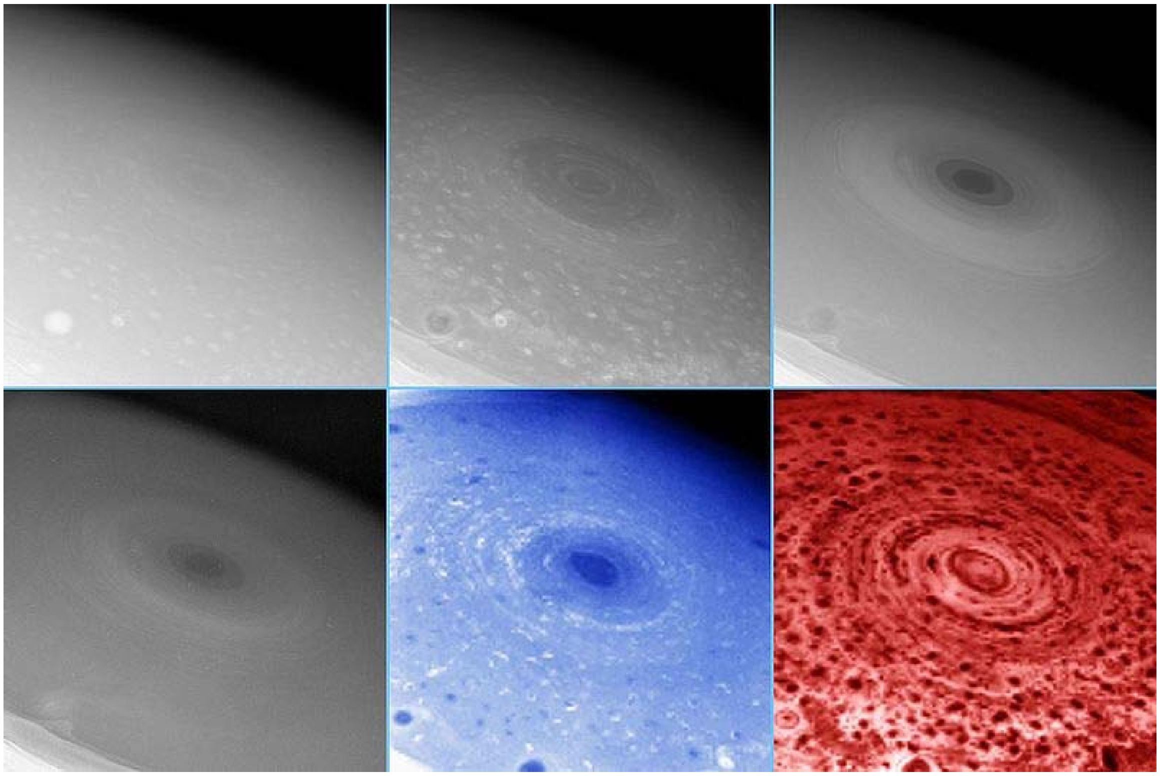
Polar lows

Polar lows are mesoscale weather systems (typically smaller than 1,000 km or 600 miles (970 km) across) found near the poles. Like tropical cyclones, they form over relatively warm water, can feature deep convection (thunderstorms), and feature winds of gale force (51 km/h, 32 mph) or greater. Unlike storms of tropical nature, however, they thrive in much colder temperatures and at much higher latitudes. They are also smaller and last for shorter durations (few last longer than a day or so). Despite these differences, they can be very similar in structure to tropical cyclones, featuring a clear eye surrounded by an eyewall and rain/snow bands.

Extratropical storms



The North American blizzard of 2006, an extratropical storm, showed an eye-like structure at its peak intensity (here seen just to the east of the Delmarva Peninsula).



A hurricane-like storm on the south pole of Saturn displaying an eyewall tens of kilometers high

Extratropical storms are areas of low pressure which exist at the boundary of different air masses. Almost all storms found at mid-latitudes are extratropical in nature, including classic North American nor'easters and European windstorms. The most severe of these can have a clear "eye" at the site of lowest barometric pressure, though it is usually surrounded by lower, non-convective clouds and is found near the back end of the storm.

Subtropical storms

Subtropical storms are cyclones which have some extratropical characteristics and some tropical characteristics. As such, they may have an eye, but are not true tropical storms. Subtropical storms can be very hazardous, with high winds and seas, and often evolve into true tropical storms. As such, the National Hurricane Center began including subtropical storms in their naming scheme in 2002.

Tornadoes

Tornadoes are destructive, small-scale storms, which produce the fastest winds on earth. There are two main types—single-vortex tornadoes, which consist of a single spinning column of air, and multiple-vortex tornadoes, which consist of small *suction vortices*, resembling mini-tornadoes themselves, all rotating around a common center. Both of these types of tornadoes are theorized to have calm centers, referred to by some meteorologists as "eyes". These theories are supported by doppler velocity observations by weather radar and eyewitness accounts.

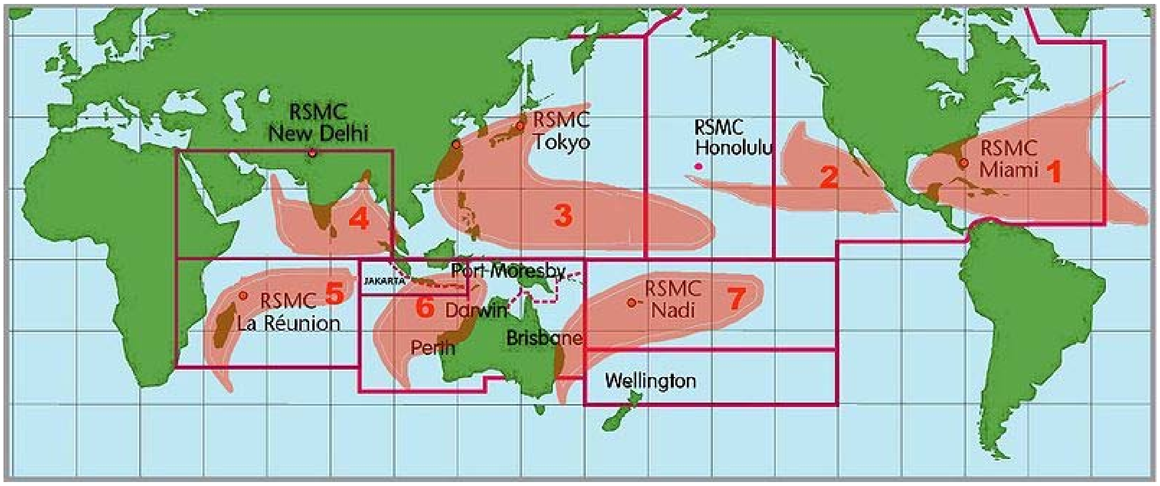
Extraterrestrial storms

NASA reported in November 2006 that the Cassini spacecraft observed a 'hurricane-like' storm locked to the south pole of Saturn that had a clearly defined eyewall. This observation is particularly notable because eyewall clouds had not previously been seen on any planet other than Earth (including a failure to observe an eyewall in the Great Red Spot of Jupiter by the Galileo spacecraft). In 2007, very large vortices on both poles of Venus were observed by the Venus Express mission of the European Space Agency to have a dipole eye structure.

Chapter 3

Tropical Cyclone Basins and Tropical Cyclogenesis

Tropical cyclone basins



Basins and WMO Monitoring Institutions

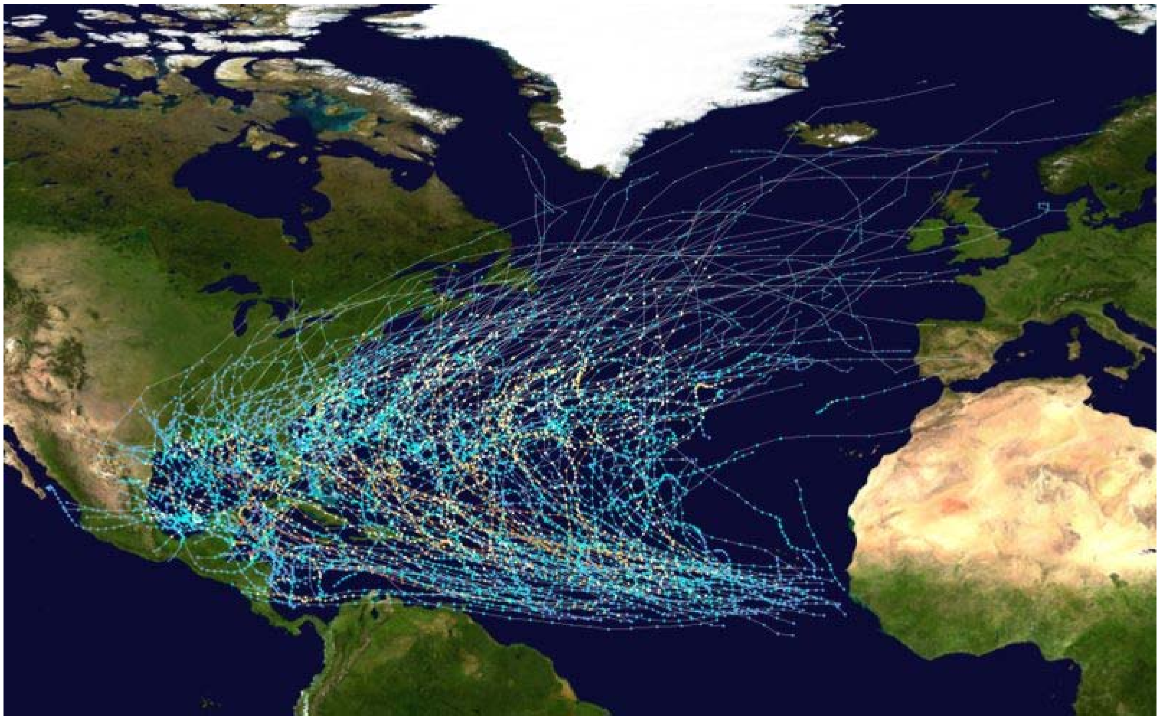
Basin	Responsible RSMCs and TCWCs
North Atlantic	National Hurricane Center (USA)
North Eastern Pacific	National Hurricane Center (USA)
North Central Pacific	Central Pacific Hurricane Center (USA)
North West Pacific	Japan Meteorological Agency
North Indian	Indian Meteorological Department
South-West Indian	Météo-France
South Pacific	Fiji Meteorological Service Meteorological Service of New Zealand[†]

Australian Region	Bureau of Meteorology† (Australia) Indonesian Meteorological and Geophysical Agency Papua New Guinea National Weather Service†

†: ***Indicates a Tropical Cyclone Warning Centre***

Traditionally, areas of tropical cyclone formation are divided into **eight basins**. These include the north Atlantic Ocean, the eastern, central, and western parts of the Pacific Ocean, the southwestern Pacific, the southwestern and southeastern Indian Oceans, and the northern Indian Ocean. The western Pacific is the most active and the north Indian the least active. An average of 86 tropical cyclones of tropical storm intensity form annually worldwide, with 47 reaching hurricane/typhoon strength, and 20 becoming intense tropical cyclones (at least of Category 3 intensity).

Northern Atlantic Ocean

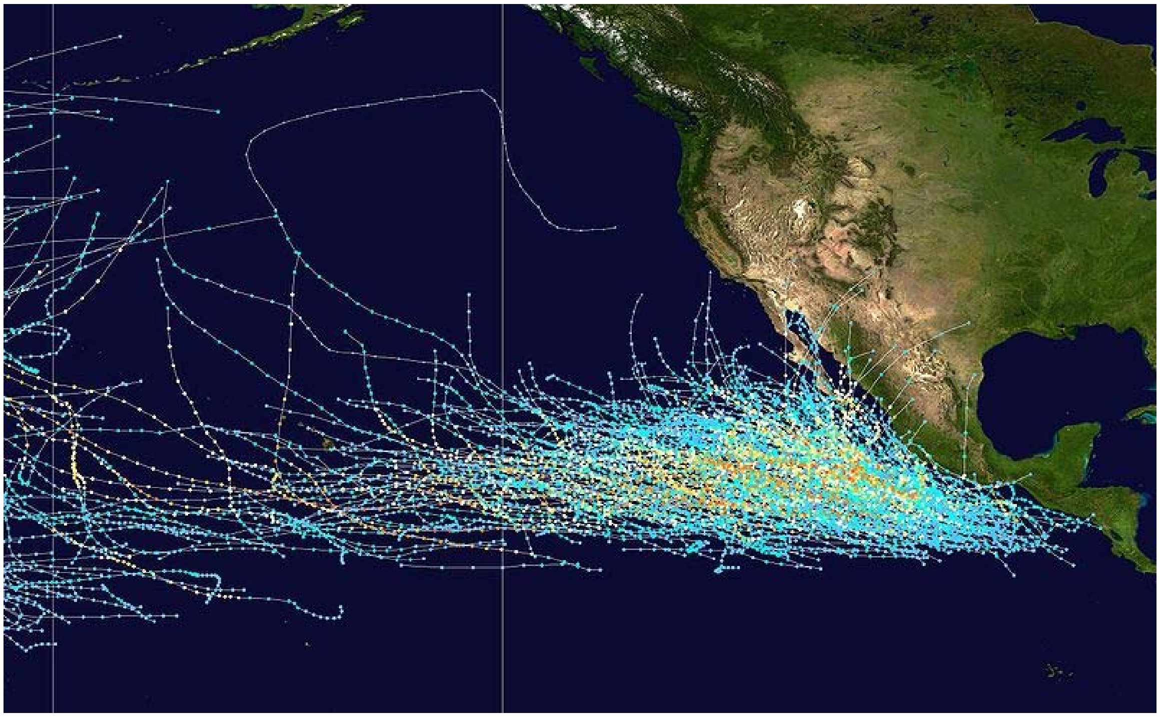


Tracks of all tropical cyclones in the northern Atlantic Ocean between 1980 and 2005

This region includes the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Tropical cyclone formation here varies widely from year to year, ranging from one to over twenty-five per year. Most Atlantic tropical storms and hurricanes form between June 1 and November 30. The United States National Hurricane Center monitors the basin and issues reports, watches and warnings about tropical weather systems for the Atlantic Basin as one of the Regional Specialized Meteorological Centres for tropical cyclones as defined by the World Meteorological Organization. On average, 11 named storms (of tropical storm or higher strength) occur each season, with an average of 6 becoming hurricanes and 2 becoming major hurricanes. The climatological peak of activity is around September 10 each season.

The United States Atlantic coast, Mexico, Central America, the Caribbean Islands, and Bermuda are frequently affected by storms in this basin. Venezuela, the south-east of Canada and Atlantic Macaronesian islands also are occasionally affected. Many of the more intense Atlantic storms are Cape Verde-type hurricanes, which form off the west coast of Africa near the Cape Verde islands. Occasionally, a hurricane that evolves into an extratropical cyclone can reach western Europe, including Hurricane Gordon, which spread high winds across Spain and the British Isles in September 2006. Hurricane Vince, which made landfall on the southwestern coast of Spain as a tropical depression in October 2005, is the only known system to impact mainland Europe as a tropical cyclone.

Northeast Pacific Ocean



Tracks of all tropical cyclones in the northern Pacific Ocean east of the International Date Line between 1980 and 2005; the vertical line through the center separates the Central Pacific basin (under the Central Pacific Hurricane Center's watch) from the Northeastern Pacific basin (under the National Hurricane Center's area of responsibility).

The Northeastern Pacific is the second most active basin and has the highest number of storms per unit area. The hurricane season runs between May 15 and November 30 each year, and encompasses the vast majority of tropical cyclone activity in the region. In the 1971–2005 period, there were an average of 15–16 tropical storms, 9 hurricanes, and 4–5 major hurricanes (storms of Category 3 intensity or greater) annually in the basin.

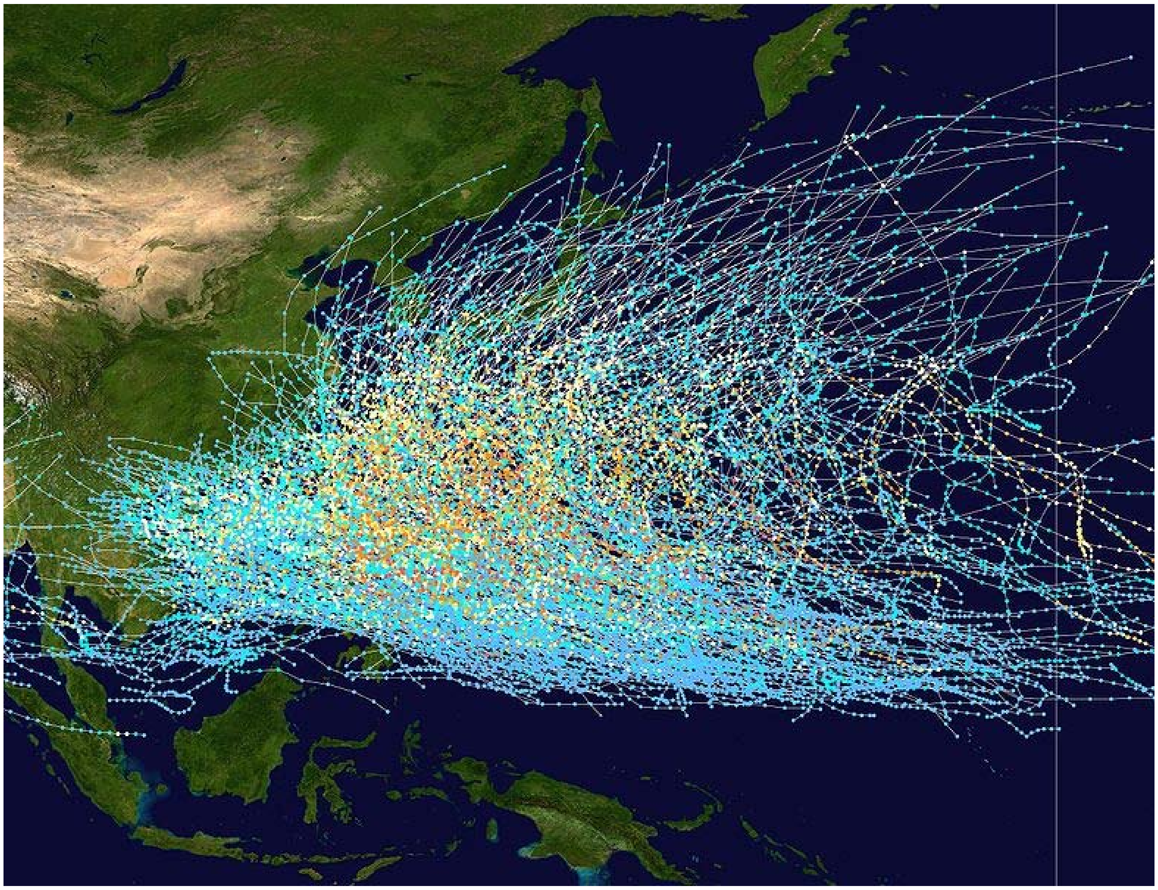
Storms that form here often affect western Mexico, and less commonly the Continental United States (in particular California), or northern Central America. No hurricane included in the modern database has made landfall in California; however, historical records from 1858 speak of a storm that brought San Diego winds over 75 mph/65 kts (marginal hurricane force), though it is not known if the storm actually made landfall. Tropical storms in 1939, 1976 and 1997 brought gale-force winds to California.

North Central Pacific Ocean

The North Central Pacific basin begins at the boundary with the Northeastern Pacific (at 140 °W), and ends at the International Date Line, where the Northwestern Pacific begins. The hurricane season in the North Central Pacific runs annually from June 1 to November 30; The Central Pacific Hurricane Center is the RSMC for this basin and monitors the storms that develop or move into the defined area of responsibility. The agency previously tasked with monitoring tropical activity in the basin was originally known as the Joint Hurricane Warning Center; today it is called the Joint Typhoon Warning Center.

Central Pacific hurricanes are rare and on average 4 to 5 storms form or move in this area annually. As there are no large contiguous landmasses in the basin, direct hits and landfalls are rare; however, they occur occasionally, as with Hurricane Iniki in 1992, which made landfall on Hawaii, and Hurricane Ioke in 2006, which made a direct hit on Johnston Atoll.

Northwestern Pacific Ocean

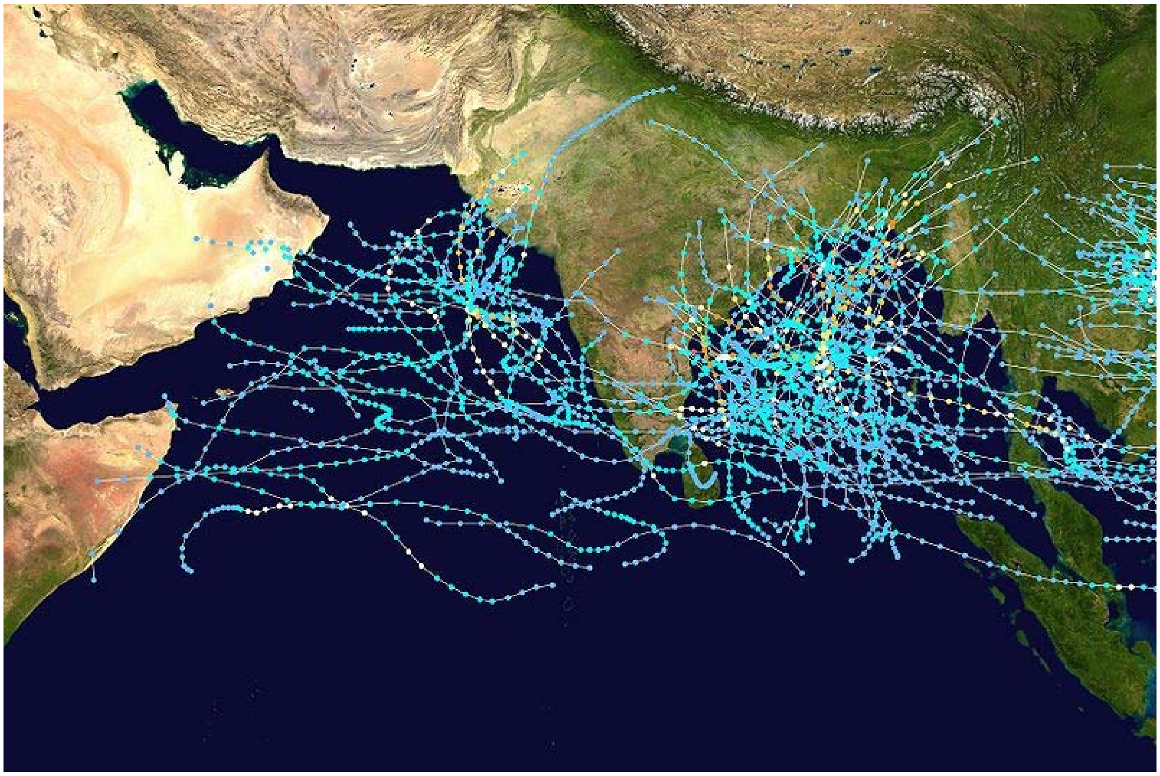


Tracks of all tropical cyclones in the northernwestern Pacific Ocean between 1980 and 2005. The vertical line to the right is the International Date Line.

The Northwest Pacific Ocean is the most active basin on the planet. Annually, an average of 25.7 tropical cyclones in the basin acquire tropical storm strength or greater; also, an average of 16 typhoons occurred each year during the 1968–1989 period. The basin occupies all the territory north of the equator and west of the International Date Line, including the South China Sea. The basin sees activity year-round; however, tropical activity is at its minimum in February and March.

Tropical storms in this region often affect China, Japan, South Korea, Hong Kong, the Philippines, and Taiwan, as well as countries in Southeast Asia such as Vietnam and parts of Indonesia, plus numerous Oceanian islands. This is by far the most active basin, accounting for one-third of all tropical cyclone activity. The coast of China sees the most landfalling tropical cyclones worldwide. The Philippines archipelago receives an average of 6-7 tropical cyclone landfalls per year.

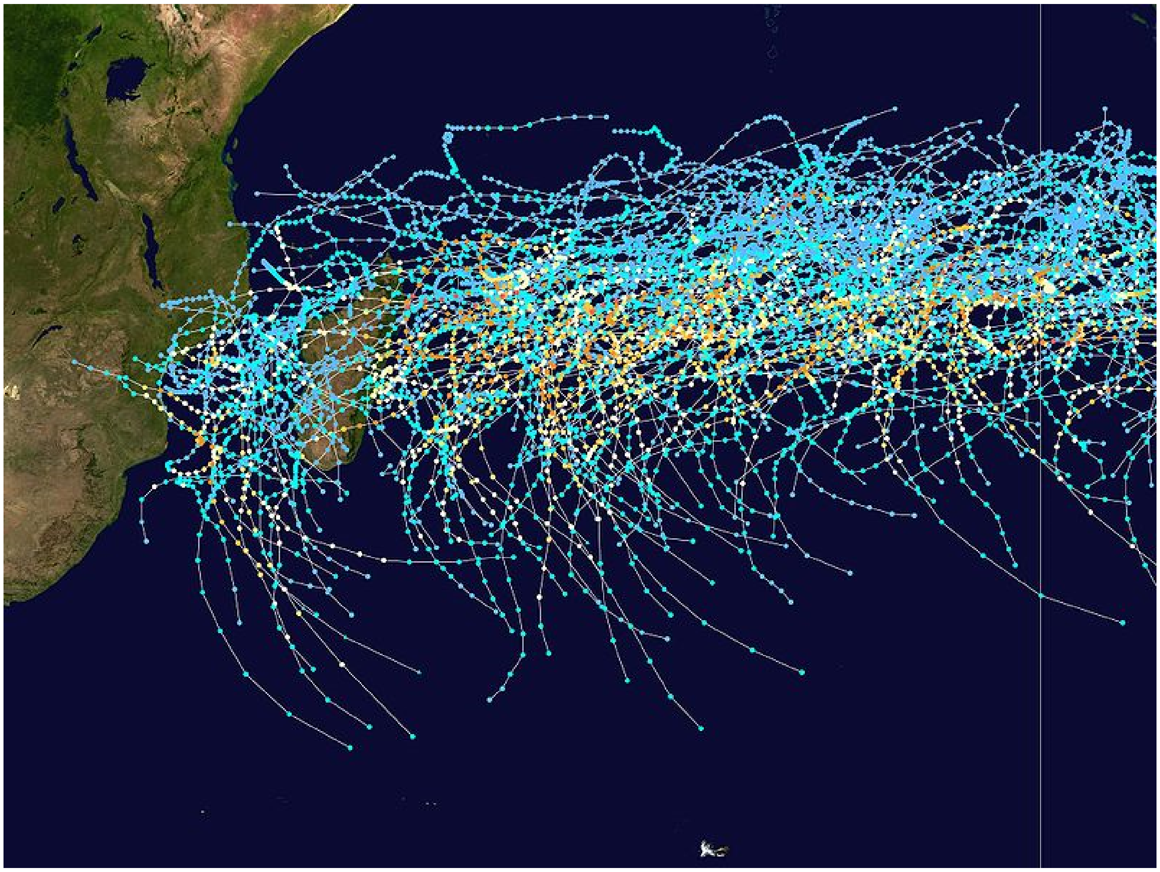
North Indian Ocean



Tracks of all tropical cyclones in the northern Indian Ocean between 1980 and 2005

This basin is divided into two areas by India: the Bay of Bengal and the Arabian Sea, with the Bay of Bengal dominating (5 to 6 times more activity). Still, this basin is the most inactive worldwide, with only 4 to 6 storms per year. This basin's season has a double peak: one in April and May, before the onset of the monsoon, and another in October and November, just after. Although it is an inactive basin, the deadliest tropical cyclones in the world have formed here, including the 1970 Bhola cyclone, which killed 500,000 people. Nations affected include India, Bangladesh, Sri Lanka, Thailand, Myanmar, and Pakistan. Rarely do tropical cyclones that form in this basin affect the Arabian Peninsula or Somalia; however, Cyclone Gonu caused heavy damage in Oman on the peninsula in 2007.

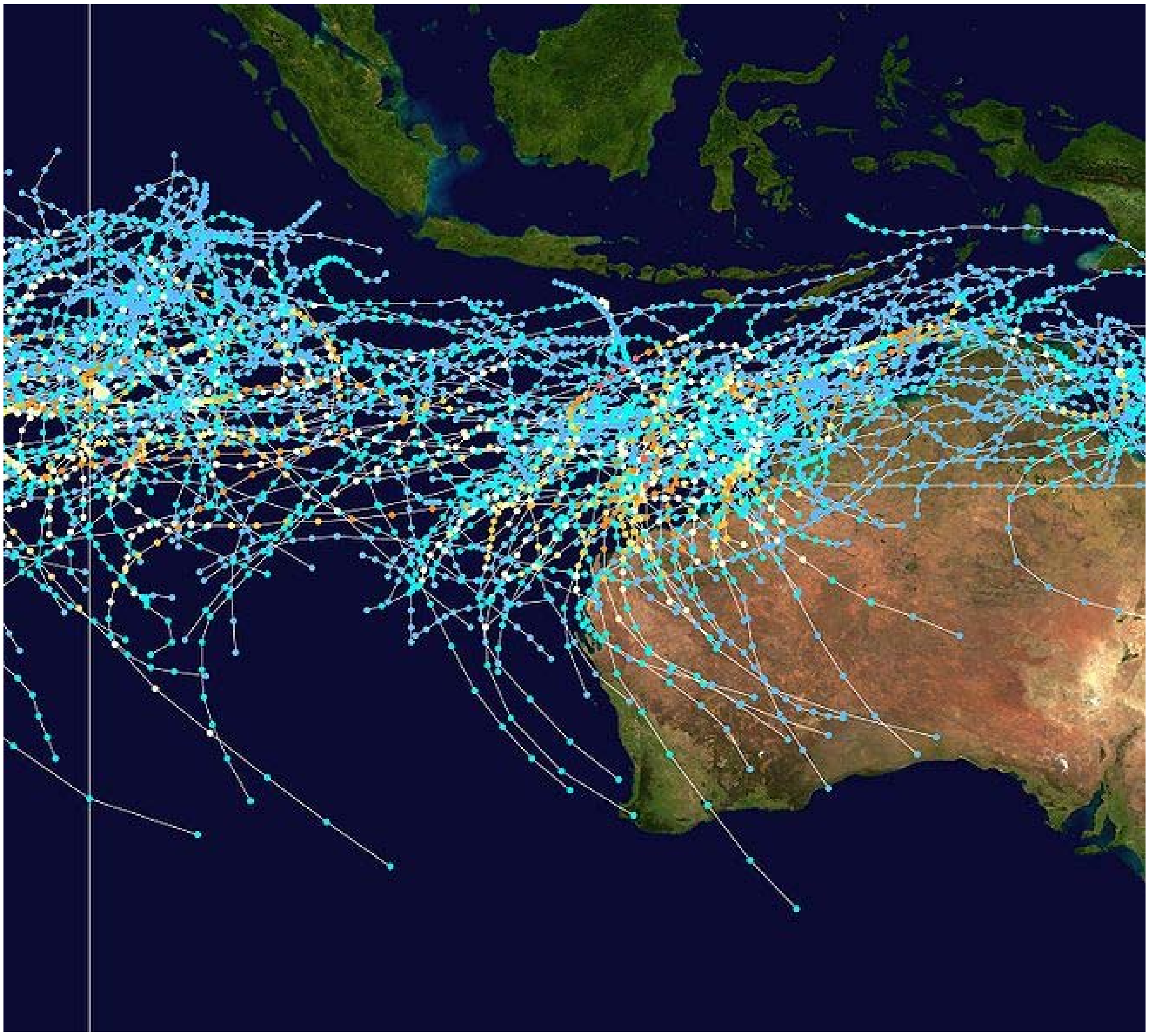
South-West Indian Ocean



Tracks of all tropical cyclones in the southwestern Indian Ocean between 1980 and 2005

Despite nearly a half century of historical data, research at Reunion Island into tropical cyclones has been a priority only since 1999, when Météo-France began assigning additional personnel for research purposes. Cyclones forming in this area can affect Madagascar, Mozambique, Mauritius, Réunion, Comoros, Tanzania, and Kenya. An average of about ten tropical cyclones form in this basin per year, and this basin, annually, is the deadliest worldwide, with up to 80 deaths in every season.

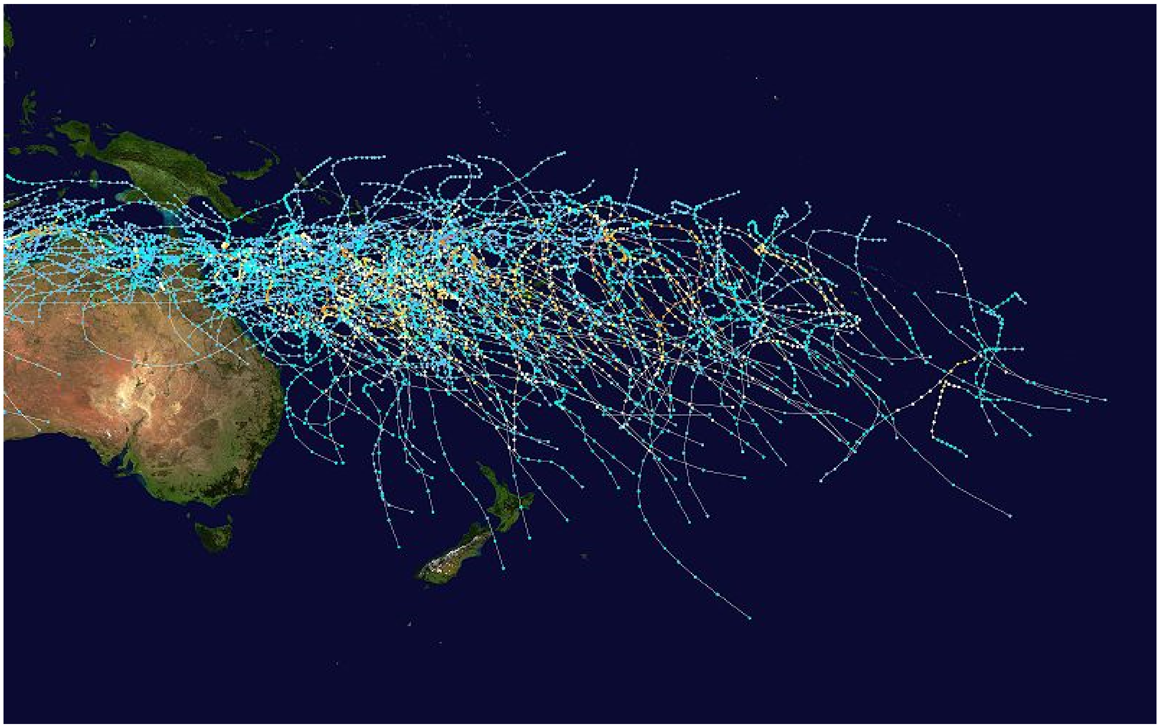
Australian region



Tracks of all tropical cyclones in the southeastern Indian Ocean between 1980 and 2005

Tropical activity in this region affects Australia and Indonesia. According to the Australian Bureau of Meteorology, the most frequently hit portion of Australia is between Exmouth and Broome in Western Australia. The basin sees an average of about seven cyclones each year, although more can form or come in from other basins, like the South Pacific. Only about five cyclones reach Category 5 each year. The tropical cyclone Cyclone Vance in 1999 produced the highest recorded speed winds in an Australian town or city at around 267 km/h.

South Pacific Ocean



Tracks of all tropical cyclones in the southwestern Pacific Ocean between 1980 and 2005

Tropical activity in this region largely affects Australia and Oceania. Tropical storms rarely reach the vicinity of Brisbane, Australia and into New Zealand, usually during or after extratropical transition. The entire basin sees an average of about nine cyclones annually. Very few cyclones in this regions have been recorded to have reached Category 5, one of which was Cyclone Larry in 2006.

Other areas

South Atlantic Ocean

Cyclones form rarely or never in other tropical ocean areas, which are not formally considered tropical cyclone basins. Tropical depressions and tropical storms occur occasionally in the South Atlantic, and the only full-blown tropical cyclones on record were 2004's Cyclone Catarina, which made landfall in Brazil, and 2010's Tropical Storm Anita, which formed off the coast of Rio Grande do Sul.

Mediterranean Sea

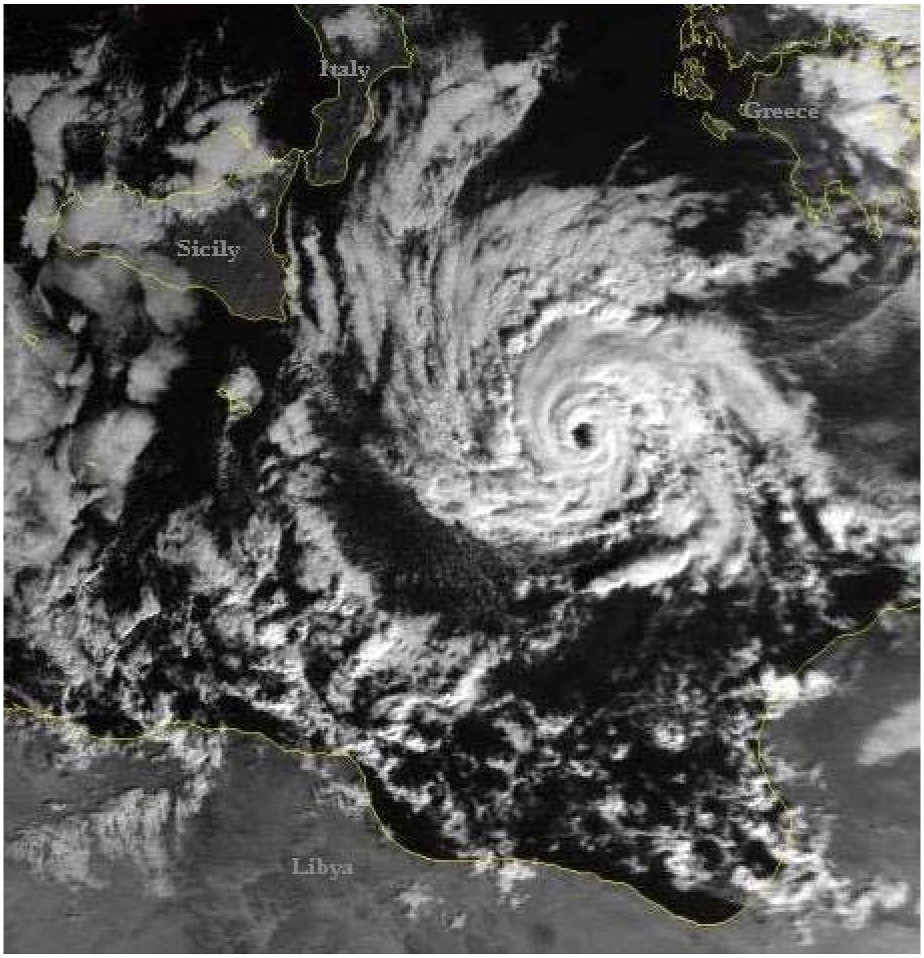


Image of January 1995 system

On rare occasions, tropical-like systems occur over the Mediterranean Sea. These systems are a subject of some debate within meteorological circles whether they closely fit the definition of tropical cyclones, subtropical cyclones, or polar lows. Their origins are typically non-tropical, and develop over open waters under strong, initially cold-core cyclones, similar to subtropical cyclones in the Atlantic Basin. Sea surface temperatures in late-August and early-September are quite high over the basin (+24/+28°C), though research indicates water temperatures of 20 °C/68 °F are normally required for development.

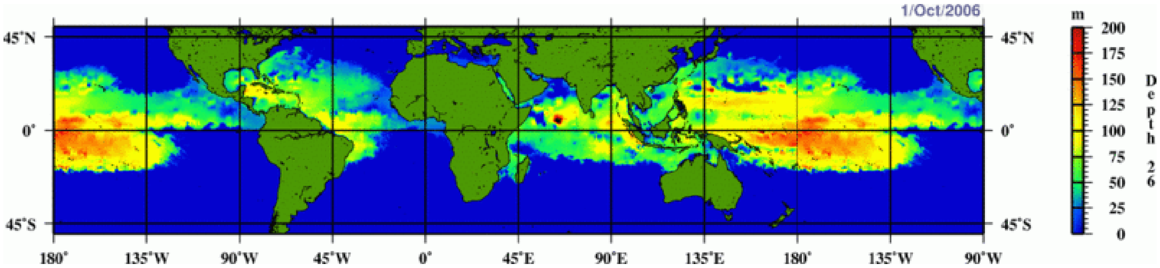
Meteorological literature documents that such systems occurred in September 1947, September 1969, August 1976, January 1982, September 1983, December 1985, October 1996 and January 1995. The last system developed a well-defined eye, and a ship recorded 85 mph (140 km/h) winds, along with an atmospheric pressure of 975 mbar. Although it had the structure of a tropical cyclone, it occurred over 61 °F (16 °C) water temperatures, suggesting it could have been a polar low.

Tropical cyclogenesis

Tropical cyclogenesis is the technical term that describes the development and strengthening of a tropical cyclone in the atmosphere. The mechanisms through which tropical cyclogenesis occurs are distinctly different from those through which mid-latitude cyclogenesis occurs. Tropical cyclogenesis involves the development of a warm-core cyclone, due to significant convection in a favorable atmospheric environment. There are six main requirements for tropical cyclogenesis: sufficiently warm sea surface temperatures, atmospheric instability, high humidity in the lower to middle levels of the troposphere, enough Coriolis force to develop a low pressure center, a preexisting low level focus or disturbance, and low vertical wind shear.

Tropical cyclones tend to develop during the summer, but have been noted in nearly every month in most basins. Climate cycles such as ENSO and the Madden-Julian Oscillation modulate the timing and frequency of tropical cyclone development. There is a limit on tropical cyclone intensity which is strongly related to the water temperatures along its path. An average of 86 tropical cyclones of tropical storm intensity form annually worldwide. Of those, 47 reach hurricane/typhoon strength, and 20 become intense tropical cyclones (at least Category 3 intensity on the Saffir-Simpson Hurricane Scale).

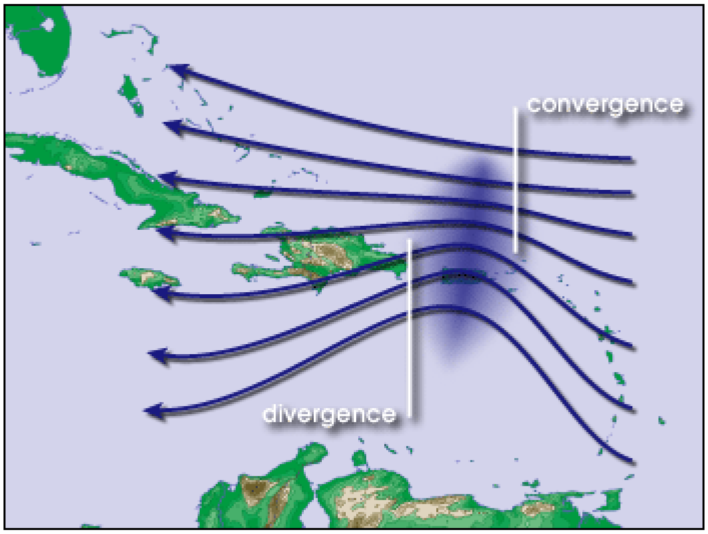
Requirements for tropical cyclone formation



Depth of 26 °C isotherm on October 1, 2006

There are six main requirements for tropical cyclogenesis: sufficiently warm sea surface temperatures, atmospheric instability, high humidity in the lower to middle levels of the troposphere, enough Coriolis force to sustain a low pressure center, a preexisting low level focus or disturbance, and low vertical wind shear. While these conditions are necessary for tropical cyclone formation, they do not guarantee that a tropical cyclone will form.

Warm waters, instability, and mid-level moisture



Waves in the trade winds in the Atlantic Ocean—areas of converging winds that move slowly along the same track as the prevailing wind—create instabilities in the atmosphere that may lead to the formation of hurricanes.

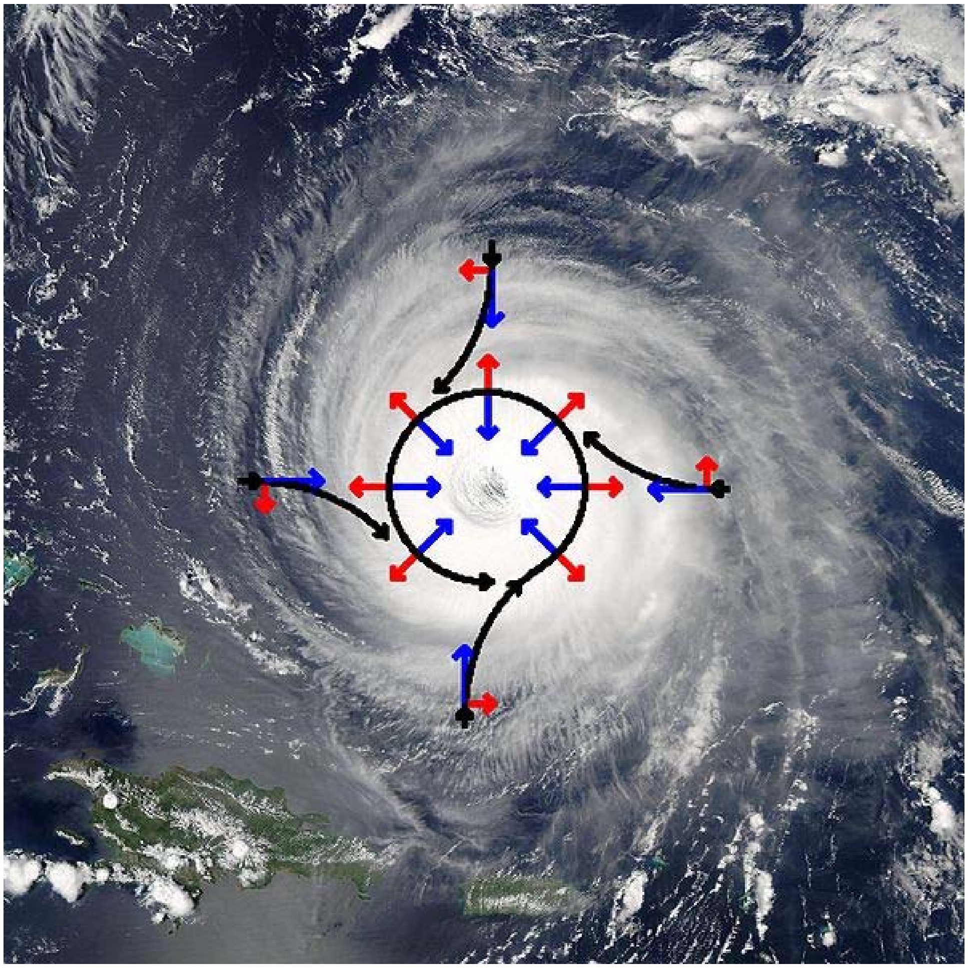
Normally, an ocean temperature of 26.5°C (79.7°F) spanning through at least a 50-metre depth is considered the minimum to maintain the special mesocyclone that is the tropical cyclone. These warm waters are needed to maintain the warm core that fuels tropical systems. This value is well above 16.1 °C (60.9 °F), the global average surface temperature of the oceans. However, this requirement can be considered only a general baseline because it assumes that the ambient atmospheric environment surrounding an area of disturbed weather presents average conditions.

Tropical cyclones are known to form even when normal conditions are not met. For example, cooler air temperatures at a higher altitude (e.g., at the 500 hPa level, or 5.9 km) can lead to tropical cyclogenesis at lower water temperatures, as a certain lapse rate is required to force the atmosphere to be unstable enough for convection. In a moist atmosphere, this lapse rate is 6.5 °C/km, while in an atmosphere with less than 100% relative humidity, the required lapse rate is 9.8 °C/km.

At the 500 hPa level, the air temperature averages -7 °C (18 °F) within the tropics, but air in the tropics is normally dry at this level, giving the air room to wet-bulb, or cool as it moistens, to a more favorable temperature that can then support convection. A wetbulb temperature at 500 hPa in a tropical atmosphere of -13.2 °C is required to initiate convection if the water temperature is 26.5 °C, and this temperature requirement increases or decreases proportionally by 1 °C in the sea surface temperature for each 1 °C change at 500 hpa. Under a cold cyclone, 500 hPa temperatures can fall as low as -30 °C, which can initiate convection even in the driest atmospheres. This also explains why moisture in the mid-levels of the troposphere, roughly at the 500 hPa level, is normally a requirement for development. However, when dry air is found at the same height, the wet bulb temperature normally witnessed at 500 hPa does not promote large areas of thunderstorms due to a lack of instability. At heights near the tropopause, the 30-year average temperature (as measured in the period encompassing 1961 through 1990) was -77 °C (-132 °F). Recent examples of tropical cyclones that maintained themselves over cooler waters include Delta, Epsilon, and Zeta of the 2005 Atlantic hurricane season.

Role of Maximum Potential Intensity (MPI)

Kerry Emanuel created a mathematical model around 1988 to compute the upper limit of tropical cyclone intensity based on sea surface temperature and atmospheric profiles from the latest global model runs. Emanuel's model is called the *maximum potential intensity*, or MPI. Maps created from this equation show regions where tropical storm and hurricane formation is possible, based upon the thermodynamics of the atmosphere at the time of the last model run (either 0000 or 1200 UTC). This does not take into account vertical wind shear.



Schematic representation of flow around a low-pressure area (in this case, Hurricane Isabel) in the Northern hemisphere. The pressure gradient force is represented by blue arrows, the Coriolis acceleration (always perpendicular to the velocity) by red arrows

Coriolis force

A minimum distance of 500 km (300 miles) from the equator is normally needed for tropical cyclogenesis. The Coriolis force imparts rotation on the flow and arises as winds begin to flow in toward the lower pressure created by the pre-existing disturbance. In areas with a very small or non-existent Coriolis Force (e.g. near the Equator), the only significant atmospheric forces in play are the *pressure gradient force* (the pressure difference that causes winds to blow from high to low pressure) and a smaller friction force; these two alone would not cause the large-scale rotation required for tropical cyclogenesis. The existence of a significant Coriolis Force allows the developing vortex to achieve gradient wind balance. This is a balance condition found in mature tropical cyclones that allows latent heat to concentrate near the storm core; this results in the maintenance or intensification of the vortex if other development factors are neutral.

Low level disturbance

Whether it be a depression in the intertropical covergence zone (ITCZ), a tropical wave, a broad surface front, or an outflow boundary, a low level feature with sufficient vorticity and convergence is required to begin tropical cyclogenesis. Even with perfect upper level conditions and the required atmospheric instability, the lack of a surface focus will prevent the development of organized convection and a surface low.

Weak vertical wind shear

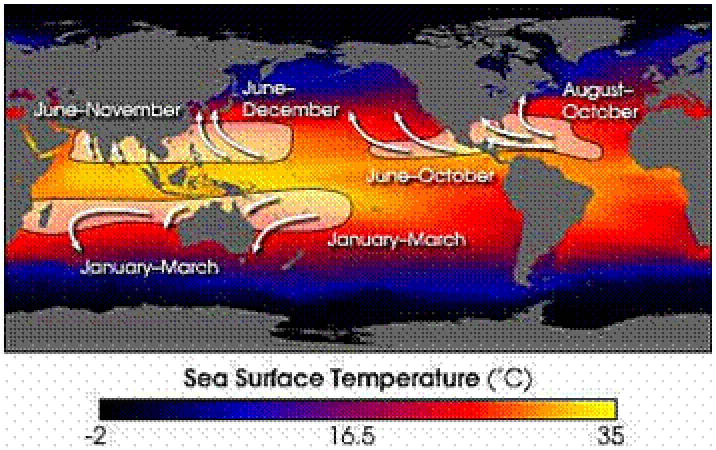
Vertical wind shear of less than 10 m/s (20 kt, 22 mph) between the surface and the tropopause is required for tropical cyclone development. Strong wind shear can "blow" the tropical cyclone apart, as it displaces the mid-level warm core from the surface circulation and dries out the mid-levels of the troposphere, halting development. In smaller systems, the development of a significant mesoscale convective complex in a sheared environment can send out a large enough outflow boundary to destroy the surface cyclone. Moderate wind shear can lead to the initial development of the convective complex and surface low similar to the mid-latitudes, but it must relax to allow tropical cyclogenesis to continue.

Favorable trough interactions

Limited vertical wind shear can be positive for tropical cyclone formation. When an upper-level trough or upper-level low is roughly the same scale as the tropical disturbance, the system can be steered by the upper level system into an area with better diffluence aloft, which can cause further development. Weaker upper cyclones are better candidates for a favorable interaction. There is evidence that weakly sheared tropical cyclones initially develop more rapidly than non-sheared tropical cyclones, although this comes at the cost of a peak in intensity with much weaker wind speeds and higher minimum pressure. This process is also known as *baroclinic initiation* of a tropical cyclone. Trailing upper cyclones and upper troughs can cause additional outflow channels and aid in the intensification process. It should be noted that developing tropical disturbances can help create or deepen upper troughs or upper lows in their wake due to the outflow jet emanating from the developing tropical disturbance/cyclone.

There are cases where large, mid-latitude troughs can help with tropical cyclogenesis when an upper-level jet stream passes to the northwest of the developing system, which will aid divergence aloft and inflow at the surface, spinning up the cyclone. This type of interaction is more often associated with disturbances already in the process of recurvature.

Times of formation



Peaks of activity worldwide

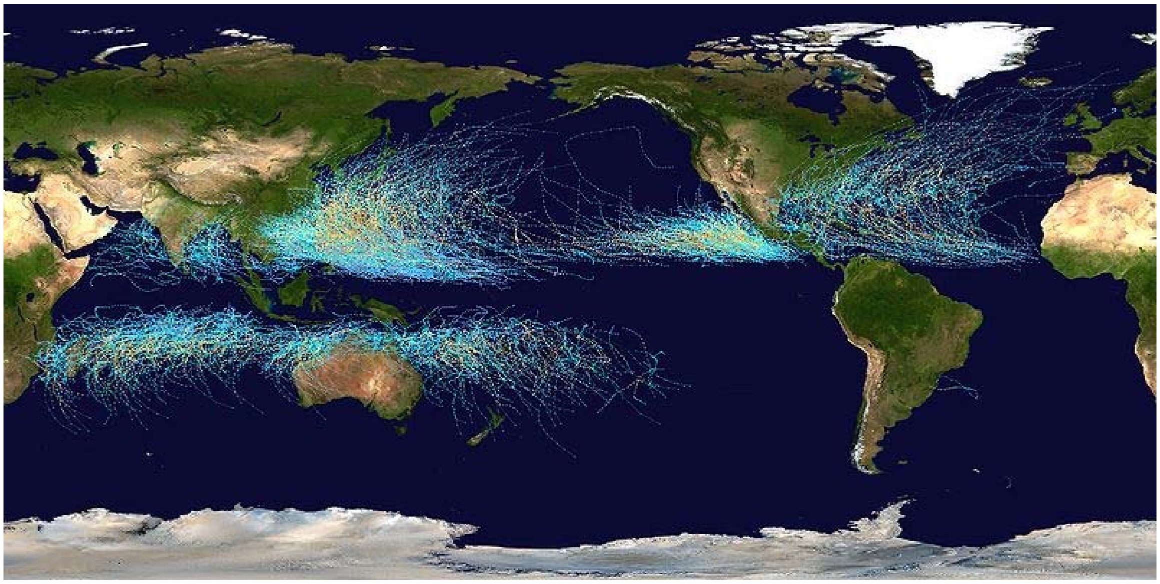
Worldwide, tropical cyclone activity peaks in late summer when water temperatures are warmest. Each basin, however, has its own seasonal patterns. On a worldwide scale, May is the least active month, while September is the most active. This can be explained by the greater tropical cyclone activity across the Northern hemisphere than south of the equator.

In the North Atlantic, a distinct hurricane season occurs from June 1 through November 30, sharply peaking from late August through October. The statistical peak of the North Atlantic hurricane season is September 10. The Northeast Pacific has a broader period of activity, but in a similar time frame to the Atlantic. The Northwest Pacific sees tropical cyclones year-round, with a minimum in February and a peak in early September. In the North Indian basin, storms are most common from April to December, with peaks in May and November.

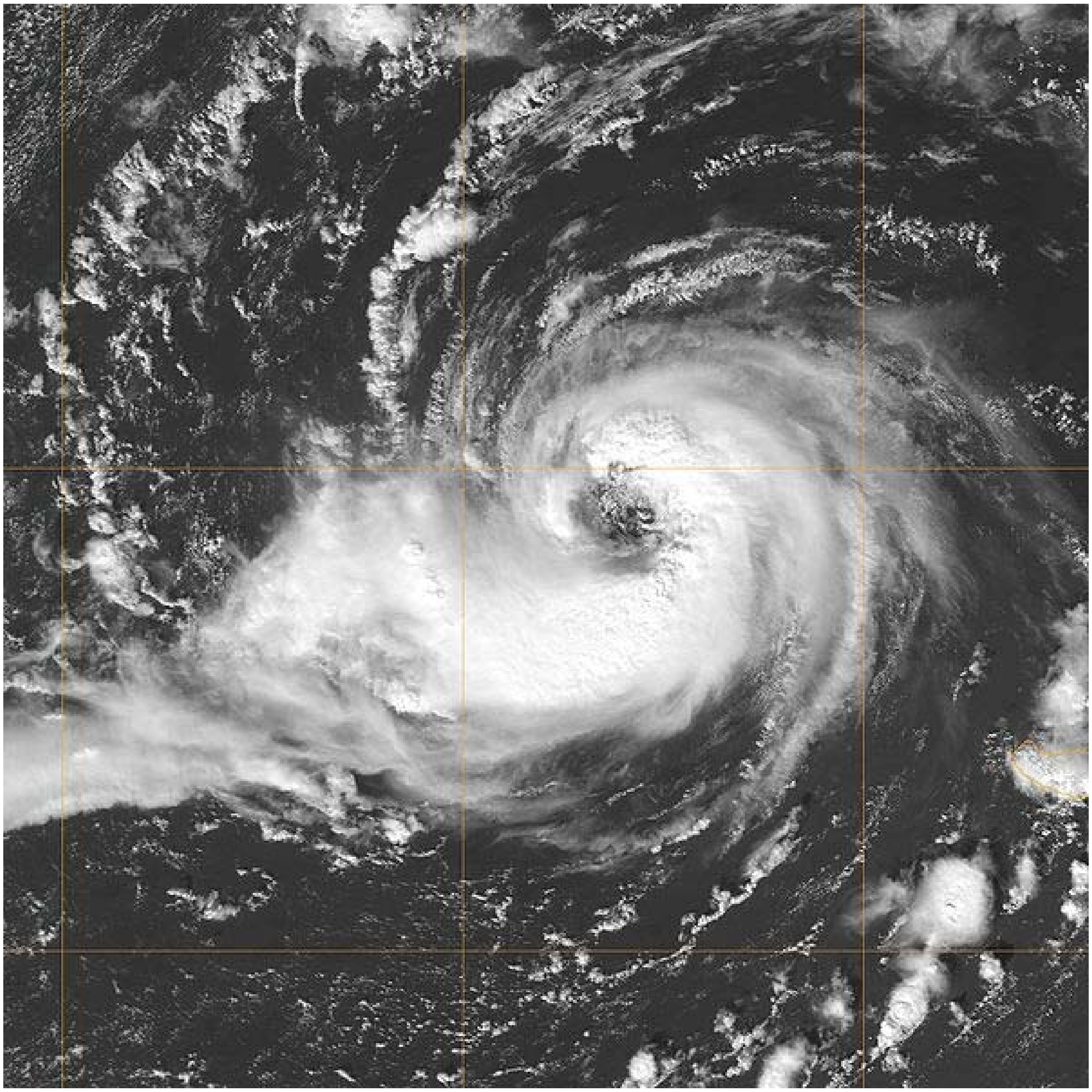
In the Southern Hemisphere, tropical cyclone activity begins on November 1 and ends in late April. Southern Hemisphere activity peaks in mid-February to early March. Virtually all the Southern Hemisphere activity is seen from the southern African coast eastward towards South America. Tropical cyclones are rare events across the south Atlantic ocean and the southeastern Pacific ocean.

Season Lengths and Seasonal Averages					
Basin	**Season Start**	**Season End**	**Tropical Storms (>34 knots)**	**Tropical Cyclones (>63 knots)**	**Category 3+ Tropical Cyclones (>95 knots)**
North Atlantic	June	November	10.6	5.9	2.0
Northeast Pacific	May	November	16.3	9.0	4.1
Northwest Pacific	January	December	26.7	16.9	8.5
North Indian	April	December	5.4	2.2	0.4
South Indian	October	May	20.6	10.3	4.3
Australia & Southwest Pacific	November	May	9	4.5	1.9

Unusual areas of formation



Global Tropical Cyclone Tracks between 1985 and 2005, indicating the areas where tropical cyclones usually develop



Hurricane Vince formed in the temperate subtropics during the 2005 Atlantic season.

Middle latitudes

Areas farther than 30 degrees from the equator (except in the vicinity of a warm current) are not normally conducive to tropical cyclone formation or strengthening, and areas more than 40 degrees from the equator are often very hostile to such development. The primary limiting factor is water temperatures, although higher shear at increasing latitudes is also a factor. These areas are sometimes frequented by cyclones moving poleward from tropical latitudes. On rare occasions, such as in 2004, 1988, and 1975, storms may form or strengthen in this region. Storms surviving beyond 50 degrees as a tropical cyclone are also quite rare (although it is not uncommon for a storm to become extratropical at high intensity in the high latitudes).

Near the Equator

Areas within approximately ten degrees latitude of the equator do not experience a significant Coriolis Force, a vital ingredient in tropical cyclone formation. In December 2001, however, Typhoon Vamei formed in the southern South China Sea and made landfall in Malaysia. It formed from a thunderstorm formation in Borneo that moved into the South China Sea.

South Atlantic

A combination of wind shear and a lack of tropical disturbances from the Intertropical Convergence Zone (ITCZ) makes it very difficult for the South Atlantic to support tropical activity. Five tropical cyclones have been observed here — a weak tropical storm in 1991 off the coast of Africa near Angola, Cyclone Catarina (sometimes also referred to as Aldonça), which made landfall in Brazil in 2004 at Category 2 strength, and a smaller storm in January 2004, east of Salvador, Brazil. The January storm is thought to have reached tropical storm intensity based on scatterometer wind measurements. A weak tropical storm formed in 2006 and Cyclone Anita became the first officially named cyclone in the South Atlantic in 2010.

Mediterranean Sea

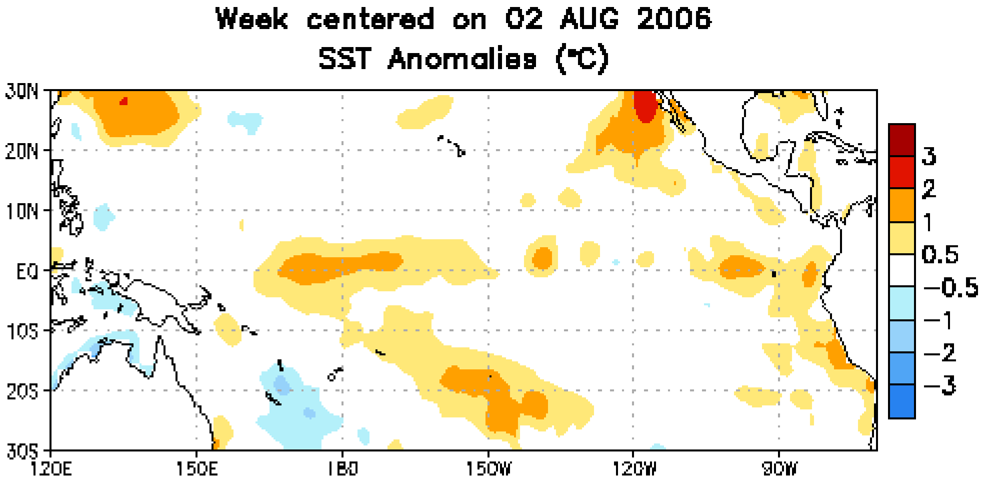
Storms that appear similar to tropical cyclones in structure sometimes occur in the Mediterranean basin. Examples of these "Mediterranean tropical cyclones" formed in September 1947, September 1969, September 1973, August 1976, January 1982, September 1983, December 1984, December 1985, October 1994, January 1995, October 1996, September 1997, December 2005, September 2006. However, there is debate on whether these storms were tropical in nature. The Black Sea has, on occasion, produced or fueled storms that begin cyclonic rotation, and appear to be similar to cyclones seen in the Mediterranean.

Elsewhere

Vortices have been reported off the coast of Morocco in the past. However, it is debatable if they are truly tropical in character. Tropical activity is also extremely rare in the Great Lakes. However, a storm system that appeared similar to a subtropical or tropical cyclone formed in 1996 on Lake Huron. It formed an eye-like structure in its center, and it may have briefly been a subtropical or tropical cyclone.

Influence of large-scale climate cycles

Influence of ENSO

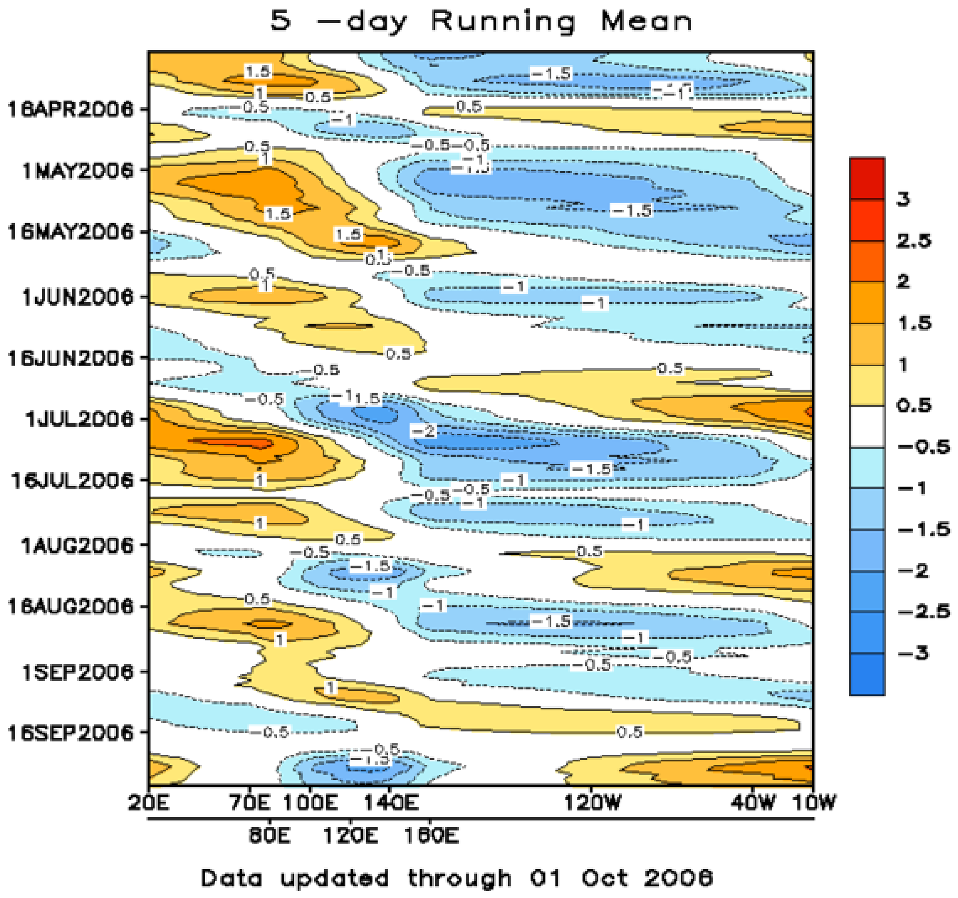


Loop of SST anomalies in the Tropical Pacific

Warm waters during the El Niño-Southern Oscillation lower the potential of tropical cyclone formation primarily in the Atlantic Basin and around Australia. Because tropical cyclones in the northeastern Pacific and north Atlantic basins are both generated in large part by tropical waves from the same wave train, decreased tropical cyclone activity in the north Atlantic translates to increased tropical cyclone activity in the Eastern North Pacific.

In the Northwestern Pacific, El Niño shifts the formation of tropical cyclones eastward. During El Niño episodes, tropical cyclones tend to form in the eastern part of the basin, between 150°E and the International Date Line (IDL). Coupled with an increase in activity in the North-Central Pacific (IDL to 140°W) and the South-Central Pacific (east of 160°E), there is a net increase in tropical cyclone development near the International Date Line on both sides of the equator. While there is no linear relationship between the strength of an El Niño and tropical cyclone formation in the Northwestern Pacific, typhoons forming during El Niño years tend to have a longer duration and higher intensities. Tropical cyclogenesis in the Northwestern is suppressed west of 150°E in the year following an El Niño event.

Influence of the MJO



5-day running mean of MJO. Note how it moves eastward with time.

In general, westerly wind increases associated with the Madden-Julian Oscillation lead to increased tropical cyclogenesis in all basins. As the oscillation propagates from west to east, it leads to an eastward march in tropical cyclogenesis with time during that hemisphere's summer season. There is an inverse relationship between tropical cyclone activity in the western Pacific basin and the north Atlantic basin, however. When one basin is active, the other is normally quiet, and vice versa. The main reason for this appears to be the phase of the Madden-Julian oscillation, or MJO, which is normally in opposite modes between the two basins at any given time.

Influence of equatorial Rossby waves

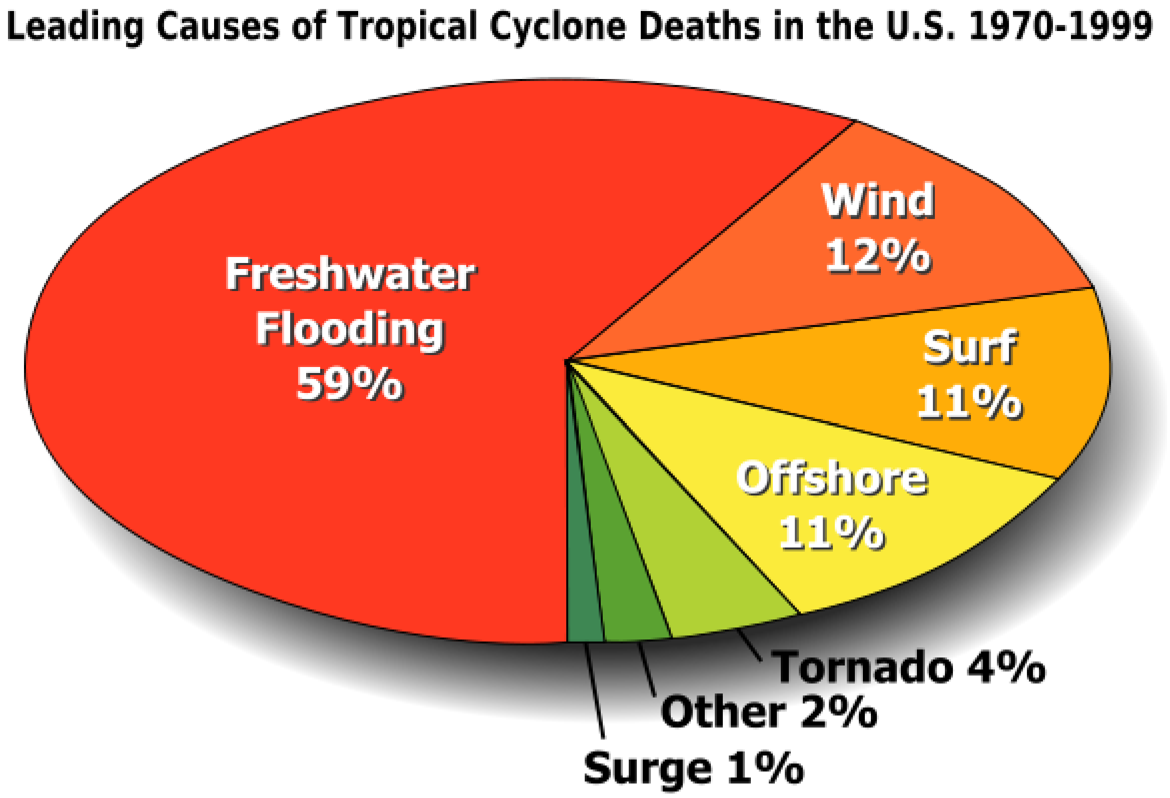
Research has shown that trapped equatorial Rossby wave packets can increase the likelihood of tropical cyclogenesis in the Pacific Ocean, as they increase the low-level westerly winds within that region, which then leads to greater low-level vorticity. The individual waves can move at approximately 1.8 m/s (4 mph) each, though the group tends to remain stationary.

Seasonal forecasts

Since 1984, Colorado State University has been issuing seasonal tropical cyclone forecasts for the north Atlantic basin, with results that are better than climatology. The university has found several statistical relationships for this basin that appear to allow long range prediction of the number of tropical cyclones. Since then, numerous others have followed in the university's steps, with some organizations issuing seasonal forecasts for the northwest Pacific and the Australian region. The predictors are related to regional oscillations in the global climate system: the Walker circulation which is related to the El Niño-Southern Oscillation; the North Atlantic oscillation or NAO; the Arctic oscillation or AO; and the Pacific North American pattern or PNA.

Chapter 4

Effects of Tropical Cyclones



Source: Edward Rappaport—Chief, Technical Support Branch, Tropical Prediction Center

Pie graph of American tropical cyclone casualties by cause from 1970-1999

The main effects of tropical cyclones include heavy rain, strong wind, large storm surges at landfall, and tornadoes. The destruction from a tropical cyclone depends mainly on its intensity, its size, and its location. Tropical cyclones act to remove forest canopy as well as change the landscape near coastal areas, by moving and reshaping sand dunes and causing extensive erosion along the coast. Even well inland, heavy rainfall can lead to mudslides and landslides in mountainous areas. Their effects can be sensed over time by studying the concentration of the Oxygen-18 isotope within caves within the vicinity of cyclones' paths.It can also hurt Cudin du

After the cyclone has passed, devastation often continues. Standing water can cause the spread of disease, and transportation or communications infrastructure may have been destroyed, hampering clean-up and rescue efforts. Nearly two million people have died globally due to tropical cyclones. Despite their devastating effects, tropical cyclones are also beneficial, by potentially bringing rain to dry areas and moving heat from the tropics poleward. Out at sea, ships take advantage of their known characteristics by navigating through their weaker, western half.

At sea

A mature tropical cyclone can release heat at a rate upwards of $6x10^{14}$ watts. Tropical cyclones on the open sea cause large waves, heavy rain, and high winds, disrupting international shipping and, at times, causing shipwrecks. Generally, after its passage, a tropical cyclone stirs up ocean water, lowering sea surface temperatures behind it. This cool wake can cause the region to be less favorable for a subsequent tropical cyclone. On rare occasions, tropical cyclones may actually do the opposite. 2005's Hurricane Dennis blew warm water behind it, contributing to the unprecedented intensity of Hurricane Emily, which followed it closely. Hurricanes help to maintain the global heat balance by moving warm, moist tropical air to the mid-latitudes and polar regions. Were it not for the movement of heat poleward (through other means as well as hurricanes), the tropical regions would be unbearably hot.

North American colonization

Shipwrecks are common with the passage of strong tropical cyclones. Such shipwrecks can change the course of history, as well as influence art and literature. A hurricane led to a victory of the Spanish over the French for control of Fort Caroline, and ultimately the Atlantic coast of North America, in 1565. The *Sea Venture* was wrecked near Bermuda in 1609 which led to the colonization of Bermuda and provided the inspiration for Shakespeare's *The Tempest*.

Shipping

Mariners have a way to safely navigate around tropical cyclones. They split tropical cyclones into two halves, based on its direction of motion. They avoid the right half of the cyclone and termed it the **dangerous semicircle** since the heaviest rain and strongest winds and seas were located in this half of the storm. The other half of the tropical cyclone was called the **navigable semicircle** since weather conditions are less extreme in this half of the storm. The rules of thumb for ship travel when a tropical cyclone is in their vicinity are to avoid them if at all possible and do not cross their forecast path (crossing the T). Those travelling through the dangerous semicircle are advised to keep to the true wind on the starboard bow and make as much headway as possible. Ships moving through the navigable semicircle are advised to keep the true wind on the starboard quarter while making as much headway as possible.

Upon landfall

The most significant effects of a tropical cyclone occur when they cross coastlines, making landfall.

Strong winds

Strong winds can damage or destroy vehicles, buildings, bridges, and other outside objects, turning loose debris into deadly flying projectiles. In the United States, major hurricanes comprise just 21% of all landfalling tropical cyclones, but account for 83% of all damage. Tropical cyclones often knock out power to tens or hundreds of thousands of people, preventing vital communication and hampering rescue efforts. Tropical cyclones often destroy key bridges, overpasses, and roads, complicating efforts to transport food, clean water, and medicine to the areas that need it. Furthermore, the damage caused by tropical cyclones to buildings and dwellings can result in economic damage to a region, and to a diaspora of the population of the region.

Storm surge

The aftermath of Hurricane Katrina in Gulfport, Mississippi. Katrina was the costliest tropical cyclone in United States history.

The storm surge, or the increase in sea level due to the cyclone, is typically the worst effect from landfalling tropical cyclones, historically resulting in 90% of tropical cyclone deaths. The relatively quick surge in sea level can move miles/kilometers inland, flooding homes and cutting off escape routes. The storm surges and winds of hurricanes may be destructive to human-made structures, but they also stir up the waters of coastal estuaries, which are typically important fish breeding locales.

Heavy rainfall

The thunderstorm activity in a tropical cyclone produces intense rainfall, potentially resulting in flooding, mudslides, and landslides. Inland areas are particularly vulnerable to freshwater flooding, due to residents not preparing adequately. Heavy inland rainfall eventually flows into coastal estuaries, damaging marine life in coastal estuaries. The wet environment in the aftermath of a tropical cyclone, combined with the destruction of sanitation facilities and a warm tropical climate, can induce epidemics of disease which claim lives long after the storm passes. Infections of cuts and bruises can be greatly amplified by wading in sewage-polluted water. Large areas of standing water caused by flooding also contribute to mosquito-borne illnesses. Furthermore, crowded evacuees in shelters increase the risk of disease propagation.

Flooding in Seminole County, Florida from Tropical Storm Fay (2008)

Although cyclones take an enormous toll in lives and personal property, they may be important factors in the precipitation regimes of places they affect and bring much-needed precipitation to otherwise dry regions. Hurricanes in the eastern north Pacific often supply moisture to the Southwestern United States and parts of Mexico. Japan receives over half of its rainfall from typhoons. Hurricane Camille averted drought conditions and ended water deficits along much of its path, though it also killed 259 people and caused $9.14 billion (2005 USD) in damage.

On the other hand, the occurrence of tropical cyclones can cause tremendous variability in rainfall over the areas they effect: indeed cyclones are the primary cause of the most extreme rainfall variability in the world, observed in places such as Onslow and Port Hedland in subtropical Australia where the annual rainfall can range from practically nothing with no cyclones to over 1,000 millimetres (39 in) if cyclones are abundant.

Tornadoes

The broad rotation of a landfalling tropical cyclone often spawns tornadoes, particularly in their right front quadrant. While these tornadoes are normally not as strong as their non-tropical counterparts, heavy damage or loss of life can still occur. Tornadoes can also be spawned as a result of eyewall mesovortices, which persist until landfall.

Deaths

Deaths per year from tropical cyclones	
Australia	5
United States	25
East Asia	740
Globally	10000

During the last two centuries, tropical cyclones have been responsible for the deaths of about 1.9 million persons worldwide. It is estimated that 10,000 people per year perish due to tropical cyclones. The deadliest tropical cyclone was the 1970 Bhola cyclone, which had a death toll of anywhere from 300,000 to 500,000 lives.

United States

Before Hurricane Katrina, the average death rate for tropical cyclones in the United States was decreasing. The main cause of storm-related fatalities was shifting away from storm surge and towards freshwater flooding. However, the median death rate per storm had increased through 1979, with a lull during the 1980-1995 period. This was due to greater numbers of people moving to the coastal margins and into harm's way. Despite advances in warning strategies and reduction in track forecast error, this increase in fatalities is expected to continue for as long as people migrate towards the shore.

Reconstruction and repopulation

Aerial image of destroyed homes in Punta Gorda, Florida, following Hurricane Charley

While tropical cyclones may well seriously damage settlement, total destruction encourages rebuilding. For example, the destruction wrought by Hurricane Camille on the Gulf coast spurred redevelopment, greatly increasing local property values. However, disaster response officials point out that redevelopment encourages more people to live in clearly dangerous areas subject to future deadly storms. Hurricane Katrina is the most obvious example, as it devastated the region that had been revitalized after Hurricane Camille. Many former residents and businesses do relocate to inland areas away from the threat of future hurricanes as well.

In isolated areas with small populations, tropical cyclones may cause enough casualties to contribute to the founder's effect as survivors repopulate their place. For example, around 1775, a typhoon hit Pingelap Atoll, and in combination with a subsequent famine, reduced the island's population to a low level. Several generations after the disaster, as many as 10% of Pingelapese have a genetic form of color-blindness called achromatopsia. This is due to one of the survivors of the depopulation brought on by the typhoon having a mutated gene, which the population bottleneck caused to be at a higher-than-usual level in succeeding generations.

Hurricane Isabel (2003)'s effect on the North Carolina Outer Banks

Effects on natural resources

Geomorphology

Tropical cyclones reshape the geology near the coast by eroding sand from the beach as well as offshore, rearranging coral, and changing dune configuration onshore. Their rain water gets absorbed into stalagmites within caves, creating a record of past tropical cyclone impacts.

Coastal ridges

Waves and storm surges accompanying tropical cyclones erode undersea sands, erode shell deposits, break off corals from near shore reefs in their paths, and carry all this detritus landwards in a rolling wave of material that is deposited onshore, above highest astronomical tide as a ridge of sand, shell and coral. For example, each severe tropical cyclone (i.e. Category 4-5 on the Saffir-Simpson scale) crossing northeast Australia's tropical coastline since the last significant change in sea levels (about 5000 years ago) has 'emplaced' such ridges within the coastal landscape forming, in some places, series of ridges and a geomorphological record of highest magnitude cyclones hitting the coast over 3000 – 5000 years.

Eyewitness accounts verify ridges of this kind are formed by severe tropical cyclones and two clear examples cited are the 18 kilometres (11 mi) long, 35 metres (115 ft) wide, 3.5 metres (11 ft) high coral shingle ridge deposited on Funafuti Atoll (Central South Pacific) by Tropical Cyclone Bebe in October 1971, and the large coral shingle ridge deposited on Jaluit Atoll (Marshall Islands) by Typhoon Ophelia in January 1958. In tropical northeast Australia, an intense tropical cyclone hit in March 1918 (crossing over the town of Innisfail), at which time there were eyewitness accounts of a 4.5 metres (15 ft) to 5.1 metres (17 ft) high ridge of pumice being deposited by that cyclone's surge as it crossed the coast.).

Limestone cave stalagmites

When tropical cyclones cross land, thin layers of calcium carbonate of unusually 'light' Oxygen isotope (Oxygen-18) composition are deposited onto stalagmites in limestone caves up to 300 kilometres (190 mi) from the cyclone's path.

As the cloud tops of tropical cyclones are high and cold, and their air is humid - their rainwater is 'lighter'. In other words, the rainfall contains significantly higher quanties of unevaporated Oxygen-18 than other tropical rainfall. The isotopically lighter rainwater soaks into the ground, percolates down into caves, and, within a couple of weeks, Oxygen-18 transfers from the water into calcium carbonate, before being deposited in thin layers or 'rings' within stalagmites. A succession of such events created within stalagmites maintain a record of cyclones tracking within a 300 kilometres (190 mi) radius of caves going back centuries, millennia, or even millions of years.

At Actun Tunichil Muknal cave in central Belize, researchers drilling stalagmites with a computer- controlled dental drill accurately identified and verified evidence of isotopically light rainfall for 11 tropical cyclones occurring over a 23 year period (1978–2001).

At the Chillagoe limestone caves in northeast Australia (130 kilometres (81 mi) inland from Cairns) researchers identified and matched evidence of isotopically light rainfall with 100 years of cyclone records, and from this have created a record of tropical cyclones from 2004 back to 1200 A.D. (an 800 year record).

Landscapes

Severe tropical cyclones defoliate tropical forest canopy trees, remove vines and epiphytes from the trees, break tree crown stems, and cause tree falls. The degree of damage they do along their paths, at a landscape level (i.e. > 10 kilometres (6.2 mi)), can be catastrophic yet variable and patchy. Stripping trees and scattering forest debris also provides fuel for wildfires, such as a blaze that lasted three months in 1989 and burned 460 square miles (1,200 km^2) of forest that had been stripped by Hurricane Gilbert.

- Wind velocity gradients or horizontal wind shear (size of cyclone, the intensity of cyclone, proximity to the cyclone, and local scale cyclonic convection effects).

- Degree of exposure (windward exposure, leeward acceleration, or local topographic sheltering/shading); and

- Ecosystem species composition and forest structure

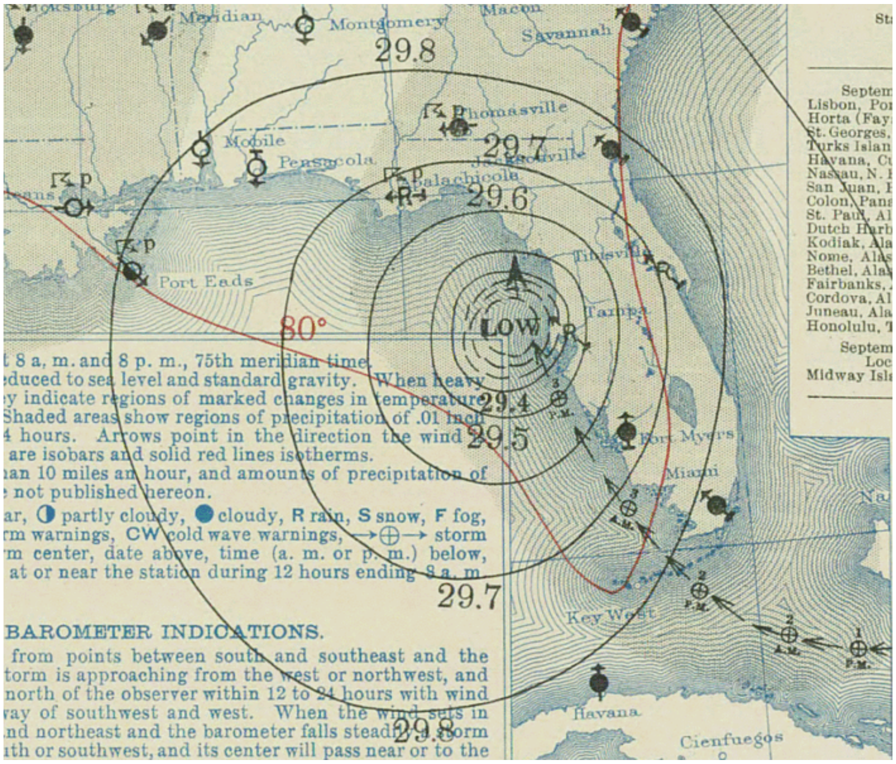
Assessments of cyclone damage done to tropical rainforest landscapes in northeast Australia, have produced the following typology for describing and 'mapping' the variable impacts they have along their paths, as follows:

1. **Severe and extensive** closest to the centre of cyclone: impact appears to be multidirectional and is evidenced by crowns of most trees having been broken, smashed or windthrown
2. **Severe and localised** closer to the cyclone centre than its edge: direction of the destructive winds is clearly identifiable, and severe canopy disruption is limited to the windward aspect of these forested areas
3. **Moderate canopy disturbance** closer to cyclone edge than its centre: most of the tree stems are still standing, with only some treefalls, and most of the damage is the defoliation of the canopy and branch breakage;
4. **Slight canopy disturbance** closest to cyclone edge: occasional stem fall or branch breakage, with most of the damage consisting of loss of foliage on the forest edges only, subsequently followed by leaf damage and heavy leaf litter falls.

Chapter 5

Tropical Cyclone Observation and Tropical Cyclone Track Forecasting

Tropical cyclone observation



Surface weather map of the Labor Day Hurricane of 1935 moving up the west coast of Florida

Tropical cyclone observation has been carried out over the past couple of centuries in various ways. The passage of typhoons, hurricanes, as well as other tropical cyclones have been detected by word of mouth from sailors recently coming to port or by radio transmissions from ships at sea, from sediment deposits in near shore estuaries, to the wiping out of cities near the coastline. Since World War II, advances in technology have included using planes to survey the ocean basins, satellites to monitor the world's oceans from outer space using a variety of methods, radars to monitor their progress near the coastline, and recently the introduction of unmanned aerial vehicles to penetrate storms. Recent studies have concentrated on studying hurricane impacts lying within rocks or near shore lake sediments, which are branches of a new field known as paleotempestology.

Geological markers of past activity

Stalagmites in caves

Recent studies of the ^{18}O and ^{13}C isotopes found in stalagmites in Belize show that tropical cyclone events can leave markers that can be separated out on a week-by-week basis. The error rate of this type of microanalysis was 1 error in 1,200 sampling points.

Markers in coral

Rocks contain certain isotopes of elements, known as natural tracers, which describe the conditions under which they formed. By studying the calcium carbonate in coral rock, past sea surface temperature and hurricane information can be revealed. Lighter oxygen isotopes (^{18}O) are left behind in coral during periods of very heavy rainfall. Since hurricanes are the main source of extreme rainfall in the tropical oceans, past hurricane events can be dated to the days of their impact on the coral by looking at the increased ^{18}O concentration within the coral.

Sediment deposition in coastal lakes

Kam Biu-Liu, a professor at Louisiana State University, has been studying sediment lying at the bottom of coastal lakes and marshes in order to study the frequency and intensity of hurricanes over the past 5,000 years. Since storm surges sweep coastal sands with them as they progress inland, a layer of sand is left behind in coastal lakes and marshes. Radiocarbon dating is then used to date the layers.

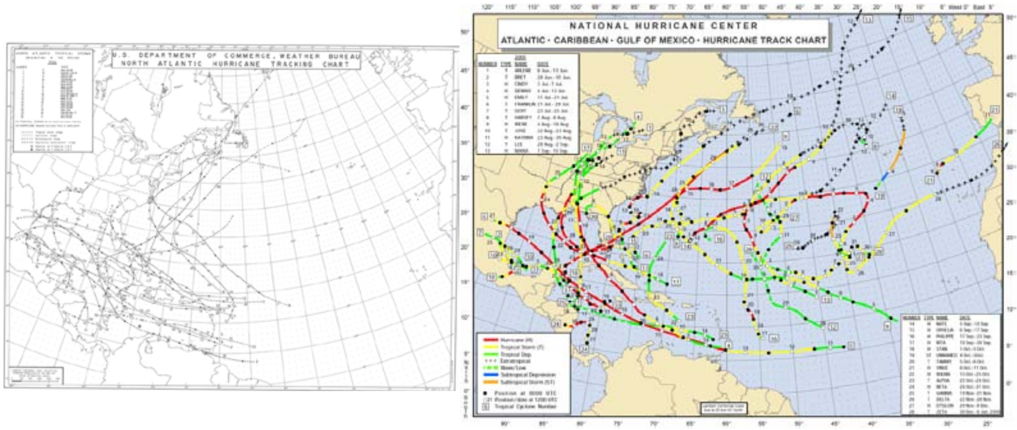
Newspapers

Before the invention of the telegraph in the early to mid 19th century, news was as fast as the quickest horse, stage, or ship. Normally, there was no advance warning of a tropical cyclone impact. However, the situation changed in the 19th century as sea-faring people and land-based researchers, such as Father Viñes in Cuba, came up with systematic methods of reading the sky's appearance or the sea state, which could foretell a tropical cyclone's approach up to a couple days in advance.

In China, the abundance of historical documentary records in the form of *Fang Zhi* (semiofficial local gazettes) offers an extraordinary opportunity for providing a high-resolution historical dataset for the frequency of typhoon strikes. Kam-biu Liu *et al.*

(2001) reconstructed a 1,000-year time series of typhoon landfalls in the Guangdong Province of southern China since AD 975 and found that on a decadal timescale, the twenty-year interval from AD 1660 to 1680 is the most active period on record, with twenty-eight to thirty-seven typhoon landfalls per decade. The variability in typhoon landfalls in Guangdong mimics that observed in other paleoclimatic proxies (e.g., tree rings, ice cores) from China and the northern hemisphere. Remarkably, the two periods of most frequent typhoon strikes in Guangdong (AD 1660-1680, 1850–1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age.

Surface observations



Maps of the 1933 and 2005 Atlantic hurricane season, the two most active on the record. 28 storms formed in 2005 of which 17 made landfall, while 19 of 21 detected storms formed in 1933 hit the coast. Note that no hurricane was detected on Mid-Atlantic in 1933.

Ship reports

For centuries, people have sailed the world's oceans and seas, and for just as long, they have encountered storms. The worst of the cyclones over the open seas likely took those that observed them into the depths of the oceans. However, some did survive to report harrowing tales. Before the invention of the wireless telegraph in 1905, reports about storms at sea either coincided with their arrival at the coast as ships scrambled into port, or came weeks and months afterwards from remote ports of call. Ship and buoy reports, available since the 1970s, are used in real-time not only for their temperature, pressure, and wind measurements, but also for their sea surface temperature and wave height measurements.

Wind reports from ships at sea have become increasingly based on anemometers, and less so on the Beaufort Scale. This is important to note as the Beaufort Scale underestimates winds at higher wind speeds, indicating ship wind observations taken for older storms are likely to underrepresent their true value.

As Christopher Landsea *et al.* point out, many tropical cyclones that formed on the open sea and did not affect any coast usually went undetected prior to satellite observation since the 1970s. They estimated an undercount bias of zero to six tropical cyclones per year between 1851 and 1885 and zero to four per year between 1886 and 1910. These undercounts roughly take into account the typical size of tropical cyclones, the density of shipping tracks over the Atlantic basin, and the amount of populated coastline.

Land-based observations

In the early 20th century, forecasting the track of cyclones was still confined to areas of the greatest surface pressure falls, based upon surface weather observations, and climatology. These methods proved to be the cutting edge of tropical cyclone forecasting through the mid 20th century. Land-based surface observations remain invaluable as a source of real-time information at locations near the coastline and inland. Combined with ship observations and newspapers, they formed the total information network for hurricane detection until radiosondes were introduced in 1941 and reconnaissance aircraft began in 1944. Land-based observations of pressure and wind can show how quickly a tropical cyclone is decaying as it moves inland. Their rainfall reports show where significant rainfall is occurring, and can be an alert for possible flooding. With the establishment of the ASOS network in the United States during the 1990s, more locations are reporting around the clock than ever before.

Mobile platforms

Since the 1990s, academic researchers have begun to deploy mobile weather stations fortified to withstand hurricane-force winds. The two largest programs are the Florida Coastal Monitoring Program and the Wind Engineering Mobile Instrumented Tower Experiment. During landfall, the NOAA Hurricane Research Division compares and verifies data from reconnaissance aircraft, including wind speed data taken at flight level and from GPS dropwindsondes and stepped-frequency microwave radiometers, to wind speed data transmitted in real time from weather stations erected near or at the coast. The National Hurricane Center uses the data to evaluate conditions at landfall and to verify forecasts.

Upper air observations

Reconnaissance aircraft

The idea of aircraft reconnaissance of tropical cyclones first was put forth by Captain W. L. Farnsworth of the Galveston Commercial Association in the early 1930s. Supported by the United States Weather Bureau, it passed both the United States Senate and United States House of Representatives in 1936. Since 1944, aircraft have been flying out to sea to find tropical cyclones. Before regular satellite coverage, this was a hit-or-miss affair.

Thereafter, aircraft flights into tropical systems became more targeted and precise. Nowadays, a C-130 is used as a hurricane hunter by the Air Force, while the P-3 Orion is used by the National Oceanic and Atmospheric Administration for research projects used to better understand tropical cyclones and improve hurricane forecasts. The implementation of synoptic observation missions by a Gulfstream jet, where dropwinsondes are used to investigate a tropical cyclone's environment, has led to a 15-20 percent reduction in track forecast errors where such missions were present.

Historical aircraft used for weather and hurricane tracking include:

- RK-47 USAF
- WB-29 USAF
- WB-57F - NASA
- B-50 USAF
- WB-50D USAF
- WC-135B USAF
- WC-130 USAF

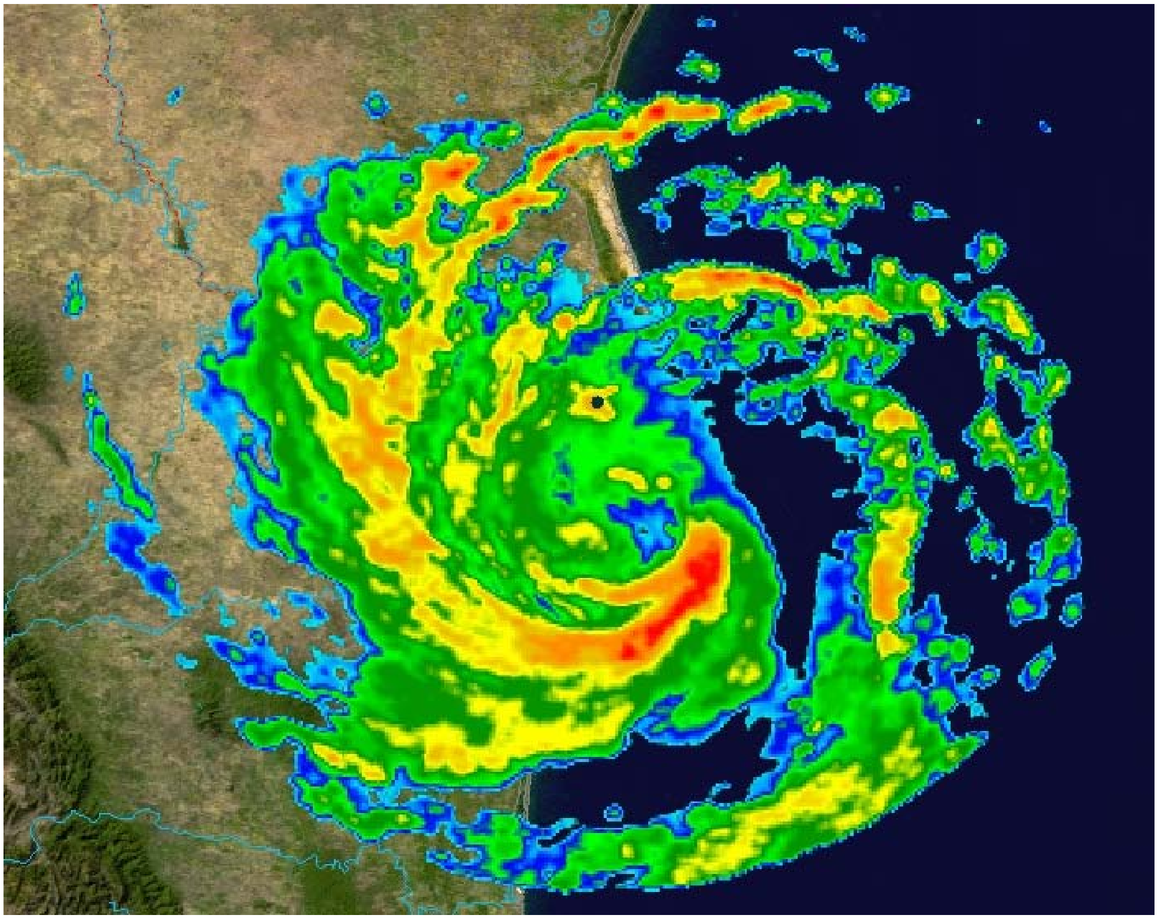
In Canada, the Convair 580 is used by National Research Council to track hurricanes.

Unmanned aerial vehicles

The era of the aerosonde began in 1998, when the Australian Bureau of Meteorology flew an aerosonde into Tropical Cyclone Tiffany. In 2005, Hurricane Ophelia became the first Atlantic tropical cyclone where an unmanned aerial vehicle, known as an aerosonde, mission was used for a tropical cyclone. The first typhoon was penetrated by an aerosonde in 2005 as well. Unlike normal reconnaissance flights, the aerosonde stayed near the surface after a 10-hour flight within the tropical cyclone.

Remote sensing

Radar



Radar image of Hurricane Erika making landfall over Northeastern Mexico

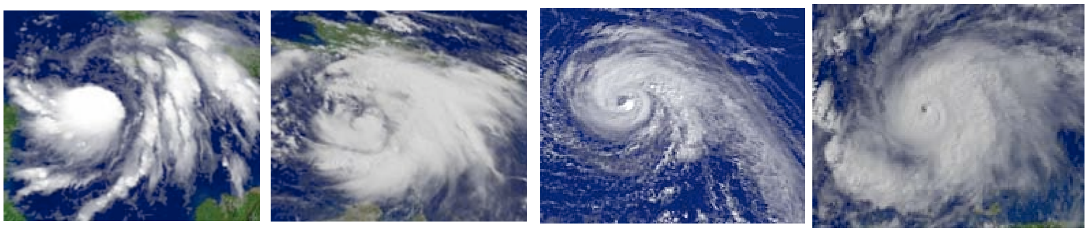
During World War II, radar technology was developed to detect aircraft. It soon became apparent that large areas became obscured when significant weather was in the area. In 1957, the National Weather Service established the United States' first radar network to cover the coastline and act as first warning of an impending tropical cyclone. Upgraded in the 1990s to use doppler technology, radar can provide rainfall estimates, wind estimates, possible locations of tornadoes within a system's spiral bands, as well as the center location of a tropical cyclone.

Satellite

Beginning with the launching of TIROS-I in April 1960, satellites have been used to look for tropical cyclones. The Dvorak technique was developed from early satellite images of tropical cyclones to determine real-time a tropical cyclone's strength from characteristics seen on satellite imagery. In most tropical cyclone basins, use of the satellite-based

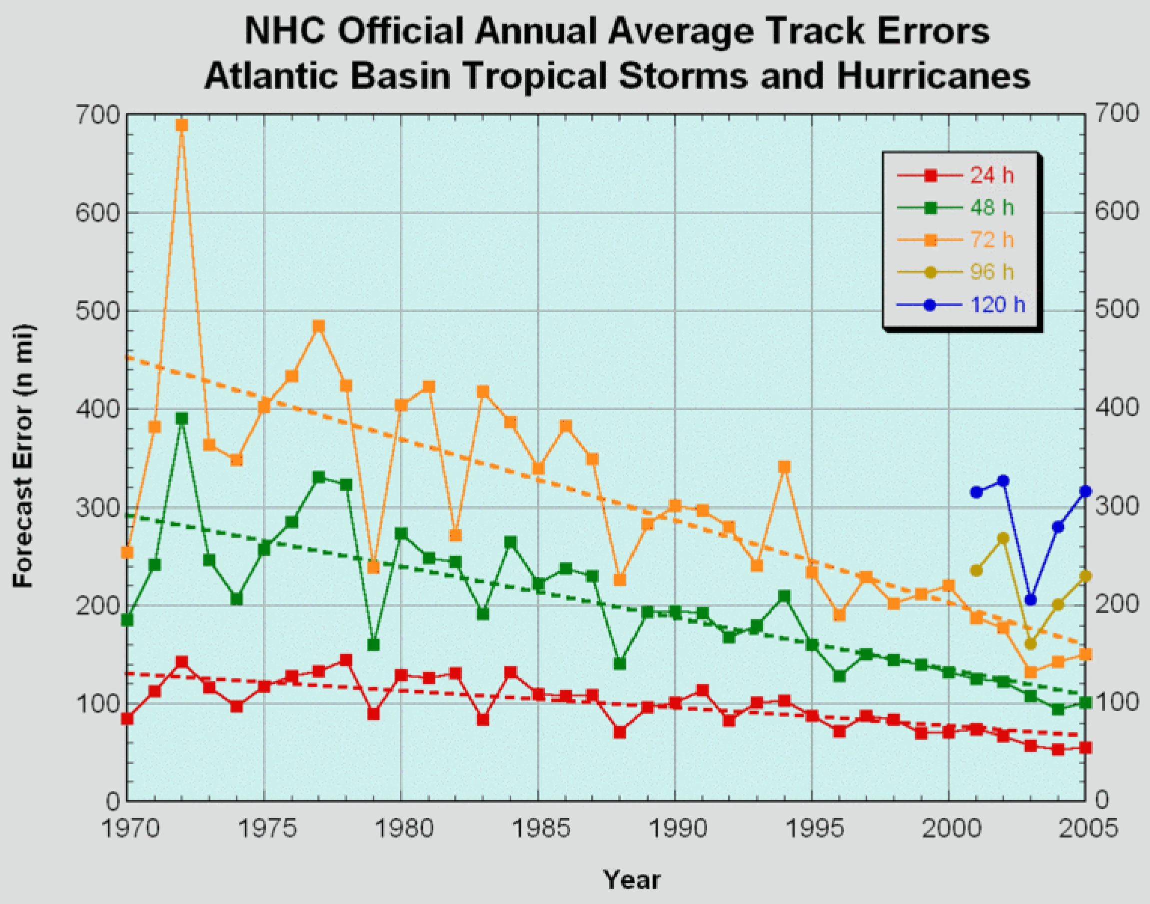
Dvorak technique is the primary method used to determine a tropical cyclone's maximum sustained winds. The extent of banding and difference in temperature between the eye and eyewall is used within the technique to assign a maximum sustained wind and pressure. Since the mid 1990s, microwave imagery has been able to determine the center of rotation when that center is obscured by mid to high level cloudiness. Cloud top temperatures are used in real-time to estimate rainfall rates within the cyclone.

Satellite Images of Selected Tropical Storms and Associated T-Number using Dvorak technique



Tropical Storm Wilma at T3.0 Tropical Storm Dennis at T4.0 Hurricane Jeanne at T5.0 Hurricane Emily at T6.0

Tropical cyclone track forecasting



Track errors for the Atlantic Basin

Tropical cyclone track forecasting involves predicting where a tropical cyclone is going to track over the next five days, every 6 to 12 hours. The history of tropical cyclone track forecasting has evolved from a single station approach to a comprehensive approach which uses a variety of meteorological tools and methods to make predictions. The weather of a particular location can show signs of the approaching tropical cyclone, such as increasing swell, increasing cloudiness, falling barometric pressure, increasing tides, squalls, and heavy rainfall.

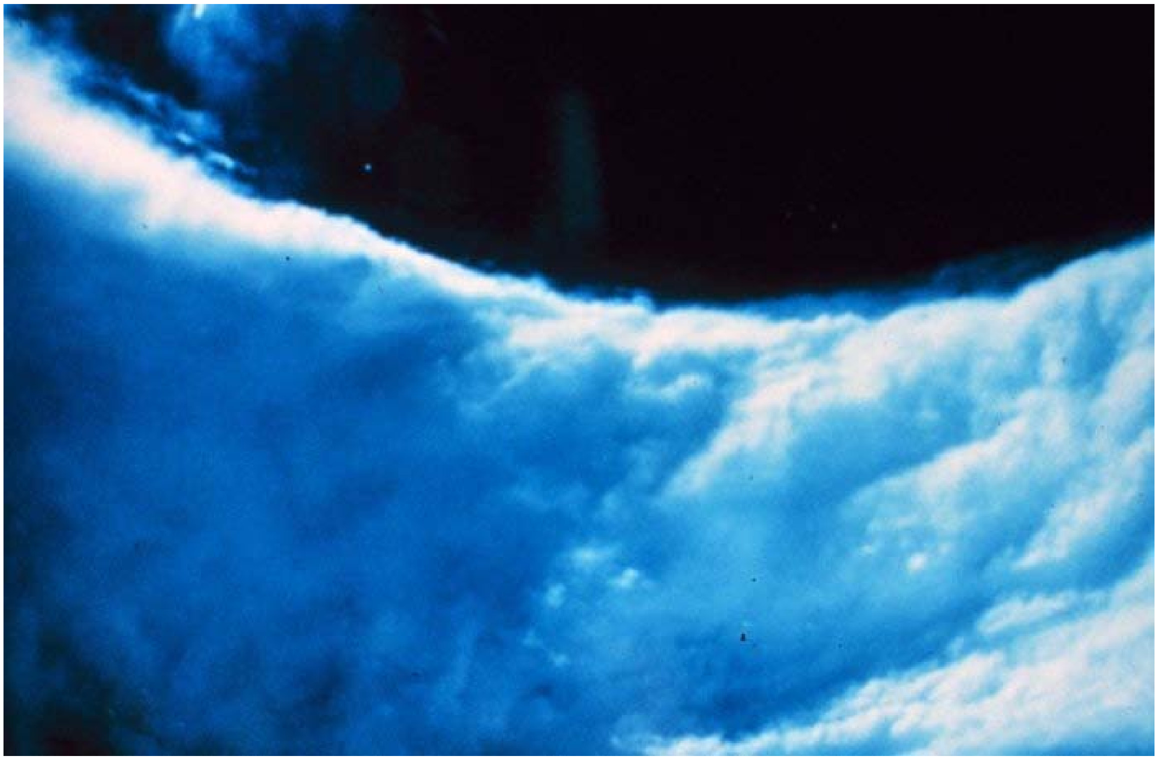
The forces that affect tropical cyclone steering are the higher latitude westerlies, the subtropical ridge, and the beta effect caused by changes of the coriolis force within fluids such as the atmosphere. Accurate track predictions depend on determining the position and strength of high and low pressure areas, and predicting how those areas will migrate during the life of a tropical system. Computer forecast models are used to help determine this motion as far out as five to seven days in the future.

History

The methods through which tropical cyclones are forecast have changed with the passage of time. The first known forecasts in the Western Hemisphere were made by Lt. Col. William Reed of the Corps of Royal Engineers at Barbados in 1847. Reed mostly utilized barometric pressure measurements as the basis of his forecasts. Benito Vines introduced a forecast and warning system based on cloud cover changes in Havana during the 1870s. Before the early 1900s, though, most forecasts were done by direct observations at weather stations, which were then relayed to forecast centers via telegraph. It was not until the advent of radio in the early twentieth century that observations from ships at sea were available to forecasters. The 1930s saw the usage of radiosondes in tropical cyclone forecasting. The next decade saw the advent of aircraft-based reconnaissance by the military, starting with the first dedicated flight into a hurricane in 1943, and the establishment of the Hurricane Hunters in 1944. In the 1950s, coastal weather radars began to be used in the United States, and research reconnaissance flights by the precursor of the Hurricane Research Division began in 1954.

With the launch of the first weather satellite, TIROS-I, in 1960, introduced new forecasting techniques that remain important to tropical cyclone forecasting to the present. In the 1970s, buoys were introduced to improve the resolution of surface measurements, which until that point, were not available at all over sea surfaces.

Single station forecasting of a tropical cyclone passage

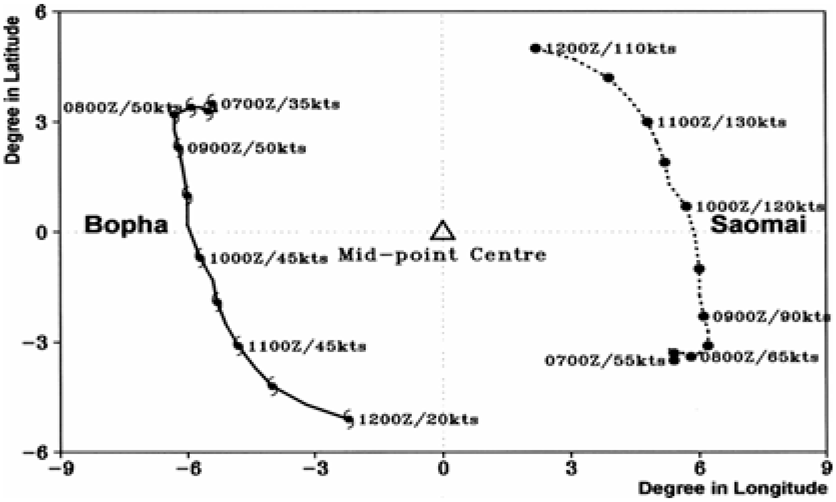


Picture of the sky within the eye of a tropical cyclone

About four days in advance of a typical tropical cyclone, an ocean swell of 1 metre (3.3 ft) in height will roll in about every 10 seconds, moving towards the coast from the direction of the tropical cyclone's location. The ocean swell will slowly increase in height and frequency the closer a tropical cyclone gets to land. Two days in advance of the center's passage, winds go calm as the tropical cyclone interrupts the environmental wind flow. Within 36 hours of the center passage, the pressure begins to fall and a veil of white cirrus clouds approaches from the cyclone's direction. Within 24 hours of the closest approach to the center, low clouds begin to move in as the barometric pressure begins to fall more rapidly and the winds begin to increase. Within 18 hours of the center's approach, squally weather is common, with sudden increases in wind accompanied by rain showers or thunderstorms. Winds increase within 12 hours of the center's approach, occasionally reaching hurricane force. The ocean's surface becomes whipped with foam. Small items begin flying in the wind. Within 6 hours of the center's arrival, rain becomes continuous and the storm surge begins to come inland. Within an hour of the center, the rain becomes very heavy and the highest winds within the tropical cyclone are experienced. When the center arrives with a strong tropical cyclone, weather conditions improve and the sun becomes visible as the eye moves overhead. At this point, the pressure ceases to drop as the lowest pressure within the storm's center is reached. This is also when the peak depth of the storm surge occurs. Once the system departs, winds reverse and, along with the rain, suddenly increase. The storm surge retreats as the pressure suddenly rises in the wake of its center. One day after the center's passage, the low overcast is replaced with a higher overcast, and the rain becomes intermittent. By 36 hours after the center's passage, the high overcast breaks and the pressure begins to level off.

Basics

The large scale synoptic flow determines 70 to 90 percent of a tropical cyclone's motion. The deep layer mean flow is considered to be the best tool in determining track direction and speed. If storms experience significant vertical wind shear, use of a lower level wind such as the 700 hPa pressure level (at a height of 3,000 metres (9,800 ft) above sea level) will work out as a better predictor. Knowledge of the beta effect can be used to steer a tropical cyclone, since it leads to a more northwest heading for tropical cyclones in the Northern Hemisphere due to differences in the coriolis force around the cyclone. For example, the beta effect will allow a tropical cyclone to track poleward and slightly to the right of the deep layer steering flow while the system lies the south of the subtropical ridge. Northwest moving storms move quicker and left, while northeast moving storms move slower and left. The larger the cyclone, the larger the impact of the beta effect is likely to be.



Interaction of two typhoons

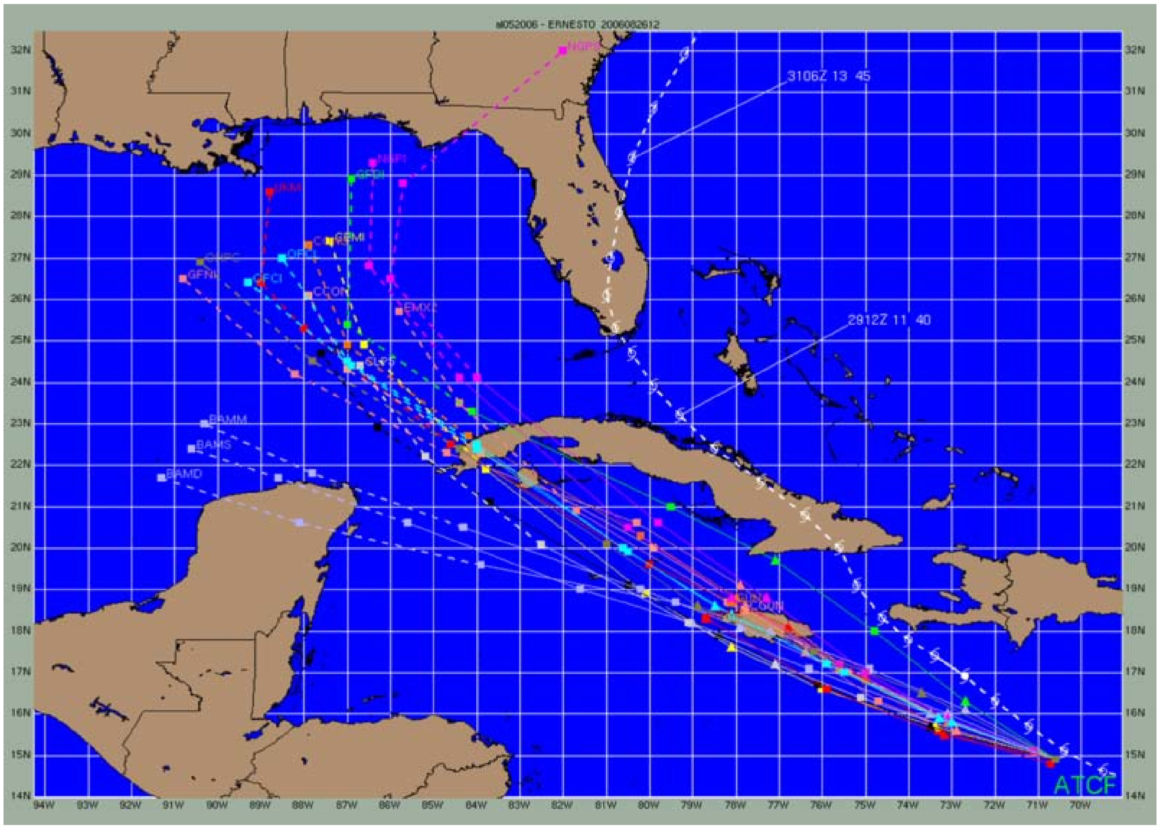
Fujiwhara effect

When two or more tropical cyclones are in proximity to one another, they begin to rotate cyclonically around the midpoint between their circulation centers. In the northern hemisphere, this is in a counterclockwise direction, and in the southern hemisphere, a clockwise direction. Usually, the tropical cyclones need to be within 1,450 kilometres (900 mi) of each other for this effect to take place. It is a more common phenomenon in the northern Pacific ocean than elsewhere, due to the higher frequency of tropical cyclone activity which occurs in that region.

Trochoidal motions

Small wobbles in a tropical cyclone's track can occur when the convection is distributed unevenly within its circulation. This can be due to changes in vertical wind shear or inner core structure. Because of this effect, forecasters use a longer term (6 to 24 hours) motion to help forecast tropical cyclones, which acts to smooth out such wobbles.

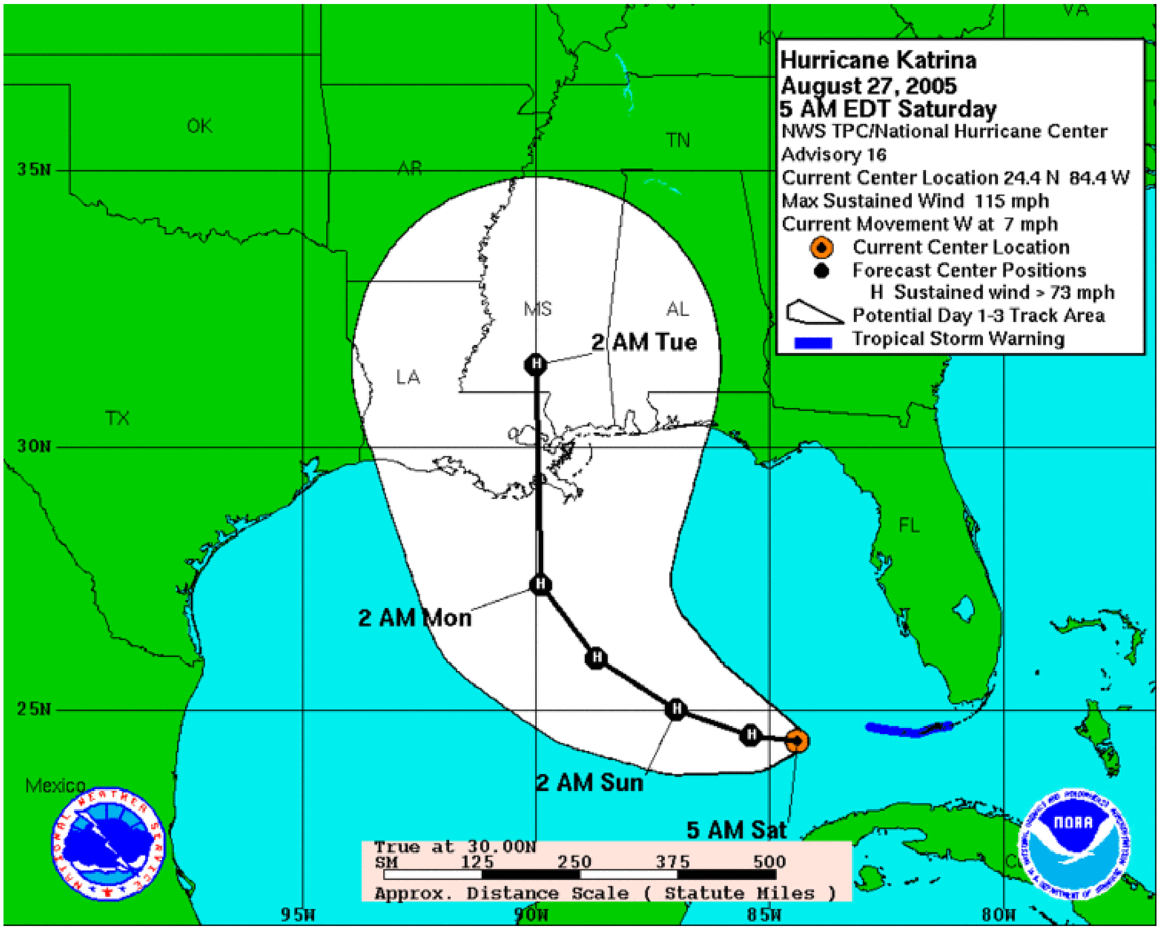
Forecast models



Significant errors in track still occur on occasion, as seen in one of Ernesto's (2006) early forecasts. The National Hurricane Center's official forecast is in light blue.

High-speed computers and sophisticated simulation software allow meteorologists to run computer models that forecast tropical cyclone tracks based on the future position and strength of high- and low-pressure systems. Combining forecast models with increased understanding of the forces that act on tropical cyclones, and a wealth of data from Earth-orbiting satellites and other sensors, scientists have increased the accuracy of track forecasts over recent decades. The addition of dropwindsonde missions around tropical cyclones in what are known as synoptic flow missions in the Atlantic Basin decreased track error by 15-20 percent. Using a consensus of forecast models, as well as ensemble members of the various models, can help reduce forecast error. However, regardless how small the average error becomes, large errors within the guidance are still possible. An accurate track forecast is important, because if the track forecast is incorrect, forecasts for intensity, rainfall, storm surge, and tornado threat will also be incorrect.

Length of forecast period



A three day National Hurricane Center track forecast for Katrina in 2005

For decades, tropical cyclone tracks were routinely issued out to 72 hours in the future. Starting in the mid to late 1990s, research into tropical cyclones and how forecast models handle the systems led to substantial improvements in track error. By 2001, the error had reduced sufficiently to extend track out to 5 days in the future on public advisories. In addition, at 1600 UTC during the hurricane season, a medium range coordination call takes place between the Hydrometeorological Prediction Center and the National Hurricane Center to coordinate tropical cyclone placement on the medium range pressure forecasts 6 and 7 days into the future for the northeast Pacific and Atlantic basins. Every so often, even at this time range, successful predictions can be made.

Chapter 6

Tropical Cyclone Scales and Tropical Cyclone Naming

Tropical cyclone scales

Tropical systems are officially ranked on one of several **tropical cyclone scales** according to their maximum sustained winds and in what oceanic basin they are located. Only a few scales of classifications are used officially by the meteorological agencies monitoring the tropical cyclones, but some alternative scales also exist, such as Accumulated Cyclone Energy, the Power Dissipation Index, the Integrated Kinetic Energy Index, and Hurricane Severity Index.

Should a tropical cyclone form in the North Atlantic Ocean or the North-eastern Pacific Ocean, it will be classified using one of the categories in the Saffir-Simpson Hurricane Scale. In the Western Pacific, tropical cyclones will be ranked using the Japan Meteorological Agency's scale. The Regional Specialized Meteorological Centre (RSMC) in New Delhi, India also uses a different scale to assess the maximum sustained winds of a tropical cyclone. In the Southern Hemisphere, the Météo-France forecast center on La Reunion uses a scale that covers the whole of the South West Indian Ocean. Both the Australian Bureau of Meteorology and the RSMC in Nadi, Fiji use the Australian tropical cyclone intensity scale.

The definition of sustained winds recommended by the World Meteorological Organization (WMO) and used by most weather agencies is that of a 10-minute average at a height of 10 m (33 ft). However, the Saffir-Simpson Hurricane Scale is based on wind speed measurements averaged over a 1-minute period, at 10 m (33 ft) above the surface. The scale used by RSMC New Delhi applies a 3-minute averaging period, and the Australian scale is based on both 3-second wind gusts and maximum sustained winds averaged over a 10-minute interval. These make direct comparisons between basins difficult.

Atlantic and East Pacific

Saffir–Simpson Hurricane Scale

Category	Wind speed mph (km/h)	Storm surge ft (m)
Five	≥ 156 (≥ 250)	> 18 (> 5.5)
Four	131–155 (210–249)	13–18 (4.0–5.5)
Three	111–130 (178–209)	9–12 (2.7–3.7)
Two	96–110 (154–177)	6–8 (1.8–2.4)
One	74–95 (119–153)	4–5 (1.2–1.5)
Additional classifications		
Tropical storm	39–73 (63–117)	0–3 (0–0.9)
Tropical depression	0–38 (0–62)	0 (0)

The Saffir-Simpson Hurricane Scale is the classification system used for tropical cyclones in the Atlantic Ocean and in the Pacific Ocean east of the anti-meridian. In these oceanic basins, tropical cyclones with maximum sustained winds below 34 kt (65 km/h, 39 mph) are labelled as *tropical depressions* by either the National Hurricane Center (if it is in the North Atlantic or North-east Pacific Basin) or the Central Pacific Hurricane Center (if located in the North Central Pacific Ocean). Should a tropical depression should reach 35 kt (65 km/h, 40 mph), it will receive a name and will be classified as a *tropical storm*. If the tropical storm continues to intensify and reaches maximum sustained winds of 64 kt (119 km/h, 74 mph) then the tropical storm will be designated as a *hurricane*.

The Saffir-Simpson scale counts with five different classifications for the intensity of a hurricane, with a Category 1 storm having the lowest maximum winds, whilst a Category 5 hurricane having the highest. Storms that meet the 64-knot threshold, but do not possess maximum sustained winds in excess of 83 kt (177 km/h, 96 mph) are classified as Category 1 hurricanes. A Category 1 storm will be upgraded to a Category 2 hurricane if its maximum sustained winds reach 83 knots. Tropical cyclones that possess wind speeds of at least 96 kt (178 km/h, 111 mph) are classified as Category 3 hurricanes. Category 3 also marks the point at which the NHC and CPHC classify strong storms as *major hurricanes*. If a hurricane's maximum sustained winds reach 114 kt, (210 km/h, 131 mph), it will be ranked as a Category 4 hurricane. Storms with winds that surpass

136 kt (250 km/h, 156 mph) are of Category 5 intensity. The SSHS was originally created using both wind speed and storm surge, but since the relationship between wind speed and storm surge is not necessarily definite, the scale was changed to the Saffir-Simpson Hurricane Wind Scale (SSHWS), based entirely on wind speed.

Although increasing echelons of the scale correspond to stronger winds, the rankings are not absolute in terms of effects. Lower-category storms can inflict greater damage than higher-category storms, depending on factors such as local terrain, population density and total rainfall. For instance, a Category 2 that strikes a major urban area will likely do more damage than a large Category 5 hurricane that strikes a mostly rural region. In fact, tropical systems of less than hurricane strength can produce significant damage and human casualties, especially from flooding and landslides.

Historically, the term *great hurricane* was used to describe storms that possessed winds of at least 110 kt (200 km/h, 125 mph), large radii (over 100 mi / 160 km) and that caused large amounts of destruction. This term fell into disuse after the introduction of the Saffir-Simpson scale in the early 1970s.

West Pacific

RSMC Tokyo's
Tropical Cyclone Intensity Scale

Category	Sustained winds
Typhoon	≥64 kt ≥118 km/h
Severe Tropical Storm	48–63 kt 89–117 km/h
Tropical Storm	35–48 kt 62–88 km/h
Tropical Depression	<33 kt <61 km/h

Any tropical cyclone that forms to the west of 180° and east of 100°E in the Northern Hemisphere is officially monitored by the Regional Specialized Meteorological Center in Tokyo, Japan. The Japan Meteorological Agency, which runs RSMC Tokyo, uses four different categories to measure the wind speed produced by a tropical cyclone. These classifications are based on the maximum sustained winds produced by the storm averaged over a 10-minute interval.

A *tropical depression* is the lowest category that the Japan Meteorological Agency uses and is the term used for a tropical system that has wind speeds not exceeding 35 knots, (40 mph, 65 km/h). A tropical depression is upgraded to a *tropical storm* should its sustained wind speeds exceed 35 knots, (40 mph, 65 km/h). Tropical storms also receive official names from RSMC Tokyo. Should the storm intensify further and reach sustained wind speeds of 50 knot (60 mph, 95 km/h) then it will be classified as a *severe tropical storm*. Once the system's maximum sustained winds reach wind speeds of 65 knots (70 mph 120 km/h), the JMA will designate the tropical cyclone as a *typhoon*—the highest category on its scale. From 2009 the Hong Kong observatory started to further divide typhoon into two further classifications *severe typhoon* and *super typhoon*. A severe typhoon has winds of at least 80 knot (95 mph, 150 km/h) whilst a super typhoon has winds of at least 100 knot (115 mph, 185 km/h).

The United States' Joint Typhoon Warning Center (JTWC) unofficially classifies typhoons with wind speeds of at least 130 knots (67 m/s; 150 mph; 241 km/h)—the equivalent of a strong Category 4 storm in the Saffir-Simpson scale—as *super typhoons*. However, the maximum sustained wind speed measurements that the JTWC uses are based on a 1-minute averaging period, akin to the U.S.' National Hurricane Center and Central Pacific Hurricane Center. As a result, the JTWC's wind reports are higher than JMA's measurements, as the latter are based on a 10-minute averaging interval.

North Indian Ocean

India Meteorological Department
Tropical Cyclone Intensity Scale

Category	Sustained winds (3-min average)
Super Cyclonic Storm	>120 kt >222 km/h
Very Severe Cyclonic Storm	64–119 kt 118–221 km/h
Severe Cyclonic Storm	48–63 kt 88–117 km/h
Cyclonic Storm	34–47 kt 62–87 km/h
Deep Depression	28–33 kt 52–61 km/h
Depression	≤27 kt ≤51 km/h

Any tropical cyclone that forms between longitude 45°E and 100°E in the Northern Hemisphere is monitored by the India Meteorological Department (IMD), who run the Regional Specialized Meteorological Center in New Delhi, India. Since 1998, RSMC New Delhi has used six different categories to measure the wind speed of a tropical cyclone based on the maximum sustained winds over a 3-minute averaging period.

A *depression* is the lowest category that RSMC New Delhi uses to designate tropical systems, and systems designated as depressions have wind speeds of under 27 kt (51 km/h, 31 mph). A depression is classified as a *deep depression* when it has maximum sustained winds between 27 kt (51 km/h, 31 mph) and 33 kt (61 km/h, 38 mph). Should a deep depression intensify further, it will be classified as a *cyclonic storm* if its sustained winds reach 34 kt (62 km/h, 39 mph). When a tropical system is classified as a cyclonic storm, it is assigned a name by the IMD.

In cases where cyclonic storms possess wind speeds greater than 48 kt, (88 km/h, 55 mph), they are classified as *severe cyclonic storms*. A severe cyclonic storm is labelled as a *very severe cyclonic storm* when it reaches wind speeds greater than 64 kt, (118 km/h, 74 mph). Finally, a *super cyclonic storm* is the highest category that the India Meteorological Department uses in its scale, and is used to refer to tropical cyclones that have maximum sustained winds exceeding 120 kt, (222 km/h, 138 mph).

Prior to 1988, cyclones were classified into 4 categories, which were depression, deep depression, cyclonic storms and severe cyclonic storms. However in 1988 the IMD started to rate cyclones with wind speeds of more than 64 kt, (118 km/h, 74 mph) as severe cyclonic storms. The IMD then made another change in 1998 to introduce a category for super cyclonic storms, which are cyclonic storms with wind speeds of more than 120 kt, (222 km/h, 138 mph).

South-West Indian Ocean

Southwest Indian Ocean
Tropical Cyclone Intensity Scale

Category	Sustained winds
Very Intense Tropical Cyclone	>115 kt >212 km/h
Intense tropical cyclone	90–115 kt 166–212 km/h
Tropical Cyclone	64–89 kt 118–165 km/h
Severe Tropical Storm	48–63 kt 89–117 km/h
Moderate Tropical Storm	34–47 kt 63–88 km/h
Tropical Depression	28–33 kt 51–62 km/h
Tropical Disturbance	<28 kt <50 km/h

Any Tropical Cyclone that forms within the Southern Indian Ocean to the west of 90°E, is monitored by Météo-France who run the Regional Specialized Meteorological Center in La Reunion. RSMC La Reunion uses seven different categories to measure the wind speed of a tropical cyclone. It is based on a 10-minute average maximum sustained winds, rather than 1-Minute Maximum Sustained winds, which is what the Saffir-Simpson Hurricane Scale uses.

A Tropical Disturbance is the lowest category on the South-west Indian Ocean Tropical Cyclone scale, and has wind speeds 28 knots (32 mph, 50 km/h). A Tropical Disturbance is designated as a Tropical Depression, when the disturbance reaches wind speeds above 28 knots (32 mph, 50 km/h). Should a Tropical Depression reach wind speeds of 35 knots (40 mph, 65 km/h.) then it will be classified as a Moderate Tropical Storm and assigned a name by either the Sub Regional Center in Mauritius or Madagascar.

Should the named storm intensify further and reach winds speeds of 48 knots (55 mph, 89 km/h), then it will be classified as a Severe Tropical Storm. A Severe Tropical Storm is designated as a Tropical Cyclone when it reaches wind speeds of 64 knots (74 mph, 118 km/h). Should a Tropical Cyclone intensify further and reach wind speeds of 90 knots (103 mph, 166 km/h), it will be classified as an Intense Tropical Cyclone. A Very Intense Tropical Cyclone is the highest category on the South-West Indian Ocean Tropical Cyclone scale, and has winds of over 115 knots (132 mph 212 km/h).

Australia

Australian Region
Tropical Cyclone Intensity Scale

Category	Sustained winds	Gusts
Five	>107 kt >200 km/h	>151 kt >279 km/h
Four	86-107 kt 160-200 km/h	122-151 kt 225-279 km/h
Three	64-85 kt 118-159 km/h	90-121 kt 165-224 km/h
Two	48-63 kt 89-117 km/h	68-89 kt 125-164 km/h
One	34-47 kt 63-88 km/h	49-67 kt 91-125 km/h
Tropical Low	<34 kt <63 km/h	<49 kt <91 km/h

Any Tropical Cyclone that forms to the east of 90°E in the Southern Hemisphere, is monitored by either the Australian Bureau of Meteorology and or the Regional Specialized Meteorological Center in Nadi, Fiji. Both warning centres use the Australian tropical cyclone intensity scale, which measures tropical cyclones using a six category system. It is based on estimated maximum wind gusts, which are a further 30-40% stronger than the 10-minute average sustained winds. This is different from the Saffir-Simpson Hurricane Scale, which uses 1-Minute Maximum Sustained winds.

When a Tropical Cyclone that has wind speeds below 35 knots (40 mph, 65 km/h) forms east of 160°E it is labelled as either a Tropical Disturbance or a Tropical Depression by RSMC Nadi. If it forms to the west of 160°E it is labelled as a Tropical Low by the Australian Bureau of Meteorology. However if it forms to the north of 10°S and between 90°E to 125°E the low is labelled as a Tropical Depression by the Tropical Cyclone Warning Center in Jakarta, Indonesia.

If a tropical depression should reach 35 knots (40 mph, 65 km/h), it will be named by the TCWC or RSMC and be classified as a Tropical Cyclone. Should the cyclone intensify further reaching maximum sustained winds of 65 knots (75 mph 145 km/h) then the cyclone will be designated as a Category Three Severe Tropical Cyclone. A Severe Tropical Cyclone will be classified as a Category Five Severe Tropical Cyclone should the cyclones maximum sustained wind speeds be greater than 110 Knots (130 mph, 200 km/h) and the gusts be above 150 knots (175 mph, 280 km/h).

Comparisons across basins

The terminology for tropical cyclones differs from one region to another. Below is a summary of the classifications used by Regional Specialized Meteorological Centres worldwide:

Tropical Cyclone Classifications (all winds are 10-minute averages)

Beaufort scale	10-minute sustained winds (knots)	N Indian Ocean IMD	SW Indian Ocean MF	Australia BOM	SW Pacific FMS	NW Pacific JMA	NW Pacific JTWC	NE Pacific & N Atlantic NHC & CPHC
0–6	<28	Depression	Tropical Disturbance	Tropical Low	Tropical Depression	Tropical Depression	Tropical Depression	Tropical Depression
7	28-29	Deep Depression	Tropical Depression					
	30-33							
8–9	34–47	Cyclonic Storm	Moderate Tropical Storm	Tropical Cyclone (1)	Tropical Cyclone (1)	Tropical Storm	Tropical Storm	Tropical Storm
10	48–55	Severe Cyclonic Storm	Severe Tropical Storm	Tropical Cyclone (2)	Tropical Cyclone (2)	Severe Tropical Storm		
11	56–63							
12	64–72	Very Severe Cyclonic Storm	Tropical Cyclone	Severe Tropical Cyclone (3)	Severe Tropical Cyclone (3)	Typhoon	Typhoon	Hurricane (1)
13	73–85							Hurricane (2)
14	86–89			Severe Tropical Cyclone (4)	Severe Tropical Cyclone (4)			Major Hurricane (3)
15	90–99		Intense Tropical Cyclone					
16	100–106							Major Hurricane (4)
17	107-114			Severe Tropical Cyclone (5)	Severe Tropical Cyclone (5)			
	115–119		Very Intense Tropical Cyclone				Super Typhoon	
	>120	Super Cyclonic Storm						Major Hurricane (5)

Alternative scales

There are other scales that are not officially used by any of the Regional Specialized Meteorological Centres or the Tropical Cyclone Warning Centres. However they are used by other organizations, such as the National Oceanic and Atmospheric Administration. An example of such scale is the Integrated Kinetic Energy index, which measures the destructive potential of the storm surge; it works on a scale that ranges from one to six, with six having the highest destructive potential.

Accumulated Cyclone Energy (ACE), is used by the National Oceanic and Atmospheric Administration and other agencies, to express the activity of individual tropical cyclones that are above tropical storm strength and entire tropical cyclone seasons. It is calculated by taking the squares of the estimated maximum sustained velocity of every active tropical storm (wind speed 35 knots or higher), at six-hour intervals. The numbers are usually divided by 10,000 to make them more manageable. The unit of ACE is 10^4 kt^2, and for use as an index the unit is assumed. As well as being squared ACE can also be cubed, and this version is known as the Power Dissipation Index (PDI).

The Hurricane Severity Index (HSI) is another scale used and rates the severity of all types of tropical and subtropical cyclones based on both the intensity and the size of their wind fields. The HSI is a 0 to 50 point scale, allotting up to 25 points for a Tropical cyclone's intensity and up to 25 points for wind field size. Points are awarded on a sliding scale, with the majority of points reserved for hurricane force and greater wind fields.

Wind speed conversions

The definition of sustained winds recommended by the World Meteorological Organization (WMO) and used by most weather agencies is that of a 10-minute average at a height of 10 m (33 ft). However, RSMC Miami and Honolulu, as well as the Joint Typhoon Warning Center, define sustained winds based on 1-minute average speed, and are also measured 10 m (33 ft) above the surface. To convert a one-minute wind speed from a tropical cyclone to a ten minute wind speed, the 1 minute speed is multiplied by 0.88.

Tropical cyclone naming

Tropical cyclones have officially been named since 1945 and are named for a variety of reasons, which include to facilitate communications between forecasters and the public when forecasts, watches, and warnings are issued. Names also reduce confusion about what storm is being described, as more than one can occur in the same region at the same time. The official practice of naming tropical cyclones started in 1945 within the Western Pacific and was gradually extended out until 2004, when the North Indian Ocean started to name cyclonic storms within the Bay of Bengal and Arabian sea. Before the official practice of naming of tropical cyclones began, significant tropical cyclones were named after annoying politicians, mythological creatures, saints and place names. Names are drawn in order from predetermined lists and are usually assigned to tropical cyclones with one, three or ten minute sustained windspeeds of more than 65 km/h (40 mph) depending on which area it originates. However, standards vary from basin to basin with some tropical depressions named in the Western Pacific, while within the Southern Hemisphere tropical cyclones have to have a significant amount of gale force winds occurring around the center before it is named.

History of tropical cyclone naming

Before the official naming of tropical cyclones began in each basin, significant tropical cyclones were named after annoying politicians, mythological creatures, saints and place names, or were just simply numbered with a set of code letters before it.

Atlantic

From 1950 the United States Weather Bureau (USWB), began to assign names to tropical cyclones that were judged to have intensified into tropical storms. Storms were originally named in alphabetical order using the World War II version of the Phonetic Alphabet. In 1953 a new set of 23 women's names were used, to avoid any confusion as a secondary phonetic alphabet had been developed. After the active but mild 1953 Atlantic hurricane season, public reception to the idea seemed favorable, so the same list was adopted for the next year with only one change; Gilda for Gail. After storms like Carol and Hazel got a lot of publicity during the 1954 season, forecasters developed a new set of names in time for the 1955 season. However before this could happen, a tropical storm developed on January 2 1955 and was named as Alice. The new set of names was developed and were used during 1955 beginning with Brenda and continued through the alphabet to Zelda. For each season before 1960, a new set of names was developed before in 1960 forecasters decided to begin rotating names in a regular sequence and thus four alphabetical lists were established to be repeated every four years. The sets followed the example of the western Pacific typhoon naming lists and excluded names beginning with the letters Q, U, X, Y and Z. These four lists were used until 1972 when National Oceanic and Atmospheric Administration (NOAA), replaced them with nine lists designed to be used annually from 1972. In 1977, NOAA decided to relinquish control over the name selection and allow a regional committee of the World Meteorological Organization (WMO) to select the names. The WMO decided that the names would be used from 1979, with six new lists which contained male names and some Spanish and French names to reflect all the cultures and languages used within the Atlantic Ocean. Since 1979 the same six lists have been used, with names of significant tropical cyclones removed from the lists and replaced with new names. In 2002, subtropical cyclones started to be assigned names from the main list of names set up for that year. In 2005 as all the names preselected for the season was exhausted, the contingency plan of using the Greek alphabet for names had to be used. Since then there have been a few attempts to get rid of the Greek names as they are seen to be inconsistent with the standard naming convention used for tropical cyclones and are generally unknown and confusing to the public. However none of the attempts have succeeded and thus the Greek alphabet will be used should the lists ever be used up again.

Eastern Pacific

Beginning in 1960, tropical cyclones that were judged by the USWB to have intensified into a tropical storm, with winds of more than 65 km/h (40 mph), started to be assigned female names. The original naming lists were designed to be used year after year in sequence before, early in the 1965 season, it was decided to rotate the same lists every four years. In 1977, after protests by various women's rights groups, NOAA made the decision to relinquish control over the name selection by allowing a regional committee of the WMO to select new sets of names. The WMO selected six lists of names which contained male names and rotated every six years. They also decided that the new lists of hurricane name would start to be used in 1978 which was a year earlier than the Atlantic. Since 1978 the same lists of names have been used, with names of significant tropical cyclones removed from the lists and replaced with new names. As in the Atlantic basin, should the names preselected for the season be exhausted the contingency plan of using the Greek alphabet for names would be used. However unlike in the Atlantic basin the contingency plan has never had to be used, although in 1985 to avoid using the contingency plan, the letters X, Y, and Z were added to the lists. Since the contingency plan was used during the 2005 Atlantic hurricane season, there have been attempts to get rid of the Greek names as they are seen to be inconsistent with the standard naming convention used for tropical cyclones and are generally unknown and confusing to the public. However none of the attempts have succeeded and thus the Greek letters will still be used should the lists ever be exhausted.

Central Pacific

Beginning in 1950 tropical cyclones that were judged by the Joint Hurricane Warning Center to have intensified into a tropical storm, with winds of more than 65 km/h (40 mph), started to be assigned names. Between 1950 and 1957, tropical storms were given names from the Hawaiian language before the decision was made in 1957 to take names from the Western Pacific list. In 1979, Hawaiian names were reinstated for tropical depressions intensifying in tropical storms within the Central Pacific. Five sets of Hawaiian names, using only the 12 letters of the Hawaiian alphabet, were drafted with the intent being to use the sets of names on an annual rotation basis. However as no tropical cyclones had formed in this region between 1979 and 1981, the original lists were scrapped and replaced with four sets of names. Also, the plan of how to allocate the names was changed to allow all the names to be used consecutively. The naming lists were used until 2007 the lists were revised in conjunction with the University of Hawaii with one-third of the names being retired or replaced.

Western Pacific

In 1945, the United States armed services, publicly adopted a list of names that they would name tropical depressions that intensified into tropical storms within the western Pacific. During the 1959 season the US armed services combined to form the Joint Typhoon Warning Center (JTWC) who took on responsibility for naming all tropical storms between the 100°E and 180. Initially the lists of names only consisted of female names before in April 1979, the naming lists were revised to include male names. In 1998 the WMO's/ESCAP typhoon committee, decided that the current naming lists were too English and decided that they would control the list of names with the names assigned to tropical storms by the Japan Meteorological Agency instead of the JTWC.

In 1963 the Philippine Atmospheric, Geophysical and Astronomical Services Administration decided to start naming tropical depressions with the names of Filipino women which ended in "ng," when they formed or moved into their area of responsibility. They continued the practice of naming tropical depressions, until the 2001 season when they started to name tropical cyclones with male names and scrapped the requirement for them to end in "ng".

North Indian ocean

The WMO/ESCAP Panel on North Indian Tropical Cyclones at its 27th session in 2000, agreed to assign names to the tropical cyclones in the North Indian Ocean. After long deliberations among the member countries, the naming of Depressions developing into a Cyclonic Storm in the North Indian Ocean began from September 2004. With the first name assigned to Cyclone Onil which developed over the Arabian Sea in late September 2004 with the name assigned by the India Meteorological Department.

South-West Indian ocean

Formal naming of tropical cyclones, in the South-West Indian Ocean began during the 1960-61 season, with the first name (Anna) assigned to a zone of disturbed weather during November 1960. Over the years, there have been various selection processes for selecting the names, that will be assigned to tropical/subtropical storms during the season. During the 1980's and 1990's, names were chosen by the national Meteorological Services of the region, in turn for several seasons, with Madagascar's Direction de la Météorologie et de l'Hydrologie, choosing the names at the end of the 1980 and early 1990's while the Seychelles national meteorological service selected the names at the end of the 1990s. Since the start of the 2000-01 season, the names have been selected by the WMO's South West Indian Ocean Tropical Cyclone Committee for a couple of seasons in advance. Until the WMO took over the naming, all off the names selected were female; since then, both men and women names have been used. Unlike other basins; RSMC La Reunion does not name tropical cyclones as they intensify into tropical or subtropical storms. For historic reasons they instead delegate this responsibility to the Mauritius Meteorological Service (MMS) and the Direction de la Météorologie et de l'Hydrologie.

Australian region

Tropical lows or tropical depressions that intensify into tropical cyclones within the Australian region have been named since the 1963-64 tropical cyclone season. Between 1963-64 and 1974-75, female names were used exclusively by the warning centers, before the current convention of alternating male and female names began at the start of the 1975-76 cyclone season. Until the start of the 2007-08 season, tropical cyclones were assigned names by the tropical cyclone warning centers in Perth, Darwin, Port Moresby and Brisbane from four different lists. However during the 2007-08 season TCWC Jakarta started to name tropical cyclones before at the start of 2008-09 season, TCWC Perth, Darwin and Brisbane merged their lists into one list.

Southern Pacific

Within the Southern Pacific, tropical depressions that develop into tropical cyclones have been officially named since the 1964-65 tropical cyclone season. However some records show that names have been assigned on an irregular basis since the start of the 1955-56 season. Female names were used exclusively until the start of the 1974-75 season, when the current convention of alternating male and female names began. Names are developed by a regional committee of the WMO and are assigned, by the Fiji Meteorological Service and the Meteorological Service of New Zealand Limited.

Other areas

Tropical cyclone formation is rare within the Mediterranean sea, South Atlantic, and to the east of the 120th meridian west in the Southern Pacific, and as a result there are no official naming lists for these areas. In 2004 & 2010 when tropical cyclones formed within the South Atlantic they were named as Catarina and Anita.

Renaming of tropical cyclones

When a tropical cyclone moves from one basin to another.

Generally, when a tropical storm moves from one warning center's area of responsibility to another, its original name will be retained. However, before 2001, the National Hurricane Center, used to rename tropical storm when they moved from the Atlantic to the Eastern Pacific or visa versa. Also when a tropical cyclone moves from the Australian region into the South-West Indian Ocean, the Mauritius Meteorological Service will rename it. However when a tropical cyclone moves from the South-West Indian Ocean into the Australian region, it is not renamed. Prior to the 1984-85 season, tropical cyclones were renamed when they crossed 80°E. After the Australian region was shortened for the start of the 1985-86 season, tropical cyclones were renamed when they crossed the 90°E instead of 80°E.

Uncertainties of the continuation

When the remnants of a tropical cyclone redevelop, the redeveloping system will be treated as a new tropical cyclone if there are uncertainties of the continuation, even though the original system may contribute to the forming of the new system. An example of this is Severe Tropical Cyclone Wasa-Arthur and Tropical Storm Upana-Chanchu in 2000.

Human error

Sometimes, there may be human faults leading to the renaming of a tropical cyclone. This is especially true if the system is poorly organized, such as Tropical Storm Ken-Lola in 1989, or if it passes from the area of responsibility of one forecaster to another.

Retirement

Those cyclones that have their names retired tend to be exceptionally destructive storms that often become household names in the regions they affected. Within the North Atlantic Ocean, the Pacific Ocean and the Australian region, the names of significant tropical cyclones are removed from the lists and retired in a meeting of the WMO's regional committee. As a name is generally not used more than once and fresh naming lists are developed each year, there is no need for significant tropical cyclone names to be retired within the South-West Indian Ocean. While there currently is not a public policy of retiring names in the North Indian Ocean. As it is rare for a name to be assigned within TCWC Port Moresby's area of responsibility, the name is automatically retired regardless of any damage caused.

Chapter 7

Saffir–Simpson Hurricane Scale

Saffir–Simpson Hurricane Scale

Category	Wind speed mph (km/h)	Storm surge ft (m)
Five	≥ 156 (≥ 250)	> 18 (> 5.5)
Four	131–155 (210–249)	13–18 (4.0–5.5)
Three	111–130 (178–209)	9–12 (2.7–3.7)
Two	96–110 (154–177)	6–8 (1.8–2.4)
One	74–95 (119–153)	4–5 (1.2–1.5)
Additional classifications		
Tropical storm	39–73 (63–117)	0–3 (0–0.9)
Tropical depression	0–38 (0–62)	0 (0)

The **Saffir–Simpson Hurricane Scale**, also referred to as the **Saffir–Simpson Hurricane Wind Scale**, is a classification used for some Western Hemisphere tropical cyclones that exceed the intensities of tropical depressions and tropical storms. The scale divides hurricanes into five categories distinguished by the intensities of their sustained winds. To be classified as a hurricane, a tropical cyclone must have maximum sustained winds of at least 74 mph (33 m/s; 64 kn; 119 km/h). The highest classification in the scale, Category 5, is reserved for storms with winds exceeding 155 mph (69 m/s; 135 kn; 249 km/h).

The classifications are intended primarily for use in measuring the potential damage and flooding a hurricane will cause upon landfall, although they have been criticized as being too simple. Officially, the Saffir–Simpson Hurricane Scale is used *only* to describe hurricanes forming in the Atlantic Ocean and northern Pacific Ocean east of the International Date Line. Other areas use different scales to label these storms, which are called "cyclones" or "typhoons", depending on the area.

History

The scale was developed in 1971 by civil engineer Herbert Saffir and meteorologist Bob Simpson, who at the time was director of the U.S. National Hurricane Center (NHC). The scale was introduced to the general public in 1973, and saw widespread use after Neil Frank replaced Simpson at the helm of the NHC in 1974.

The initial scale was developed by Saffir, a structural engineer, who in 1969 went on commission for the United Nations to study low-cost housing in hurricane-prone areas. While performing the study, Saffir realized there was no simple scale for describing the likely effects of a hurricane. Mirroring the utility of the Richter magnitude scale in describing earthquakes, he devised a 1–5 scale based on wind speed that showed expected damage to structures. Saffir gave the scale to the NHC, and Simpson added the effects of storm surge and flooding. However, in 2009, the NHC made moves to eliminate pressure and storm surge ranges from the categories, transforming it into a pure wind scale. The new scale became operational on May 15, 2010. The scale does not take into account rainfall or location, which means a Category 2 hurricane which hits a major city will likely do far more cumulative damage than a Category 5 hurricane that hits a rural area.

The NHC decided that for its 2010 hurricane season, it would use the experimental Saffir–Simpson Hurricane Wind Scale (SSHWS), which would be based on the SSHS, but exclude flood ranges and storm surge estimations. The agency cited various hurricanes as reasons for removing the "scientifically inaccurate" information, including Hurricane Katrina and Hurricane Ike which both had stronger than estimated storm surge and Hurricane Charley which had weaker than estimated storm surge.

Categories

The scale separates hurricanes into five different categories based on wind. The U.S. National Hurricane Center classifies hurricanes of Category 3 and above as *major hurricanes*. Most weather agencies use the definition for sustained winds recommended by the World Meteorological Organization (WMO), which specifies measuring winds at a height of 33 ft (10.1 m) for 10 minutes, and then taking the average. By contrast, the U.S. National Weather Service defines sustained winds as average winds over a period of one minute, measured at the same 33 ft (10.1 m) height. Central pressure and storm surge values are approximate and often dependant on other factors, such as the size of the storm and the location. Intensity of example hurricanes is from both the time of landfall and the maximum intensity. As a result, it is not uncommon for a pressure to be significantly higher or lower than expected for a specific category. Generally, large storms with very large radii of maximum winds have the lowest pressures relative to its intensity.

The scale is roughly logarithmic in wind speed, and the top wind speed for Category "*c*" (*c*=1 to 4) can be expressed as $83 \times 10^{c/15}$ miles per hour rounded to the nearest multiple of 5.

The five categories are, in order of increasing intensity:

Category 1

Category 1			
	33–42 m/s	64–82 kn	 Karen as a minimal hurricane
Sustained winds	119–153 km/h	74–95 mph	
Normal central pressure	980–994 mbar	28.94 inHg	

Category 1 storms usually cause no significant structural damage to building structures; however, they can topple unanchored mobile homes, as well as uproot or snap trees. Poorly attached roof shingles or tiles can blow off. Coastal flooding and pier damage are often associated with Category 1 storms.

Examples of storms of this intensity include: Hurricane Alice (1954), Danny (1985), Jerry (1989), Ismael (1995), Claudette (2003), Gaston (2004), Humberto (2007), and Richard (2010).

Category 2

Category 2			
	43–49 m/s	83–95 kn	 Alex approaching Mexico
Sustained winds	154–177 km/h	96–110 mph	
Normal central pressure	965–979 mbar	28.50–28.91 inHg	

Storms of Category 2 are strong enough that they can lift a house, and inflict damage upon poorly constructed doors and windows. Vegetation, poorly constructed signs, and piers can receive considerable damage. Mobile homes, whether anchored or not, are typically damaged, and many manufactured homes also suffer structural damage. Small craft in unprotected anchorages may break their moorings.

Hurricanes that peaked at Category 2 intensity, and made landfall at that intensity, include Diana (1990), Erin (1995), Alma (1996), Marty (2003), Juan (2003), Dolly (2008), and Alex (2010).

Category 3

Category 3			
Sustained winds	50–58 m/s 178–209 km/h	96–113 kn 111–130 mph	 Bertha in the open Atlantic
Normal central pressure	945–964 mbar	27.91–28.47 inHg	

Tropical cyclones of Category 3 and higher are described as major hurricanes in the Atlantic or Eastern Pacific basins. These storms can cause some structural damage to small residences and utility buildings, particularly those of wood frame or manufactured materials with minor curtainwall failures. Buildings that lack a solid foundation, such as mobile homes, are usually destroyed, and gable-end roofs are peeled off. Manufactured homes usually sustain severe and irreparable damage. Flooding near the coast destroys smaller structures, while larger structures are struck by floating debris. Additionally, terrain may be flooded well inland.

Examples of storms of this intensity include Carol (1954), Alma (1966), Alicia (1983), Fran (1996), Isidore (2002), Jeanne (2004), Lane (2006), Bertha (2008), Karl (2010).

Category 4

Category 4			
Sustained winds	59–69 m/s 210–249 km/h	114–135 kn 131–155 mph	

Normal central pressure	920–944 mbar	27.17–27.88 inHg	Igor in the open Atlantic

Category 4 hurricanes tend to produce more extensive curtainwall failures, with some complete roof structural failure on small residences. Heavy, irreparable damage and near complete destruction of gas station canopies and other wide span overhang type structures are common. Mobile and manufactured homes are leveled. These storms cause extensive beach erosion, while terrain may be flooded far inland.

The Galveston Hurricane of 1900, the deadliest natural disaster to hit the United States, peaked at an intensity that corresponds to a modern-day Category 4 storm. Other examples of storms at this intensity are Hazel (1954), Carmen (1974), Iniki (1992), Luis (1995), Iris (2001), Charley (2004).

Category 5

Category 5			
Sustained winds	≥ 70 m/s	≥ 136 kn	 John in the central Pacific Ocean
	≥ 250 km/h	≥ 156 mph	
Normal central pressure	< 920 mbar	< 27.17 inHg	

Category 5 is the highest category a tropical cyclone can obtain in the Saffir-Simpson scale. These storms cause complete roof failure on many residences and industrial buildings, and some complete building failures with small utility buildings blown over or away. Collapse of many wide-span roofs and walls, especially those with no interior supports, is common. Very heavy and irreparable damage to many wood frame structures and total destruction to mobile/manufactured homes is prevalent. Only a few types of structures are capable of surviving intact, and only if located at least 3 to 5 miles (5 to 8 km) inland. They include office, condominium and apartment buildings and hotels that are of solid concrete or steel frame construction, public multi-story concrete parking garages, and residences that are made of either reinforced brick or concrete/cement block and have hipped roofs with slopes of no less than 35 degrees from horizontal and no overhangs of any kind, and if the windows are either made of hurricane resistant safety glass or covered with shutters.

The storm's flooding causes major damage to the lower floors of all structures near the shoreline, and many coastal structures can be completely flattened or washed away by the storm surge. Storm surge damage can occur up to four city blocks inland, with flooding, depending on terrain, reaching six to seven blocks inland. Massive evacuation of residential areas may be required if the hurricane threatens populated areas.

Storms of this intensity can be severely damaging. Historical examples that reached the Category 5 status and made landfall as such, include the Labor Day Hurricane of 1935, the 1959 Mexico Hurricane, Camille in 1969, Gilbert in 1988, Andrew in 1992, Dean, and Felix (both in 2007).

Criticism

Some scientists, including Kerry Emanuel and Lakshmi Kantha, have criticized the scale as being too simplistic, indicating that the scale does not take into account the physical size of a storm, nor the amount of precipitation it produces. Additionally, they and others point out that the Saffir-Simpson scale, unlike the Richter scale used to measure earthquakes, is not open-ended, and is quantized into a small number of categories. Proposed replacement classifications include the Hurricane Intensity Index, which is based on the dynamic pressure caused by a storm's winds, and the Hurricane Hazard Index, which bases itself on surface wind speeds, the radius of maximum winds of the storm, and its translational velocity. Both of these scales are continuous, akin to the Richter scale; however, neither of these scales have been used by officials.

Category 6

After the series of powerful storm systems of the 2005 Atlantic hurricane season, a few newspaper columnists and scientists brought up the suggestion of introducing Category 6, and they have suggested pegging Category 6 to storms with winds greater than 174 or 180 mph (78 or 80 m/s); 150–155 knots (280–287 km/h). Only a few storms in history have reached into this hypothetical category. Many of these storms were West Pacific super typhoons, most notably Typhoon Tip in 1979 with sustained winds of 190 mph (310 km/h).

According to Robert Simpson, there is no reason for a Category 6 on the Saffir-Simpson Scale because it is designed to measure the potential damage of a hurricane to manmade structures. If the wind speed of the hurricane is above 155 mph (249 km/h), then the damage to a building will be "serious no matter how well it's engineered".