Tropical cyclone

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Cyclone Catarina, a rare South Atlantic tropical cyclone viewed from the International Space Station on March 26, 2004

A **tropical cyclone** is a type of storm system characterized by a low pressure center and thunderstorms, producing strong wind and flooding rain. A tropical cyclone feeds on the heat released when moist air rises and the water vapor condenses. Because tropical cyclones are "warm core" storm systems, they are fueled by a different heat mechanism than other cyclonic windstorms such as nor'easters, European windstorms, and polar lows.

"Tropical cyclone" is a meteorological term. The adjective "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 noun "cyclone" refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere. Depending on their location and strength, there are various terms by which tropical cyclones are known, such as **hurricane**, **typhoon**, **tropical storm**, **cyclonic storm**, and **tropical depression**.

Tropical cyclones can produce extremely strong and powerful winds, torrential rain, high waves, and storm surge. They are born and sustained over large bodies of warm water, and lose their strength over land. This is the reason 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 25 mi (40 km) inland. Although their effects on human populations can be devastating, tropical cyclones can also relieve drought conditions. They carry heat and energy away from the tropics towards the temperate latitudes, an important mechanism of the global atmospheric circulation that helps maintain equilibrium in the Earth's troposphere, and to maintain a relatively stable and warm temperature worldwide.

Tropical cyclones

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Many tropical cyclones develop when the atmospheric conditions around a weak disturbance in the atmosphere are favorable. 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 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 dissipates.

Contents

Physical structure

See also: Eye (cyclone)

All tropical cyclones are areas of low atmospheric pressure near the Earth's surface. The pressures recorded at the centers of tropical cyclones are among the lowest that occur on Earth's surface at sea level.[1] Tropical cyclones are characterized and driven by the release of large amounts of latent heat of condensation as 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.[2] Rainbands are bands of showers and thunderstorms that spiral cyclonically toward the storm center. High wind gusts and heavy downpours often occur in individual rainbands, with relatively calm weather between bands. Tornadoes often form in the rainbands of landfalling tropical cyclones.[3] Intense annular tropical cyclones are distinctive for their lack of rainbands.[4] While all surface low pressure areas require divergence aloft to continue deepening, the divergence over tropical cyclones is in all directions away from the center. The upper levels of a tropical cyclone feature winds headed away from the center of the storm with an anticyclonic rotation, due to the Coriolis force. Winds at the surface are strongly cyclonic, weaken with height, and eventually reverse themselves. Tropical cyclones owe this unique characteristic to requiring a relative lack of vertical wind shear to maintain the warm core at the center of the storm.[5][6]

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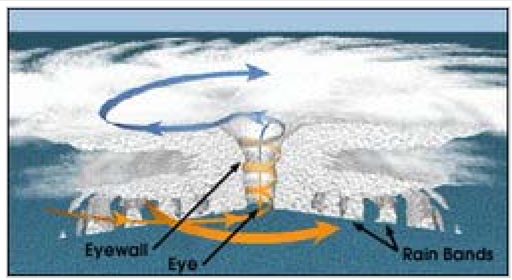
A strong tropical cyclone will harbor an area of sinking air at the center of circulation, developing into an eye. Weather in the eye is normally calm and free of clouds, however, the sea may be extremely violent.[3] The eye is normally circular in shape, and may range in size from 3 to 370 km (2–230 miles) in diameter.[7][8] Intense, mature hurricanes can sometimes exhibit an inward curving of the eyewall top that resembles a football stadium; this phenomenon is thus sometimes referred to as the stadium effect.[9]

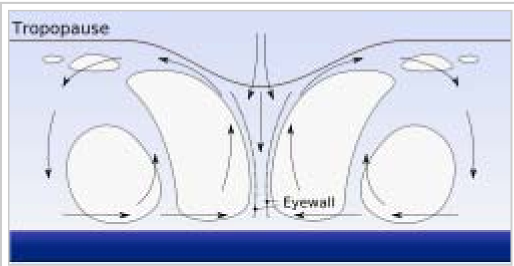
There are other features that either surround the eye, or cover it. The central dense overcast is the concentrated area of strong thunderstorm activity near the center of a tropical cyclone;[10] in weaker tropical cyclones, the CDO may cover the center completely.[11] The eyewall is a circle of strong thunderstorms which surrounds around the eye, where the greatest wind speeds are found, and where clouds reach the highest and precipitation is the heaviest. The heaviest wind damage occurs where a hurricane's eyewall passes over land.[3] Associated with eyewalls are eyewall replacement cycles, which occur naturally in intense tropical cyclones. When cyclones reach peak intensity they usually - but not always - have an eyewall and radius of maximum winds that contract to a very small size, around 10–25 km (5 to 15 miles). At this point, some of the outer rainbands may organize into an outer ring of thunderstorms that slowly moves inward and robs the inner eyewall of its needed moisture and angular momentum. During this phase, the tropical cyclone weakens (i.e. the maximum winds die off a bit and the central pressure goes up), but eventually the outer eyewall replaces the inner one completely. The storm can be of the same intensity as it was previously or, in some cases, it can be even stronger after the eyewall replacement cycle. Even if the cyclone is weaker at the end of the cycle, the fact that it has just undergone one and will not undergo another one soon will allow it to strengthen further, if other conditions allow it to do so.[12]



Structure of a tropical cyclone

Mechanics

Structurally, a tropical cyclone is a large, rotating system of clouds, wind, and thunderstorms. Its primary energy source is the release of the heat of condensation from water vapor condensing at high altitudes, with heat derived from the sun 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.[13] 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. Condensation leads to higher wind speeds, as a tiny fraction of the released energy is converted into mechanical energy;[14] 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.[15] This gives rise to factors that provide the system with enough energy to be self-sufficient and cause a positive feedback loop, where it can draw more energy as long as the source of heat, warm water, remains. 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



Tropical cyclones form when the energy released by the condensation of moisture in rising air causes a positive causes the system to spin, an effect known as the Coriolis effect, giving it a cyclonic characteristic and affecting the trajectory of the storm.

feedback loop over warm ocean waters.

The factors to form a tropical cyclone include a pre-existing weather disturbance, warm tropical oceans, moisture, and relatively light winds aloft. If the right conditions persist and allow it to create a feedback loop by maximizing the energy intake possible – for example, such as high winds to increase the rate of evaporation – they can combine to produce the violent winds, incredible waves, torrential rains, and floods associated with this phenomenon.

Deep convection as a driving force is what primarily distinguishes tropical cyclones from other meteorological phenomena.[16] Because this is strongest in a tropical climate, this 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.[16] To continue to drive its heat engine, a tropical cyclone must remain over warm water, which provides the needed atmospheric moisture. The evaporation of this moisture is accelerated by the high winds and reduced atmospheric pressure in the storm, resulting in a positive feedback loop. As a result, when a tropical cyclone passes over land, its strength diminishes rapidly.[17]

The passage of a tropical cyclone over the ocean can cause the upper ocean to cool substantially, which can influence subsequent cyclone development. Cooling is primarily caused by upwelling of cold water from below due to the wind stresses the tropical cyclone itself induces upon the upper layers of the ocean. Additional cooling may come from cold water from falling raindrops. 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.[18]

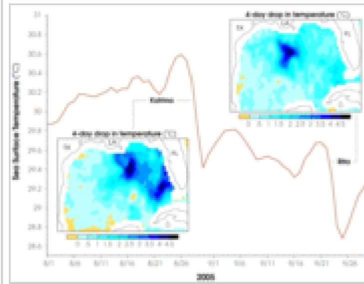


Chart displaying the drop in surface temperature in the Gulf of Mexico as Hurricanes Katrina and Rita passed over

Scientists at the National Center for Atmospheric Research estimate that a tropical cyclone releases heat energy at the rate of 50 to 200 trillion joules per day.[15] For comparison, this rate of energy release is equivalent to exploding a 10-megaton nuclear bomb every 20 minutes[19] or 200 times the world-wide electrical generating capacity per day.[15]

While the most obvious motion of clouds is toward the center, 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.[13] This outflow produces high, thin cirrus clouds that spiral away from the center. The high cirrus clouds may be the first signs of an approaching tropical cyclone.[20]

Major basins and related warning centers

Warning centers

There are six Regional Specialised Meteorological Centres (RSMCs) worldwide. These organizations are designated by the World Meteorological Organization and are responsible for tracking and issuing bulletins, warnings, and advisories about tropical cyclones in their designated areas of responsibility. Additionally, there are five Tropical Cyclone Warning Centres (TCWCs) that provide information to smaller regions.[22] The RSMCs and TCWCs, however, are not the only organizations that provide information about tropical cyclones to the public. The Joint Typhoon Warning Center (JTWC) issues informal advisories in all basins except the Northern Atlantic and Northeastern Pacific. The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) issues informal advisories, as well as names, for tropical cyclones that approach the Philippines in the Northwestern Pacific. The Canadian Hurricane Centre (CHC) issues advisories on hurricanes and their remnants that affect Canada.

Basins and WMO Monitoring Institutions[21]

Basin	Responsible RSMCs and TCWCs
Northern Atlantic	National Hurricane Center
Northeastern Pacific	National Hurricane Center
North central Pacific	Central Pacific Hurricane Center
Northwestern Pacific	Japan Meteorological Agency
Northern Indian	Indian Meteorological Department
Southwestern Indian	Météo-France
South and Southwestern Pacific	Fiji Meteorological Service Meteorological Service of New Zealand† Papua New Guinea National Weather Service† Bureau of Meteorology† (Australia)
Southeastern Indian	Bureau of Meteorology† (Australia)
	†: *Indicates a Tropical Cyclone Warning Centre*

On March 26, 2004, Cyclone Catarina became the first recorded South Atlantic cyclone and subsequently struck southern Brazil as the equivalence of a Category 2 hurricane on the Saffir-Simpson Hurricane Scale. As the cyclone formed outside of the authority of another warning center, Brazilian meteorologists initially treated the system as an extratropical cyclone, though subsequently classified it as tropical.[23]

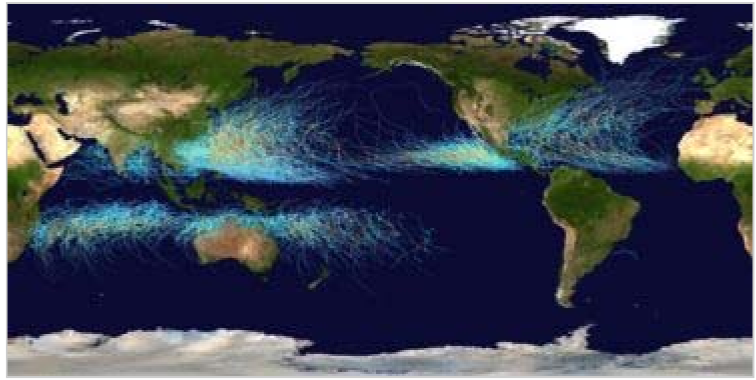
Times of formation

Worldwide, tropical cyclone activity peaks in late summer when the difference between temperatures aloft and sea surface temperatures are the greatest. However, each particular basin has its own seasonal patterns.

On a worldwide scale, May is the least active month, while September is the most active.[24]

In the North Atlantic, a distinct hurricane season occurs from June 1 to November 30, sharply peaking from late August through September. 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.[24]

In the Southern Hemisphere, tropical cyclone activity begins in late October and ends in May. Southern Hemisphere activity peaks in mid-February to early March.[24]



Map of the cumulative tracks of all tropical cyclones during the 1985–2005 time period. The Pacific Ocean west of the International Date Line sees more tropical cyclones than any other basin, while there is almost no activity in the Atlantic Ocean south of the Equator.

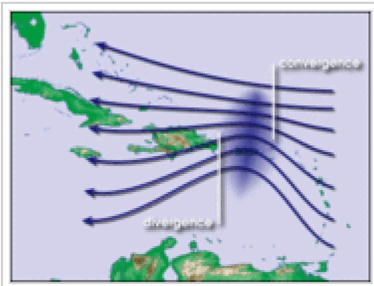
Season Lengths and Seasonal Averages[25][24]

Basin	Season Start	Season End	Tropical Storms (>34 knots)	Tropical Cyclones (>63 knots)	Category 3+ TCs (>95 knots)
Northwest Pacific	April	January	26.7	16.9	8.5
South Indian	October	May	20.6	10.3	4.3
Northeast Pacific	May	November	16.3	9.0	4.1
North Atlantic	June	November	10.6	5.9	2.0
Australia Southwest Pacific	October	May	10.6	4.8	1.9
North Indian	April	December	5.4	2.2	0.4

Formation

Factors in formation

The formation of tropical cyclones is the topic of extensive ongoing research and is still not fully understood. Six factors appear to be generally necessary, although tropical cyclones may occasionally form without meeting all of these conditions. Water temperatures of at least 26.5 °C (80 °F) are needed[26] down to a depth of at least 50 m (150 feet). Waters of this temperature cause the overlying atmosphere to be unstable enough to sustain convection and thunderstorms.[27] Another factor is rapid cooling with height. This allows the release of latent heat, which is the source of energy in a tropical cyclone.[26] High humidity is needed, especially in the lower-to-mid troposphere; when there is a great deal of moisture in the atmosphere, conditions are more favorable for disturbances to develop.[26] Low amounts of wind shear are needed, as when shear is high, the convection in a cyclone or disturbance will be disrupted, preventing formation of the feedback loop.[26] Tropical cyclones generally need to form over 500 km (310 miles) or 5 degrees from the equator. This allows the Coriolis force to deflect winds blowing towards the low pressure center, causing a circulation.[26] Lastly, a formative tropical cyclone needs pre-existing system of disturbed weather. The system must have some sort of circulation as well as a low pressure center.[26]



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

Locations of formation

Most tropical cyclones form in a worldwide band of thunderstorm activity called by several names: the Intertropical Discontinuity (ITD), the Intertropical Convergence Zone (ITCZ), or the monsoon trough. Another important source of atmospheric instability is found in tropical waves, which cause about 85% of intense tropical cyclones in the Atlantic ocean,[28] and which most of the tropical cyclones in the Eastern Pacific basin.[29][30]

Tropical cyclones form where sea temperatures are high, usually at about 27 degrees Celsius. They originate on the eastern side of oceans, but move west, intensifying as they move. Most of these systems form between 10 and 30 degrees of the equator and 87% form within 20 degrees of it. Because the Coriolis effect initiates and maintains tropical cyclone rotation, tropical cyclones rarely form or move within about 5 degrees of the equator, where the Coriolis effect is weakest.[31] However, it is possible for tropical cyclones to form within this boundary as did Typhoon Vamei in 2001 and Cyclone Agni in 2004.

Movement and track

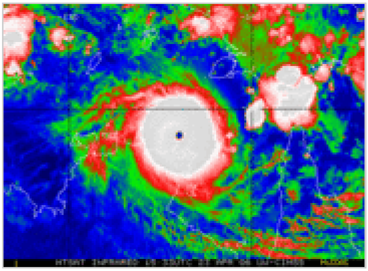
Steering winds

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 analogized by Dr. Neil Frank, former director of the National Hurricane Center, to "leaves carried along by a stream."[32]

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.[32] 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.[29] These waves are the precursors to many tropical cyclones within this region.[28] In the Indian Ocean and Western Pacific (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.[33]

Coriolis effect

The Earth's rotation imparts an acceleration known as the *Coriolis Acceleration* or *Coriolis Effect.* This acceleration causes cyclonic systems to turn towards the poles in the absence of strong steering currents.[34] The poleward portion of a tropical cyclone has winds blowing towards the west, and the Coriolis acceleration pulls them slightly more poleward. The winds blowing towards the east on the equatorward portion of the cyclone are pulled slightly towards the equator. But because the Coriolis acceleration is increasingly weak as you move toward the equator, the net drag on the cyclone is poleward. Thus, tropical cyclones in the Northern Hemisphere normally turn north (before being blown east), and tropical cyclones in the Southern Hemisphere normally turn south (before being blown east), if no strong pressure systems counteract the Coriolis acceleration.



Infrared image of Cyclone Monica near peak intensity, showing clockwise rotation due to the Coriolis effect.

The Coriolis acceleration also initiates cyclonic rotation, but it is not the driving force that brings this rotation to high speeds. These speeds instead result from the conservation of angular momentum. This means that air is drawn in from an area much larger than the cyclone such that the tiny rotational speed (originally imparted by the Coriolis acceleration) is magnified greatly as the air is drawn into the low pressure center.[35]

Interaction with the mid-latitude westerlies

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.*[36] A typhoon moving through the Pacific Ocean towards Asia, for example, will recurve to the north and then northeast offshore of Japan if the typhoon encounters winds blowing northeastward toward a low-pressure system passing over China or Siberia. Many tropical cyclones are eventually forced toward the northeast by extratropical cyclones, which move from west to east to the north of the subtropical ridge.

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. For a storm moving inland, the landfall area experiences half the storm by the time of actual landfall. 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.[37] For a list of notable and unusual landfalling tropical cyclones, see list of notable tropical cyclones. For a list of unusual formation areas, see Unusual areas of formation.

Dissipation

Factors

A tropical cyclone can cease to have tropical characteristics in several ways. One such way is if it moves over land, thus depriving it of the warm water it needs to power itself, and quickly loses 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 they could regenerate if they manage to get back over open warm water. If a storm is over mountains for even a short time, it can rapidly lose its structure. Many storm fatalities occur in mountainous terrain, as the dying storm unleashes torrential rainfall which can lead to deadly floods and mudslides, as 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 30 meters (100 feet) of water, which draws up colder water due to upwelling and becomes too cool to support the storm. Without warm surface water, the storm cannot survive.[38]

A tropical cyclone can dissipate when it moves over waters significantly below 26 °C. 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.[39] Weakening or dissipation can occur if it experiences vertical wind shear, causing the convection and heat engine to move away from the center which normally ceases development of a tropical cyclone.[40] 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.[41] Even after a tropical cyclone is said to be extratropical or dissipated, it can still have tropical storm force (or occasionally hurricane 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-force wind speeds when they reach the west coast of North America or Europe, where they are known as European windstorms. The extratropical remnants of Hurricane Iris in 1995 became such a windstorm.[42] 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.[40]

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

Artificial dissipation

In the 1960s and 1970s, the United States government attempted to weaken hurricanes in its 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 dropped as much as 30%, but then regained their 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.[43] 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.[44]

Other approaches have been suggested over time, including cooling the water under a tropical cyclone by towing icebergs into the tropical oceans, dropping large quantities of ice into the eye at very early stages so that latent heat is absorbed by ice at the entrance (storm cell perimeter bottom) instead of heat energy being converted to kinetic energy at high altitudes vertically above, covering the ocean in a substance that inhibits evaporation, or blasting the cyclone apart with nuclear weapons. Project Cirrus even involved throwing dry ice on a cyclone.[45] These approaches all suffer from the same flaw: tropical cyclones are simply too large for any of them to be practical.[46]

Effects

See also: Effects of tropical cyclones

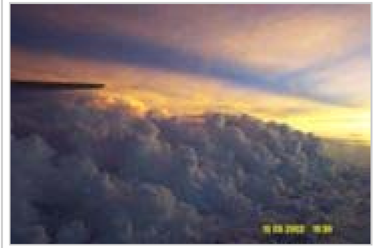
The aftermath of Hurricane Katrina in Gulfport, Mississippi. Katrina was the costliest tropical cyclone in United States history.

Tropical cyclones out at sea cause large waves, heavy rain, and high winds, disrupting international shipping and, at times, causing shipwrecks.[47] Tropical cyclones stir up water, leaving a cool wake behind them,[18] which causes the region to be less favourable for subsequent tropical cyclones. Strong winds can damage or destroy vehicles, buildings, bridges, and other outside objects, turning loose debris into deadly flying projectiles. 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.[48] The broad rotation of a landfalling tropical cyclone, and vertical wind shear at its periphery, spawns tornadoes. Tornadoes can also be spawned as a result of eyewall mesovortices, which persist until landfall.[49] Within the last two centuries, tropical cyclones have been responsible for the deaths of about 1.9 million persons worldwide. Large areas of standing water caused by flooding lead to infection, as well as contributing to mosquito-borne illnesses. Crowded evacuees in shelters increase the risk of disease propagation.[50] Tropical cyclones sigificantly interrupt infrastructure, leading to power outages, bridge destruction, and hamper reconstruction efforts.[51][50] Although cyclones take an enormous toll in lives and personal property, they may be important factors in the precipitation regimes of places they impact and bring much-needed precipitation to otherwise dry regions.[52] Tropical cyclones also help maintain the global heat balance by moving warm, moist tropical air to the mid-latitudes and polar regions.[53] 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. Tropical cyclone destruction spurs redevelopment, greatly increasing local property values.[54]

Observation and forecasting

Observation

Intense tropical cyclones pose a particular observation challenge. As they are a dangerous oceanic phenomenon and are relatively small, weather stations are rarely available on the site of the storm itself. Surface observations are generally available only if the storm is passing over an island or a coastal area, or if there is a nearby ship. Usually, real-time measurements are taken in the periphery of the cyclone, where conditions are less catastrophic and its true strength can not be evaluated. For this reason, there are teams of meteorologists that move into the path of tropical cyclones to help evaluate their strength at the point of landfall.



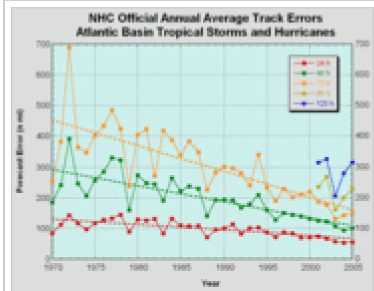
Sunset view of Hurricane Isidore's rainbands photographed at 7,000 feet.

Tropical cyclones far from land are tracked by weather satellites capturing visible and infrared images from space, usually at half-hour to quarter-hour intervals. As a storm approaches land, it can be observed by land-based Doppler radar. Radar plays a crucial role around landfall because it shows a storm's location and intensity minute by minute.

In-situ measurements, in real-time, can be taken by sending specially equipped reconnaissance flights into the cyclone. In the Atlantic basin, these flights are regularly flown by United States government hurricane hunters.[55] The aircraft used are WC-130 Hercules and WP-3D Orions, both four-engine turboprop cargo aircraft. These aircraft fly directly into the cyclone and take direct and remote-sensing measurements. The aircraft also launch GPS dropsondes inside the cyclone. These sondes measure temperature, humidity, pressure, and especially winds between flight level and the ocean's surface.

A new era in hurricane observation began when a remotely piloted Aerosonde, a small drone aircraft, was flown through Tropical Storm Ophelia as it passed Virginia's Eastern Shore during the 2005 hurricane season. A similar mission was also completed successfully in the western Pacific ocean. This demonstrated a new way to probe the storms at low altitudes that human pilots seldom dare.[56]

Forecasting



A general decrease in error trends in tropical cyclone path prediction is evident since the 1970s

See also: Tropical cyclone forecasting, Tropical cyclone prediction model, and Tropical cyclone rainfall forecasting

Because of the forces that affect tropical cyclone tracks, accurate track predictions depend on determining the position and strength of high- and low-pressure areas, and predicting how those areas will change during the life of a tropical system. The deep layer mean flow is considered to be the best tool in determining track direction and speed. If storms are significantly sheared, use of a lower level wind such as the 700 hpa pressure surface (3000 meters or 10000 feet above sea level) will work out as a better predictor. It is also best to smooth out short term wobbles of the storm center in order to determine a more accurate trajectory.[57] High-speed computers and sophisticated simulation software allow forecasters to produce 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.[58] However, scientists say they are less skillful at predicting the intensity of tropical cyclones.[59] They attribute the lack of improvement in intensity forecasting to the complexity of tropical systems and an incomplete understanding of factors that affect their development.

Classifications, terminology, and naming

Intensity classifications

Tropical cyclones are classified into three main groups, based on intensity: tropical depressions, tropical storms, and a third group of more intense storms, whose name depends on the region. For example, if a tropical storm in the Northwestern Pacific reaches hurricane-strength winds on the Beaufort scale, it is referred to as a *typhoon*; if a tropical storm passes the same benchmark in the North-East Pacific Ocean, or in the Atlantic, it is called a *hurricane*.[37] Neither term is used in the South Pacific.

Three tropical cyclones at different

Additionally, as indicated in the table below, each basin uses a separate system of terminology, making comparisons between different basins difficult. In the Pacific Ocean, hurricanes from the Central North Pacific sometimes cross the International Date Line into the Northwest Pacific, becoming typhoons (such as Hurricane/Typhoon Ioke in 2006); on rare occasions, the reverse will occur.[60] It should also be noted that typhoons with sustained winds greater than 130 knots (240 km/h or 150 mph) are called *Super Typhoons* by the Joint Typhoon Warning Center.[61]

A **tropical depression** is an organized system of clouds and thunderstorms with a defined surface circulation and maximum sustained winds of less than 17 m/s (33 kt, 38 mph, or 62 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."[13] 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.[62]

A **tropical storm** is an organized system of strong thunderstorms with a defined surface circulation and maximum stages of development. The weakest, on the left, demonstrates only the most basic circular shape. The storm at the top right, which is stronger, demonstrates spiral banding and increased centralization, while the storm in the lower right, the strongest, has developed an eye.

sustained winds between 17 and 32 m/s (34–63 kt, 39–73 mph, or 62–117 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*).[13]

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 m/s (64 kt, 74 mph, or 118 km/h).[13] 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 16–80 km (10–50 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 m/s (165 kt, 190 mph, 305 km/h).[63]

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

Origin of storm terms

The word *typhoon*, used today in the Northwest Pacific, has two possible and equally plausible origins. The first is from the Chinese 大風 (Cantonese: daaih fūng; Mandarin: dà fēng) which means "great wind."[64] (The Chinese term as 颱風 or 台风 táifēng, and 台風 *taifū* in Japanese, has an independent origin traceable variously to 風颱, 風篩 or 風癡 *hongthai*, going back to Song 宋 (960-1278) and Yuan 元(1260-1341) dynasties. The first record of the character 颱 appeared in 1685's edition of *Summary of Taiwan* 臺灣記略).[65] Alternatively, the word may be derived from Urdu, Persian and Arabic *ṭūfān*[65] (طوفان), which in turn originates from Greek *tuphōn* (Τυφών), a monster in Greek mythology responsible for hot winds.[66] The related Portuguese word *tufão*, used in Portuguese for any tropical cyclone, is also derived from Greek *tuphōn*.

The word *hurricane*, used in the North Atlantic and Northeast Pacific, is derived from the name of a native Caribbean Amerindian storm god, Huracan, via Spanish *huracán*.[67] (Huracan is also the source of the word *Orcan*, another word for the European windstorm. These events should not be confused.)

Naming

Storms reaching tropical storm strength were initially given names to eliminate confusion when there are multiple systems in any individual basin at the same time which assists in warning people of the coming storm.[68] In most cases, a tropical cyclone retains its name throughout its life; however, under special circumstances, tropical cyclones may be renamed while active. These names are taken from lists which vary from region to region and are drafted a few years ahead of time. The lists are decided upon, depending on the regions, either by committees of the World Meteorological Organization (called primarily to discuss many other issues), or by national weather offices involved in the forecasting of the storms. Each year, the names of particularly destructive storms (if there are any) are "retired" and new names are chosen to take their place.

Notable tropical cyclones

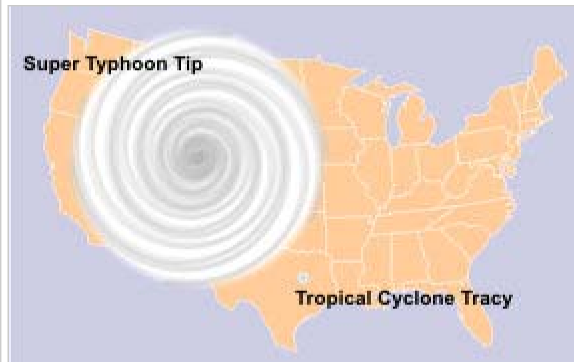
Tropical cyclones that cause extreme destruction are rare, though when they occur, then can cause great amounts of damage or thousands of fatalities.

The 1970 Bhola cyclone is the deadliest tropical cyclone on record, killing over 300,000 people[69] and potentially as many as 1 million[70] after striking the densely population Ganges Delta region of Bangladesh on November 13, 1970. Its powerful storms surge was responsible for the high death toll.[69] The North

Indian cyclone basin has historically been the deadliest basin, with several cyclones since 1900 killing over 100,000 people, each in Bangladesh.[50][71] Elsewhere, Typhoon Nina killed 29,000 in China due to 2000-year flooding which caused 62 dams along the Banqiao Dam to fail, with another 145,000 killed during subsequent famine and epidemic.[72] The Great Hurricane of 1780 is the deadliest Atlantic hurricane on record, killing about 22,000 people in the Lesser Antilles.[73] A tropical cyclone does need not be particularly strong to cause memorable damage, primarily if the deaths are from rainfall or mudslides. Tropical Storm Thelma in November 1991 killed thousands in the Philippines,[74] while in 1982, the unnamed tropical depression that eventually became Hurricane Paul killed around 1,000 people in Central America.[75]

Hurricane Katrina is estimated as the costliest tropical cyclone worldwide,[76] causing $81.2 billion in property damage (2005 USD)[77] with overall damage estimates exceeding $100 billion (2005 USD).[76] Katrina is considered the worst natural disaster caused by a hurricane in United States history,[78] killing at least 1,836 after striking Louisiana and Mississippi as a major hurricane in August 2005. Hurricane Iniki in 1992 was the most powerful storm to strike Hawaii in recorded history, hitting Kauai as a Category 4 hurricane, killing six people, and causing U.S. $3 billion in damage.[79] Other destructive Eastern Pacific hurricanes include Pauline and Kenna, both causing severe damage after striking Mexico as a major hurricane.[80][81] In March 2004, Cyclone Gafilo struck northeastern Madagascar as a powerful cyclone, killing 74, affecting more than 200,000, and becoming the worst cyclone to affect the nation for over 20 years.[82]

The most intense storm on record was Typhoon Tip in the northwestern Pacific Ocean in 1979, which reached a minimum pressure of 870 mbar and maximum sustained wind speeds of 165 knots (190 mph or 305 km/h).[83] Tip, however, does not solely hold the record for fastest sustained winds in a cyclone. Typhoon Keith in the Pacific and Hurricanes Camille and Allen in the North Atlantic currently share this record with Tip.[84] Camille was the only storm to actually strike land while at that intensity, making it, with 165 knots (190 mph or 305 km/h) sustained winds and 210 mph (335 km/h) gusts, the strongest tropical cyclone on record at landfall.[85] Typhoon Nancy in 1961 had recorded wind speeds of 185 knots (215 mph or 345 km/h), but recent research indicates that wind speeds from the 1940s to the 1960s were gauged too high, and this is no longer considered the fastest storm on record.[63] Similarly, a surface-level gust caused by Typhoon Paka on Guam was recorded at 205 knots (236 mph or 380 km/h). Had it been confirmed, it would be the strongest non-tornadic wind ever recorded on the Earth's surface, but the reading had to be discarded since the anemometer was damaged by the storm.[86]



The relative sizes of Typhoon Tip, Cyclone Tracy, and the United States.

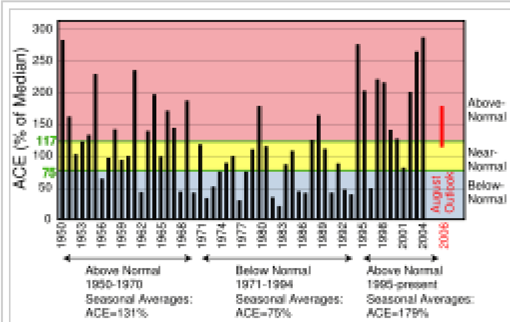
In addition to being the most intense tropical cyclone on record, Tip was the largest cyclone on record, with tropical storm-force winds 2,170 km (1,350 miles) in diameter. The smallest storm on record, Cyclone Tracy, was roughly 100 km (60 miles) wide before striking Darwin, Australia in 1974.[87]

Hurricane John is the longest-lasting tropical cyclone on record, lasting 31 days in 1994. Prior to the advent of satellite imagery in 1961, however, many tropical cyclones were underestimated in their durations.[88] John is the second longest-tracked tropical cyclone in the Northern Hemisphere on record, behind Typhoon Ophelia of 1960 which had a path of 8500 miles (12500 km). Reliable data for Southern Hemisphere cyclones are unavailable.[89]

Long term trends in cyclone activity

See also: Atlantic hurricane reanalysis

While the number of storms in the Atlantic has increased since 1995, there is no obvious global trend; the annual global number of tropical cyclones remains about 87 ± 10. However, there is some evidence that the intensity of hurricanes is increasing. "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."[90]



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

Atlantic storms are becoming more destructive financially, since five of the ten most expensive storms in United States history have occurred since 1990. This can be attributed to the increased intensity and duration of hurricanes striking North America,[90] and to a greater degree, the number of people living in susceptible coastal area following increased development in the region since the last surge in Atlantic hurricane activity in the 1960s.

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.[91]

The number and strength of Atlantic hurricanes may undergo a 50-70 year cycle, also known as a multi-decadal cycle. Although more common since 1995, few above-normal hurricane seasons occurred during 1970-1994.[92] Destructive hurricanes struck frequently from 1926-60, including many major New England hurricanes. A record 21 Atlantic tropical storms formed in 1933, only recently exceeded in 2005. Tropical hurricanes occurred infrequently during the seasons of 1900-1925; however, many intense storms formed 1870-1899. 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 1800s, including an 1821 storm that made a direct hit on New York City, which some historical weather experts say may have been as high as Category 4 in strength.[93]

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 ship reported a voyage through the storm or a storm hit land in a populated area.[91] 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.

Global warming

Most climatologists agree that a single storm, or even a single season, cannot clearly be attributed to a single cause such as global warming or natural variation.[94] 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 cyclones. 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."[95] 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."[96]

Similarly, P.J. Webster and others published an article in *Science* examining the "changes in tropical cyclone number, duration, and intensity" over the last 35 years, the period when satellite data has been available. The 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.[97] Both Emanuel and Webster et al. consider sea surface temperatures to be vital in the development of cyclones. The increase in temperatures is believed to be due to global warming and the hypothesized Atlantic Multidecadal Oscillation (AMO), a possible 50–70 year pattern of temperature variability. However, Emanuel observed the recent temperature increase as outside the range of previous sea surface temperature peaks. Thus, both global warming and a natural variation such as the AMO could have contributed to the warming of the tropical Atlantic over the past decades, though an exact attribution has not been defined.[94]

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, and other climate changes. The report concluded the observed increase in hurricane intensity is larger than climate models predict. Additionally, the report considered it likely that hurricane intensity will continue to increase through the 21st century, and declared it more likely than not that there have been some human contribution to the increases in hurricane intensity.[98]

Related cyclone types

See also: Cyclone, Extratropical cyclone, and Subtropical cyclone

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.[99]

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;[2] 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 very 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 latitude, from the equator to 50°. Although subtropical storms rarely have hurricane-force winds, they may become tropical in nature as their cores warm.[100] From an operational standpoint, a tropical cyclone is usually not considered to become subtropical during its extratropical transition.[101] At this time, subtropical cyclones are handled operationally similarly to tropical cyclones only in the northern half of the Western Hemisphere and the southwest Indian Ocean.

Tropical cyclones in popular culture

In popular culture, tropical cyclones have made appearances in different types of media, including films, books, television, music, and electronic games. The media can have tropical cyclones that are entirely fictional, or can be based on real events.[102] For example, George Rippey Stewart's *Storm*, a best-seller published in 1941, is thought to have influenced meteorologists into giving female names to Pacific tropical cyclones.[103] Another example is the hurricane in *The Perfect Storm*, which describes the sinking of the *Andrea Gail* by the 1991 Halloween Nor'easter.[104] Also, hypothetical hurricanes have also been featured in parts of the plots of series such as *The Simpsons*, *Invasion*, *Family Guy*, *Seinfeld*, *CSI Miami*, and Dawson's Creek.

See also

Tropical cyclones Portal

Current seasons

- 2007 Atlantic hurricane season
- 2007 North Indian Ocean cyclone season
- 2007 Pacific hurricane season
- 2007 Pacific typhoon season
- 2006-07 Southern Hemisphere tropical cyclone season

Meteorology

- Lists of tropical cyclone names
- Mesoscale Convective Complex
- Tropical cyclogenesis

Forecasting and preparation

- Catastrophe modeling
- Effects of tropical cyclones
- Hong Kong Tropical Cyclone Warning Signals
- Hurricane preparedness
- Hurricane proof building
- Tropical cyclone forecasting
- Tropical cyclone watches and warnings

Categories

- Category:Lists of tropical cyclones
- Category:Tropical cyclones by basin
- Category:Tropical cyclones by region
- Category:Tropical cyclones by season
- Category:Tropical cyclones by strength

Cyclones and Anticyclones of the world
Extratropical - Meso-scale - Polar - Polar low - Subtropical - **Tropical**

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External links

Learning resources

- WMO guide on cyclone terminology (http://www.bom.gov.au/bmrc/pubs/tcguide/ch1/ch1_3.htm)
- Summary of cyclone terminology from NOAA FAQ (http://www.aoml.noaa.gov/hrd/tcfaq/A1.html)
- NOVA scienceNOW: Hurricanes (http://www.pbs.org/wgbh/nova/teachers/viewing/3204_02_nsn.html)
- Mariner's Guide for Hurricane Awareness (http://www.nhc.noaa.gov/marinersguide.pdf)PDF (1.23 MiB)
- World Meteorological Organization Severe Weather Information Center (http://severe.worldweather.org/) - Shows all current tropical systems worldwide and their tracks
- Tropical Storms Worldwide (http://www.solar.ifa.hawaii.edu/Tropical/tropical.html) - by Hawaii University
- FEMA for Kids: Hurricanes (http://www.fema.gov/kids/hurr.htm)

Regional specialised meteorological centers

- US National Hurricane Center (http://www.nhc.noaa.gov/) - North Atlantic, Eastern Pacific
- Central Pacific Hurricane Center (http://www.prh.noaa.gov/hnl/cphc/) - Central Pacific
- Japan Meteorological Agency (http://www.jma.go.jp/en/typh/) - NW Pacific
- India Meteorological Department (http://www.imd.gov.in/) - Bay of Bengal and the Arabian Sea
- Météo-France - La Reunion (http://www.meteo.fr/temps/domtom/La_Reunion/) - South Indian Ocean from Africa to 90° E
- Fiji Meteorological Service (http://www.met.gov.fj/advisories.html) - South Pacific east of 160°, north of 25° S

Past storms

- Global climatology of tropical cyclones (http://www.bom.gov.au/bmrc/pubs/tcguide/ch1/ch1_3.htm)
- Tropical cyclone images and movies, from the United Kingdom Met Office (http://www.metoffice.com/weather/tropicalcyclone/images.html)
- Unisys historical and contemporary hurricane track data (http://weather.unisys.com/hurricane/)
- United States Tropical Cyclone Rainfall Climatology (http://www.hpc.ncep.noaa.gov/tropical/rain/tcrainfall.html) - Nearly 30 years of tropical cyclone histories with an emphasis on storm total rainfall, in color, up to present. Broken up by year, region, by point of landfall, and North American countries impacted

- Global ISCCP B1 Browse System Satellite Archive (http://www.ncdc.noaa.gov/oa/rsad/gibbs/gibbs.html)

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