

# **Hurricanes: Science and Society**

**Hurricane Science**

**Hurricane Forecasts, Observations, and Models**

**Impacts, Preparation, and Mitigation**



[www.hurricanescience.org](http://www.hurricanescience.org)  
Graduate School of Oceanography  
University of Rhode Island

The *Hurricanes: Science and Society* website ([www.hurricanescience.org](http://www.hurricanescience.org)) and associated educational resources provide information on the science of hurricanes, methods of observing hurricanes, modeling and forecasting of hurricanes, how hurricanes impact society, and how people and communities can prepare for and mitigate the impacts of hurricanes. There is also a hurricane history interactive, hurricane case studies, and a special section for educators.

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Hurricanes threaten more than 47 million people along the United States coast from Maine to Texas, and the number of people threatened is growing. From 1990-2008, population density increased by 32% in Gulf of Mexico coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii. Much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above mean sea level. Not only people are threatened, as over half of the United States economic productivity is located within coastal zones.

Worldwide, some of the most deadly natural disasters have been tropical weather events, including the Great Bholá Cyclone of 1970, which struck Bangladesh and killed as many as 500,000 people, and Cyclone Nargis, which made landfall in Myanmar in 2008, causing catastrophic destruction and at least 138,000 fatalities. In the U.S., the most deadly hurricane has been the Galveston Hurricane of 1900, which caused more than 6,000 fatalities.

Each year, an average of eleven tropical storms develop over the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Many of these remain over the ocean and never impact the U.S. coastline. Hurricane Katrina in 2005, however, provided a grim reminder of what can happen when a hurricane does make landfall.

With Atlantic hurricane activity well above average in 2004 and 2005, the relationship between hurricanes and climate change has become a source of public interest, significant scientific debate, and a focus for current research. The potential relationship between hurricanes and climate change has great implications for society, especially in coastal regions affected by these extreme storms.

Scientific advances in understanding the behavior of hurricanes have dramatically improved the ability to prepare for hurricanes and protect homes and businesses when they do strike. Yet despite this progress, millions of people still fail to adequately protect their homes against hurricanes, putting themselves and their family at serious risk. Major goals of the *Hurricanes: Science and Society* website ([www.hurricanesociety.org](http://www.hurricanesociety.org)) are to provide foundational science for understanding complex scientific content, inform visitors about current scientific and technological advances, and to help visitors make good decisions prior to and during a hurricane emergency.

The *Hurricanes: Science and Society* website and associated resources provide information on hurricane related topics: the basic science of hurricanes, methods of observing hurricanes, modeling and forecasting of hurricanes, how hurricanes impact society, how people and communities can prepare for and mitigate the impacts of hurricanes, information about significant hurricanes through history, and a special section for educators. The following information is based solely on published scientific research and is a result of the *Hurricanes: Science and Society* project. All content has undergone thorough peer review by a panel of scientific experts.



Courtesy of NASA/NOAA GOES Project

Tropical cyclones are intense low-pressure weather systems that form in tropical waters. In the North Atlantic Ocean and Eastern Pacific Ocean, tropical cyclones are called hurricanes, and in the Western Pacific Ocean, they are called typhoons. The beginning of life for any hurricane is a pre-existing disturbance, which is an area of

## Tropical cyclones require warm water to form.

All hurricanes begin as an area of low pressure in the atmosphere, where surface winds are converging toward each other. This low-pressure area is called a tropical disturbance. If suitable conditions exist, the circulation may become more organized and wind speeds may increase. Once the system obtains a clearly identifiable circulation center, the system is upgraded to a tropical depression. If winds continue to intensify to greater than 63 km/hr (39 mph), the system will be classified as a tropical storm, and once winds are sustained above 119 km/hr (74mph), the system is officially upgraded to a hurricane (in the Atlantic, Central Pacific, and Eastern Pacific regions).



Courtesy of NOAA

**Tropical Depression**- maximum surface wind speeds less than or equal to 61 km/hr (38 mph).

**Tropical Storm**- maximum sustained wind speeds of 63–117.5 km/hr (39–73mph).

**Hurricane**- maximum sustained wind speed greater than or equal to 119 km/hr (74 mph).

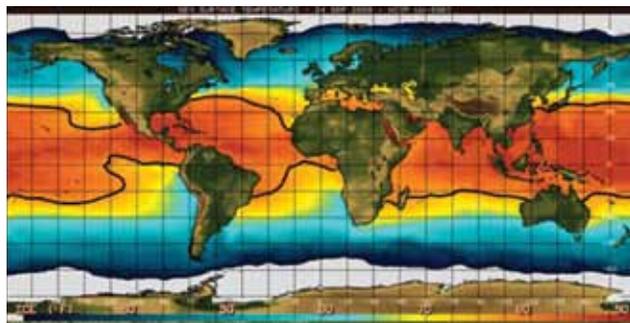
### Saffir-Simpson Hurricane Wind Scale

Category	Wind km/hr	Wind mph
1	119–153	74–95
2	154–177	96–110
3	178–209	111–130
4	210–249	131–155
5	249+	155+

### Hurricane Lifecycle

low pressure over the tropical ocean. This disturbance and other necessary conditions must be located in an environment that is favorable for development. Favorable conditions include:

- A sea surface temperature (SST) of at least  $\sim 26.5^{\circ}\text{C}$  ( $\sim 80^{\circ}\text{F}$ ).
- A vertical temperature profile in the atmosphere that cools enough with height to support thunderstorm activity.
- Sufficient water vapor in the middle of the troposphere (the lowest layer of the atmosphere). Even over the tropical oceans, dry air sometimes exists in the middle of the troposphere, and this dry air suppresses thunderstorms, preventing tropical depression formation.
- Sufficient distance from the equator for the Coriolis Force to be significant, usually at least 483 km (300 miles). Closer to the equator, the Coriolis Force is weak; therefore, it is difficult to establish cyclonic rotation.
- Low values of vertical wind shear from the surface of the earth to the upper troposphere (about 8 miles up). For reasons that remain unclear, wind shear inhibits the development of tropical depressions. Some research shows this inhibition may be due to the injection of dry air into the storm system.



Courtesy of the Space Science and Engineering Center, University of Wisconsin-Madison

Even when all the above favorable conditions are present, a tropical depression still may not form. For this reason, understanding and forecasting the genesis of a tropical depression is a difficult challenge. In the North Atlantic and Northeast Pacific Oceans, most of the atmospheric disturbances that can intensify into a hurricane are associated with an African easterly wave, an area of low atmospheric pressure that is embedded in the easterly trade winds and that generally forms over Africa. In other ocean basins, different kinds of atmospheric disturbances may become tropical cyclones. For example, many Northwest Pacific typhoons originate from a disturbance in a monsoon trough (locations of relatively minimal sea level pressure in a monsoon region).

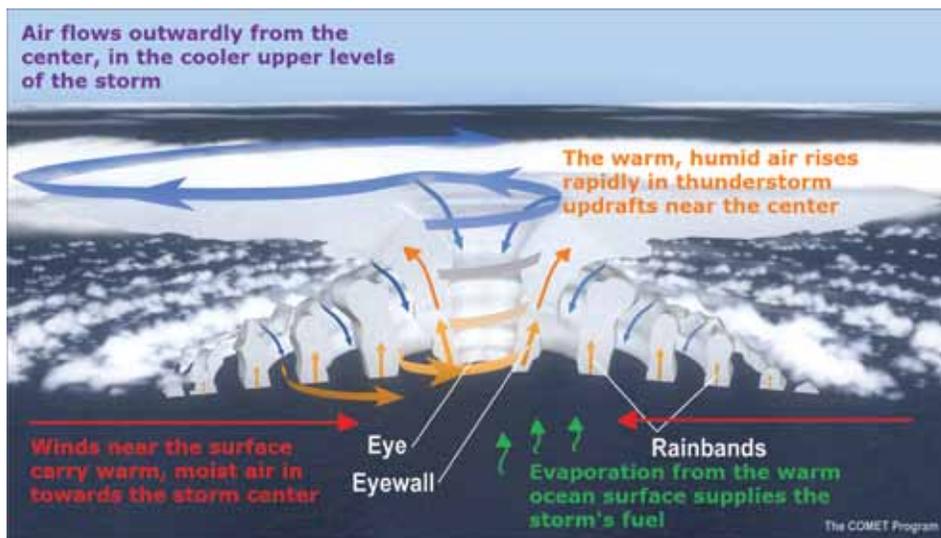


Courtesy of NOAA

Development of a tropical depression into a mature hurricane requires heat energy from the ocean surface. For this reason, hurricanes do not usually



## A hurricane can be compared to an engine.



develop over land or outside of the warm tropical oceans where the sea surface temperature (SST) is colder than  $\sim 26.5^{\circ}\text{C}$  ( $\sim 80^{\circ}\text{F}$ ). Heat is transferred from the ocean to the atmosphere when water at the ocean's surface evaporates to become water vapor. This causes the ocean to cool slightly. The heat transferred to the atmosphere from the ocean is stored in atmospheric water vapor as latent heat.

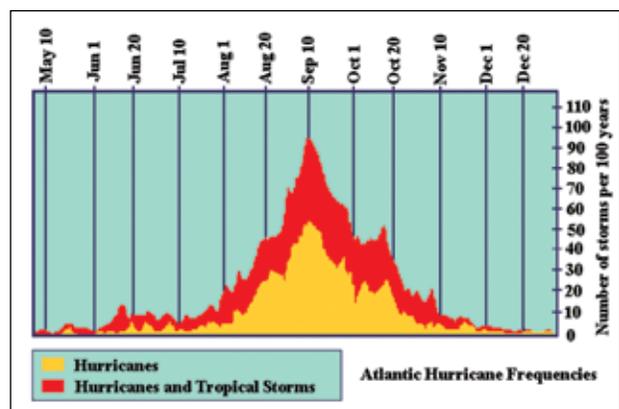
In the lower troposphere, air parcels carry heat energy obtained from the ocean. These air parcels spiral inward towards the center of a developing hurricane. Once the air parcels reach a hurricane's eyewall, they turn upward and rise due to a process called convection. The added heat from the ocean causes the air rising in the eyewall to be warmer than the surrounding environment, allowing it to continue to rise.

Once the rising air parcels reach the tropopause, the boundary between the troposphere and the stratosphere, they begin to spiral outward. As the air parcels spiral outward, they lose heat to outer space. At some point far away from the center of the hurricane, the cooled air parcels begin to sink back towards the lower troposphere. At this point, this cycle, which is known as the hurricane's secondary circulation, is complete.

Since the conversion of heat energy to mechanical energy drives the hurricane's secondary circulation, a hurricane can be regarded as a heat engine. For the engine to continue working, air entering the system (the hurricane) must be at a higher temperature than that which exits the system. As long as the air parcels can rise in the eyewall and then spiral outward at the tropopause faster than other air parcels can spiral inward towards the eyewall in the lower troposphere, the central pressure in the developing hurricane will fall. A falling central pressure is one way to measure how much a hurricane is intensifying. When the central pressure falls, air parcels begin to spiral inward towards the eyewall faster to fill the vacuum. If the air parcels spiral inward faster, then the maximum wind speed will increase. Increasing winds boost the transfer of heat from the ocean, creating a positive feedback.

## Hurricane Variability

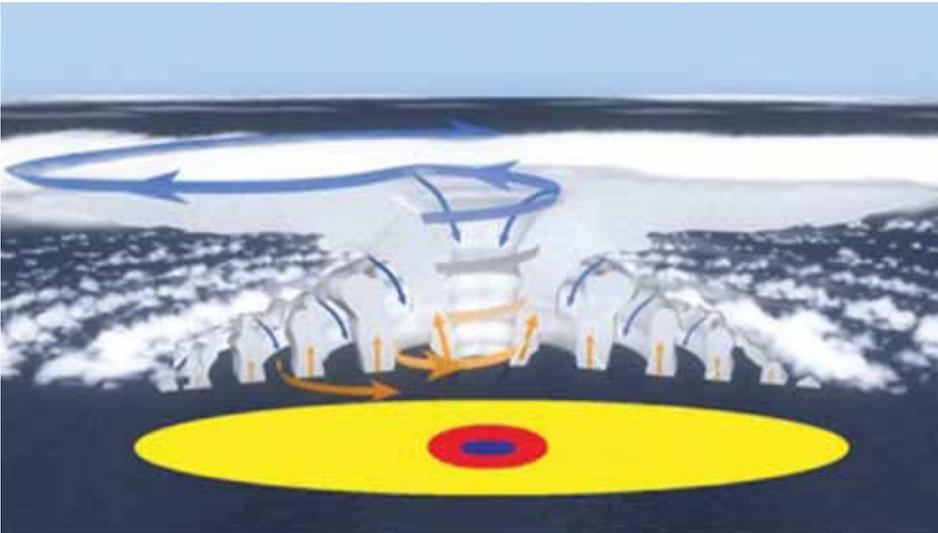
Hurricane activity varies over different time cycles, and the reasons for this variability are not all well understood. One cycle that is well-defined in the Atlantic Region is the annual Atlantic hurricane season, which runs from June 1st to November 30th each year. The graph below shows the average distribution of hurricane and tropical storm activity throughout the year. From this graph, it is clear that the majority of tropical cyclones in the Atlantic Basin occur between August and October with a peak in September. Another cause of tropical cyclone variability is the El Niño-Southern Oscillation (ENSO). ENSO is the term used to define the oceanic El Niño/La Niña cycle (extreme phases of a naturally occurring climate cycle) and its associated atmospheric component termed the Southern Oscillation. In addition to the seasonal cycle and ENSO, other natural climate variations may influence Atlantic hurricane activity on time scales of a few weeks to a few years. On longer (e.g. multidecadal) time scales, there is strong variability in the Atlantic that affects storm activity.



A mature hurricane is nearly circular in shape. The winds of a hurricane are very light in the center of the storm (small blue circle in the image below) but increase rapidly to a maximum 10–50 km (6–31 miles) from the center (red) and then fall off slowly toward the outer extent of the storm (yellow).

The size of a hurricane's wind field is usually a few hundred miles across, although the size of the hurricane-force wind field (with wind speed  $>117.5$  km/h [73 mph]) is typically much smaller, averaging about 161 km (100 miles) across. The area over which tropical storm-force winds occur is greater, ranging as far out as almost 500 km (300 miles) from the eye of a large hurricane.

## The strength of a hurricane is not necessarily related to its size.



Adapted from the UCAR/COMET Program

One of the largest tropical cyclones ever measured was Typhoon Tip (Northwest Pacific Ocean, October 12, 1979), which at one point had a diameter of about 2100 km (~1350 miles). One of the smallest tropical cyclones ever measured was Cyclone Tracy (Darwin, Australia, December 24, 1974), which had a wind field of only 60 miles (~100 km) across at landfall.

In mature hurricanes, strong surface winds move inward towards the center of the storm and encircle a column of relatively calm air. This nearly cloud-free area of light winds is called the eye of a hurricane and is generally 20–50 km (12–30 miles) in diameter. From the ground, looking up through the eye, skies may be so clear that you might see the stars at night or the sun during the day. Surrounding the eye is a violent, stormy eyewall, formed as inward-moving, warm air turns upward into the storm. Usually, the strongest winds and heaviest precipitation are found in the eyewall area.

A mature hurricane can be broken down into three main parts: the eye, eyewall, and outer region. In the Northern Hemisphere, the most destructive section of the storm is usually in the eyewall area to the right of the eye, known as the right-front quadrant. Based on the direction of movement of a hurricane during landfall, this section of the storm tends to have higher winds, causing high seas and storm surge on land.

Outside the eyewall of a hurricane, rainbands spiral inwards towards the eyewall. These rain bands are capable of producing heavy rain and wind (and occasionally tornadoes). Sometimes, there are gaps between the bands where no rain is found. In fact, if one were to travel from the outer edge of a hurricane to its center, one would typically experience a progression from light rain to no rain back to slightly more intense rain many times with each period of rainfall being more intense and lasting longer until reaching the eye.



In the tropical oceans, the sea surface temperature (SST) is much warmer than that of the deeper water below the surface. At an ocean boundary layer called the thermocline, the transition from warm water to cold water occurs rapidly. Above the thermocline, in the upper ocean mixed layer, the water is fairly uniform in temperature and is approximately as warm as the sea surface. Below the thermocline, the water is also nearly uniform in temperature, but it is colder.

The thickness of the oceanic mixed layer varies in different parts of the tropical oceans. In most parts of the Gulf of Mexico, for example, the oceanic mixed layer during the summer and fall is relatively thin and the thermocline is relatively close to the sea surface. In the Caribbean Sea, the oceanic mixed layer is relatively thick and so the thermocline is deeper.

Vertical mixing occurs when a hurricane passes over the surface of the ocean. The hurricane's winds create turbulence in the ocean, which mixes the surface water with the water below. This mixing brings the colder water from below the thermocline up into the surface layer, thereby thickening and cooling the surface layer. Since this vertical mixing process happens within a few hours, it usually cools the sea surface underneath a hurricane, restricting evaporation and therefore limiting the heat available to the hurricane for intensification and maintenance.

Another process that can cool the sea surface under a hurricane is upwelling. Winds from the hurricane cause the water in the upper ocean to move away from the storm center. Colder water from below then moves upward towards the sea surface to fill the void. Unlike vertical mixing, upwelling caused by a hurricane usually occurs over a period of a half day or more, so its contribution to sea surface cooling only occurs underneath the storm if a storm is moving slowly.

The thicker the oceanic mixed layer is before a hurricane arrives, the less vertical mixing and upwelling can cool the sea surface. In the image to the right, the combined effects of vertical mixing and upwelling on hurricane intensity are shown if the oceanic mixed layer is initially thin versus if the oceanic mixed layer is initially thick.

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## Deep, warm water can increase a hurricane's intensity.

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The three-dimensional cartoon of the temperature distribution in the upper ocean shown below illustrates the impact of a hurricane passing over the ocean when the oceanic mixed layer is thin like much of the Gulf of Mexico (left) and thick like the Caribbean Sea (right). In both cases, the hurricane propagates down and left over the warm sea surface (red), creating a cold wake behind the storm as colder water (blue) is brought towards the sea surface by the hurricane's wind stress. If the oceanic mixed layer is initially thin (left), the cold wake is colder so the hurricane remains weaker than if the oceanic mixed layer is initially thick (right), all else being equal. A hurricane in the Caribbean Sea is less likely to be limited by cold water than a hurricane in the Gulf of Mexico.



Just as there are many factors that contribute to the birth and survival of a hurricane, there are also many causes for a hurricane to weaken and/or die.

Landfall usually causes a hurricane to quickly decay. Hurricanes require evaporation from the warm ocean surface to survive. Once a hurricane makes landfall, it is separated from its ocean energy source, and hence, can no longer extract heat from the ocean. Since the air masses over land are drier and contain more aerosol particles than over the ocean, less moisture is carried into the storm, cloud coverage lessens, and air is cooled and then sinks, disrupting the hurricane's secondary circulation and hindering critical thunderstorm development. To a lesser extent, the increased roughness of the land surface also weakens a hurricane as increased friction causes a reduction in surface circulation.



Satellite image of Tropical Storm Ida (2009), showing the classic signature of a tropical storm undergoing transition to an extratropical cyclone. There is heavy thunderstorm activity near the center, but the long band of clouds to the east of Ida doesn't look much like a spiral band—it looks more like a front.

Even if a hurricane remains over the ocean, once the storm moves northward (in the Northern Hemisphere) out of the tropical ocean and into the mid-latitudes, it begins to move over colder water, again losing the warm water source necessary to drive the hurricane. As less moisture is evaporated into the atmosphere to supply cloud formation, the storm weakens. Sometimes, even in the tropical oceans, colder water churned up from beneath the sea surface by the hurricane can cause the hurricane to weaken. Even when the ocean conditions are favorable for the hurricane to be maintained, a hurricane may encounter an area of particularly dry and dusty air causing the hurricane to weaken.

Hurricane decay can also be caused by strong vertical wind shear, a change in wind direction or speed with height. This change in wind speed or direction with height can enhance the mixing of drier environmental air into the storm eyewall leading to downdrafts, which inhibit intensification. Fast, upper-tropospheric winds can create very high values of wind shear and can separate cloud tops from their bases and cause the vertical circulation around a hurricane's eyewall to tilt. As heat and moisture at upper levels are advected away from the low-level circulation of the hurricane, its development is inhibited. Midlevel warming within the storm's center also reduces convective activity and inhibits intensification. Without a strong secondary circulation, a hurricane cannot be sustained. The response to vertical shear partially depends on the storm circulation, so the response to similar values of vertical shear can vary from storm to storm. Vertical wind shear is common in the mid-latitudes, although it can also occur over the tropical oceans where it cannot only weaken a hurricane but also help to prevent one from forming in the first place.

When a hurricane moves into the mid-latitudes, it may be absorbed by a different kind of low-pressure weather system called an extratropical cyclone. Extratropical cyclones are responsible for much of the sensible weather (such as rain and snow) that people who live in the mid-latitudes experience, especially during the winter months.



Long-term variations in hurricane activity due to climate change are distinct from short-term year-to-year variations in hurricane activity or changes in hurricane activity during a given hurricane season. Climate change may affect hurricane intensity, frequency, track, size, and/or rainfall. As the global climate warms, the sea surface temperature also increases in the tropical oceans where hurricanes form. In theory, hurricanes may then become more intense or better able to survive at a high intensity for longer periods of time.

Current models project a 6 to 34% decrease in the global frequency of tropical cyclones by the late 21st century; but in individual ocean basins, these models project that the frequency may either increase or decrease by a substantial percentage. Scientists have a low confidence in current model projected changes to tropical storm activity in individual ocean basins. There is some agreement among hurricane climate scientists that it is likely for the global frequency of tropical cyclones to either decrease or remain essentially unchanged in response to 21st century climate warming.

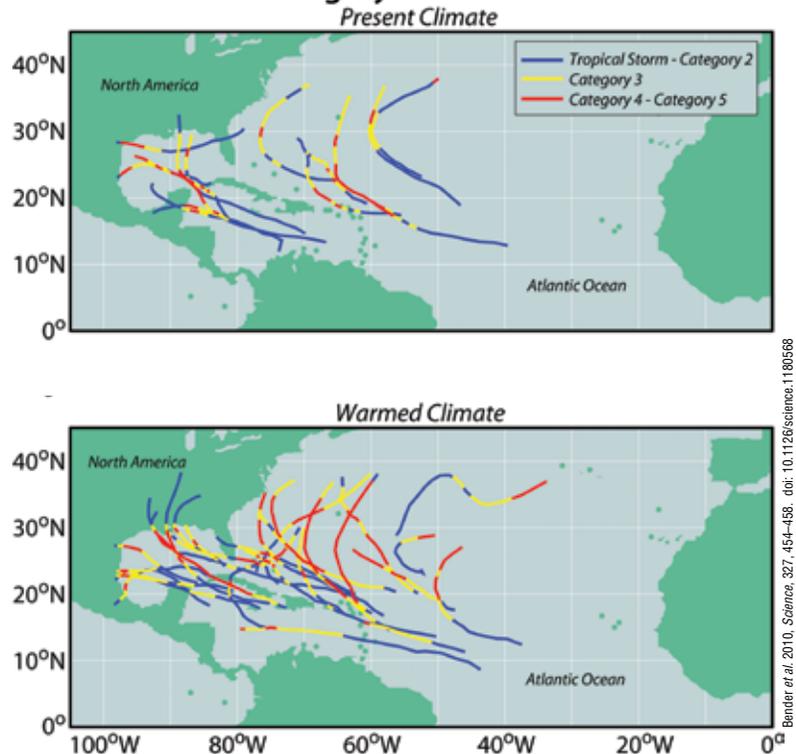
A recent assessment concluded that with projected climate warming “an increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally)” (Knutson *et al.*, 2010). However, this may not occur in all ocean basins. “The frequency of the most intense storms will more likely than not increase by a substantially larger percentage in some basins” (Knutson *et al.*, 2010).

It is important to note, however, that owing to difficulties in measuring hurricanes, separating the effects of anthropogenically-influenced climate change from the natural variability of hurricane activity is very difficult. At present, it remains uncertain whether past changes in hurricane activity have exceeded the variability from natural causes.

Another concern is the complication of sea level rise due to climatic warming, as increasing ocean temperatures and increased melt water from melting glaciers and ice sheets cause the ocean to expand. Higher sea levels mean that storm surges and waves ride on a higher base level, causing storm surge impacts such as coastal erosion—even from minor storms—to increase, possibly dramatically. Low-lying coastal ecosystems are greatly threatened by continued sea level rise and increased risk from extreme weather events. Increased hurricane rainfall rates and storm surge levels would increase the risk of inland flood damage and coastal flood damage, respectively, in areas affected by landfalling hurricanes.

Consensus statements on the potential link between hurricanes and climate change can be found within the Intergovernmental Panel on Climate Change Fourth Assessment Report\* and in a recent assessment produced by a World Meteorological Organization expert team on climate change impacts on tropical cyclones.†

### Modeled Category 4 & 5 Hurricane Tracks



Bender *et al.* 2010, *Science* 327, 454-458. doi: 10.1126/science.1180568

\* IPCC Fourth Assessment Report; [http://www.ipcc.ch/publications\\_and\\_data/ar4/syr/en/contents.html](http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html)

† Knutson *et al.*, 2010; <http://www.nature.com/ngen/journal/v3/n3/abs/ngen779.html>

# Hurricane Forecasts, Observations, and Models

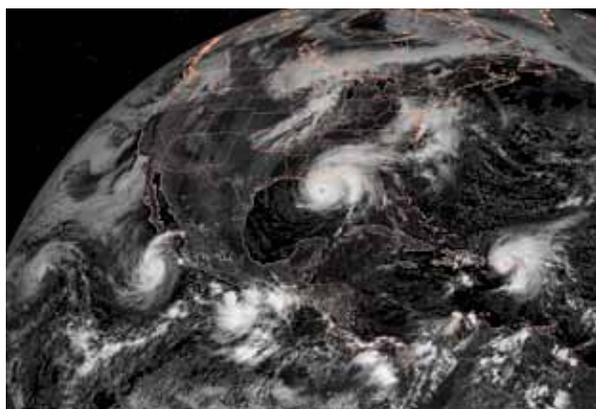
Hurricane forecasting requires a coordinated effort that involves five main components: hurricane observations, hurricane forecast models, operational hurricane forecasts and warnings, dissemination to the public, and public response.

Before forecasters can predict a hurricane's track or intensity, they need to gather as much data as possible on that storm and the current state of the atmosphere and the ocean. Satellite imagery and airplane reconnaissance are considered to be the primary platforms for hurricane observation, but critical measurements are also taken at sea by buoys and ships, and over land by radar and radiosondes.

Observations from satellites, reconnaissance aircraft, ships, buoys, radar, and other land-based platforms are the basis for all forecast and warning products issued by U.S. National Oceanic and Space Administration's (NOAA) National Hurricane Center (NHC) and other worldwide hurricane forecast centers. These observations are checked for quality, analyzed, and fed into a suite of computer models. Results from the hurricane forecast models are interpreted and used as guidance for the appropriate forecast centers and local weather offices to help them issue official hurricane forecasts and warnings. The timely and reliable distribution of these forecast and warning products allows members of the public and their local emergency managers to make appropriate plans in the days and hours prior to a hurricane landfall.



Air Force Photo/Tech. Sgt. James Pritchett



NOAA

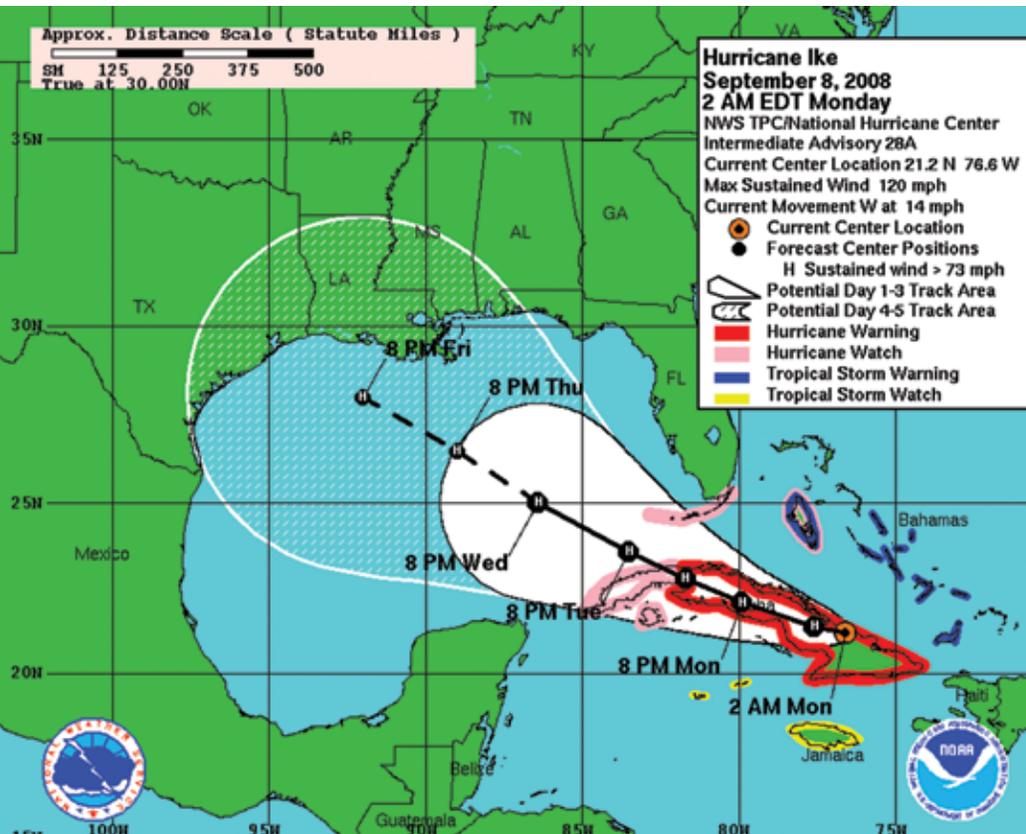


The National Hurricane Center (NHC), in coordination with one or more National Weather Service (NWS) Weather Forecast Offices (WFOs), issues a hurricane watch for specific coastal areas when hurricane force winds (sustained winds of 119.1 km/h [74 mph] or higher) are possible within 48 hours. This hurricane watch is upgraded to a hurricane warning when hurricane force winds are expected within 36 hours or less. A hurricane warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continue, even though winds may be less than hurricane force. If only tropical storm force winds are expected (sustained winds of 62.8- 117.5 km/h [39-73 mph]), then a tropical storm watch or tropical storm warning will be issued for that area.

In addition to watches and warnings, the NHC issues a variety of text and graphical products designed to inform the public of forecasted hurricane threats. A complete description of all of these products can be found in the National Hurricane Center Product Description Document: A User's Guide to Hurricane Products.

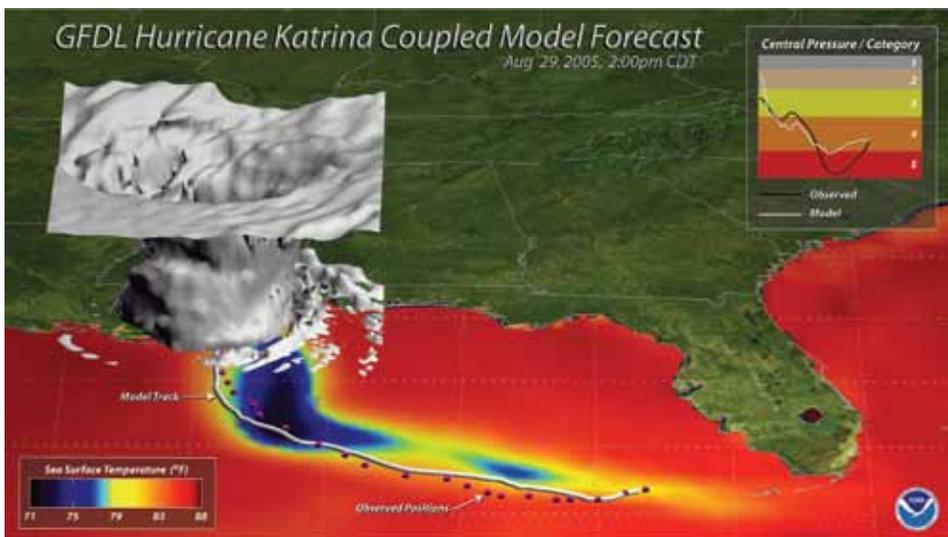
Once hurricane season begins, it is important for anyone at risk of being impacted by a hurricane to pay attention to these local weather updates and advisories on the television and radio as well as to view the NHC products available online ([www.nhc.noaa.gov](http://www.nhc.noaa.gov)).

## The National Hurricane Center forecast cone represents the probable track of the center of a tropical cyclone.



National Hurricane Center Forecast Graphic

This image shows the Tropical Cyclone Track Forecast Cone and Watch/Warning Graphic for Hurricane Ike (2008). This graphic depicts the NHC forecast track for the center of a hurricane along with an approximate representation of associated coastal areas under a hurricane warning (red), hurricane watch (pink), tropical storm warning (blue), and tropical storm watch (yellow). The orange circle indicates the current position of the center of the tropical cyclone. The black dots show the NHC forecast position of the storm center at the times indicated. The letter inside the dot indicates the forecast strength of the cyclone category: (D)epression, (S)torm, (H)urricane, (M)ajor hurricane, or remnant (L)ow. Systems forecast to be extratropical are indicated by white dots (with black letters indicating intensity). The cone represents the probable track of the center of a tropical cyclone, and is formed by enclosing the area covered by a set of circles (not shown) along the forecast track (at 12, 24, 36 hours, etc). The size of each circle is set so that two-thirds of historical official forecast errors over a 5-year sample fall within the circle.

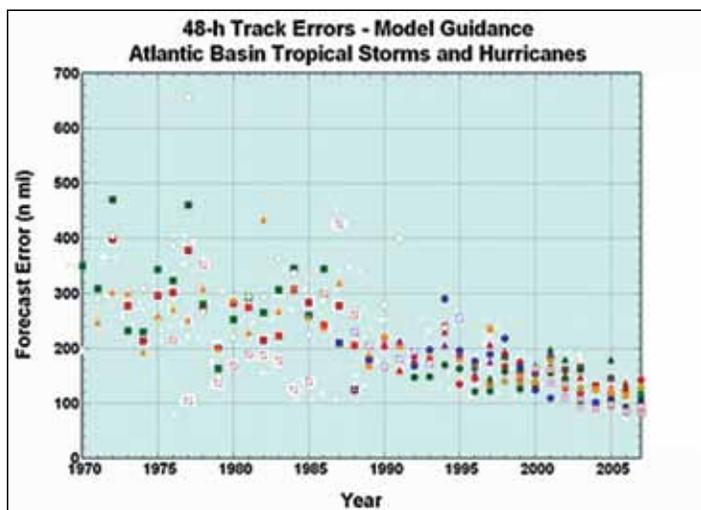


## Naming Hurricanes

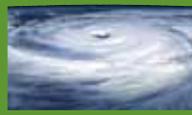
The National Hurricane Center (NHC) assigns a number to each new tropical depression that forms in the Atlantic basin. This number depends on how many other tropical cyclones have formed so far during that hurricane season in that ocean basin. For example, Hurricane Frances in 2004 was originally classified as Tropical Depression Six because it was the sixth tropical cyclone to form in the Atlantic Basin during the 2004 hurricane season. Once a system is classified as a tropical storm, it is given a name by the NHC. Starting in the early 1950's, six separate lists of alphabetical storm names were developed. Each list is recycled every six years, although storm names that have resulted in substantial damage or death (e.g. Ike, Katrina, Andrew, Betsy) are retired. As of the end of the 2009 Atlantic hurricane season, seventy-three storm names have been retired in the Atlantic Basin.

historical relationships between storm behavior and atmospheric variables provided by dynamical models. Trajectory models move a hurricane along a forecasted track based on the large-scale environmental wind field obtained from a separate dynamical model. Ensemble models (above left) use multiple forecasts created with different models, different physical parameterizations, or varying model initial conditions to create a single ensemble forecast. Finally, numerical models of storm surge, waves, and coastal flooding are used to forecast hurricane impacts at landfall instead of hurricane track and intensity.

The NHC evaluates hurricane forecast model accuracy every year by evaluating forecast errors. Track forecast errors are defined as the difference between the predicted and actual positions of the storm center at a given lead time (e.g. 24 hours in advance). To the right is a graph showing the average 48-hour Atlantic Basin tropical storm and hurricane track errors from various models for the period from 1970 to 2007. Each dot color represents a specific model. During this period, model track error decreased significantly, which was largely responsible for improved official track forecasts made at NHC. In contrast, forecast model intensity and NHC official hurricane intensity accuracy has not shown significant improvement over time.



Courtesy of NOAA/NHC



Every year, improvements are made to the hurricane forecast models, and large efforts are currently ongoing to research ways to improve dynamical hurricane model forecasts: increasing model resolution, improving representation of modeled physical processes both within the atmosphere and at the air-sea interface where the hurricane interacts with ocean, verifying model output with observations of atmospheric variables, and improving data assimilation techniques within the model. These efforts should prove particularly useful for the complicated problem of predicting hurricane intensity, which unlike track forecasting involves horizontal scales both larger than a hurricane and smaller than a raindrop.

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## Hurricane forecast models have improved significantly.

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### Hurricane History

The deadliest tropical cyclone in world history is the Great Bhola Cyclone, which struck Bangladesh in 1970 and caused approximately 500,000 fatalities. More recently, Cyclone Nargis, which made landfall in Myanmar in 2008, caused catastrophic destruction and at least 138,000 fatalities. The Galveston Hurricane of 1900 was responsible for over 6,000 deaths and still remains to be the deadliest hurricane to strike the United States. When Atlantic hurricanes have caused extensive devastation, their names have been retired, never to be used again by the National Hurricane Center.

Many tropical cyclones have left important marks on regional and global history. The Great Bhola Hurricane is actually linked to the creation of the state of Bangladesh, and the Hakata Bay Typhoon wiped out the Mongol fleet during their second and final attempt at invading Japan in 1281. In 1609, a fleet of ships carrying settlers from England to Virginia was struck by a hurricane and some of these settlers became Bermuda's first inhabitants as they found refuge on the island after the storm (their stories also helped inspire Shakespeare's *The Tempest*).

An average of about 2 major hurricanes every 3 years made landfall somewhere along the U.S. Gulf or Atlantic coast. The 2005 hurricane season set the record for the most U.S. major hurricane strikes since 1851 and tied for second-most hurricane strikes. When looking at historical storms that have occurred in the Atlantic ocean basin from 1851 to 2006: one-third of the deadliest hurricanes were category four or higher, and fourteen out of the fifteen deadliest hurricanes were category 3 or higher. Also, large death totals were primarily a result of storm surge (10 ft or greater) associated with many of these major hurricanes, and a large portion of the damage in four of the twenty costliest tropical cyclones resulted from inland floods caused by torrential rain.



All North Atlantic (1851–2008) and Eastern North Pacific (1949–2008) hurricanes. Major hurricanes (at least Category 3 on the Saffir-Simpson Hurricane Scale) are in yellow. Category 1 and 2 hurricanes are in red. Dashed lines are remnant lows, extratropical and waves.

Hurricanes are among the most powerful natural hazards known to humankind. During a hurricane, residential, commercial, and public buildings, as well as critical infrastructure such as transportation, water, energy, and communication systems may be damaged or destroyed by several of the impacts associated with hurricanes. Wind and water are the twin

perilous agents of devastation associated with hurricanes, and both can be tremendously destructive and deadly.

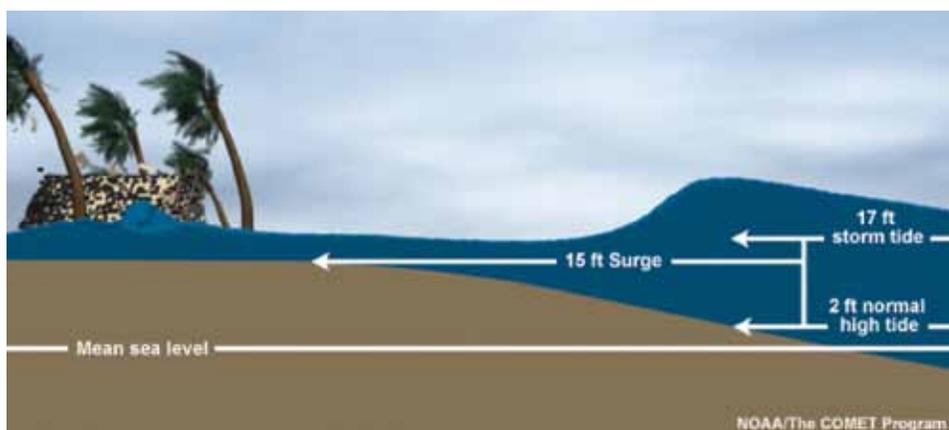
When a hurricane makes landfall, the sheer force of hurricane strength winds can

destroy buildings, topple trees, bring down power lines, and blow vehicles off roads. When flying debris, such as signs, roofing material, building siding, and small items left outside are added to the mix, the potential for building damage is even greater.

The coastal flooding triggered by hurricanes is as destructive as the high winds, but can be even more deadly, and it is by far the greatest threat to life and property along the coastline. Storm surge, waves, and tides are the greatest contributors to coastal flooding, while precipitation and river flow also contribute to damage during some storms. Storm surge is the pulse of water that washes onto shore during a storm, measured as the difference between the height of the storm tide and the predicted astronomical tide. It is driven by wind and the inverse barometric effect of low atmospheric pressure, and is influenced by waves, tides, and uneven bathymetric and topographic surfaces.

In addition to high winds and storm surge, hurricanes threaten coastal areas with their heavy rains. All tropical cyclones can produce widespread torrential rains, which cause massive flooding and trigger landslides and debris flows. Flash flooding, a rapid rise in water levels, can occur quickly due to intense rainfall over a relatively short period of time. In 2001, Tropical Storm Allison brought rain to the Texas and Louisiana coasts for nearly 6 days. Thirty-seven inches of rain fell in the port of Houston, TX, and nearly 30 inches inundated Thibodaux, LA. Tropical Storm Allison was actually the most costly tropical storm in U.S. history with more than \$5 billion in flood damage to southeast Texas and southern Louisiana.

## Inland flooding and storm surge are responsible for most of the deaths from tropical cyclones in the U.S.



Courtesy of NOAA

## Hurricanes vs. Tornadoes



Courtesy of MODIS Rapid Response Team at NASA GSFC



Justin Hobson, 2007

	<b>Hurricanes</b>	<b>Tornadoes</b>
Where they form	Hurricanes form over warm water in the tropical oceans and develop best when far from the jet stream.	Tornadoes form over land and form within storms that are often very close to the jet stream.
How big they are	Can be several hundred miles across	Usually no more than ¼ mile wide
How long they last	Can last up to 3 weeks	Usually lasts no more than 1 hour
How strong the winds are	Usually less than 290 km/hr (180 mph)	The most severe ones can be up to 480 km/hr (300mph)
Occurrence per year	An average of 10 tropical storms in the Atlantic Ocean	In the United States, 800–1,000
Advance warning from forecasters	Several days	Usually no more than 15–30 minutes



Some of the world's most deadly natural disasters have been tropical weather events including the Great Bhola Cyclone of 1970, which struck Bangladesh and killed as many as 500,000 people (primarily as a result of storm surge), and Cyclone Nargis, which made landfall in Myanmar in 2008, causing catastrophic destruction and at least 138,000 fatalities. The most deadly U.S. hurricane was the 1900 Galveston Hurricane that killed more than 6,000 people and recently hurricane Katrina killed more than 1,800 people in Louisiana and Mississippi.

The greatest threat to personal safety exists during a storm and in the immediate aftermath when high winds can topple trees and cause flying debris. Heavy rain can produce flash floods and storm surge can present another deadly threat.

The most critical step in preparing for a hurricane is to understand the risk in terms of property damage and threat of personal injury. The key hazards from hurricanes come from wind and flooding, due to storm surge or intense rainfall. Important questions to ask about one's home include: Is a home at risk of flooding due to storm surge or intense rainfall? Is the home in an evacuation zone? If so, to where should homeowners evacuate? Most people only need to evacuate a few miles from the coast to avoid the dangers of storm surge. Does a home have proper insurance coverage for both wind and flood losses? Taking time to answer these critical questions before hurricane season is essential. FEMA has published almost 100,000 individual Flood Insurance Rate Maps (FIRMs\*) to enable individuals to make informed decisions about protecting property.

The science of hurricane protection has evolved significantly over the past decade, fueled by the intensely destructive decade of hurricane activity, 1996 to 2005, that was one of the most destructive decades in the last century with a total economic hurricane damage of \$198 billion. Applied scientific research is taking place on multiple fronts to give engineers, inventors, and entrepreneurs new data with which to develop the next generation of hurricane protection products.

Another factor driving the advancement of hurricane protection technologies was the development of the 2000 International Residential and Commercial Building Codes, which, for the first time, required the use of impact-resistant windows, doors and other components for homes built in hurricane-prone areas. Subsequent editions of the International Building Codes are adopted every 3 years.

Regardless of the advances in home protection, making smart, informed decisions is the best way to ensure safety during a tropical cyclone.

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## Preparation can protect you and your home from damage in a hurricane.

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Courtesy of FEMA

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\*<http://www.fema.gov/hazard/map/firm.shtm>

# Hurricanes: Science and Society



## Internet Resources

*Hurricanes: Science and Society* ([www.hurricanescience.org](http://www.hurricanescience.org)) is one of the most comprehensive Internet resources on hurricanes. In addition to in-depth content on hurricane science, forecasting, and preparation, there are educational resources, case studies, and a historical storm interactive.

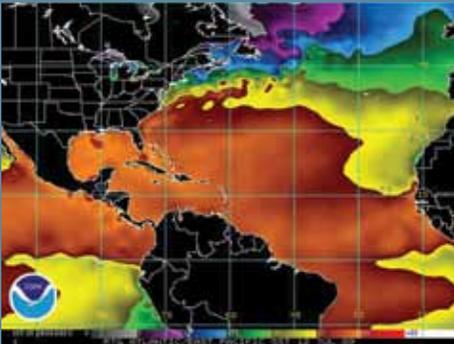
The **Interactive Hurricane History Timeline** contains summaries and images of significant storms throughout history, from the Hakata Bay Typhoon in 1281 to Hurricane Rick in 2009. There are also decadal summaries as well as storm totals for the North Atlantic for the last 100 years.

The **Basic Science** section provides foundational science on key concepts in meteorology and oceanography that are important for understanding hurricanes.

The **Teacher Resources** section contains classroom activities developed by K–12 educators along with a list of select classroom resources. There is also a list of links to image and data sources for hurricanes.

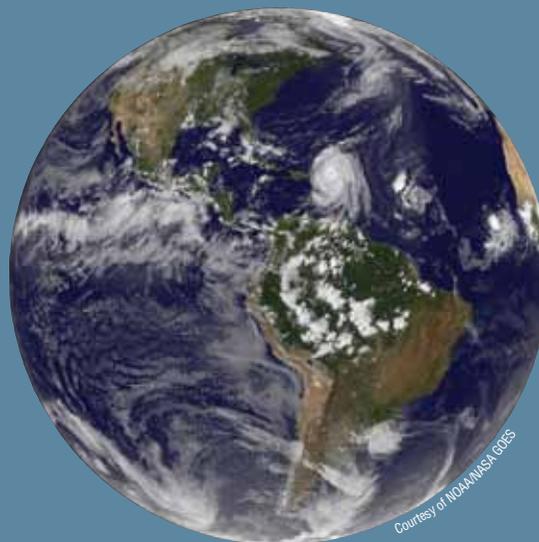
The **Student Resources** section contains features designed for students.

**PowerPoint presentations** for classroom use are available on the website.



## Print Resources

This booklet and other printable material are available on the website as PDF documents.



[www.hurricanescience.org](http://www.hurricanescience.org)

Graduate School of Oceanography  
University of Rhode Island



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