Hurricane force

Understanding the physics of hurricanes can help scientists make better forecasts of these devastating phenomena and determine whether the recent increase in the number of intense storms is linked to global warming, as **Roger Smith** explains

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In August 2005 Hurricane Katrina wreaked havoc on New Orleans, claiming 1300 lives and causing $125bn of damage. Just two months later, the most intense Atlantic hurricane ever recorded – Hurricane Wilma – devastated parts of Mexico, Cuba and Florida. Indeed, there were a record 27 tropical storms in the Atlantic during 2005, 15 of which developed into hurricanes. For the first time since it was established in 1953, the alphabetical list of names assigned annually by the World Meteorological Organization (WMO) was exhausted. This brought us our first ever Greek-letter-named hurricanes, Beta and Epsilon, and the WMO recently announced that five names (yet another record) would be permanently retired from the rotating list – a fate reserved for those hurricanes causing the most devastation.

To reduce the catastrophic loss of life and material damage caused by hurricanes we need better forecasts both of their paths and intensities. Currently forecasts of path are too error-prone to be of much practical use beyond three days in advance, and predictions of intensity change are even less developed. Furthermore, last year's record-breaking Atlantic hurricane season has fuelled fears that global warming may be responsible for increasing the frequency and intensity of hurricanes. Although controversial, such a link would be of vital importance to the hundreds of millions of people living in hurricane-prone areas.

Many features of hurricanes can be explained in terms of classical physics – such as Newton's second law and the thermodynamics of moist air. By understanding the basic physics behind the growth and progress of hurricanes, physicists are contributing to a global effort to obtain better hurricane forecast models.

At a Glance: Hurricanes

- A record number of intense hurricanes in the North Atlantic in 2005 highlighted the need to improve hurricane forecasting
- The basic dynamics of hurricanes can be explained in terms of classical physics such as mechanics and thermodynamics, and understanding the physics of hurricanes can help improve forecasting models
- Forecasters need to predict both the path a hurricane will take and how its intensity will change. Track forecasts are reasonably accurate in the short term, but intensity forecasts are much less developed
- Researchers have recently linked the increased frequency and intensity of hurricanes to global temperature rises, although this remains to be confirmed
- A concerted effort to improve the historical database of hurricanes has begun, in order to better establish whether global warming is linked to hurricane incidence

Spirals and eyes

Hurricanes are rotating low-pressure weather systems that develop mostly over the warm tropical oceans. Strictly speaking, the term hurricane applies only to storms that occur over the Atlantic Ocean, Caribbean Sea, Gulf of Mexico and Eastern Pacific Ocean, while storms elsewhere are called typhoons or tropical cyclones. On average 80 such storms form globally each year, mostly in the summer months, and are classified by average wind speeds in excess of 33 m s^{-1} at 10 m above the ocean surface.

Most readers will be familiar with satellite images of hurricanes (figure 1). They consist of a characteristic spiral formed by dense cirrus clouds, which surround a cloud-free eye that can vary from a few kilometres to over 100 km across. Around the eye there is an annular region of deep convective clouds. These are called the eyewall clouds since their inner edge forms an outward-sloping "wall" to the eye. The eyewall has the fastest wind speeds and heaviest precipitation, making it the most-feared part of the hurricane.

Hurricane formation is a complex process that is not completely understood, but certain conditions do need to be met. Hurricanes usually form over ocean water that is warmer than 26.5 °C to a depth of about 50 m and they are seeded by a pre-existing low-pressure disturbance. The air above the ocean also needs to be very humid and the wind speed fairly constant with height. Almost all hurricanes form at a latitude of greater than 5° from the equator due to the Coriolis force, which causes the air to rotate. The rotation strengthens the hurricane and leads to the spiral shape.

The Coriolis force, which appears in the equations of motion when Newton's second law is formulated in a rotating reference frame like the Earth, tries to deflect moving air to the right of its direction of travel in the northern hemisphere and to the left in the southern hemisphere. As a result, hurricanes rotate anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. The Coriolis force is zero at the equator and increases with latitude, explaining why hurricanes rarely form close to the equator.

The physics of hurricanes

The dynamics of hurricanes are quite subtle, but it is convenient to think of the motion of air in terms of two coupled components of flow. The first of these is the "primary circulation", which describes the tangential motion of the air about the central rotation axis. The second component, which is more complex, is the "sec-

Destructive spiral Hurricane Katrina just before it made landfall in New Orleans in September 2005.

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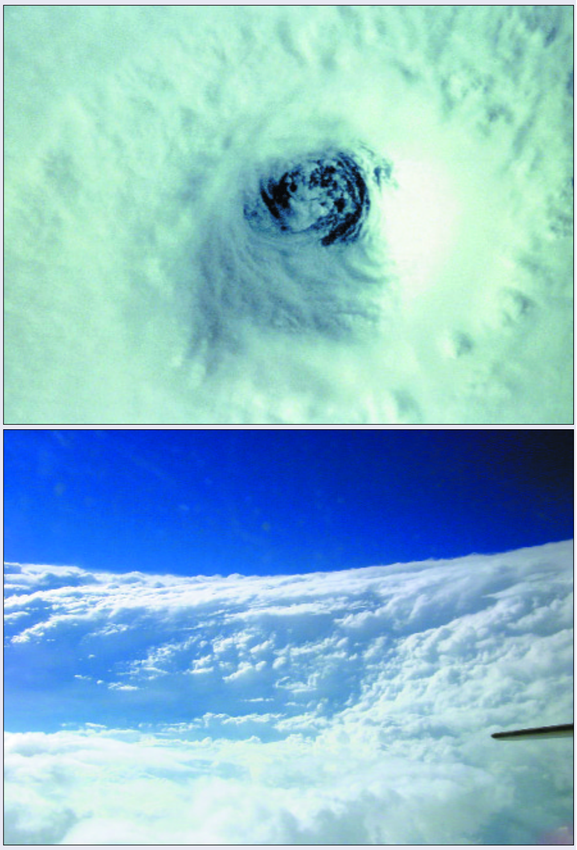
1 Bird's eye view



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Close-up A satellite image shows the cloud-free eye of a hurricane in detail (top). Photographs have also been taken inside hurricanes by research aircraft, such as this one of Hurricane Isabel in 2003 that shows the sloping eyewall clouds (bottom).

ondary circulation". This describes the motion of air in the radial direction, whereby it flows inwards nearer the ocean surface and outwards at higher altitudes. These two components are not independent, and they combine to form a picture of air parcels spiralling inwards, upwards and outwards (see box opposite).

The primary circulation is governed by competing forces in the inward and outward radial directions. Since the centre of the storm has a lower pressure than the surrounding region, the resulting pressure gradient tries to make air parcels move towards the centre. As they do so, however, two additional forces come into play: the Coriolis force deflects the parcels perpendicularly to their motion; while a centrifugal force begins to kick in that drives them radially outwards. The net result is that the air rotates in a circular fashion, with the inward pressure-gradient force approximately in balance with the outward centrifugal and Coriolis forces.

The wind damage produced by hurricanes rises roughly as the cube of the wind speed

The secondary circulation is thought to be important for the intensification of the hurricane. In order for this to happen, air must move inwards and upwards, allowing moisture within it to condense and release its latent heat energy. This inward and upward motion arises because the pressure-gradient force, Coriolis force and centrifugal force are not quite in balance: in particular, friction between the moving air and the ocean surface slows the winds flowing close to the ocean. Since the Coriolis force is proportional to the wind speed and the centrifugal force to the square of the wind speed, these forces weaken. But because the inward force provided by the pressure gradient remains approximately unchanged, air spirals inwards to the centre of the storm and is forced to rise. Furthermore, conservation of angular momentum dictates that as air moves to a smaller radius its velocity must increase, so the hurricane begins to rotate faster.

Now thermodynamics plays its part. The inflowing air progressively becomes more moist as it flows inwards because of evaporation from the warm ocean surface. When it rises and cools, the water vapour condenses to produce clouds and rain. The highest moisture content occurs at small radii, where the air rises to form the thick eyewall clouds. The temperature of the rising air increases with its moisture content through the release of latent heat. Thus the moisture gradient at low levels sets up a negative radial temperature gradient in the clouds, causing air at inner radii to become more buoyant and therefore rise relative to air further out. As the wind speed increases and the surface pressure falls, the evaporation rate and the moisture gradient increase, and hence so does the negative radial temperature gradient. This positive-feedback cycle is what turns a storm into a hurricane, although there is a brake to the process: evaporation at the ocean surface ceases when the relative humidity of the air reaches 100%.

The cloudless eye of the hurricane arises from subsiding air in the centre of the storm, where the decline in tangential wind speed with height leads to a small net downward force. This subsidence compresses air parcels, resulting in an increase in temperature that causes any water drops or ice crystals to rapidly evaporate and stops clouds from forming.

Forecasting hurricanes

If we wish to reduce the devastation caused by storms like Katrina, we need to be able to predict how a hurricane will develop. In particular, forecasters need to know where a storm is heading and how intense it will be when it gets there. Thanks to extensive research into the dynamics of hurricane motion during the late 1980s and early 1990s, we are now able to predict the path of hurricanes with reasonable short-term accuracy.

To a first approximation, hurricanes are carried along by the larger-scale airflow in which they are embedded. Thus at low latitudes, storms tend to move westwards with the trade winds, though they also drift polewards due to the increasing influence of the Earth's rotation with latitude. Often this poleward motion is accentuated by the flow of air around larger-scale weather systems such as subtropical high-pressure systems, which rotate in the opposite direction to hurricanes.

When a storm is swept round the western side of such a system, it may "recurve" and begin moving towards the east as it is carried by the predominantly westerly winds at higher latitudes. In fact, about 40% of Atlantic hurricanes do precisely this as they move out of the tropics; some of them becoming intense extra-tropical cyclones, while others decay over the cooler seas. Vertical variations in wind speed can also have an effect on hurricane motion and cause the storm centre to wobble about its mean track.

Over the last decade, improvements in the numerical weather-forecasting models that predict the global airflow have led to more accurate short-term (24–48 hours) track forecasts. But the accuracy is still often unacceptably large beyond about 72 hours, which can be a problem when trying to prepare heavily populated areas such as the cities on the Gulf Coast for a hurricane impact. In the Atlantic during 2004 the US National Hurricane Center's mean track error (the difference between the forecast position and the actual path of a hurricane) was 107 km after 24 hours, increasing to 187 km after 48 hours, 280 km after 72 hours, 395 km after 96 hours, and 546 km after 120 hours.

The intensity of a hurricane can also change dramatically over its lifecycle, but forecasts of intensity change are still much less developed than track forecasts. In order to make better intensity forecasts – which are critically important when storms are close to making landfall – we need to improve the way physical processes are represented in forecast models.

One example is the problem of concentric eyewall cycles. In strong hurricanes a new eyewall can form outside the initial eyewall, for reasons which are not well understood. The new outer eyewall then moves radially inwards and the inner eyewall disappears. These cycles of eyewall formation and contraction correspond to changes in the intensity of the hurricane: the hurricane weakens when the new eyewall forms but re-intensifies as it contracts. One possible explanation is that the subsidence associated with the outer eyewall weakens the convection in the inner eyewall, allowing the inner-core region to spin down because of friction. Another possibility is that air converging into the inner eyewall is redirected to the outer eyewall, reducing the supply of angular momentum and moisture to the inner eyewall.

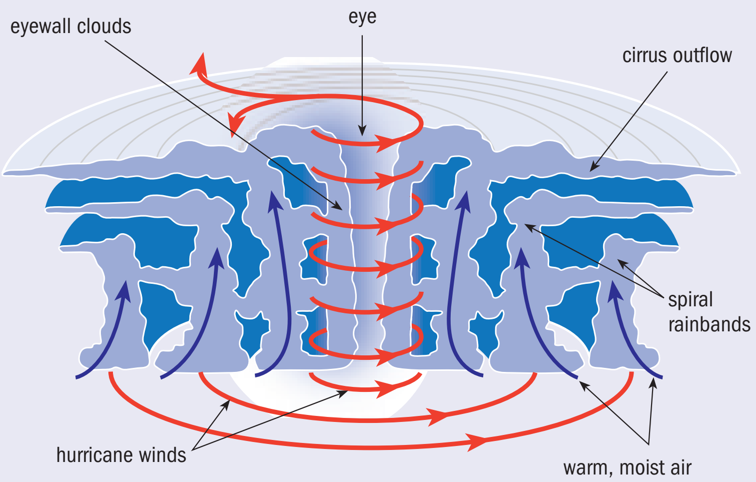
The ocean is another factor. The supply of moisture that gives the storm its energy depends strongly on the temperature of the ocean surface. But deeper, cooler water can be drawn up to the surface by the turbulence caused by the hurricane-force winds, reducing the surface temperature and weakening the hurricane. The amount of cooling depends on the depth of the warm layer before the storm hits and on the length of time the storm lingers over a particular spot. It is therefore greatest for slow-moving storms.

A major challenge is to accurately quantify the rate of moisture supply at the high wind speeds found near the centre of a hurricane. Making measurements in these extreme conditions is very difficult: it requires an aircraft to fly several journeys through turbulent air at less than 100 m above a rough sea (figure 2).

During the last few Atlantic hurricane seasons, researchers at the National Oceanic and Atmospheric Administration's Hurricane Research Laboratory in Miami carried out such measurements in order to determine the "exchange coefficients" that represent the moisture supply and surface exchange of momentum in hurricane models. Meanwhile, researchers at the Hurricane Research Laboratory led by Peter Black and at the University of Miami led by Lynn Shay have been gathering ocean data by dropping instrumented ocean probes at regular intervals along the flight path before and after the passage of a hurricane.

Researchers at the Geophysical Fluid Dynamics Laboratory in Princeton, led until recently by Yoshio Kurihara, have developed a sophisticated hurricane forecast model that includes the changes in ocean structure brought about by the storm. The ocean data gathered by aircraft are therefore important for verifying the predictions of this model. This model is currently one of the most accurate for short-term

The ins and outs of intensification

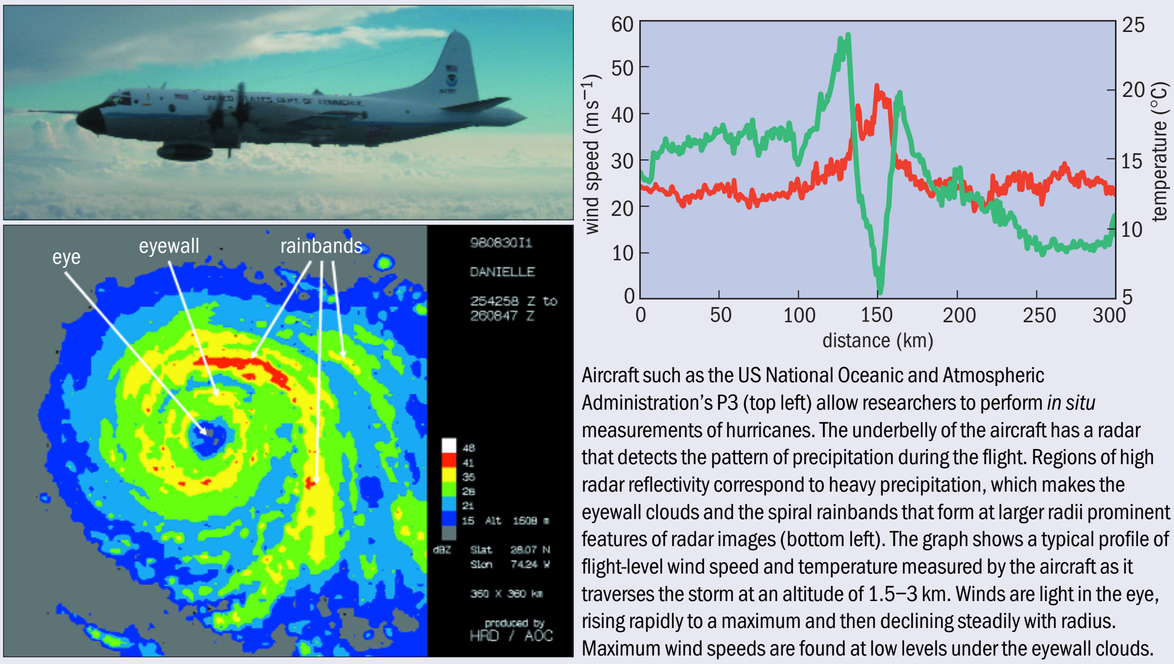


A mature hurricane consists of a largely cloud-free eye surrounded by deep "eyewall" clouds and then further out by spiral "rainbands". These clouds are regions of very heavy rain and strong gusts of wind. The strongest winds are found under the inner edge of the eyewall. Warm, moist air spirals inwards at low levels and rises in the eyewall and the rainbands. Most of the air spirals out in the upper troposphere and the circulation eventually reverses direction, but a little air slowly subsides in the eye. The outward-flowing air forms dense cirrus clouds – the characteristic spiral seen in satellite images.

The inflow near the ocean surface is caused by friction between the air and the ocean. This effect can be demonstrated by placing tea leaves in a beaker of water and vigorously stirring the water to set it in rotation: the leaves gradually congregate at the bottom of the beaker near the axis, where they are swept by the inflow in the thin (~1 mm) layer of friction between the water and the beaker. As the water moves outwards above the friction layer, it conserves angular momentum and spins more slowly, so the rotation in the beaker gradually declines.

The same process would lead to the decay of a hurricane if the outflow of air was to occur just above the friction layer. For a hurricane to intensify, air must flow *inwards* above the friction layer. This allows conservation of angular momentum to speed up the air as it converges towards the axis. The mechanism for producing inflow above the friction layer is the (negative) radial gradient of the upward "buoyancy force" associated with the release of latent heat in the clouds (see text).

2 Storm chasers



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Aircraft such as the US National Oceanic and Atmospheric Administration's P3 (top left) allow researchers to perform *in situ* measurements of hurricanes. The underbelly of the aircraft has a radar that detects the pattern of precipitation during the flight. Regions of high radar reflectivity correspond to heavy precipitation, which makes the eyewall clouds and the spiral rainbands that form at larger radii prominent features of radar images (bottom left). The graph shows a typical profile of flight-level wind speed and temperature measured by the aircraft as it traverses the storm at an altitude of 1.5–3 km. Winds are light in the eye, rising rapidly to a maximum and then declining steadily with radius. Maximum wind speeds are found at low levels under the eyewall clouds.

hurricane forecasting. However, it is due to be replaced in the next year or so by a new model that is currently being developed by a team at the National Centers for Environmental Prediction in Washington, DC led by Naomi Surgi.

Hurricanes always decay in intensity as they move over land, not so much because the friction at the surface is increased, but because the lifeline to the moisture supply from the sea is cut off. This leads to cooling in the eyewall clouds, and hence reduces the radial gradient of buoyancy force that maintains the secondary circulation. But even when the winds have slowed and the surface-moisture supply has greatly diminished, hurricanes can still produce copious amounts of rainfall and flash-flooding. Also, because hurricanes constitute regions of air rich in angular momentum, they often spawn tornadoes on making landfall.

Worst-case scenario

Both from a practical and theoretical standpoint, we would like to know what sets the maximum intensity a storm can achieve in a given environment. In a series of papers, the first in 1988, Kerry Emanuel at the Massachusetts Institute of Technology has tried to answer this question by likening a mature hurricane to a Carnot heat engine. The idea is that the hurricane acquires heat energy (primarily in the form of latent heat) at the sea surface, where the temperature is typically 26–30 °C, and exports it to the upper troposphere, some 15 km above the sea, where the temperature is typically –60 to –70 °C. Using this analogy, Emanuel calculated the maximum intensity that a storm can achieve at a given location and time.

Such calculations are important not only to forecasters but also for making assessments of the impact of global warming on hurricane intensity. For example, they enable the maximum possible increase in intensity to be calculated for particular scenarios of a global increase in temperature. The accuracy of Emanuel's theory has recently been called into question by Michael Montgomery at Colorado State University on the basis that numerically simulated hurricanes can significantly exceed the calculated maximum intensity. In reality, however, the majority of observed storms have significantly lower intensities than the predicted maximum. This suggests that there are frequently processes at work in the atmosphere that are detrimental to intensification.

Hurricanes decay in intensity as they move over land because their lifeline to the moisture supply from the sea is cut off

While the basic dynamics of hurricanes can be understood in terms of processes that are symmetric about the rotation axis, non-axisymmetric processes are very important as well. Large-scale asymmetries arising from the interaction of storms with their environment can have an important effect on storm motion and perhaps also on intensity. Moreover, hurricanes are able to support different types of asymmetric waves in which air parcels move radially inwards or outwards during a cycle.

One particular type of wave – the "vortex Rossby wave" – propagates in the opposite direction to the tangential wind. These waves are almost certainly excited by moist convection, and also by external influences such as changes in the large-scale vertical wind-shear. In the last decade Montgomery and Wayne Schubert at Colorado State University have carried out pioneering studies of these waves and the instabilities they produce. In particular, they have shown that vortex Rossby waves can transport angular momentum radially in a hurricane, which means that the waves can play an important role in the intensification of storms. The team also found that the waves may become unstable, which may be an important mechanism for transporting angular momentum and heat across the eyewall into the eye itself.

During the last Atlantic hurricane season, researchers at the Universities of Washington and Miami, and at the National Center for Atmospheric Research, supported by the Hurricane Research Division, carried out a major programme to document the asymmetries in hurricanes, and especially the structure of the spiral rainbands. The researchers, led by Robert Houze at the University of Washington, obtained *in situ* measurements in hurricanes Katrina, Rita and Ophelia using multiple research aircraft. The first results from the wealth of data collected are just beginning to emerge and should provide a deeper insight into the role of spiral rainbands in the intensity change of hurricanes.

Recently, Sang Nguyen in my group at the University of Munich carried out numerical calculations that suggest the intensification of the hurricane core is intrinsically asymmetric. This is due to the irregular patterns of convective clouds that form, and the calculations suggest that the core region is inherently unpredictable.

Global warming

One of the most controversial topics at present is the possible effect of global warming on the frequency and intensity of hurricanes. Since the Earth has warmed considerably in the last 50 years, it seems reasonable to expect that warmer temperatures at the sea surface will provide more-favourable conditions for hurricane formation. However, a particular problem of attributing changes in hurricane frequency and intensity to global warming is the large natural variation in the frequency of storms, which also follows long-term cycles.

Nevertheless, last year Peter Webster and co-workers at the Georgia Institute of Technology attempted such an analysis of 35 years' worth of storm records in all ocean basins. They reported a large increase in the number of intense storms in most basins with, perhaps surprisingly, the smallest percentage increase being in the North Atlantic Ocean. However, the number of less-intense storms has decreased in all basins except the North Atlantic during the last decade. The increased frequency of intense storms coincides with an average increase in the surface temperatures of 0.5 °C for these basins in the same period.

In 2005 Kerry Emanuel pointed out that while the frequency of hurricanes is an important scientific issue, it is not the best measure of the threat posed by such storms. He showed that the wind damage produced by hurricanes increases roughly as the cube of the wind speed, and therefore defined a "power dissipation index" by integrating the cube of the maximum wind speed over the life of a storm. He showed that fluctuations in this index correlate rather well with the mean sea-surface temperatures in the North Atlantic and North Pacific – the two basins that have the most reliable data on storm intensities – suggesting that warming of the oceans will increase the damage potential of hurricanes. In view of the population growth in many coastal areas prone to hurricanes, this suggests that devastating storms like hurricanes Katrina and Wilma could become the norm in coming decades.

However, some researchers, including Chris Landsea at the National Hurricane Center in Miami and William Gray at Colorado State University, have expressed scepticism about the quality of the data used to examine links between global warming and hurricane frequency. The problem is that in most areas where tropical cyclones occur there are virtually no *in situ* data, so intensities have to be inferred from satellite images. The methods for doing this have improved over the years, but most have a significant subjective element. In fact, Gray claims that there has been no significant increase in the number of intense hurricanes in all basins except in the Atlantic over the last 20 years and there has even been a slight decline in the Northwest Pacific. Such controversies highlight an urgent need to improve the historical tropical-cyclone database. To this end a major reanalysis project is now under way, coordinated by Greg Holland at the National Center for Atmospheric Research in Boulder, Colorado.

3 Potential devastation

NOAA

Hurricane Katrina caused $125bn of damage in New Orleans last year, and increased speculation about whether the growing incidence of intense storms is linked to global warming. Researchers have calculated the maximum possible intensity a hurricane can achieve in a given environment, and can relate this to predicted climate-change scenarios.

Our understanding of the physics of hurricanes has greatly improved over the past two decades and forecasts of hurricanes have become ever more reliable. Even so, we still have much to learn about the basic physical processes that are responsible for the intensity of storms. Such knowledge is important for developing the next generation of hurricane forecast models, and also for determining the limitations of such forecasts. The 2006 Atlantic hurricane season officially began on 1 June, and the coming months will allow more data to be gathered to test and improve our knowledge of these devastating storms.

More about: Hurricanes

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