# TROPICAL CYCLONES

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By the time this article reaches you, the Atlantic Hurricane Season should be well under way and those of us receiving *EUMETCast* will already have sifted through many Meteosat and GOES images—and even through AVHRR material—to see with our own eyes the impressive behaviour of these monster storms. Not everybody, however, is fully aware of what a hurricane actually is, how it forms and from where it draws its enormous power.

The purpose of this article is to provide some insight into these energetic weather phenomena, commonly referred to as Tropical Cyclones.

### What exactly is a Tropical Cyclone?

Let's start out with a definition:

> *A tropical cyclone is a storm system with a closed circulation around a low pressure centre that is driven by heat energy.*

With this rather simple definition in hand we immediately recognise three important aspects:

- they form in the tropics,
- are cyclonic in nature,
- and are heat engines.

Three types of tropical cyclone can be distinguished depending on the windspeeds reached:

1. A Tropical Depression, which is an organised system of clouds and thunderstorms that, as a whole, already possesses a distinct surface circulation. The maximum sustained wind speed is less than 17 m/s. The depression has no organised overall spiral shape and no eye. Again, as the name implies, it is a depression in a tropical region. They are plentiful, can be inconvenient, but seldom cause disruption of daily life.
2. A Tropical Storm, which is an organised system of strong thunderstorms with a pronounced surface circulation and maximum sustained winds between 17 and 32 m/s. Although a distinctive cyclonic shape starts to form, an eye is usually not present. It is common practice in most regions in the world to identify the Tropical Storm with a name or number at this stage of its formation, .
3. Hurricane, Typhoon or Cyclone. Once a tropical storm system has reached an intensity such that it produces sustained wind speeds greater than 33 m/s (118 km/h), we no longer call it a tropical storm but a hurricane, a typhoon or just a cyclone, depending on the region in which it occurs. At this stage, a strong spiral shape has formed and we can normally clearly recognise an eye.

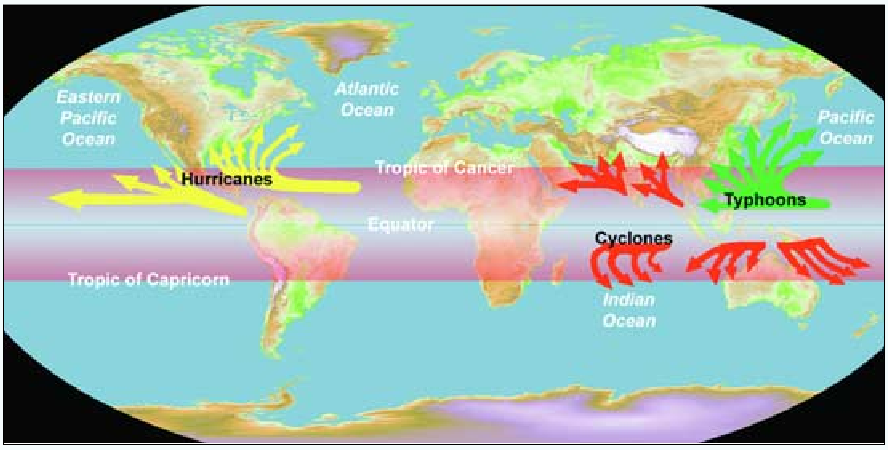



Figure 1 - Basins of Tropical Cyclone Formation

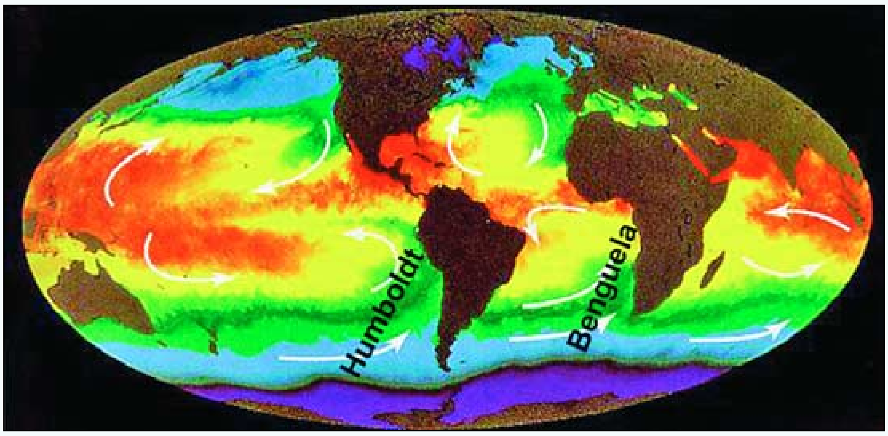



Figure 2 - Global Ocean Surface Currents

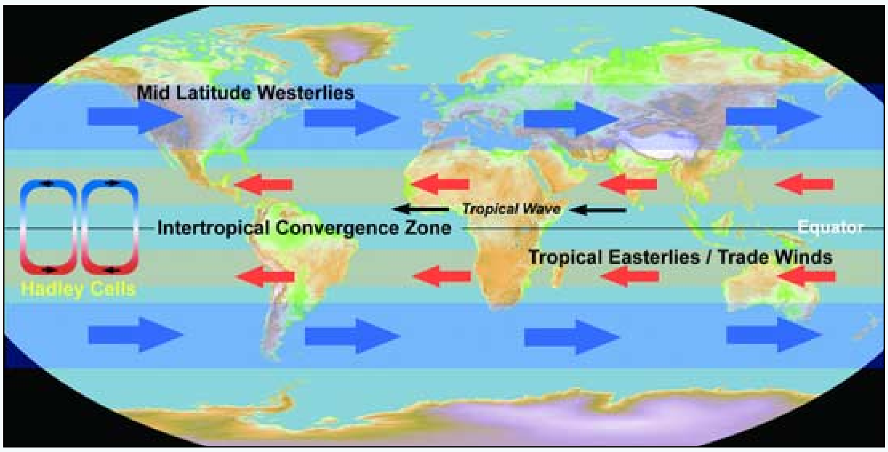



Figure 3 - Atmospheric Belts

There are seven regions along the equator where Tropical Cyclones of the third type form (figure 1). Those that form within the Tropic of Cancer, east and west of Central America, are called Hurricanes while all those that form in the Pacific, north of the equator and west of Hawaii, are labelled Typhoons. All other Tropical Cyclones of the third type are simply referred to as 'Cyclones'. These include tropical cyclones occurring east and west of India, all those that form south of the equator in the Indian Ocean and those to both the northwest and northeast of Australia.

The same figure also shows that there are regions in the Tropics where, apparently, no cyclone formation takes place. Large parts of the Pacific Ocean south of the Equator, and the entire Atlantic Ocean south of the Equator, seem to lack the conditions for cyclone formation. The reason for this is reflected in figure 2 where the temperatures of the major ocean currents have been plotted (red is warm and purple is cold) as well as the flow direction of the surface currents.

Along the western South American coast we find the Humboldt stream, a cold upwelling current that causes the waters near the equator to be far too cold to trigger tropical cyclone formation. Also, the waters flowing along the West African coasts of Namibia and Angola in the Benguela current are very frigid, due to their Antarctic origin. The low surface temperatures are not conducive to the formation of a tropical cyclone.

Not surprisingly, the basins associated with Cyclone formation coincide largely with the areas shown in red in the image. It is important to note, however, that the figure is drawn for northern hemisphere summertime. During winter, the region of warm ocean surface waters moves south, explaining the seasonal nature of cyclone formation.

### Preconditions for the Formation of Tropical Cyclones

Tropical Cyclones can only form when a number of environmental conditions are met. First of all, as can be understood from figure 2, *the ocean water temperature should be high*. A minimum temperature of 26.5°C is required and that value should extend down to a depth of at least 50 meters. The reasons for this are twofold: waters of this temperature cause enough instability in the overlying atmosphere to sustain convection and thunderstorm systems, and on the other hand the warm waters form the reservoir of energy on which the cyclone feeds.

A second precondition is that the *air temperature should be decreasing quite rapidly with increasing altitude*. The quicker the air cools down the greater the rate at which latent heat (energy stored in water vapour) is released from the atmosphere. The principle behind this is that, when air saturated with water vapour gets cooled down, the water vapour transitions to a liquid (condenses). The amount of energy released during the transition from vapour to liquid is a physical property of the substance in question. For water this is about 2240 kJ/kg of water produced—about five times the energy needed to heat water from 0 to 100°C. If we calculate the total number of kilograms of water produced in an active hurricane it becomes apparent that the quantity of latent energy available in the water vapour must be enormous. Scientists at the National Centre for Atmospheric Research (Boulder, Colorado) have estimated that the rate at which a hurricane releases heat energy is of the order of 100 to 200 terawatt. And all of this is *green* energy. By comparison, the total energy production capacity of the whole world is estimated at one terawatt.

Note: *one terawatt = one million megawatts.*

*High humidity*, especially in the lower-to-middle troposphere, is another requirement. When there is a significant amount of moisture in the atmosphere conditions are more favourable for the development of disturbances. And, as all things big start out small, the atmospheric disturbance is at the root of any major tropical cyclone. For clarity of definition I mention here that the troposphere is the lowermost portion of the atmosphere; it extends from the surface up to the tropopause, where the stratosphere begins. The extent of the troposphere varies around the globe but is greatest in the tropics, reaching up to about 16 kilometres, and smallest at the poles where the tropopause starts at around 8 km above the surface.

*Low Wind Shear*. In the definition of a Tropical Cyclone provided at the beginning of the article, mention was made of a closed circulation pattern around a low pressure centre. When there are high winds passing the region of closed circulation with a different tangent (not necessarily at the same atmospheric level), wind shear will disrupt the required convection in a cyclonic system which then loses its coherence. Conditions that are conducive to hurricane formation include a troposphere in which wind shear is virtually absent.

*Source of Bad Weather*. Again, for a weather system to grow to impressive proportions it has to have originated from something small. It is therefore not surprising that a system of disturbed weather must already be in place, and that *that* system should have some sort of circulation as well as a low pressure centre that can serve as the catalyst for cyclone formation and for rotation.

#### The Coriolis Effect

The last in the list of requirements has to do with *a minimum distance from the Equator*. In this context, two aspects are relevant: the Inter-tropical Convergence Zone, a low pressure belt around the Equator caused by the constant updraft of warm air, and the Coriolis force. As the world turns around its axis, the rotational movement influences the motion of both the atmosphere and large bodies of water via the so-called Coriolis force. The strength of this force is greatest in the polar regions, because there, the surface of the Earth is at right angles to the axis of rotation; it is weakest near the equator because there the surface of the Earth is parallel with the axis of rotation. If the Earth were not rotating, air would flow directly into the low pressure belt (towards the equator), but as the Earth is spinning, the Coriolis force causes that air to be deviated and to travel around the low pressure centre. We have seen that rotation is a prime ingredient in cyclone formation. The fact that the Coriolis force can impart considerable rotational momentum to a forming cyclone makes it understandable that hurricanes do not form at or very near to the equator, where that force is weakest. It needs to be sufficiently distant from the equator to be strong enough to deflect winds blowing into the low pressure centre. In practice this is at a distance of 500 km or more from the equator. It is the Coriolis force that is responsible for the direction of rotation of both air and water masses on earth: cyclonic or anti-clockwise in the northern hemisphere, anti-cyclonic or clockwise in the southern hemisphere.

#### Setting the Stage

All of the aforementioned variables need to be in place simultaneously for a tropical storm to attain hurricane proportions. However, we still need to set the stage upon which the performance is going to take place.

This stage is well depicted in figure 3. Starting out from the equator we first encounter the Inter-Tropical Convergence Zone, a belt of low pressure that girdles the Earth. The Tropics of Cancer and Capricorn are both home to a belt of subtropical high pressure, bordering winds with a fixed westward orientation, the Trade Winds or Tropical Easterlies. At higher latitudes, outside the Tropics, we find in both hemispheres a rather wide band of principally eastward flowing air, the Mid-Latitude Westerlies, which is bordered on one side by the subtropical high (30°) and on the other by a belt of sub polar low (60°).

All these belts are organised parallel with the equator. One more essential actor in the show is the *Hadley Cell*. This is essentially a global air transportation system that moves warm air away from the Tropics to higher latitudes and colder air away from the higher latitudes back towards the Tropics. Finally, the *Tropical Wave* illustrated in figure 3 is the source of the bad weather I mentioned earlier under 'Preconditions for Hurricane Formation'.

Now that the stage is set, the actors identified and all props are available, we can try to attend the show itself. In the example below I have considered events in the Atlantic Basin.

**The Life and Times of a Hurricane**

The proverbial butterfly has been busy flapping its wings in sunny western India, setting off a tiny rhythmic local oscillation in a pocket of air; this acts as an amplifier and vehicle for the propagation of a signal destined for greater things. Left in the hands of Mother Nature, chaos theory takes over, transforming the flapping into an area of low pressure, also called a Tropical Wave; this travels westward with the prevailing air currents over the warm waters of the Indian Ocean. The funnel formed by the Gulf of Aden directs the wind flow straight into the Ethiopian highlands where the interplay between warm moist air brought in from the Indian Ocean and the cold air from the highlands causes the formation of strong gusty winds and thunderstorms with heavy rain.

By this time the Tropical Wave has transformed into a Tropical Disturbance, which in turn crosses the full width of the continent of Africa, increasing in intensity but remaining structurally unchanged. When a Tropical Disturbance persists for more than 24 hours and increases in intensity, as is the case in our example, it is upgraded to the level of a Tropical Depression. During its crossing of the continent the Tropical disturbance also obtains a more pronounced Coriolis driven rotational motion. Once it has reached the west coast, the system is blown off Africa into the Atlantic Ocean, well within the region of persistent low we call the Inter Tropical Convergence Zone (figures 5-8).

Once the depression has entered the Convergence Zone, it arrives in an area where there is a constant influx of moist air. The *Hadley Cell* mechanism that is always at work causes an updraft of the warm moist air towards the colder upper air. When the cooling is rapid enough the warm water-vapour condenses on a large scale, thus releasing huge quantities of latent heat energy (see the explanation earlier under ‘Preconditions’).

The energy that is freed in the condensation process is used in two different ways. Part of the heat energy is converted into kinetic energy which causes the wind speed to increase. It should be remembered that the rotation—in our example anti-clockwise—is already present in the system. Those higher wind speeds and the consequential lower pressure result in the capacity to suck in much more warm saturated air, driving storm intensity up in the process. Another substantial part of the energy freed up by condensation goes towards increasing the height of the storm clouds. The fact that the heights of the clouds increase means that the system reaches into a colder environment. It also means that the total surface exposed to the cold condensing environment will increase and thus the capacity for condensation is greatly enhanced.

Eventually, the amount of energy within the cyclonic system may increase to a point where enough energy is released for it to become self-sustaining. This positive feedback loop ensures that the system remains self-supporting until one or more of the input requirements starts failing.

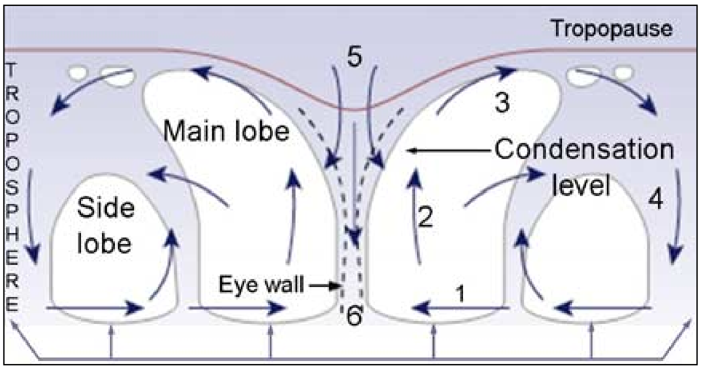



Figure 4 - Rain Bands

Left undisturbed in the positive feedback loop, the Tropical Cyclone progresses naturally through the stages from Tropical Depression and Tropical Storm to a real hurricane. Wind speeds within the system keep increasing, as do height, diameter and the rate of rotation. The pressure at the centre of rotation drops dramatically and the fast rotation of the system causes an eye to form. Although wind speeds within a hurricane system can reach values from 120 to over 250 kph, the total hurricane complex in fact flows with the prevailing wind currents at a speed that is often comparable with that of a cyclist.

At this stage, when we have a full-fledged hurricane in place, a cross section of the system would look something like figure 4.

We recognise the eye chimney in the middle, the main lobes and a number of side lobes on each side. Arrow 1 represents the influx of air which, by passing over the warm ocean surface, has absorbed great quantities of moisture. As this hot air is loaded with water vapour it rises up the centre (arrow 2) to the level where condensation takes place. The faster the updraft of this air the more explosive the release of latent heat. The energy released by condensation speeds up the wind movement and increases the height and volume of the cloud column. At point 3 the ceiling of the troposphere has been reached and the air stops climbing further. This typically occurs at an altitude of some 16 km. By this stage the clouds have cooled down considerably, and as indicated by arrow 4, drop back to sea level.

It should be understood that, because of the very low air pressure at the core of the hurricane, the ceiling of the troposphere is sucked in as it were, resulting in an influx of cold air from the tropopause into the chimney. This is depicted at point 5. This cold air passes downward through the chimney along the eyewall to point 6, helping to cool the ocean surface.

**The Eye and Eyewall**

There is something more to say about the eye and eyewall. Due to the rotation of the whole complex, the updraft of warm air forms an upward spiral, right up to the top of the hurricane. This spiral forms the eyewall of the hurricane and it is the region with the strongest winds, the tallest clouds and the heaviest precipitation. In really strong tropical cyclones the eyewall wraps completely around the upper portion of the eye of the storm. The greater the storm intensity the tighter the eyewall winds and consequently the more the storm speeds up. It is the same process by which a pirouetting ice skater speeds up when pulling the arms in.

Because thunderstorm activity also takes place *outside* the eyewall region this process of speeding up has a natural maximum limit. At a point when the eyewall and area of strongest winds has contracted to a diameter of between 8 and 25 km, thunderstorm activity in the periphery may become disassociated from the eyewall region and outer rain bands may organise into an outer ring of thunderstorms (an outer eyewall) that slowly moves inward and robs the inner eyewall of its necessary moisture and momentum. Such an outer eyewall typically forms some 80 km from the centre of the storm.

During this phase, the hurricane weakens, which means that the maximum winds die off a bit and the central pressure rises. Eventually, the outer eyewall may replace the inner one completely and the storm can then regain its previous intensity or, in some cases, become even stronger. This is called the *Eyewall Replacement Cycle*, and is a phenomenon that may repeat itself several times during the life of a hurricane, effectively placing an upper limit to possible wind speeds. The schematic overview in figure 4 also shows the regions of heaviest precipitation or rain bands. The wider the hurricane system, the more side lobes and hence rain bands will be present.

Figure 5 - The Ethiopian highlands

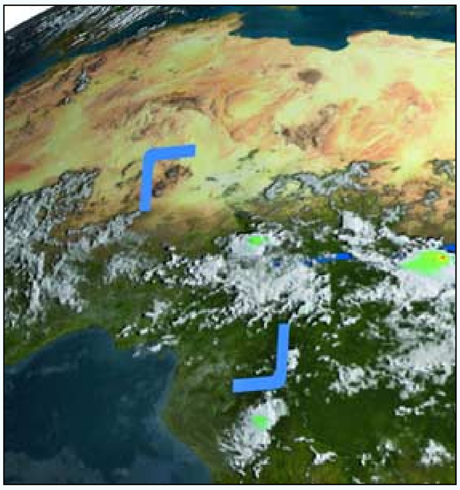


Figure 6 - The complex crosses Africa

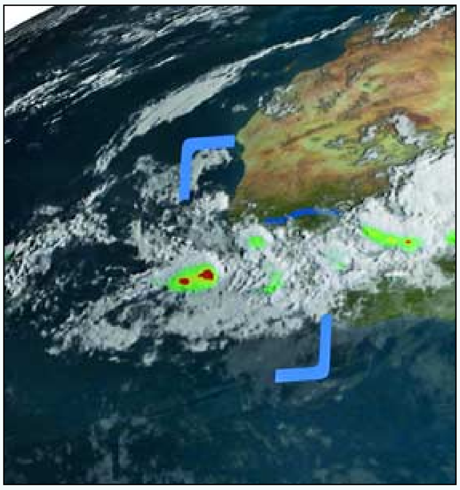


Figure 7 - Arrival at the west Coast

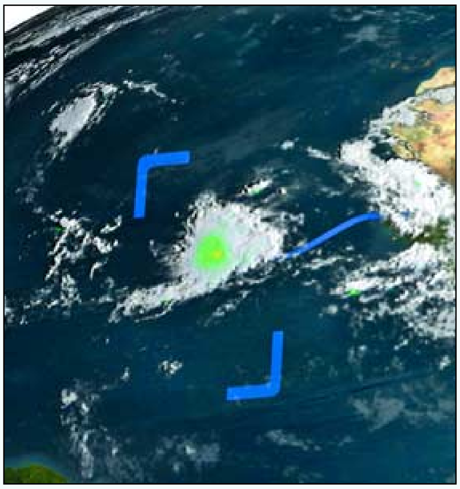


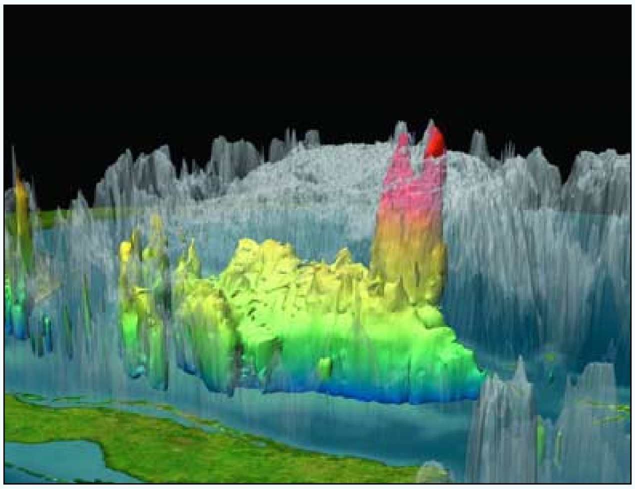
**Figure 8** (left)
Over the Atlantic ocean

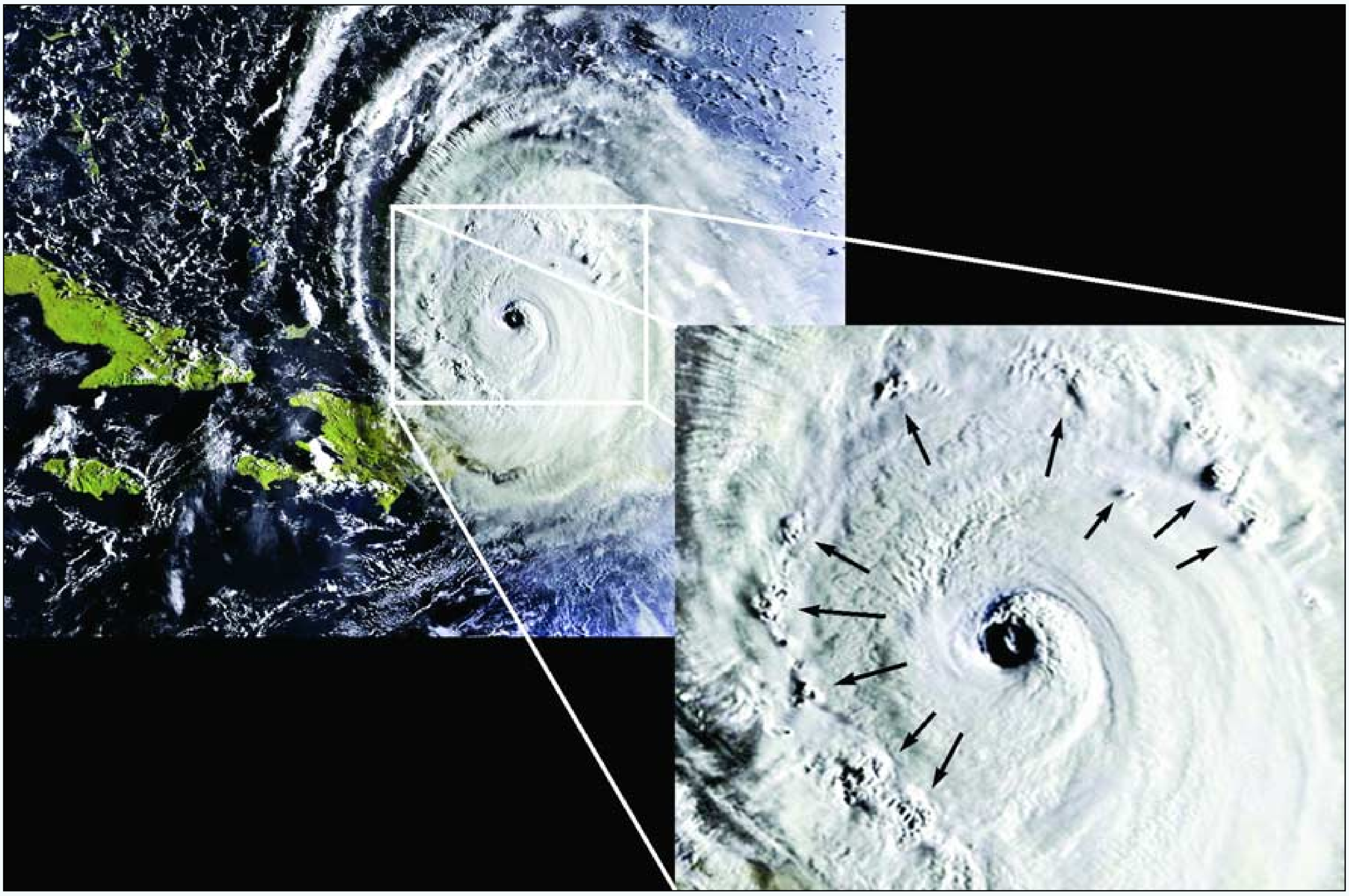
**Figure 9** (right)

A 3D rain intensity graph by the TRMM satellite

**Figure 10** (below)
Hot towers in hurricane Ivan

*Figures 5-8: Credit NASA*
*Figure 9: NASA/JAXA*





There is another quite remarkable aspect of very active hurricanes which has to do with the rain intensity and concentration throughout the storm complex. Since the launch of NASA's Tropical Rainfall Measuring Mission (TRMM), it has become possible to study this in a detailed and structured way. Figure 9 is a 3D product from TRMM (rather in the style of a CAT scan) in which we see the distribution of rain within the cloud complex of hurricane Rita. The colour is a measure of the storm's rain intensity with red being most intense and blue least, while the height of the each peak refers to the actual elevation of the cloud column. In this true-to-reality graph, two spikes appear in the rain structure. These spikes are termed *Hot Towers* and are in fact tall cumulonimbus clouds that, in the case of hurricane Rita, reached an altitude of almost 20 km. The phenomenon has a rather limited diameter when compared with the hurricane itself and it is of quite short duration. Still, it is one of the mechanisms by which the intensity of a tropical cyclone is maintained or enhanced. This is, in itself, quite understandable, because when, in a very short time, a huge column of hot wet air soars to the very cold stratosphere, the resulting condensation and release of energy must be truly explosive. This energy can do but one thing: drive the hurricane to greater intensity.

Figure 10 shows an AVHRR image from hurricane Ivan taken at daybreak on September 1, 2004. The very low angle of incoming sunlight clearly demonstrates the presence of a significant number of hot towers outside of the eye region. They are already starting to form an independent ring (outer eyewall) that, at a later stage, will replace the inner eyewall. The occurrence of hot towers is now being used as an accurate parameter in forecasting the intensification of hurricanes.

### Assessing Hurricane Intensity

It has always been very difficult to provide an objective measure of the force associated with a particular Tropical Cyclone. Even today, classification is not commonly done outside the northeast Pacific and western Atlantic. However, for these two regions, *Herbert Saffir* developed a scale to classify them in accordance with objective and measurable criteria (largely based on wind speeds and the typical damage associated with certain wind speed categories). *Bob Simpson*, working on behalf of insurance companies, realised that certain damage not directly attributable to high winds remained unaddressed. This was the damage inflicted by the surge of water that usually accompanies a heavy storm. He incorporated this information into the scale, mainly to have a measure for assessing inflicted damage more accurately. The resulting *Saffir-Simpson scale* has since been widely adopted within the Western World to classify all hurricane-force tropical cyclones.

| Saffir-Simpson Category | Maximum sustained wind speed (Herbert Saffir) | | Minimum surface pressure | Storm surge (Bob Simpson) |
|---|---|---|---|---|
| | m/s | kph | millibar (mB) | metres |
| 1 | 33-42 | 118-152 | >980 | 1.0 - 1.7 |
| 2 | 43-49 | 153-177 | 979-965 | 1.8 - 2.6 |
| 3 | 50-58 | 178-209 | 964-945 | 2.7 - 3.8 |
| 4 | 59-69 | 210-249 | 944-920 | 3.9 - 5.6 |
| 5 | 70+ | 250+ | <920 | 5.7+ |

Table 1 - The Saffir-Simpson Scale

### The Demise of a Hurricane

I noted earlier that, as long as there are no changes to the conditions present once the hurricane is established, it will sustain itself 'indefinitely'. Fortunately, the strict conditions required for the formation of a hurricane are also instrumental to its stagnation and dissipation. This can be summarised as follows:

**Landfall**: When the storm's centre reaches land (i.e. the centre of the eye, not its edge) then no more moist air is fed from the ocean surface into the system and thus the condensation motor runs out of fuel and switches off.

**Westerlies**: It has been noted that the entire hurricane complex drifts with the prevailing winds and currents. Such currents may drive the hurricane out of the Tropics into the belt of westerly winds, which may destroy its structure and/or drive it into colder waters. In the first case the hurricane will hiccough and stop, whereas in the second, it loses its tropical characteristics and may convert into an extra-tropical cyclone.

**High wind shear**: When a hurricane drifts into a region where there is a strong higher level wind, wind shear takes the stability out of the circulation pattern and the direction out of the convection. The hurricane cannot then support itself any further.

**Semi-stationary**: When a hurricane remains in the same area of ocean for too long, it draws heat from the ocean surface until locally, there is no longer enough sufficiently warm water available to feed it (remember: 26.5°C and 50 m deep). Again the heat engine will stop and the hurricane cannot survive.

**Weakness**: Even a hurricane can fall victim to another area of low pressure and be consumed by it. Usually such a merger causes disruption, resulting in a large area of non-cyclonic thunderstorms. Of course, it may very well turn out to strengthen the non-tropical system as a whole instead, but it still spells the end for the original hurricane.

**Outer eyewall**: The formation of an outer eyewall reduces the intensity of the hurricane. Such weakening is generally temporary unless it meets other conditions such as I mentioned above. This can then lead to its demise even when the other conditions by themselves are of insufficient intensity to cause the dissipation.

### Caveat

This article has focused exclusively on generic tropical cyclones and the mechanisms involved in their creation and demise. It by no means implies that this is the full story, as many unknowns remain and many deviations from the standard description occur in Nature.

### Examples of Non-Standard Tropical Cyclones

*Typhoon Vamei* defied the Coriolis restriction when it appeared in the South China Sea a mere 1.5° north of the Equator. Very specific local conditions took over the function of the Coriolis force. *Cyclone Catarina* was, in March 2004, the first ever recorded hurricane-force storm south of the equator in the Atlantic ocean, in an area where the prevailing ocean surface currents are normally too cold to allow hurricane formation.

### Non Tropical Cyclones

<u>Extra-tropical cyclones</u> draw a portion of their energy from the evaporation and condensation of ocean water, and some through horizontal temperature gradients in the atmosphere. They occur in-between tropical and mid-latitude cyclones. Many tropical cyclones turn into extra-tropical ones at the end of their life cycle. Extra-tropical storms seldom transition into tropical ones.

<u>Subtropical cyclones</u>, like their extra-tropical counterparts, constitute an intermediate form between tropical and mid-latitude cyclones. They are, however, mostly associated with the region south of the Azores and the Mediterranean basin

<u>Mid-latitude cyclones</u> are driven by baroclinic processes, which means that the temperature contrast between warm and cold air masses is the driving process behind their energy influx. They are found in the temperate regions (between the tropical and polar regions) and occur above land as well as sea.

<u>The sub-Arctic and sub-Antarctic</u> systems are basically the same as mid-latitude ones, but they occur at very high latitudes and involve very cold winds.

### Acknowledgement

Thanks to Jonathan Valk for proofreading this article and for suggesting helpful improvements.