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Hurricanes, Typhoons, and Tropical Cyclones

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FAQ : HURRICANES, TYPHOONS, AND TROPICAL CYCLONES

FAQ Main Page

By

Christopher W. Landsea

AOML/Hurricane Research Division

NOAA / AOML
4301 Rickenbacker Causeway
Miami, Florida 33149

Version 2.9
5 April, 2000

New for this version

A7a) Why do tropical cyclones spawn tornadoes?
A7b) What percentage of tropical cyclones spawn tornadoes?
A7c) What parts of a tropical cyclone are most favored for tornado formation?
A7d) How long after landfall are TC tornadoes a threat?
A7e) Are TC tornadoes weaker than midlatitude tornadoes?
A7f) What is the largest known outbreak of TC tornadoes?
A7g) What is the deadliest single TC-spawned tornado?
A7h) What is the most damaging single TC-spawned tornado?
A7i) Why are TC tornadoes especially difficult to deal with?

This is currently a multi-part FAQ (Frequently Asked Questions report) that is in its fourteenth incarnation (version 2.8). However, there may be some errors or discrepancies that have not yet been found. If you do see an item that needs correction, please contact me directly. This file contains various definitions, answers for some specific questions, information about the various tropical cyclone basins, provides sites that you can access both real-time information about tropical cyclones, what is available on-line for historical storms, as well as good books to read and various references for tropical cyclones. Keep in mind that this FAQ is not considered a reviewed paper to reference. Its main purpose is to provide quick answers for (naturally) frequently asked questions as well as to be a pointer to various sources of information.

I'd like to thank various people for helping to put together this FAQ: Sim Aberson, Jack Beven, Gary Padgett, Tom Berg, Julian Heming, Neal Dorst, Gary Gray, Stephen Caparotta, Steven Young, D. Walston all provided substantial bits to this FAQ. Also thanks to the many people who provided additional questions and information for this FAQ: Ilana Stern, Dave Pace, Dave Blanchard, Ken Fung, James (I R A Aggie) Stricherz, Mike Dettinger, Jan Schloerer, Eric Blake, Jeff Kepert, Frank Woodcock, Roger Edson, Bill Cherepy, Stephen Jascourt, Kelly Dean, Malcolm ???, Jon Gill, Ken Waters, Derek West, Gert van Dijken, George Gumbert III, Edward Reid, Tim Trice, Michael Scott, Kerry Emanuel, George Sambataro, James Lewis Free, Sam Biller, David Faciane, Eric Gross, Jeff Hawkins, Mike Fiorino, Madeleine Hall, Mike Schneider, Jennifer Collins, dhmuzz, Alan Gregersen, Hugh Willoughby and David Roth. Many thanks also to Jan Null for providing the first .html version of the FAQ. If I didn't get to all the suggested FAQs, I'll try to include them in future versions.

Much of the on-line information is pulled from Ilana Stern's wonderful "Sources of Meteorological Data FAQ" and I acknowledge the time and effort she has put in in originally compiling this information. Also Gary Gray has put together a very comprehensive listing of tropical cyclone Web sites that I've included here with his permission.

Where can I get an ASCII version of this document?????

- A two part ascii edition of this FAQ is posted monthly on **sci.geo.meteorology** and on

sci.environment usually early in each month. One can also ftp to retrieve the latest files at:

TC FAQ I (Sections A - H)
TC FAQ II (Sections I - J)

Login as 'anonymous' and password as your email address. The files are in the *papers* directory **(TCfaqI and TCfaqII). If you do not have ftp access, you can request copies from me directly via email.**

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REFERENCES

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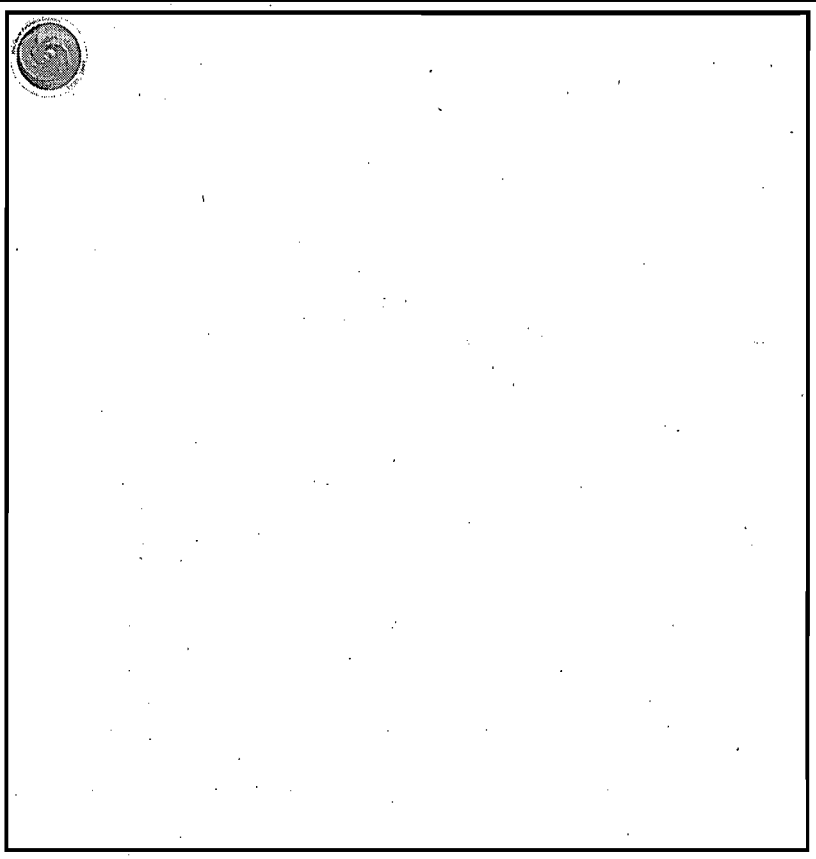

FAQ : HURRICANES, TYPHOONS, AND TROPICAL CYCLONES

Part A : Basic Definitions

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Version 2.9
5 April, 2000

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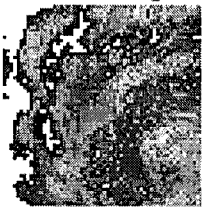
Subject: A1) What is a hurricane, typhoon, or tropical cyclone?



NOAA

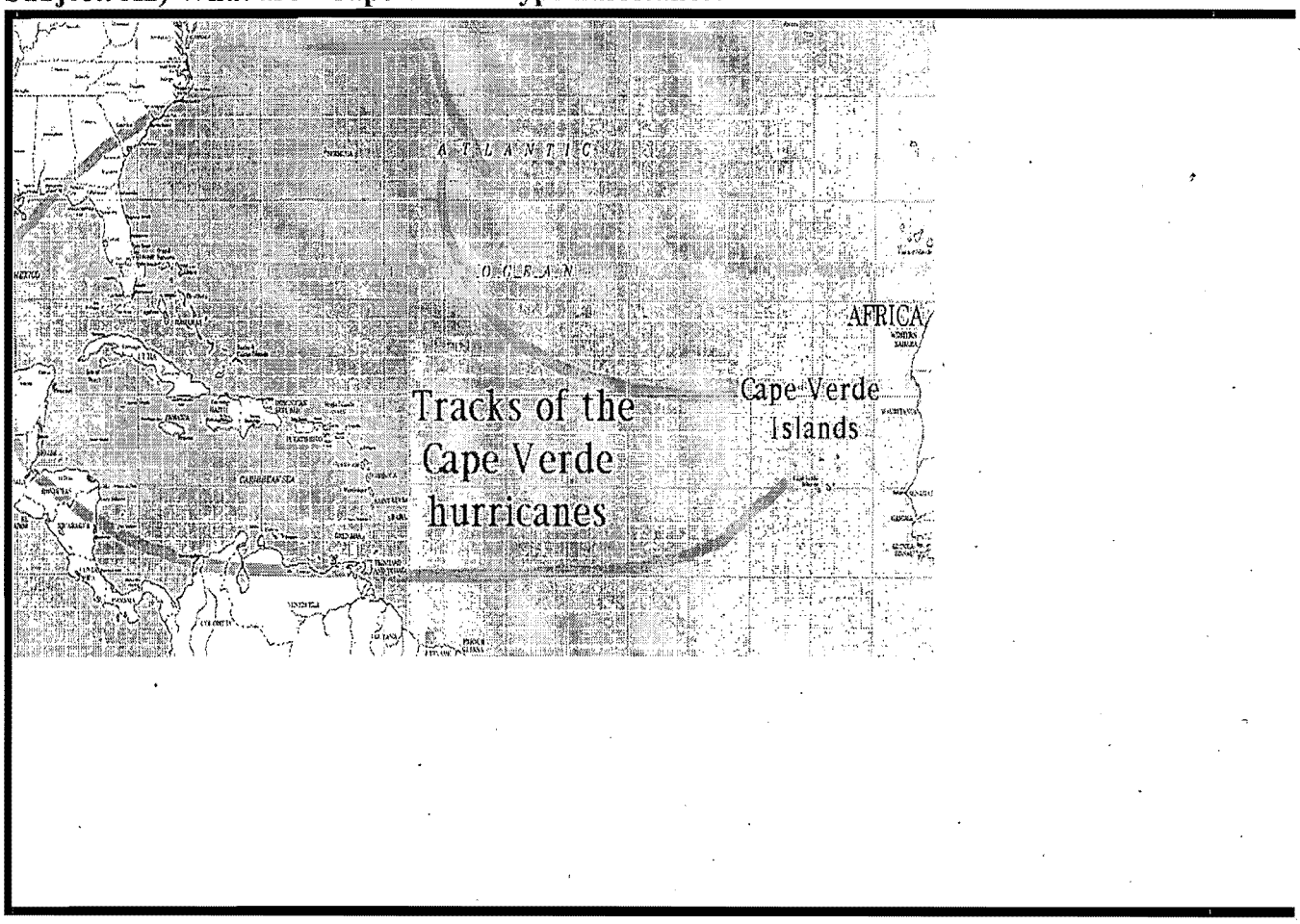
The terms "hurricane" and "typhoon" are regionally specific names for a strong "tropical cyclone". A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation *(Holland 1993)*.

Tropical cyclones with maximum sustained surface winds of less than 17 m/s (34 kt, 39 mph) are called "tropical depressions". (This is not to be confused with the condition mid-latitude people get during a long, cold and grey winter wishing they could be closer to the equator ;-)) Once the tropical cyclone reaches winds of at least 17 m/s they are typically called a "tropical storm" and assigned a name. If winds reach 33 m/s (64 kt, 74 mph)), then they are called: a "hurricane" (the North Atlantic Ocean, the Northeast Pacific Ocean east of the dateline, or the South Pacific Ocean east of 160E); a "typhoon" (the Northwest Pacific Ocean west of the dateline); a "severe tropical cyclone" (the Southwest Pacific Ocean west of 160E or Southeast Indian Ocean east of 90E); a "severe cyclonic storm" (the North Indian Ocean); and a "tropical cyclone" (the Southwest Indian Ocean) *(Neumann 1993)*.

Note that just the definition of **"maximum sustained surface winds"** depends upon who is taking the

measurements. The World Meteorology Organization guidelines suggest utilizing a 10 min average to get a sustained measurement. Most countries utilize this as the standard. However the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) of the USA use a 1 min averaging period to get sustained winds. This difference may provide complications in comparing the statistics from one basin to another as using a smaller averaging period may slightly raise the number of occurrences *(Neumann 1993)*.

Subject: A2) What are "Cape Verde"-type hurricanes?



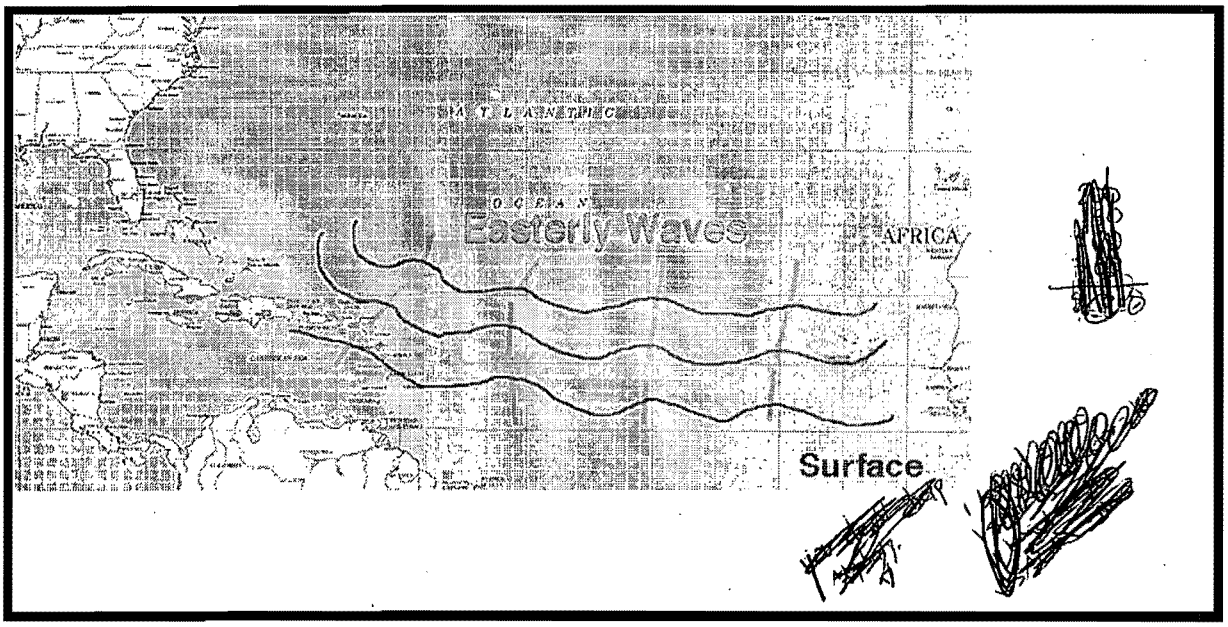
Cape Verde-type hurricanes are those Atlantic basin tropical cyclones that develop into tropical storms fairly close (<1000 km [600 mi] or so) of the Cape Verde Islands and then become hurricanes before reaching the Caribbean. (That would be my definition, there may be others.) Typically, this may occur in August and September, but in rare years (like 1995) there may be some in late July and/or early October. The numbers range from none up to around five per year - with an average of around 2.

Subject: A3) What is a super-typhoon?

typhoon definition

A "super-typhoon" is a term utilized by the U.S. Joint Typhoon Warning Center in Guam for typhoons that reach maximum sustained 1-minute surface winds of at least 65 m/s (130 kt, 150 mph). This is the equivalent of a strong Saffir-Simpson category 4 or category 5 hurricane in the Atlantic basin or a category 5 severe tropical cyclone in the Australian basin.

Subject: A4) Where do these easterly waves come from and what causes them?



It has been recognized since at least the 1930s *(Dunn 1940)* that lower tropospheric (from the ocean surface to about 5 km [3 mi] with a maximum at 3 km [2 mi]) westward traveling disturbances often serve as the "seedling" circulations for a large proportion of tropical cyclones over the North Atlantic Ocean. *Riehl (1945)* helped to substantiate that these disturbances, now known as African easterly waves, had their origins over North Africa. While a variety of mechanisms for the origins of these waves were proposed in the next few decades, it was *Burpee (1972)* who documented that the waves were being generated by an instability of the African easterly jet. (This instability - known as baroclinic-barotropic instability - is where the value of the potential vorticity begins to decrease toward the north.) The jet arises as a result of the reversed lower-tropospheric temperature gradient over western and central North Africa due to extremely warm temperatures over the Saharan Desert in contrast with substantially cooler temperatures along the Gulf of Guinea coast.

The waves move generally toward the west in the lower tropospheric tradewind flow across the Atlantic Ocean. They are first seen usually in April or May and continue until October or November. The waves have a period of about 3 or 4 days and a wavelength of 2000 to 2500 km [1200 to 1500 mi], typically *(Burpee 1974)*. One should keep in mind that the "waves" can be more correctly thought of as the convectively active troughs along an extended wave train. On average, about 60 waves are generated over North Africa each year, but it appears that the number that is formed has no relationship to how much tropical cyclone activity there is over the Atlantic each year.

While only about 60% of the Atlantic tropical storms and minor hurricanes (Saffir-Simpson Scale categories 1 and 2) originate from easterly waves, nearly 85% of the intense (or major) hurricanes have their origins as easterly waves *(Landsea 1993)*. It is suggested, though, that nearly all of the tropical cyclones that occur in the Eastern Pacific Ocean can also be traced back to Africa *(Avila and Pasch 1995)*.

It is currently completely unknown how easterly waves change from year to year in both intensity and location and how these might relate to the activity in the Atlantic (and East Pacific).

Subject: A5) What is a sub-tropical cyclone?

A sub-tropical cyclone is a low-pressure system existing in the tropical or subtropical latitudes (anywhere from the equator to about 50°N) that has characteristics of both tropical cyclones and mid-latitude (or extratropical) cyclones. Therefore, many of these cyclones exist in a weak to moderate horizontal temperature gradient region (like mid-latitude cyclones), but also receive much of their energy from convective clouds (like tropical cyclones). Often, these storms have a radius of maximum

winds which is farther out (on the order of 100-200 km [60-125 miles] from the center) than what is observed for purely "tropical" systems. Additionally, the maximum sustained winds for sub-tropical cyclones have not been observed to be stronger than about 33 m/s (64 kts, 74 mph)).

Many times these subtropical storms transform into true tropical cyclones. A recent example is the Atlantic basin's Hurricane Florence in November 1994 which began as a subtropical cyclone before becoming fully tropical. Note there has been at least one occurrence of tropical cyclones transforming into a subtropical storm (e.g. Atlantic basin storm 8 in 1973).

Subtropical cyclones in the Atlantic basin are classified by the maximum sustained surface winds:

- less than 18 m/s (34 kts, 39 mph) - "subtropical depression",
- greater than or equal to 18 m/s (34 kts, 39 mph) - "subtropical storm"

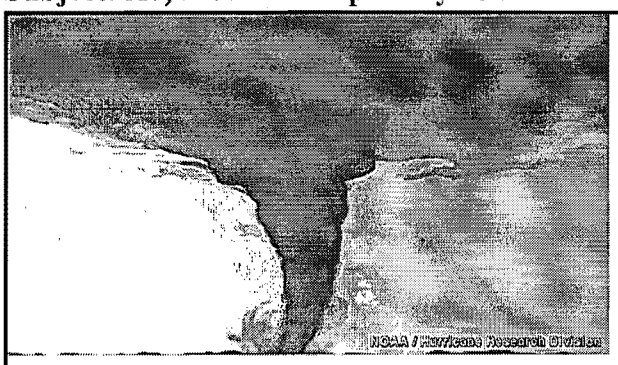
Note that while these are not given names, they are warned on and forecasted for by the National Hurricane Center similar to the treatment received by tropical cyclones in the region.

Subject: A6) How are tropical cyclones different from mid-latitude storms?

The tropical cyclone is a low-pressure system which derives its energy primarily from evaporation from the sea in the presence of high winds and lowered surface pressure and the associated condensation in convective clouds concentrated near its center *(Holland 1993)*. Mid-latitude storms (low pressure systems with associated cold fronts, warm fronts, and occluded fronts) primarily get their energy from the horizontal temperature gradients that exist in the atmosphere.

Structurally, tropical cyclones have their strongest winds near the earth's surface (a consequence of being "warm-core" in the troposphere), while mid-latitude storms have their strongest winds near the tropopause (a consequence of being "warm-core" in the stratosphere and "cold-core" in the troposphere). "Warm-core" refers to being relatively warmer than the environment at the same pressure surface ("pressure surfaces" are simply another way to measure height or altitude).

Subject: A7) How are tropical cyclones different from tornadoes?



While both tropical cyclones and tornadoes are atmospheric vortices, they have little in common. Tornadoes have diameters on the scale of 100s of meters and are produced from a single convective storm (i.e. a thunderstorm or cumulonimbus). A tropical cyclone, however, has a diameter on the scale of 100s of *kilometers* and is comprised of several to dozens of convective storms. Additionally, while tornadoes require substantial vertical shear of the horizontal winds (i.e. change of wind speed and/or direction with height) to provide ideal conditions for tornado genesis, tropical cyclones require very low values (less than 10 m/s [20 kt, 23 mph]) of tropospheric vertical shear in order to form and grow. These vertical shear values are indicative of the horizontal temperature fields for each phenomenon: tornadoes are produced in regions of large temperature gradient, while tropical cyclones are generated in regions of near zero horizontal temperature gradient. Tornadoes are primarily an over-land phenomena as solar heating of the land surface usually contributes toward the development of the thunderstorm that spawns the vortex (though over-water tornadoes have occurred). In contrast, tropical cyclones are purely an oceanic phenomena - they die out over-land due to a loss of a moisture source. Lastly, tropical cyclones have a lifetime that is measured in days, while tornadoes typically last on the scale of minutes.

An interesting side note is that tropical cyclones at landfall often provide the conditions necessary for tornado formation. As the tropical cyclone makes landfall and begins decaying, the winds at the surface die off quicker than the winds at, say, 850 mb. This sets up a fairly strong vertical wind shear that allows for the development of tornadoes, especially on the tropical cyclone's right side (with respect to the forward motion of the tropical cyclone). For the southern hemisphere, this would be a concern on the tropical cyclone's left side - due to the reverse spin of southern hemisphere storms. *(Novlan and Gray 1974)*

Subject : A7a) Why do tropical cyclones spawn tornadoes?

Tropical cyclones spawn tornadoes when certain instability and vertical shear criteria are met, in a manner similar to other tornado-producing systems. However, in tropical cyclones, the vertical structure of the atmosphere differs somewhat from that most often seen in midlatitude systems. In particular, most of the thermal instability is found near or below 10,000 feet altitude, in contrast to midlatitude systems, where the instability maximizes typically above 20,000 feet. Because the instability in TC's is focussed at low altitudes, the storm cells tend to be smaller and shallower than those usually found in most severe midlatitude systems. But because the vertical shear in TC's is also very strong at low altitudes, the combination of instability and shear can become favorable for the production of small supercell storms, which have an enhanced likelihood of spawning tornadoes compared to ordinary thunderstorm cells (*Novlan and Gray 1974*, *Gentry 1983*, *McCaul 1991*).

Subject : A7b) What percentage of tropical cyclones spawn tornadoes?

Almost all tropical cyclones making landfall in the United States spawn at least one tornado, provided enough of the TC's circulation moves over land. This implies that Gulf coast landfalling TC's are more likely to produce tornadoes than Atlantic coast TC's that "sideswipe" the coastline. The rate at which TC's produce tornadoes (waterspouts) over the ocean is unknown, although Doppler radars have identified many cases where storm cell rotation suggestive of the presence of tornadoes was observed over water (*Novlan and Gray 1974*, *Spratt et al. 1997*).

Subject : A7c) What parts of a tropical cyclone are most favored for tornado formation?

In the northern hemisphere, the right-front quadrant (relative to TC motion) is strongly favored. In the southern hemisphere, the left-front quadrant presumably is favored, although there is little research on this point. Most of the tornadoes form in outer rainbands some 50-200 miles from the TC center, but some have been documented to occur in the inner core, or even in the TC eyewall (*Novlan and Gray*

1974, McCaul et al. 1996, Spratt et al. 1997).

Subject : A7d) How long after landfall are TC tornadoes a threat?

TC's may spawn tornadoes up to three days after landfall. Statistics show that most of the tornadoes occur on the day of landfall, or the next day. The most likely time for tornadoes is during daylight hours, although they can occur during the night too (*Novlan and Gray 1974, Gentry 1983*).

Subject : A7e) Are TC tornadoes weaker than midlatitude tornadoes?

In general, it appears that TC tornadoes are somewhat weaker and briefer than midlatitude tornadoes. There have been no F5-rated TC tornadoes in the past 50 years of reliable data, and only two F4's. There have, however, been numerous F3's, and some of these have caused many casualties and much damage. Of course, we cannot rule out the possibility that a future TC might spawn an F5 tornado (*Gentry 1983, McCaul 1991*).

Subject : A7f) What is the largest known outbreak of TC tornadoes?

Hurricane Beulah spawned a reported 141 tornadoes in southeast Texas during the first several days after its landfall in September 1967 (*Orton 1970*). This number of tornadoes represents one of the largest tornado outbreaks of any kind in the U. S. tornado climatology. In 1992, Hurricane Andrew spawned 62 tornadoes. It is difficult to predict which TCs will produce large tornado outbreaks, although there is some indication that the likelihood of a major outbreak increases as TC size and intensity increase.

Subject : A7g) What is the deadliest single TC-spawned tornado?

One of the tornadoes spawned in October 1964 by Hurricane Hilda killed 22 people in Larose, LA (*Novlan and Gray 1974*).

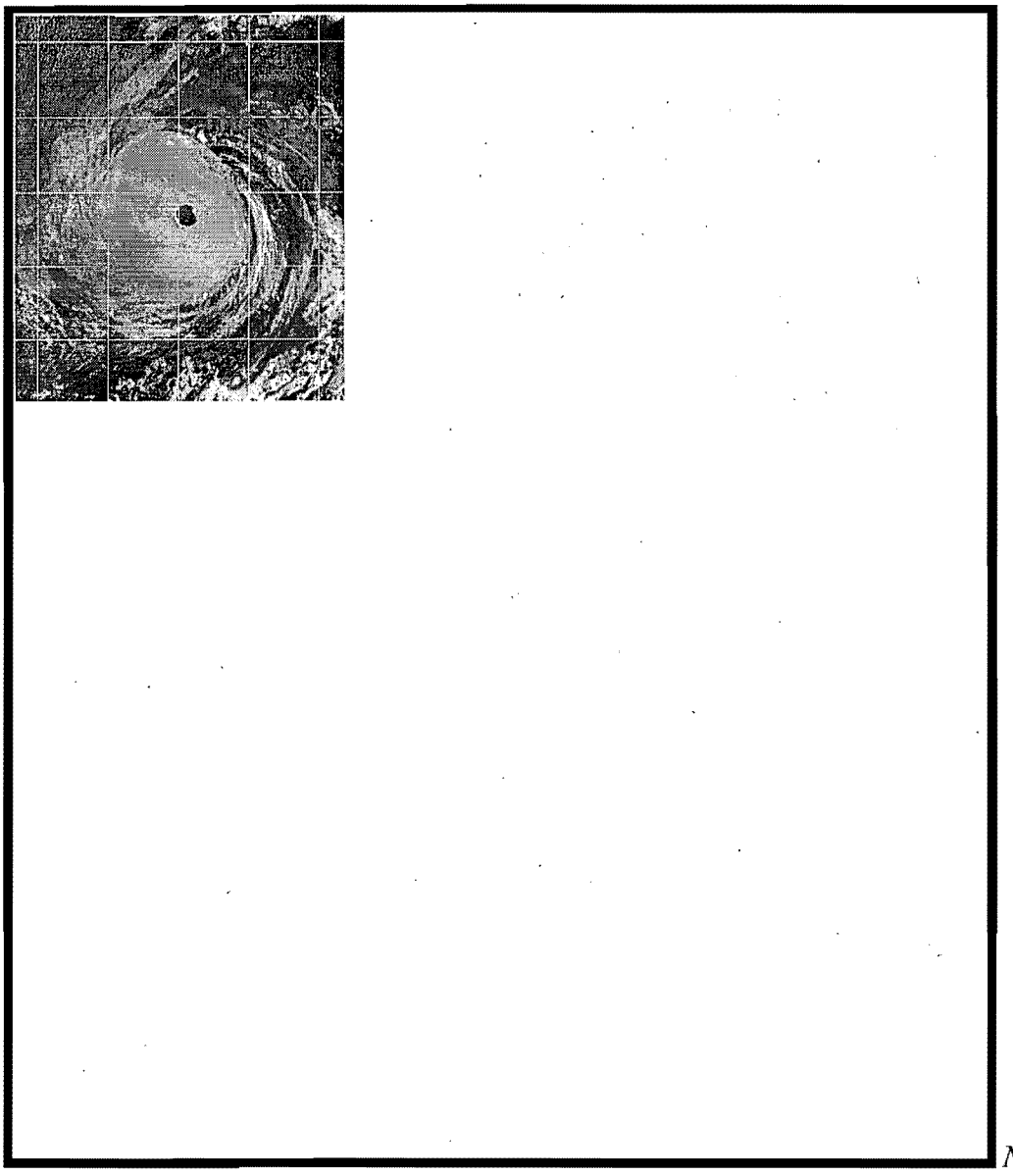
Subject : A7h) What is the most damaging single TC-spawned tornado?

One of the tornadoes produced by Hurricane Allen in 1980 did about $100 million damage, in recent dollars, in the Austin, TX, area (*Gentry 1983*).

Subject : A7i) Why are TC tornadoes especially difficult to deal with?

TC tornadoes are often spawned by unusually small storm cells that may not appear particularly dangerous on weather radars, especially if the cells are located more than about 60 miles from the radar. In addition, these small storms often tend to produce little or no lightning or thunder, and may not look very threatening visually to the average person. Furthermore, the tornadoes are often obscured by rain, and the storm cells spawning them may move rapidly, leaving little time to take evasive action once the threat has been perceived. (*McCaul et al. 1996, Spratt et al. 1997*).

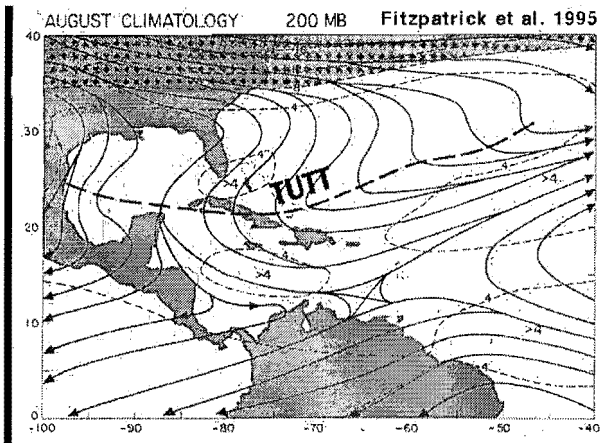
Subject: A8) What does the acronym "CDO" in a discussion of tropical cyclones mean?



NRL - Monterey

"CDO" is an acronym that stands for "central dense overcast". This is the cirrus cloud shield that results from the thunderstorms in the eyewall of a tropical cyclone and its rainbands. Before the tropical cyclone reaches hurricane strength (33 m/s, 64 kts, 74mph), typically the CDO is uniformly showing the cold cloud tops of the cirrus with no eye apparent. Once the storm reaches the hurricane strength threshold, usually an eye can be seen in either the infrared or visible channels of the satellites. Tropical cyclones that have nearly circular CDO's are indicative of favorable, low vertical shear environments.

Subject: A9) What is a "TUTT"?



Fitzpatrick et al. 1995

A "TUTT" is a **Tropical Upper Tropospheric Trough**. A TUTT low is a TUTT that has completely cut-off. TUTT lows are more commonly known in the Western Hemisphere as an "upper cold low". TUTTs are different than mid-latitude troughs in that they are maintained by subsidence warming near the tropopause which balances radiational cooling. TUTTs are important for tropical cyclone forecasting as they can force large amounts of harmful vertical wind shear over tropical disturbances and tropical cyclones. There are also suggestions that TUTTs can assist tropical cyclone genesis and intensification by providing additional forced ascent near the storm center and/or by allowing for an efficient outflow channel in the upper troposphere. For a more detailed discussion on TUTTs see the article by *Fitzpatrick et al. (1995).*

Subject: A10) How do tropical cyclones form ?

To undergo tropical cyclogenesis, there are several favorable pre cursor environmental conditions that must be in place *(Gray 1968,1979)* :

1. Warm ocean waters (of at least 26.5°C [80°F]) throughout a sufficient depth (unknown how deep, but at least on the order of 50 m [150 ft]). Warm waters are necessary to fuel the heat engine of the tropical cyclone.

2. An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. It is the thunderstorm activity which allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.

3. Relatively moist layers near the mid-troposphere (5 km [3 mi]). Dry mid levels are not conducive

for allowing the continuing development of widespread thunderstorm activity.

4. A minimum distance of at least 500 km [300 mi] from the equator. For tropical cyclogenesis to occur, there is a requirement for non-negligible amounts of the Coriolis force to provide for near gradient wind balance to occur. Without the Coriolis force, the low pressure of the disturbance cannot be maintained.

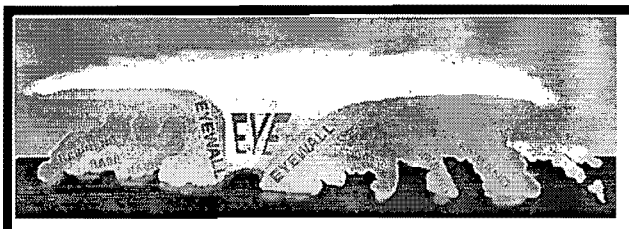
5. A pre-existing near-surface disturbance with sufficient vorticity and convergence. Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organized system with sizable spin and low level inflow.

6. Low values (less than about 10 m/s [20 kts 23 mph]) of vertical wind shear between the surface and the upper troposphere. Vertical wind shear is the magnitude of wind change with height. Large values of vertical wind shear disrupt the incipient tropical cyclone and can prevent genesis, or, if a tropical cyclone has already formed, large vertical shear can weaken or destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone center.

Having these conditions met is necessary, but not sufficient as many disturbances that appear to have favorable conditions do not develop. Recent work *(Velasco and Fritsch 1987, Chen and Frank 1993, Emanuel 1993)* has identified that large thunderstorm systems (called mesoscale convective complexes [MCC]) often produce an inertially stable, warm core vortex in the trailing altostratus decks of the MCC. These mesovortices have a horizontal scale of approximately 100 to 200 km [75 to 150 mi], are strongest in the mid-troposphere (5 km [3 mi]) and have no appreciable signature at the surface. *Zehr (1992)* hypothesizes that genesis of the tropical cyclones occurs in two stages:

- stage 1 occurs when the MCC produces a mesoscale vortex.
- stage 2 occurs when a second blow up of convection at the mesoscale vortex initiates the intensification process of lowering central pressure and increasing swirling winds.

Subject: A11) What is the "eye"? How is it formed and maintained?
(Written with major assitance from Sim Aberson)



NOAA

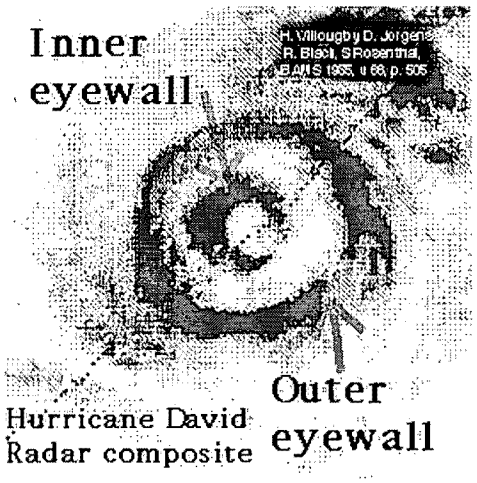
The "eye" is a roughly circular area of comparatively light winds and fair weather found at the center of a severe tropical cyclone. Although the winds are calm at the axis of rotation, strong winds may extend well into the eye. There is little or no precipitation and sometimes blue sky or stars can be seen. The eye is the region of lowest surface pressure and warmest temperatures aloft - the eye temperature may be 10 C [18 F] warmer or more at an altitude of 12 km [8 mi] than the surrounding environment, but only 0-2 C [0-3 F] warmer at the surface *(Hawkins and Rubsam 1968)* in the tropical cyclone. Eyes range in size from 8 km [5 mi] to over 200 km [120 mi] across, but most are approximately 30-60 km [20-40 mi] in diameter *(Weatherford and Gray 1988)*. The eye is surrounded by the eyewall, the roughly circular area of deep convection which is the area of highest surface winds in the tropical cyclone. The eye is

composed of air that is slowly sinking and the eyewall has a net upward flow as a result of many moderate - occasionally strong - updrafts and downdrafts. The eye's warm temperatures are due to compressional warming of of the subsiding air. Most soundings taken within the eye show a low-level layer which is relatively moist, with an inversion above - suggesting that the sinking in the eye typically does not reach the ocean surface, but instead only gets to around 1-3 km [1-2 mi] of the surface.

The general mechanisms by which the eye and eyewall are formed are not fully understood, although observations have shed some light on the problem. The calm eye of the tropical cyclone shares many qualitative characteristics with other vortical systems such as tornadoes, waterspouts, dust devils and whirlpools. Given that many of these lack a change of phase of water (i.e. no clouds and diabatic heating involved), it may be that the eye feature is a fundamental component to all rotating fluids. It has been hypothesized (e.g. *Gray and Shea 1973, Gray 1991*) that supergradient wind flow (i.e. swirling winds that are stronger than what the local pressure gradient can typically support) present near the radius of maximum winds (RMW) causes air to be centrifuged out of the eye into the eyewall, thus accounting for the subsidence in the eye. However, *Willoughby (1990b, 1991)* found that the swirling winds within several tropical storms and hurricanes were within 1-4% of gradient balance. It may be though that the amount of supergradient flow needed to cause such centrifuging of air is only on the order of a couple percent and thus difficult to measure.

Another feature of tropical cyclones that probably plays a role in forming and maintaining the eye is the eyewall convection. Convection in tropical cyclones is organized into long, narrow rainbands which are oriented in the same direction as the horizontal wind. Because these bands seem to spiral into the center of a tropical cyclone, they are sometimes called spiral bands. Along these bands, low-level convergence is a maximum, and therefore, upper-level divergence is most pronounced above. A direct circulation develops in which warm, moist air converges at the surface, ascends through these bands, diverges aloft, and descends on both sides of the bands. Subsidence is distributed over a wide area on the outside of the rainband but is concentrated in the small inside area. As the air subsides, adiabatic warming takes place, and the air dries. Because subsidence is concentrated on the inside of the band, the adiabatic warming is stronger inward from the band causing a sharp contrast in pressure falls across the band since warm air is lighter than cold air. Because of the pressure falls on the inside, the tangential winds around the tropical cyclone increase due to increased pressure gradient. Eventually, the band moves toward the center and encircles it and the eye and eyewall form (*Willoughby 1979, 1990a, 1995*).

Thus the cloud-free eye may be due to a combination of dynamically forced centrifuging of mass out of the eye into the eyewall and to a forced descent caused by the moist convection of the eyewall. This topic is certainly one that can use more research to ascertain which mechanism is primary.



Some of the most intense tropical cyclones exhibit concentric eyewalls, two or more eyewall structures centered at the circulation center of the storm (*Willoughby et al. 1982, Willoughby 1990a*). Just as the

inner eyewall forms, convection surrounding the eyewall can become organized into distinct rings. Eventually, the inner eye begins to feel the effects of the subsidence resulting from the outer eyewall, and the inner eyewall weakens, to be replaced by the outer eyewall. The pressure rises due to the destruction of the inner eyewall are usually more rapid than the pressure falls due to the intensification of the outer eyewall, and the cyclone itself weakens for a short period of time.

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FAQ : HURRICANES, TYPHOONS, AND TROPICAL CYCLONES

Part G : Tropical Cyclone

Climatology

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G : TROPICAL CYCLONE CLIMATOLOGY

G1) When is hurricane season?
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G11) What is the 20th century hurricane record for each U.S. coastal state and county?
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G13) What is the chance that my town will be hit by a tropical storm or hurricane during the each month of the season?
G14) What is the average number of tropical storms and hurricanes to affect my town?
G15)What is the peak number of tropical storms and hurricanes to affect my town?

Subject: G1) When is hurricane season ?

Subject: G1) When is hurricane season?

While the Atlantic hurricane season is "officially" from 1 June to 30 November, the Atlantic basin shows a very peaked season with 78% of the tropical storm days, 87% of the minor (Saffir-Simpson Scale categories 1 and 2 - see Subject D1) hurricane days, and 96% of the major (Saffir-Simpson categories 3, 4 and 5) hurricane days occurring in August through October (*Landsea* 1993). Peak activityis in early to mid September. Once in a few years there may be a tropical cyclone occurring "out of season" - primarily in May or December. (For more detailed information, see Subject G13 - "What is my chance of having a tropical storm or hurricane strike by each month?")

The Northeast Pacific basin has a broader peak with activity beginning in late May or early June and going until late October or early November with a peak in storminess in late August/early September.

The Northwest Pacific basin has tropical cyclones occurring all year round regularly though there is a distinct minimum in February and the first half of March. The main season goes from July to November with a peak in late August/early September.

The North Indian basin has a double peak of activity in May and November though tropical cyclones are seen from April to December. The severe cyclonic storms (>33 m/s winds [76 mph]) occur almost exclusively from April to June and late September to early December.

The Southwest Indian and Australian/Southeast Indian basins have very similar annual cycles with tropical cyclones beginning in late October/early November, reaching a double peak in activity - one in mid-January and one in mid-February to early March, and then ending in May. The Australian/Southeast Indian basin February lull in activity is a bit more pronounced than the Southwest Indian basin's lull.

The Australian/Southwest Pacific basin begin with tropical cyclone activity in late October/early November, reaches a single peak in late February/early March, and then fades out in early May.

Globally, September is the most active month and May is the least active month. *(Neumann 1993)*

Subject: G2) How does El Niño-Southern Oscillation affect tropical cyclone activity around the globe?

The effect of El Niño-Southern Oscillation (ENSO) on Atlantic tropical cyclones is described in Subject F2.

The Australian/Southwest Pacific shows a pronounced shift back and forth of tropical cyclone activity with fewer tropical cyclones between 145° and 165°E and more from 165°E eastward across the South Pacific during El Niño (warm ENSO) events. There is also a smaller tendency to have the tropical cyclones originate a bit closer to the equator. The opposite would be true in La Niña (cold ENSO) events. See papers by *Nicholls (1979)*, *Revell and Goulter (1986)*, *Dong (1988)*, and *Nicholls (1992).*

The western portion of the Northeast Pacific basin (140°W to the dateline) has been suggested to experience more tropical cyclone genesis during the El Niño year and more tropical cyclones tracking into the sub-region in the year following an El Niño *(Schroeder and Yu 1995)*, but this has not been completely documented yet.

The Northwest Pacific basin, similar to the Australian/Southwest Pacific basin, experiences a change in location of tropical cyclones without a total change in frequency. *Pan (1981)*, *Chan (1985)*, and *Lander (1994)* detailed that west of 160°E there were reduced numbers of tropical cyclone genesis with increased formations from 160E to the dateline during El Niño events. The opposite occurred during La Niña events. Again there is also the tendency for the tropical cyclones to also form closer to the equator during El Niño events than average.

The eastern portion of the Northeast Pacific, the Southwest Indian, the Southeast Indian/Australian, and the North Indian basins have either shown little or a conflicting ENSO relationship and/or have not been looked at yet in sufficient detail.

Subject: G3) What may happen with tropical cyclone activity due to global warming? The United Nation's Intergovernmental Panel on Climate Change (IPCC) has speculated that climate change due to increasing amounts of anthropogenic "greenhouse" gases may result in increased tropical sea surface temperatures (SSTs) and increased tropical rainfall associated with a slightly stronger intertropical convergence zone (ITCZ) *(Houghton et al.*, 1990, 1992, 1996). Because tropical cyclones extract latent and sensible heat from the warm tropical oceans and release the heat in its upper tropospheric outflow to fuel the storm's spin up, early work of the IPCC expressed concern that warmer SSTs will lead to more frequent and intense hurricanes, typhoons and severe tropical cyclones. These concerns prompted the IPCC *(Houghton et al.* 1990) to suggest in 1990 that:

> "There is some evidence from model simulations and empirical considerations that the frequency per year, intensity and area of occurrence of tropical disturbances may increase [in a doubled carbon dioxide world], though it is not yet compelling."

However, any changes in tropical cyclone activity are intrinsically also tied to large-scale changes in the tropical atmosphere. As a result, SSTs by themselves cannot be considered without corresponding information regarding the moisture and stability in the tropical troposphere. What has been identified in the current climate as being necessary for genesis and maintenance for tropical cyclones (e.g. SSTs of at least 26.5°C [80°F] - *Gray* 1968) would change in an enhanced doubled CO2 world because of possible changes in the moisture or stability. It is quite reasonable that an increase in tropical and subtropical

SSTs would be also accompanied by an increase in the SST threshold value needed for cyclogenesis because of compensating changes in the tropospheric moist static stability (Emanuel 1995). In addition to the thermodynamic variables, changes in the tropical dynamics also play a large role in determining changes in tropical cyclone activity. For example, if the vertical wind shear over the tropical North Atlantic moderately increased during the hurricane season in an increased CO2 world - as what is typically seen during El Nino-Southern Oscillation warm phases (El Nino events), then we would most likely see a significant decrease in tropical cyclone activity. This is due to the Atlantic basin having a marginal climatology for tropical cyclone activity because of its sensitivity to changes in vertical wind shear and lack of an oceanic monsoon trough (Gray et al. 1993). In other less marginal tropical cyclone basins, changes in the vertical shear profile typically result in alterations in the preferred location of development (e.g. *Nicholls* 1979, *Chan* 1985, *Revell and Goulter* 1986, and *Lander* 1994). These complications along with conflicting global circulation modeling (GCM) runs compelled the 1995 IPCC *(Houghton et al.* 1996) to express greater uncertainty about the nature of tropical cyclones in an enhanced CO2 environment:

> "The formation of tropical cyclones depends not only on sea surface temperature (SST), but also on a number of atmospheric factors. Although some models now represent tropical storms with some realism for present day climate, the state of the science does not allow assessment of future changes."

Most recently, *Henderson-Sellers et al.* (1998) addressed a few of the tropical cyclone-greenhouse warming problems. The first is that "there is no evidence to suggest any major changes in the area or global location of tropical cyclone genesis in greenhouse conditions." This conclusion is based upon *Holland's* (1997) thermodynamic tropical cyclone model which does show that in a greenhouse-warmed climate there is an upward alteration in the minimum SST from 26.5° to 28°C (80° to 83°F) needed for tropical cyclogenesis. The additional conclusion from *Henderson-Sellers et al.* (1998) suggests "an increase in [maximum potential intensity] MPI of 10%-20% [in central pressure or 5%-10% in maximum sustained winds] for a doubled CO2 climate but the known omissions (ocean spray, momentum restriction, and possibly also surface to 300 hPa lapse rate changes) all act to reduce these increases." This second finding is also based upon the thermodynamic models of *Emanuel* (1986) and *Holland* (1997), which also appear to corroborate similar findings for Northwest Pacific typhoons from a "downscaled" GCM to mesoscale model approach by *Knutson et al.* (1998). *Henderson-Sellers et al.* (1998) does not provide guidance for possible changes in tropical cyclone frequency, mean intensity, or area of occurrence. The most helpful paper that may predict changes in hurricane and typhoon frequency with some realism is the recent work by *Royer et al.* (1998). Based upon alterations to the large scale atmospheric and oceanic conditions (vertical shear, vorticity and thermodynamic stability), they suggest that only small changes to the tropical cyclone frequencies may result: up to 10% increase in numbers in the Northern Hemisphere (primarily in the Northwest Pacific) and up to a 5% decrease in numbers in the Southern Hemisphere. These values should be considered very preliminary. To summarize, our current assessment of how global warming may alter hurricanes, typhoons and tropical cyclones is as follows (from *Henderson-Sellers et al.* 1998, *Knutson et al.* 1998, and *Royer et al.* 1998):

- There is no evidence to suggest tropical cyclones will have any major changes in WHERE they form or occur.
- Preliminary analyses hint that only small to no change in the NUMBER of tropical cyclones may occur, and that regionally there may be areas that have small increases or small decreases in frequency.
- The PEAK INTENSITY of tropical cyclones may increase by 5-10% in wind speeds, but this may be an overestimate because of simplifications in the calculations.
- Little is known as to how the AVERAGE INTENSITY or SIZE of tropical cyclones may change due to global warming.
- Overall, these suggested changes are quite small compared to the observed large natural variability of hurricanes, typhoons and tropical cyclones. However, more study is needed to better understand

the complex interaction between these storms and the tropical atmosphere/ocean.

Subject: G4) Are we getting stronger and more frequent hurricanes, typhoons, and tropical cyclones in the last several years?

Globally, no. However, for the Atlantic basin we have seen an increase in the number of strong hurricanes since 1995. As can be seen in section E9, we have had a record 33 hurricanes in the four years of 1995 to 1999 (accurate records for the Atlantic are thought to begin around 1944). The extreme impacts from Hurricanes Marilyn (1995), Opal (1995), Fran (1996), Georges (1998) and Mitch (1998) in the United States and throughout the Caribbean attest to the high amounts of Atlantic hurricane activity lately.

As discussed in the previous section, it is highly unlikely that global warming has (or will) contribute to a drastic change in the number or intensity of hurricanes. We have not observed a long-term increase in the intensity or frequency of Atlantic hurricanes. Actually, 1991-1994 marked the four quietest years on record (back to the mid-1940s) with just less than 4 hurricanes per year. Instead of seeing a long-term trend up or down, we do see a quasi-cyclic multi-decade regime that alternates between active and quiet phases for major Atlantic hurricanes on the scale of 25-40 years each (*Gray* 1990; *Landsea* 1993; *Landsea et al.* 1996). The quiet decades of the 1970s to the early 1990s for major Atlantic hurricanes were likely due to changes in the Atlantic Ocean sea surface temperature structure with cooler than usual waters in the North Atlantic. The reverse situation of a warm North Atlantic was present during the active late-1920s through the 1960s (*Gray et al.* 1997). It is quite possible that the extreme activity since 1995 marks the start of another active period that may last a total of 25-40 years. More research is needed to better understand these hurricane "cycles".

For the region near Australia (105-160E, south of the equator), Nicholls (1992) identified a downward trend in the numbers of tropical cyclones, primarily from the mid-1980s onward. However, a portion of this trend is likely artificial as the forecasters in the region no longer classify weak systems as "cyclones" if the systems do not possess the traditional tropical cyclone inner-core structure, but have the band of maximum winds well-removed from the center (*Nicholls et al.* 1998). These changes in methodology around the mid-1980s have been prompted by improved access to and interpretation of digital satellite data, the installation of coastal and off-shore radar, and an increased understanding of the differentiation of tropical cyclones from other type of tropical weather systems. By considering only the moderate and intense tropical cyclones, this artificial bias in the cyclone record can be overcome. Even with the removal of this bias in the weak Australian tropical cyclones that the frequency of the remaining moderate and strong tropical cyclones has been reduced substantially over the years 1969/70-1995/96. *Nicholls et al.* (1998) attribute the decrease in moderate cyclones to the occurrence of more frequent El Nino occurrences during the 1980s and 1990s.

For the Northwest Pacific basin, *Chan and Shi* (1996) found that both the frequency of typhoons and the total number of tropical storms and typhoons have been increasing since about 1980. However, the increase was preceded by a nearly identical magnitude of decrease from about 1960 to 1980. It is unknown currently what has caused these decadal-scale changes in the Northwest Pacific typhoons.

For the remaining basins based upon data from the late 1960s onwards, the Northeast Pacific has experienced a significant upward trend in tropical cyclone frequency, the North Indian a significant downward trend, and no appreciable long-term variation was observed in the Southwest Indian and Southwest Pacific (east of 160E) for the total number of tropical storm strength cyclones (from *Neumann* 1993). However, whether these represent longer term (> 30 years) or shorter term (on the scale of ten years) variability is completely unknown because of the lack of a long, reliable record.

Subject: G5) Why do tropical cyclones occur primarily in the summer and autumn?

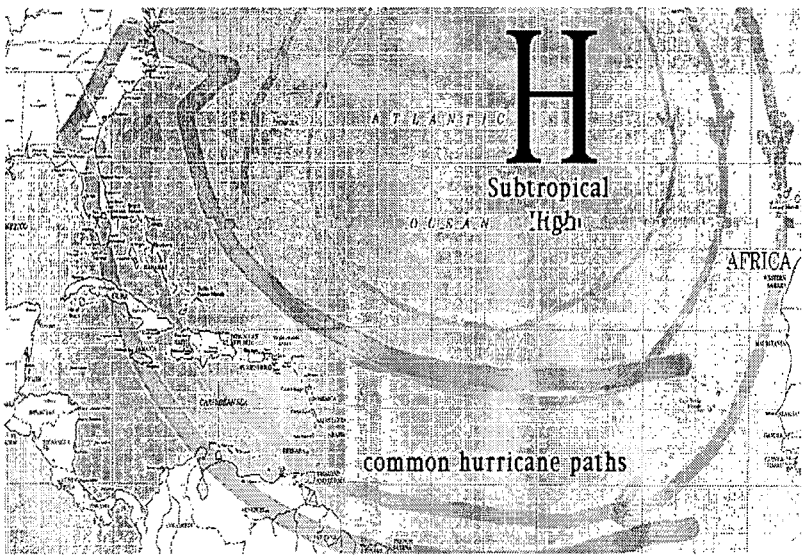
As described in Subject G1, the primary time of year for getting tropical cyclones is during the summer and autumn: July-October for the Northern Hemisphere and December-March for the Southern

Hemisphere (though there are differences from basin to basin). The peak in summer/autumn is due to having all of the necessary ingredients become most fa vorable during this time of year: warm ocean waters (at least 26°C or 80°F), a tropical atmosphere that can quite easily kick off convection (i.e. thunderstorms), low vertical shear in the troposphere, and a substantial amount of large-scale spin available (either through the monsoon trough or easterly waves).

While one would intuitively expect tropical cyclones to peak right at the time of maximum solar radiation (late June for the tropical Northern Hemisphere and late December for the tropical Southern Hemisphere), it takes several more weeks for the oceans to reach their warmest temperatures. The atmospheric circulation in the tropics also reaches its most pronounced (and favorable for tropical cyclones) at the same time. This time lag of the tropical ocean and atmospheric circulation is analogous to the daily cycle of surface air temperatures - they are warmest in mid-afternoon, yet the sun's incident radiation peaks at noon.

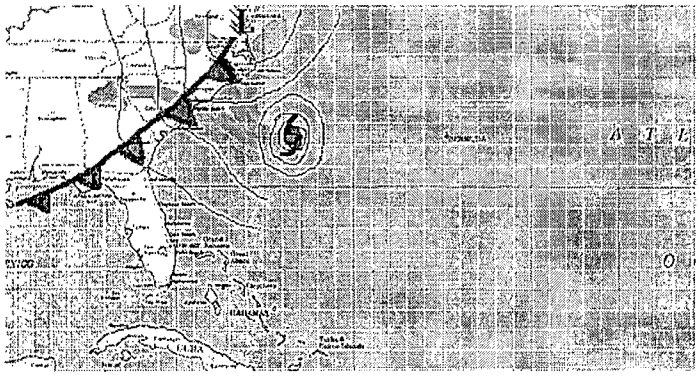
Subject: G6) What determines the movement of tropical cyclones?

Tropical cyclones - to a first approximation - can be thought of as being steered by the surrounding environmental flow throughout the depth of the troposphere (from the surface to about 12 km or 8 mi). Dr. Neil Frank, former director of the U.S. National Hurricane Center, used the analogy that the movement of hurricanes is like a leaf being steered by the currents in the stream, except that for a hurricane the stream has no set boundaries.



In the tropical latitudes (typically equatorward of 20°-25°N or S), tropical cyclones usually move toward the west with a slight poleward component. This is because there exists an axis of high pressure called the subtropical ridge that extends east-west poleward of the storm. On the equatorward side of the subtropical ridge, general easterly winds prevail. However, if the subtropical ridge is weak - often times due to a trough in the jet stream - the tropical cyclone may turn poleward and then recurve back toward

the east. On the poleward side of the subtropical ridge, westerly winds prevail thus steering the tropical cyclone back to the east. These westerly winds are the same ones that typically bring extratropical cyclones with their cold and warm fronts from west to east.



Many times it is difficult to tell whether a trough will allow the tropical cyclone to recurve back out to sea (for those folks on the eastern edges of continents) or whether the tropical cyclone will continue straight ahead and make landfall.

For more non-technical information on the movement of tropical cyclones, see Pielke and Pielke's "Hurricanes: Their Nature and Impacts on Society". For a more detailed, technical summary on the controls on tropical cyclone motion, see Elsberry's chapter in "Global Perspectives on Tropical Cyclones".

Subject: G7) Why doesn't the South Atlantic Ocean experience tropical cyclones?

Though many people might speculate that the sea surface temperatures are too cold, the primary reasons that the South Atlantic Ocean gets no tropical cyclones are that the tropospheric (near surface to 200mb) vertical wind shear is much too strong and there is typically no inter-tropical convergence zone (ITCZ) over the ocean *(Gray 1968)*. Without an ITCZ to provide synoptic vorticity and convergence (i.e. large scale spin and thunderstorm activity) as well as having strong wind shear, it becomes very difficult to nearly impossible to have genesis of tropical cyclones.

However, in rare occasions it may be possible to have tropical cyclones form in the South Atlantic. In *McAdie and Rappaport (1991)*, the US National Hurricane Center documented the occurrence of a strong tropical depression/weak tropical storm that formed off the coast of Congo in mid-April 1991. The storm lasted about five days and drifted toward the west-southwest into the central South Atlantic. So far, there has not been a systematic study as to the conditions that accompanied this rare event.

Subject: G8) Does an active June and July mean the rest of the season will be busy too?

No. The number of named storms (hurricanes) occurring in June and July correlates at an insignificant r = +0.13 (+0.02) versus the whole season activity. Actually, there is a slight negative association of early season storms (hurricanes) versus late season - August through November - r = -0.28 (-0.35). Thus, early season activity, be it very active or quite calm, has little bearing on the season as a whole. These correlations are based on the years 1944-1994.

Subject: G9) Why do hurricanes hit the East coast of the U.S., but never the West coast?

Hurricanes form both in the Atlantic basin (i.e. the Atlantic Ocean, Gulf of Mexico and Caribbean Sea) to the east of the continental U.S. and in the Northeast Pacific basin to the west of the U.S. However, the ones in the Northeast Pacific almost never hit the U.S., while the ones in the Atlantic basin strike the U.S. mainland just less than twice a year on average. There are two main reasons. The first is that hurricanes tend to move toward the west-northwest after they form in the tropical and subtropical latitudes. In the Atlantic, such a motion often brings the hurricane into the vicinity of the U.S. east coast. In the Northeast Pacific, a west-northwest track takes those hurricanes farther off-shore, well away from the U.S. west coast. In addition to the general track, a second factor is the difference in water temperatures along the U.S. east and west coasts. Along the U.S. east coast, the Gulf Stream provides a source of warm (> 80 F or 26.5 C) waters to help maintain the hurricane. However, along the U.S. west coast, the ocean temperatures rarely get above the lower 70s, even in the midst of summer. Such relatively cool temperatures are not energetic enough to sustain a hurricane's strength. So for the occasional Northeast Pacific hurricane that does track back toward the U.S. west coast, the cooler waters can quickly reduce the strength of the storm.

Subject: G10) How much lightning occurs in tropical cyclones?

Surprisingly, not much lightning occurs in the inner core (within about 100 km or 60 mi) of the tropical cyclone center. Only around a dozen or less cloud-to-ground strikes per hour occur around the eyewall of the storm, in strong contrast to an overland mid-latitude mesoscale convective complex which may be observed to have lightning flash rates of **greater than 1000 per hour** maintained for several hours.

Hurricane Andrew's eyewall had less than 10 strikes per hour from the time it was over the Bahamas until after it made landfall along Louisiana, with several hours with no cloud-to-ground lightning at all *(Molinari et al. 1994)*. However, lightning can be more common in the outer cores of the storms (beyond around 100 km or 60 mi) with flash rates on the order of 100s per hour.

This lack of inner core lightning is due to the relative weak nature of the eyewall thunderstorms. Because of the lack of surface heating over the ocean ocean and the "warm core" nature of the tropical cyclones, there is less buoyancy available to support the updrafts. Weaker updrafts lack the super-cooled water (e.g. water with a temperature less than 0° C or 32° F) that is crucial in charging up a thunderstorm by the interaction of ice crystals in the presence of liquid water *(Black and Hallett 1986)*. The more common outer core lightning occurs in conjunction with the presence of convectively-active rainbands *(Samsury and Orville 1994)*.

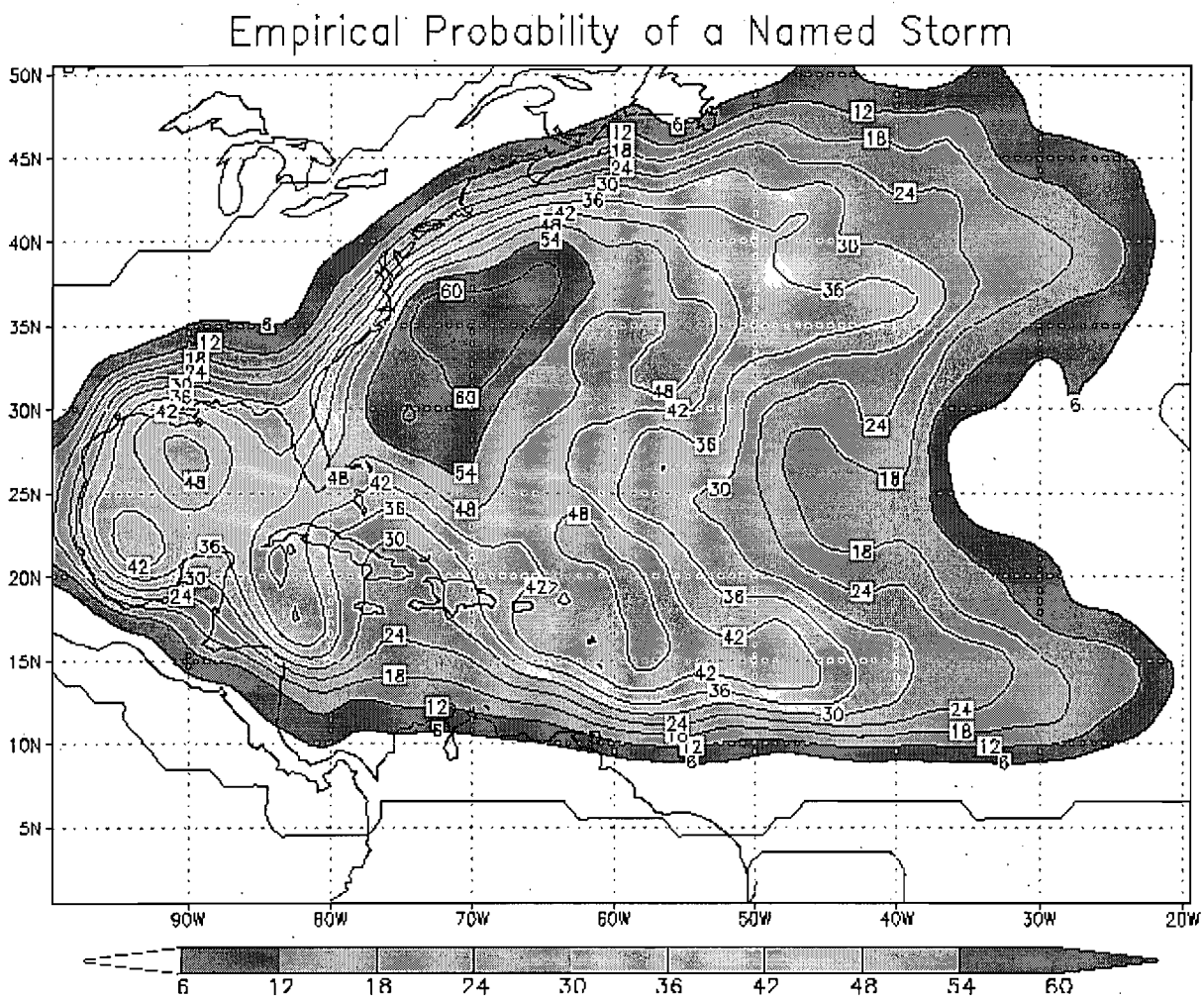
One of the exciting possibilities that recent lightning studies have suggested is that changes in the inner core strikes - though the number of strikes is usually quite low - may provide a useful forecast tool for intensification of tropical cyclones. *Black (1975)* suggested that bursts of inner core convection which are accompanied by increases in electrical activity may indicate that the tropical cyclone will soon commence a deepening in intensity. Analyses of Hurricanes Diana (1984), Florence (1988) and Andrew (1992), as well as an unnamed tropical storm in 1987 indicate that this is often true *(Lyons and Keen 1994* and *Molinari et al. 1994)*.

Subject: G11) What is the 20th century hurricane record for each U.S. coastal state and county?

Click on the state below, then select either the state histogram or a county from the list to view a histogram of that coastal entity's hurricane history. (Data provided by *Jarrell et al. (1992)*, with updates provided by Paul Hebert - personal communication. Plots created by Mr. Noel Charles.)

Texas	Louisiana	Mississippi	Alabama	Florida	Georgia
South Carolina	North Carolina	Virginia	Maryland	Delaware	New Jersey
New York	Connecticut	Rhode Island	Massachusetts	New Hampshire	Maine

Subject: G12) What is the chance of my town will be hit by a tropical storm or hurricane ?



The figure here, created by Todd Kimberlain, shows for any particular location what the chance is that a tropical storm or hurricane will affect the area sometime during the whole June to November hurricane season. We utilized the years 1944 to 1997 in the analysis and counted hits when a storm or hurricane was within about 100 miles (165 km).

For example, people living in New Orleans, LA have about a 40% chance (the olive green color) per year of experiencing a strike by a tropical storm or hurricane. For the U.S., the locations that have the highest chances are the following: Miami, FL - 48% chance; Cape Hatteras, NC - 48% chance; and San Juan, PR - 42% chance.

Subject: G13) What is the chance that my town will be hit by a tropical storm or hurricane during the each month of the season?

The following figures show that for

June
July
August

September
October
November
These figures were created by Todd Kimberlain.

at any particular location what the chance that a tropical storm or hurricane will affect the area sometime during an individual month. We utilized the years 1944 to 1997 in the analysis and counted hits when a storm or hurricane was within about 100 miles (165 km).

Subject: G14) What is the average number of tropical storms and hurricanes to affect my town?

The figure here (created by Todd Kimberlain) shows for any particular location what the average number of tropical storms and hurricanes is that affect the area sometime during the whole June to November hurricane season. We utilized the years 1944 to 1997 in the analysis and counted hits when a storm or hurricane was within about 100 miles (165 km).

Subject: G15) What is the peak number of tropical storms and hurricanes to affect my town?

The figure here (created by Todd Kimberlain) shows for any particular location what the highest number of tropical storms and hurricanes is that affect the area sometime during the whole June to November hurricane season. Blue indicates a peak of just 1 storm, orange is 2 storms, brick red is 3 storms, green is 4 storms and red is 5 storms. We utilized the years 1944 to 1997 in the analysis and counted hits when a storm or hurricane was within about 100 miles (165 km).

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The Saffir-Simpson Hurricane Scale

The Saffir-Simpson Hurricane Scale is a 1-5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf in the landfall region. Note that all winds are using the U.S. 1-minute average.

Category One Hurricane:

Winds 74-95 mph (64-82 kt or 119-153 kph). Storm surge generally 4-5 ft above normal. No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also, some coastal road flooding and minor pier damage. Hurricanes Allison of 1995 and Danny of 1997 were Category One hurricanes at peak intensity.

Category Two Hurricane:

Winds 96-110 mph (83-95 kt or 154-177 kph). Storm surge generally 6-8 feet above normal. Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings. Hurricane Bonnie of 1998 was a Category Two hurricane when it hit the North Carolina coast, while Hurricane Georges of 1998 was a Category Two Hurricane when it hit the Florida Keys and the Mississippi Gulf Coast.

Category Three Hurricane:

Winds 111-130 mph (96-113 kt or 178-209 kph). Storm surge generally 9-12 ft above normal. Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Damage to shrubbery and trees with foliage blown off trees and large tress blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures with larger structures damaged by battering of floating debris. Terrain continuously lower than 5 ft above mean sea level may be flooded inland 8 miles (13 km) or more. Evacuation of low-lying residences with several blocks of the shoreline may be required. Hurricanes Roxanne of 1995 and Fran of 1996 were Category Three hurricanes at landfall on the Yucatan Peninsula of Mexico and in North Carolina, respectively.

Category Four Hurricane:

Winds 131-155 mph (114-135 kt or 210-249 kph). Storm surge generally 13-18 ft above normal. More extensive curtainwall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water 3-5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 10 ft above sea level may be flooded requiring massive evacuation of residential areas as far inland as 6 miles (10 km). Hurricane Luis of 1995 was a Category Four hurricane while moving over the Leeward Islands. Hurricanes Felix and Opal of 1995 also reached Catgeory Four status at peak intensity.

Category Five Hurricane:

Winds greater than 155 mph (135 kt or 249 kph). Storm surge generally greater than 18 ft above normal. Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destructon of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 15 ft above sea level and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5-10 miles (8-16 km) of the shoreline may be required. Hurricane Mitch of 1998 was a Category Five hurricane at peak intensity over the western Caribbean. Hurricane Gilbert of 1988 was a Category Five hurricane at peak intensity and is the strongest Atlantic tropical cyclone of record.

Todd Spindler
Jack Beven

Last updated July 14, 1999

World-Wide Tropical Cyclone Names

Atlantic Names:

2000	2001	2002	2003	2004	2005
Alberto	Allison	Arthur	Ana	Alex	Arlene
Beryl	Barry	Bertha	Bill	Bonnie	Bret
Chris	Chantal	Cristobal	Claudette	Charley	Cindy
Debby	Dean	Dolly	Danny	Danielle	Dennis
Ernesto	Erin	Edouard	Erika	Earl	Emily
Florence	Felix	Fay	Fabian	Frances	Franklin
Gordon	Gabrielle	Gustav	Grace	Gaston	Gert
Helene	Humberto	Hanna	Henri	Hermine	Harvey
Isaac	Iris	Isidore	Isabel	Ivan	Irene
Joyce	Jerry	Josephine	Juan	Jeanne	Jose
Keith	Karen	Kyle	Kate	Karl	Katrina
Leslie	Lorenzo	Lili	Larry	Lisa	Lee
Michael	Michelle	Marco	Mindy	Matthew	Maria
Nadine	Noel	Nana	Nicholas	Nicole	Nate
Oscar	Olga	Omar	Odette	Otto	Ophelia
Patty	Pablo	Paloma	Peter	Paula	Philippe
Rafael	Rebekah	Rene	Rose	Richard	Rita
Sandy	Sebastien	Sally	Sam	Shary	Stan
Tony	Tanya	Teddy	Teresa	Tomas	Tammy
Valerie	Van	Vicky	Victor	Virginie	Vince
William	Wendy	Wilfred	Wanda	Walter	Wilma

Experience shows that the use of short, distinctive given names in written as well as spoken communications is quicker and less subject to error than the older more cumbersome latitude-longitude identification methods. These advantages are especially important in exchanging detailed storm information between hundreds of widely scattered stations, coastal bases, and ships at sea.

Since 1953, Atlantic tropical storms have been named from lists originated by the National Hurricane Center and now maintained and updated by an international committee of the World Meteorological Organization. The lists featured only women's names until 1979, when men's and women's names were alternated. Six lists are used in rotation. Thus, the 1999 list will be used again in 2005. Here is more information on the history of naming hurricanes.

The only time that there is a change in the list is if a storm is so deadly or costly that the future use of its name on a different storm would be inappropriate for reasons of sensitivity. If that occurs, then at an annual meeting by the WMO committee (called primarily to discuss many other issues) the offending name is stricken from the list and another name is selected to replace it.

Several names have been changed since the lists were last used. Four names from the 1995 list have been retired. On the 2001 list, Lorenzo has replaced Luis, Michelle has replaced Marilyn, Olga has replaced Opal, and Rebekah has replaced Roxanne. Three names from the 1996 list have been retired. On the 2002 list, Cristobal has replaced Cesar, Fay has replaced Fran, and Hanna has replaced

Hortense. Two names from the 1998 list have been retired. On the 2004 list, Gaston has replaced Georges and Matthew has replaced Mitch. Here is more information on the retirement of hurricane names.

Eastern North Pacific Names:

2000	2001	2002	2003	2004	2005
Aletta	Adolph	Alma	Andres	Agatha	Adrian
Bud	Barbara	Boris	Blanca	Blas	Beatriz
Carlotta	Cosme	Cristina	Carlos	Celia	Calvin
Daniel	Dalilia	Douglas	Dolores	Darby	Dora
Emilia	Erick	Elida	Enrique	Estelle	Eugene
Fabio	Flossie	Fausto	Felicia	Frank	Fernanda
Gilma	Gil	Genevieve	Guillermo	Georgette	Greg
Hector	Henriette	Hernan	Hilda	Howard	Hilary
Ileana	Israel	Iselle	Ignacio	Isis	Irwin
John	Juliette	Julio	Jimena	Javier	Jova
Kristy	Kiko	Kenna	Kevin	Kay	Kenneth
Lane	Lorena	Lowell	Linda	Lester	Lidia
Miriam	Manuel	Marie	Marty	Madelime	Max
Norman	Narda	Norbert	Nora	Newton	Norma
Olivia	Octave	Odile	Olaf	Orlene	Otis
Paul	Priscilla	Polo	Patricia	Paine	Pilar
Rosa	Raymond	Rachel	Rick	Roslyn	Ramon
Sergio	Sonia	Simon	Sandra	Seymour	Selma
Tara	Tico	Trudy	Terry	Tina	Todd
Vicente	Velma	Vance	Vivian	Virgil	Veronica
Willa	Wallis	Winnie	Waldo	Winifred	Wiley
Xavier	Xina	Xavier	Xina	Xavier	Xina
Yolanda	York	Yolanda	York	Yolanda	York
Zeke	Zelda	Zeke	Zelda	Zeke	Zelda

These lists are also re-cycled every six years (the 2000 list will be used again in 2006).

Central North Pacific Names:

LIST 1	LIST 2	LIST 3	LIST 4
Akoni	Aka	Alika	Ana
Ema	Ekeka	Ele	Ela
Hana	Hali	Huko	Halola
Io	Iolana	Ioke	Iune
Keli	Keoni	Kika	Kimo
Lala	Li	Lana	Loke
Moke	Mele	Maka	Malia
Nele	Nona	Neki	Niala
Oka	Oliwa	Oleka	Oko
Peke	Paka	Peni	Pali
Uleki	Upana	Ulia	Ulika
Wila	Wene	Wali	Walaka

The names are used one after the other. When the bottom of one list is reached, the next name is the top of the next list. Paka (1997) was the last name used from the list. Iniki has been replaced by Iolana.

Western North Pacific Names:

Contributed By:	I	II	III	IV	V
Cambodia	Damrey	Kong-rey	Nakri	Krovanh	Sarika
China	Longwang	Yutu	Fengshen	Dujuan	Haima
DPR Korea	Kirogi	Toraji	Kalmaegi	Maemi	Meari
HK, China	Kai-Tak	Man-yi	Fung-wong	Choi-wan	Ma-on
Japan	Tenbin	Usagi	Kanmuri	Koppu	Tokage
Lao PDR	Bolaven	Pabuk	Phanfone	Ketsana	Nock-ten
Macau	Chanchu	Wutip	Vongfong	Parma	Muifa
Malaysia	Jelawat	Sepat	Rusa	Melor	Merbok
Micronesia	Ewinlar	Fitow	Sinlaku	Nepartak	Nanmadol
Philippines	Bilis	Danas	Hagupit	Lupit	Talas
RO Korea	Gaemi	Nari	Changmi	Sudal	Noru
Thailand	Prapiroon	Vipa	Megkhla	Nida	Kularb
U.S.A.	Maria	Francisco	Higos	Omais	Roke
Vietnam	Saomai	Lekima	Bavi	Conson	Sonca
Cambodia	Bopha	Krosa	Maysak	Chanthu	Nesat
China	Wukong	Haiyan	Haishen	Dianmu	Haitang
DPR Korea	Sonamu	Podul	Pongsona	Mindule	Nalgae
HK, China	Shanshan	Lingling	Yanyan	Tingting	Banyan
Japan	Yagi	Kaziki	Kuzira	Kompasu	Washi
Lao PDR	Xangsane	Faxai	Chan-hom	Namtheun	Matsa
Macau	Bebinca	Vamei	Linfa	Malou	Sanvu
Malaysia	Rumbia	Tapah	Nangka	Meranti	Mawar
Micronesia	Soulik	Mitag	Soudelor	Rananin	Guchol
Philippines	Cimaron	Hagibis	Imbudo	Malakas	Talim
RO Korea	Chebi	Noguri	Koni	Megi	Nabi
Thailand	Durian	Ramasoon	Hanuman	Chaba	Khanun
U.S.A.	Utor	Chataan	Etau	Kodo	Vicete
Vietnam	Trami	Halong	Vamco	Songda	Saola

These names are also used sequentially. If the last storm of the year is Cimaron, the first storm of the next year is Chebi.

Australian Region Names (as of 1999):

Western Australian Region:

Adeline	Alison	Alex
Bertie	Billy	Bessi
Clare	Cathy	Chris
Daryl	Damien	Dianne
Emma	Elaine	Errol
Floyd	Frederic	Fiona
Glenda	Gwenda	Graham
Hubert	Hamish	Harriet
Isobel	Ilsa	Inigo
Jacob	John	Jana
Kirsty	Kirrily	Ken
Lee	Leon	Linda
Melanie	Marcia	Monty
Nicholas	Norman	Nicky
Ophelia	Olga	Oscar
Pancho	Paul	Phoebe
Rhonda	Rosita	
Selwyn	Sam	Sally
Tiffany	Taryn	Tim
Victor	Vincent	Vivienne
Zelia	Walter	Willy

Northern Australian Region:

Amelia	Alistair
Bruno	Bonnie
Coral	Craig
Dominic	Debbie
Esther	Evan
Ferdinand	Fay
Gretel	George

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Ileana	Israel	Iselle	Ignacio	Isis	Irwin
John	Juliette	Julio	Jimena	Javier	Jova
Kristy	Kiko	Kenna	Kevin	Kay	Kenneth
Lane	Lorena	Lowell	Linda	Lester	Lidia
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Lao PDR	Bolaven	Pabuk	Phanfone	Ketsana	Nock-ten
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Malaysia	Jelawat	Sepat	Rusa	Melor	Merbok
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Philippines	Bilis	Danas	Hagupit	Lupit	Talas
RO Korea	Gaemi	Nari	Changmi	Sudal	Noru
Thailand	Prapiroon	Vipa	Megkhla	Nida	Kularb
U.S.A.	Maria	Francisco	Higos	Omais	Roke
Vietnam	Saomai	Lekima	Bavi	Conson	Sonca
Cambodia	Bopha	Krosa	Maysak	Chanthu	Nesat
China	Wukong	Haiyan	Haishen	Dianmu	Haitang
DPR Korea	Sonamu	Podul	Pongsona	Mindule	Nalgae
HK, China	Shanshan	Lingling	Yanyan	Tingting	Banyan
Japan	Yagi	Kaziki	Kuzira	Kompasu	Washi
Lao PDR	Xangsane	Faxai	Chan-hom	Namtheun	Matsa
Macau	Bebinca	Vamei	Linfa	Malou	Sanvu
Malaysia	Rumbia	Tapah	Nangka	Meranti	Mawar
Micronesia	Soulik	Mitag	Soudelor	Rananin	Guchol
Philippines	Cimaron	Hagibis	Imbudo	Malakas	Talim
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Kirsty	Kirrily	Ken
Lee	Leon	Linda
Melanie	Marcia	Monty
Nicholas	Norman	Nicky
Ophelia	Olga	Oscar
Pancho	Paul	Phoebe
Rhonda	Rosita	
Selwyn	Sam	Sally
Tiffany	Taryn	Tim
Victor	Vincent	Vivienne
Zelia	Walter	Willy

Northern Australian Region:

Amelia	Alistair
Bruno	Bonnie
Coral	Craig
Dominic	Debbie
Esther	Evan
Ferdinand	Fay
Gretel	George

Hector	Helen
Jason	Jasmine
Irma	Ira
Kay	Kim
Laurence	Laura
Marian	Matt
Neville	Narelle
Olwyn	Oswald
Phil	Penny
Rachel	Russel
Sid	Sandra
Thelma	Trevor
Vance	Valerie
Winsome	Warwick

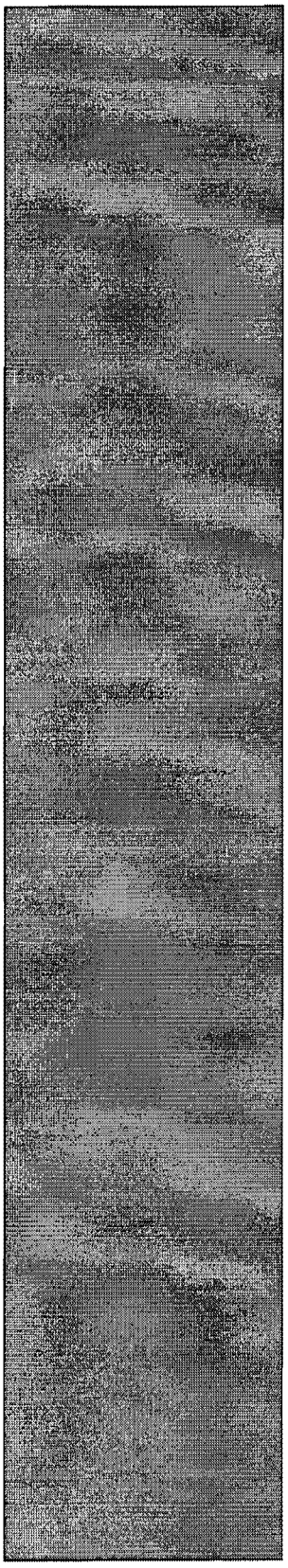
Eastern Australian Region:

Alfred	Ann	Abigail
Blanch	Bruce	Bernie
Charles	Cecily	Claudia
Denise	Dennis	Des
Ernie	Edna	Erica
Frances	Fergus	Fritz
Greg	Gillian	Grace
Hilda	Harold	Harvey
Ivan	Ita	Ingrid
Joyce	Justin	Jim
Kelvin	Katrina	Kate
Lisa	Les	Larry
Marcus	May	Monica
Nora	Nathan	Nelson
Owen	Olinda	Odette
Polly	Pete	Pierre
Richard	Rona	Rebecca
Sadie	Sandy	Steve
Theodore	Tessi	Tania
Verity	Vaughan	Vernon
Wallace	Wylva	Wendy

Each region uses these lists sequentially. If the last storm of the year is Lisa, the first storm of the next year is Marcus. This is a new set of name lists used by the Bureau of Meteorology effective in 1996.

Fiji Region Names (as of 1998):

LIST A	LIST B	LIST C	LIST D	LIST E (Standby)
Ami	Arthur	Atu	Alan	Amos
Beni	Becky	Bobby	Bart	Bune
Cilla	Cliff	Cyril	Cora	Chris
Dovi	Daman	Drena	Dani	Daphne
Eseta	Elisa	Evan	Ella	Eva
Fili	Funa	Freda	Frank	Fanny
Gina	Gene	Gavin	Gita	Garry
Heta	Hettie	Helene	Hali	Hagar
Ivy	Innis	Ian	Iris	Irene
Judy	Joni	June	Jo	Julie
Kerry	Ken	Keli	Kim	Koko
Lola	Lin	Lusi	Leo	Louise
Meena	Mick	Martin	Mona	Mike
Nancy	Nisha	Nute	Neil	Nat
Olaf	Oli	Osea	Oma	Odile
Percy	Pat	Pam	Paula	Pami
Rae	Rene	Ron	Rita	Reuben
Sheila	Sarah	Susan	Sam	Solo
Tam	Tomas	Tui	Trina	Tuni
Urmil	Usha	Ursula	Uka	Ula
Vaianu	Vania	Veli	Vicky	Victor
Wati	Wilma	Wes	Walter	Winston
Zita	Yasi	Yali	Yolande	Yalo



Zaka Zuman Zoe Zena

Lists A, B, C, and D are used sequentially one after the other. The first name in any given year is the one immediately following the last name from the previous year. List E is a list of replacement names if they become necessary.

Papua New Guinea Region Names (as of 1998):

LIST A	LIST B
Epi	Abdul
Guba	Emau
Ila	Gule
Kama	Igo
Matere	Kamit
Rowe	Tiogo
Tako	Ume
Upia	

Lists A and B are used sequentially one after the other. The first name in any given year is the one immediately following the last name from the previous year.

Southwest Indian ocean names (as of 1995):

1999/2000

Astride
Babiola
Connie
Damienne
Eline
Felicia
Gloria
Hudah
Innocente
Jonna
Kenetha
Lisanne
Maizy
Nella
Ortensia
Priscilla
Rebecca
Sophia
Terrence
Victorine
Wilna
Yanselma

These lists are used sequentially, and they are not rotated every few years as are the Atlantic and Eastern Pacific lists. The lists are maintained by the Seychelles Meteorological Service.

Problems?

Last updated May 25, 2000

HURRICANES AND TROPICAL METEOROLOGY

Contents: ***Impacts*** ***Aircraft*** ***Motion*** ***Dynamics*** ***Modification?*** ***Costs & Benefits***

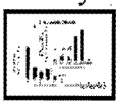
When Hurricane Andrew of 1992 came booming ashore in South Florida, it caused the United States' most expensive natural disaster-- $27 billion worth of property destroyed. Loss of life was another matter. In Miami-Dade County, Andrew killed only 15 people by direct force of wind and water. Human casualties were so light because the storm caused little flooding in populated areas and the National Hurricane Center forecast the storm track accurately. Although hurricanes are inevitable on the East Coast of North America, correct characterization of the phenomenon on all scales enables men and women to prepare effectively. Accurate forecasts of individual events give people time and motivate them to act. The climatology of the threat's occurrence and severity is the key to wise policies implemented long before the event. Intelligent responses in the years, months, days, hours and even minutes before hurricane landfall ***can*** limit human and material losses.

Widespread damage to roofs and windows (F1) of residences in Miami's southern suburbs after Andrew

Impacts

The simplest characterization of hurricane intensity is embodied in the Saffir-Simpson scale: from Category 1 ---barely a hurricane--- to Category 5 ---the worst imaginable. "Major Hurricanes" are those in Categories 3, 4, and 5 with winds stronger than 110 miles per hour equivalent to 100 kt or 50 m s^{-1}. Category 5 hurricanes are the most extreme and also the most rare. Only two, the 1935 Labor Day Storm and Camille in 1969 are recorded to have struck the United States. Andrew, at the very top of Category 4 was the third strongest U.S. landfall, and the second strongest on the mainland, given that the 1935 storm hit the Florida Keys.

In the 20th century, U.S. hurricanes destroyed > $73 billion in property, not corrected for inflation. During the 70-year period from 1925 through 1995, the toll was $61 billion. If the damage from historical hurricanes is normalized for inflation, increased population, and greater individual wealth (Pielke and C. Landsea 1998), the estimate of total damage for the shorter period is $340 billion, equivalent to an average annual loss of $5 billion. During these 70 years, 244 landfalls occurred. The average landfall would have resulted in $1.5 billion in damage with today's prices and costal development. But the average doesn't tell the story. Major hurricanes accounted for 80% of the normalized damage, although they represented only 20% of occurrence.



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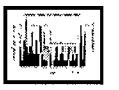
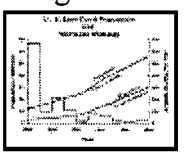
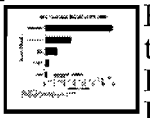
common during the 1940s through the mid 1960s. In the 1970s and 1980s, landfalls were few. Now activity appears to have returned to the high level that characterized the immediate post-World War II period. These fluctuations in activity are most pronounced for major hurricanes. They also correlate with the observed "North Atlantic Mode", a coherent, multidecadal fluctuation of global sea-surface temperatures. During the active portion of the long-term record, Atlantic Sea-Surface Temperature (SST) anomalies in tropics and high latitudes were warm, and conversely. If the hurricane climatology and the Multi-Decadal Mode prove to be reliable guides, we may expect the first decade or two of the 21st Century to produce as many of the most damaging major hurricanes annually as the last 5 years have.



In terms of hurricane-related mortality, the 20th Century started badly. In Galveston Texas, on a single windy Saturday night, 9 September 1900, the "Great Hurricane" washed > 6,000 souls to their deaths. The total mortality for the century was just a bit more than twice this figure, 13,306 U.S. residents. During the first three decades of the century, the average annual loss of life was 329, or discounting the Galveston tragedy, 129. In the forty years from 1930 through 1969, it was 70. Since 1969, the average annual loss of life has been < 20, notwithstanding a 10-fold increase in coastal population from 1930.

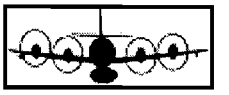


The reason for the dramatic reduction has been effective warnings and timely evacuation from coastal areas inundated by storm surge. Invariably, large loss of life in hurricanes before 1970 stemmed from wind-driven flooding. Since 1970 drowning from inland flooding caused by torrential hurricane rains has come to predominate. Experience shows that when storm surge (or wind for that matter) completely flattens buildings, about 10% of the people present die. Evacuation insures that virtually nobody is present. On the other hand, extreme (> 30 cm in 6 hr) rainfall places a much larger population at individually smaller risk. For example, Hurricane Floyd, the deadliest U.S. hurricane since Agnes of 1973, killed 49 of the more than 5 million people that it affected in the North Carolina Coastal Plain and Piedmont, for an average risk of dying of less than one in a hundred thousand. People in the developing world, who generally do not have the benefit from farsighted land-use policies or effective building standards, are at greater risk. The tragedy of Hurricane Mitch of 1998, which took 10,000 lives in Honduras, demonstrates that among the many bad consequences of poverty is vulnerability to natural disaster.



Aircraft

Tropical cyclones are ideal subjects for study from instrumented aircraft. The vortex core is relatively small--only a few hundred kilometers across. An airplane can traverse it 5-10 times in the course of a flight lasting 6-8 hours. The great rotational inertia of the swirling wind means that the balanced vortex changes slowly during the time that an airplane can remain on station. Expendable probes can report atmospheric or oceanic conditions as they drop from flight level. The size of the core is comparable with the range of 5 or 10 cm wavelength search radars. Although aircraft radars are relatively low powered and have small antennas, the ability to move through the storm enables them to observe storms in detail. The foregoing advantages compound for aircraft equipped with Doppler radars, particularly so if they can fly coordinated patterns in pairs to produce true dual-Doppler winds. NOAA's aircraft operations center flies two WP-3D turboprop that represent a unique scientific resource and are the mainstay of HRD's annual campaign of airborne hurricane observations. Starting in 1997, a third aircraft, a Gulfstream IVSP jet entered the inventory. This airplane is dedicated to synoptic surveillance to obtain observations in the environment around hurricanes to improve operational track forecasts.



Motion

When a hurricane is on the weather map, everyone wants to know where it will go. Only the people whom the storm will hit have an overwhelming concern with its winds, rainfall or storm surge. Everyone else wants ressuurance that it will miss. Forecasts are always uncertain. For individuals and enterprises there is invariably a tradeoff between the cost and effort of preparations and the probability of casualties. Hurricane conditions typically affect a swath of about 100 nautical miles wide; the error in a 24-hour forecast also is now somewhat less than 100 nautical miles. Thus, a prudent forecaster expects to raise warnings on 300 nautical miles of coastline: 100 nautical miles that actually feel the hurricane and 100 nautical miles on either side to allow for forecast error.

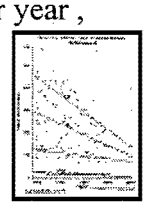
Warnings are expensive. The economic cost of raising a warning, in terms of lost productivity, safeguarding homes and industries, evacuation of aircraft and vessels, and canceled beachfront vacations averages $0.5 to 1.0 M per mile. The cost depends upon the amount of coastal development. If a major city, such as Miami or New Orleans, lies in the warning area, cost escalates dramatically. Sometimes, as happened in Hurricane Emily of 1993, models and observations combine to give forecasters particularly clear insight into the meteorological situation, so that they can exclude large sections of coastline, perhaps hundreds of miles long, from the warning area and save the economy as much as $100M. When, on the other hand, as happened in Hurricane Floyd of 1999, the storm track remains offshore running parallel with the coast, warnings extend far beyond the area affected, and overwarning costs are immense.

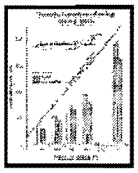
As a problem in fluid mechanics, the dominant factor in hurricane motion is the surrounding wind. In effect, the storm is carried downstream by the average environmental wind. It also "propagates" westward and poleward because it is on a rotating, spherical Earth. Local vertical is more nearly parallel with the planet's axis of rotation in high latitudes. "Beta effect" propagation arises from the poleward increase of the planet's rotation around *local* vertical. Air that moves around the the vortex center with the storm circulation tends to keep a constant value of the sum of the planetary and relative vorticity. Vorticity in the context is the tendency of the air to swirl around a vertical axis. It is the stuff of vorticies.

An anticyclonic asymmetry thus forms on the northeast side of the vortex and a cyclonic asymmetry on the southwest side. This happens because where the planetary vorticity is

larger the relative vorticty must be smaller, and conversely. These "beta" gyres induce a northwestward flow across the vortex center that pushes the storm northwestward. Hurricane motion is 80 to 90% due to large scale winds and 10 to 20% due to propagation. Nonetheless, at a typical speed of 1 m s^{-1}, the motion due to propagation is comparable with typical forecast errors.

Over the last 30 years, the decrease in forecast error has averaged about 1% per year , largely because of improved computer models. In fact, the models are now better than the knowledge of the "initial condition," the state of the atmosphere at the start of a prediction calculation. Research at AOML has demonstrated





that dropsonde observations from aircraft flying around hurricanes can lead to another 15% reduction in the error. If the more accurate forecasts translate into reduced warning areas, savings on the order of $10 to 20M in overwarning costs per hurricane landfall are possible. This dramatic result recognizes that hurricane motion is controlled by the state of the surrounding atmosphere, so that forecasts based upon accurate and timely measurements of that state are themselves more accurate.

In these "synoptic surveillance" experiments, the atmospheric state is measured by

dropwindsondes deployed by the NOAA research aircraft. Sondes are released from an altitude of 5 to 7 kilometers. They measure pressure, wind, temperature, and humidity as they fall to the sea on parachutes. Release patterns encircle the storm and reach more than 1,000 kilometers from the center. Aboard the aircraft, meteorologists process the data and transmit it to the National Centers for Environmental Prediction, where it is analyzed and used to initialize numerical models. The cost of the flight operations is about $130,000--about one percent of the potential savings from reduced overwarning.

More widespread and efficient observations of this kind are the primary reason that NOAA commissioned its new Gulfstream IV jet that has flown synoptic surveillance missions operationally since 1997. The jet procurement included the new GPS dropsonde instruments themselves and new faster in-flight processing and data-visualization software. These improvements are important contributors to the accelerated decrease in forecast errors in the late 1990s.

Dynamics

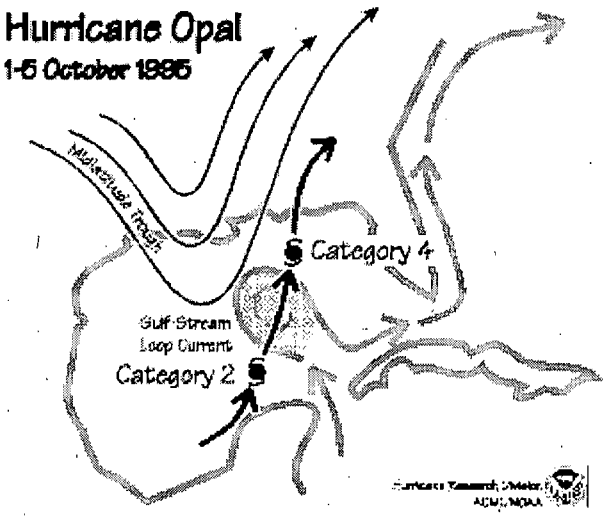
Hurricanes are nearly circular, warm-core vortices, characteristically 1000 km in radius. Strong winds and precipitation are concentrated near, but not at, their centers. Coincident with strongest winds, convective updrafts, fed by inward spiraling surface winds, release latent heat drawn from the ocean to power the storm. The clear eye, 15-30 km in radius, contains the axis of vortex rotation and is surrounded by this ring of strong winds. The eye is characterized by the warmest temperatures in the vortex, low humidity, low pressure, in extreme cases > 10% below that in the undisturbed tropical atmosphere, and calm winds at the very center. The hurricane's eye presents one of the truly magnificent vistas offered to human sight, and the hurricane's workings delight the mind as an intricate and subtle problem in hydrodynamics.

A typical radar image shows the essential structure of a hurricane: a clear eye enclosed by a ring of clouds, which is in turn surrounded by inward spiraling bands of convection. These features are common to all tropical cyclones. Hurricanes take their circular shape from the orbits of air moving in gradient balance around the low atmospheric pressure at the vortex center.

A cross section of a hurricane in the radius-height plane shows that the primary swirling flow is maintained by a radial and vertical secondary circulation. Under the influence of friction, the counter-clockwise spiraling air near the surface converges toward the lower pressure and rises around the eye in cumulus clouds. Although the inflowing air loses angular momentum to the sea, it gains heat stored as water vapor. The vapor condenses in the updrafts, releasing the stored heat and causing intense precipitation. This latent heat release is the power source for the storm. At 2-6 km altitude the updrafts entrain additional air, which is replaced by horizontal convergence that supplies both mass and angular momentum needed to spin up the wind. The updrafts may rise as high as 16 kilometers where the air flows outward to the environment. The source of the storm's energy is heat drawn from the warm sea surface at 28-29°C and returned to the surrounding upper atmosphere at -70°C.

In the center of the hurricane is the cloud-free eye. The clouds that enclose the eye form the eyewall. These clouds draw air from the eye at low levels, causing descent, drying, and warming inside the eye. As the air warms, it becomes less dense so surface pressure must fall. The clouds also draw air inward from outside the eye, thus concentrating the counter-clockwise rotation and increasing the swirling winds. In a hurricane, the strongest winds are near the surface and just outside the eyewall. An unanticipated use of the new GPS sondes was direct observation of low-level wind jets at the inner edge of the eyewall.

As the experience in Hurricane Opal of 1995 illustrates, intensity predictions compare poorly to the skill exhibited by track forecasts. Forecasters at the National Hurricane Center use a half dozen models to guide track forecasts. For intensity forecasting, only one model has been available (until recently) and that was based on climatology and persistence. These rudimentary tools reflect the challenge of forecasting intensity. It is a difficult problem and it is the focus of continuing research. AOML scientists recently developed a more complete statistical hurricane intensity prediction model that includes the effects of variations in sea-surface temperature and upper tropospheric turbulent transports. Although this model is available in real time and has had some success, there is still much to be learned before accurate intensity forecasts become routine.

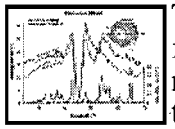


Hurricane Opal's northward careen across the Gulf of Mexico, showing schematically the storm's rapid deepening as a result of interaction with a "digging" mid-latitude trough and it's passage over the deep pool of warm water in an eddy spun off from the Gulf Stream.

A typical hurricane intensifies slowly, remaining in Category 1 or reaching 2 or even 3 before it runs ashore or drifts north out of the tropics. The strongest hurricanes, such as Andrew in 1992, intensify rapidly and go from Category 1 or 2 to Category 4 or 5 in just a day or two. The process that initiates rapid intensification may begin with atmospheric waves that form on the hurricane vortex at altitudes of greater than 12 kilometers (where the new jet will fly). These waves result from interaction with nearby low-pressure systems. The waves, through a complicated chain of cause and effect, intensify the cumulus clouds that are involved in the energy conversion mechanisms of a hurricane.

Shear of the environmental wind appears to be the mechanism by which atmospheric teleconnections modulate Atlantic hurricane activity and is generally thought to have a significant role in day-to-day intensity changes of individual storms. Airborne Doppler and reflectivity radar data collected during AOML research flights into Hurricane Olivia show that an environmental shear > 10 m s^{-1} imposes a wavenumber-one structure on the eyewall convection. Individual cells form ~45 to the right of the down-shear direction, reach maturity with reflectivities > 45 dBZ on the left side of the shear vector, and have largely rained out by the time they detach from the eyewall as they advect back to the right side of the shear. Similar observationally-based synthesis point the way to a more accurate understanding of rapid intensification and ultimately to better forecasting of the intensity of the most dangerous hurricanes.

AOML research has produced accurate, timely maps of surface winds in hurricanes. These maps, which are based upon aircraft observations, are invaluable for preparation of forecasts before landfall and for damage assessment after landfall. The maps are now prepared routinely whenever a hurricane threatens land. A particularly important application of these products is the rapid identification of the most severely devastated areas; this enables disaster response teams to reach them quickly. The same techniques are now being applied for reconstruction of historical storms.



The Stepped Frequency Microwave Radiometer (SMRF) is a promising tool for direct measurement of surface winds. This instrument has flown aboard research aircraft for more than 20 years and has finally matured enough to transition to operations. It works by sensing the increase in apparent

microwave brightness temperature of the water surface caused by more foam as the wind increases. Because rain in the air column between the airplane and the surface also produces a frequency-dependant contribution to the upwelling microwave radiation, the radiometer needs to look at several different frequencies to correct for the precipitation effect and to deduce rainfall rate as a byproduct.

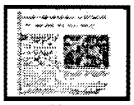
Modification?

Can human intervention diminish the force of a hurricane? From the mid-1960s through the early 1980s NOAA actively pursued Project STORMFURY, a program of experimental hurricane modification. The general strategy was to reduce the intensity of the storm by cloud seeding. The seeding, it was argued, would stimulate the formation of a new eyewall that would surround the existing eyewall. The new eyewall would contract, strangling the old eyewall and reducing the intensity of the hurricane. However, research carried out at AOML showed clearly that these "concentric eyewalls" happened often in unmodified hurricanes, thus casting doubt on the seemingly positive results of seeding in earlier experimentation. Hurricane Luis provides an example of this behavior. Moreover, observations showed that hurricanes contain little of the supercooled water necessary for cloud seeding to work.

The American Meteorological Society policy statement on planned and inadvertent weather modification, dated October 2, 1998, indicates, "There is no sound physical hypothesis for the modification of hurricanes, tornadoes, or damaging winds in general, and no related scientific experimentation has been conducted in the past 20 years." In the absence of a sound hypothesis, no Federal agencies are presently doing, or planning, research on hurricane modification.

Some techniques besides seeding clouds that have been considered over the years include: cooling the ocean with cryogenic material or icebergs, retardation of surface evaporation with monomolecular films, changing the radiational balance in the hurricane environment by absorption of sunlight with carbon black, blowing the hurricane apart with hydrogen bombs, injecting air into the center with a huge maneuverable tube to raise the central pressure, and blowing the storm away from land with windmills. As carefully reasoned as some of these suggestions are, they all fall short of the mark because they fail to appreciate the size and power of tropical cyclones. For example, when hurricane Andrew struck South Florida in 1992, the eye and eyewall devastated a swath 20 miles wide. The heat energy released around the eye was 5,000 times the combined heat and electrical power generation of the Turkey Point nuclear power plant over which the eye passed. Better building codes, wiser land use, and more accurate forecasts seem prosaic compared with environmental mega engineering but they are a great deal cheaper and have overwhelmingly favorable cost-benefit ratios.

Costs and Benefits



Tropical cyclones' impact society through damage to property, expense of safeguarding life and property, human mortality, and the expense of the research and forecasting enterprise. Is the cost of the enterprise justified by reductions in hurricane effects?

Peilke and Landsea's normalization of historical damage provides a reliable estimate of expected annual property loss, $5B. This figure is larger than the $1-3B in damage experienced during most years because a few extreme events figure disproportionally in the total. A single $100B event once a century increases the average annual toll by $1B, as might a single $10B event once a decade.

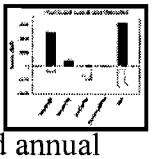
Preparation costs average between $0.5 and $1.0M per mile of shoreline warned. On average, warnings extend 300-400 miles and are raised three times each season. The total warning and emergency response cost is 3x350x$0.75= $787.5M per year.

During the last thirty hurricane seasons of the 20th century, 587 U.S. residents died in hurricanes, or 19.6 annually. In policy calculations, the economic impact of a human death is usually reckoned at $5ñ10M. A dollar value assigned to human deaths is only the beginning of their impact. One must be wary of arguments that might lead to sacrifice of lives to save money. With this qualification, mortality typically contributes 19.6x$7.5M = $146.8M to hurricanes' impact.

The cost of the forecast enterprise is dominated by satellites and the expense of launching them, figured at either a single geostationary satellite or two polar orbiters annually, about $190M. The annual budgets for hurricane work at the Hurricane Center, Hurricane Research Division, Geophysical Fluid Dynamics Laboratory, Environmental Monitoring Center, and other research and forecasting organizations appear to total less than $25M, including aircraft operations.

Thus, a reasonable estimate of the annual average total costs that hurricanes impose on the U.S. economy is just under $6M. What would this impact be without forecasting and emergency preparation?

The amount of damage prevented by warnings is poorly defined. Estimates range from 10% to 50%. The low estimate $500M is equivalent to moderate damage to 10,000 upper middle class suburban homes or destruction of a half dozen first-line commercial airliners. A great deal of expensive property is mobile, and protection of windows and doors raises the wind speed threshold for major damage substantially. The 10% figure seems low. Probably the best, though still conservative, estimate of prevented damage is 20% or $1.0M



During the 40 years between 1930 and 1959, inclusive, 70 people a year died in the U.S. hurricanes. Since 1950, the midpoint of this interval, population in the 109 coastal counties between Texas and Virginia had increased by a factor of 3.4. If the forecaster's art had not improved during the last century, expected annual mortality to this larger population from hurricanes would be 238, with an economic impact of $1785M. By this estimate the stakes of the annual hurricane game are $8.9B, of which $2.8B, or 31%, is prevented through an investment of < $0.22B in forecasting and research, for a greater than twelve to one favorable benefit to cost ratio. The prevented impact is dominated by reduced mortality.

Click here to look at Climate Processes.
Click here to go to the Hurricane Research Division's home page.

Last modified: Tuesday, 24-Jan-00 11:15:10 EDT.
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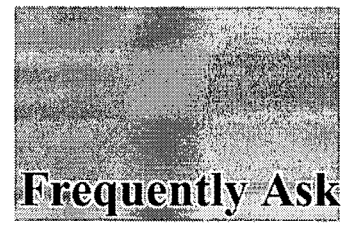
Department of Commerce

NOAA

AOML

The objectives of the Hurricane Research Division are:

To advance basic physical understanding and improve forecasts of hurricanes and of tropical weather genera



Questions Abou Hurricanes

Dr. Chris Landsea and fri commonly asked question typhoons and tropical cyc

Hurricanes and Meteorology

A general summary of th Research Division's areas

HRD Mission C

A listing of HRD flights since 1994 and of the ass

Scientific Projec

Descriptions of the variou experiments and program Principal Investigators.

Hurricane Field

Descriptions, plans, and s HRD's annual field progr

Basin-wide Hur

Tables of information on Atlantic and East Pacific, winds, lowest pressure, g etc..

2000 Hurricane Forecast

NOAA's official forecast activity in the Atlantic ba 2000.

HRD's Hurrican Analyses

Wind analyses from HRD Program. Archived by sto

Synoptic Survei Assessments

Assessment of the operat surveillance missions flow and the P-3 aircraft, and a information used to desig

HRD's Air-Sea Experiments

A list of experiments flow air-sea interactions and h hurricanes.

Interagency and International Pr

Interagency and Internati experiments that HRD ha processed data for.

AOML Local W Data

The on-line records from instruments at the AOML Virginia Key, FL; plus w

Hurricane Shut Information

Pictures and instructions hurricane shutters.

HRD History

A brief synopsis of the hi Hurricane Research Divis

HRD Personnel

Publication listings and b personnel.

WWW Links
World Wide Web links to
concerning hurricanes, tro
storms.

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Anna Richter
06/30/2000 10:56:25 AM

Record Type: Record

To: Kendra L. Brooks/OPD/EOP@EOP

cc:
Subject: POTUS Statement

Bethany asked me to check in with you and see if you can start drafting a statement off of our old press papers on accountability and class size. Do you have time this morning? We need to get it out when the Department releases their paper -- still tbd -- but we should be ready.

Thanks!