

Hurricanes and Tropical Meteorology

India/Australia - Cyclone

Eastern Asia - Typhoon

China Sea – Baguio

North America - Hurricane

Hurricane named for the Carib god of Evil - *Huracan*

Conditions Necessary for the Development of Tropical Storms

- SST at least ~27°C or ~80°F (late summer/early fall)
- Coriolis force; outside of 3-5° latitude (usually between 5° and 25°)
- Very little vertical shear (surface easterlies - upper tropospheric easterlies)
- Temperature relatively constant over large surface areas
- Relatively high mid-tropospheric moisture
- A strong disturbance

Disturbance that lead to tropical cyclone development include decaying extra-tropical systems (MCC's and fronts), waves in the ITCZ and easterly waves, especially North African easterly waves. The African waves account for 85% of major hurricanes in the Atlantic and the Eastern Pacific. Atlantic hurricanes originating directly off the coast of Africa are known as Cape Verde storms.

In a nutshell...

Thunderstorms release large amounts of latent heat which warms the mid- and upper-troposphere. As a result of this heating, air begins to diverge consequently lowering the surface pressure. Surface convergence is enhanced by friction. However, because of the warm waters, the adiabatic cooling as the air crosses the isobars is balanced by conductive heating. A warm core is thus maintained, perpetuating the storm. If there were vertical shear, the heat in the core of the hurricane would be transported away from the center, not allowing further strengthening. Friction therefore balances the storms strength by limiting its intensity but maintaining its fuel supply (latent heat).

Helpful Hurricane Links

A great start!

<http://hurricanes.noaa.gov/>

See this link for FAQ about hurricanes.

<http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html>

This is a great link to view hurricane histories and climatology.

<http://www.nhc.noaa.gov/pastall.shtml>

Here is a more advanced guide to tropical cyclone forecasting.

<http://severe.worldweather.wmo.int/TCFW/>

ENERGY

A body can have kinetic energy or potential energy. These are considered macroscopic properties of a body. However, the total energy of a body can be explained by using the internal energy of a body plus the kinetic and potential energy of the body as a whole. The internal energy of the body is a result of the potential and kinetic energy of the molecules.

One way of looking at this is the rising of a parcel of air within a cumulus cloud. The internal energy of the air parcel increases as result of latent heat transferring heat to the gas. The potential of the parcel is also increased by the lifting of the air. When air radiates to space near the top of the troposphere, it becomes cooler, losing internal energy and subsides, thus causing a loss in potential energy.

The process of the Hadley cell, likewise a hurricane, likens a Carnot engine because it loses energy at a cooler temperature than it gains it back. Therefore, the "engine" protects itself against frictional, or mechanical, dissipation by maintaining itself through the continual transfer of energy from other sources. In the Hadley Cell and the hurricane, this source of energy is sensible and latent heat from the sea.

First Law of Thermodynamics:

A measure of heat transferred into a system will result in an increase in temperature and in the system's ability to do work.

Second Law of Thermodynamics:

Only in transferring heat from a warmer body to a colder body that heat can be converted into work in a cyclical process.

The Tropical Atmosphere

ITCZ (Inter-Tropical Convergence Zone) traditionally defined as the result of the equatorial Hadley cell where air converges near the equator, rises and diverges near the tropopause thereby transporting heat away from the equatorial regions in the upper troposphere. However, for dynamical reasons, the energy budget for the equator would not be met were it not for the additional transport of latent heat by large thunderstorms called **hot towers**.

Observations have noted that the rate of precipitation greatly exceeds the rate of evaporation from the ocean in the vicinity of the ITCZ. The excess precipitation's source is vapor supplied by the converging trade winds, thereby transporting vapor from latitudes where evaporation exceeds precipitation. This indicates that the large scale flow provides the latent heat supply for the convective towers.

The ITCZ is actually a distinct number cloud clusters separated by large areas of clear air. The ITCZ is rarely over the equator but actually in a band extending from 5° to 10°

latitude, known as the meteorological equator. Cloud clusters propagate westward with weak wave disturbances with a period of 4 to 5 days.

Mass continuity dictates that regions of convergence at low levels must give way to divergence at higher levels. The change over from convergence to divergence occurs at the Level of Non-Divergence (LND), that is, the level where the mass divergence is zero. In the tropics, the LND is near 400 mb. Large scale convergence will occur cyclonically while divergence occurs anticyclonically.

As storms develop in the tropics, there is considerable entrainment of relatively dry mid-tropospheric air into the incipient storms. Only a large cluster of cumulonimbus clouds can protect the inner core from evaporational cooling and the resulting negative buoyancy. Large disturbances off of Northern Africa generate sufficient thunderstorm activity to provide these types of storm clusters.

In April, African wave disturbances begin to occur in association with intense surface heating over the Sahara Desert. This gives rise to an easterly jet near 650 mb. These synoptic scale disturbances propagate westward in the cyclonic shear just to the south of the jet core centered near 16° latitude. The average wavelength of these waves is about 2500 km with a period of 3 to 4 days and a maximum amplitude near 650 mb. These waves will continue to be produced through the late fall months resulting in, on average, about 60 waves over North Africa each year. It is currently 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. However, these convectively-induced waves generated off of Africa are responsible for much of the tropical storm activity in the Pacific as they continue west past the North American continent.

CISK (Conditional Instability of the Second Kind)

There are many phenomena in the atmosphere where the large scale flow fields help develop smaller scale convection and, in turn, the convection helps drive the larger scale circulations. This cooperative interaction between the cumulus convection and a larger-scale perturbation leads to unstable growth of the system. This is known as CISK.

Out of the many tropical depressions that develop each year, only 10% intensify. Therefore the mechanism which drives the development of the storm must be rare. Under favorable moisture supply, the CISK mechanism leads to rapid development of the hurricane. Whereas friction usually *dissipates* energy, in the development of a tropical storm, friction plays an energy *producing* role. Despite the kinetic energy loss due to frictional convergence in the boundary layer, it is the friction that leads to increased moisture convergence. Latent heat enters the atmosphere and is released in the cumulus clouds. This produces enough energy to partially or completely compensate for the energy loss due to friction.

TOWARD A GENERAL THEORY OF HURRICANES

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Most other storms arise from linear instability of time-averaged state of the atmosphere, where small perturbations amplify. Extra-tropical cyclones develop from *baroclinic* instability where a small disturbance amplifies as temperature advection changes the pressure field. The small convective clouds common in the tropics are a result of similar linear instability but the structure of the larger storms is a result from large ongoing systems. In fact, small disturbances in the tropics rarely strengthen at all. As a result, a large reservoir of potential energy of tropics lays untapped much of the year.

The maritime tropical atmosphere is a balance of turbulent fluxes of sensible and latent heat from the sea surface, cooling of the atmosphere by infrared radiation to space, transport of heat, moisture, and momentum by cumulus clouds, and horizontal and vertical transport by large-scale atmospheric motions.

The tropics can be divided into four regions:

Region 1: Cumulus towers pump latent heat high into the (cold) upper troposphere.

Region 2: Dry air subsides from Region 1 which establishes the trade inversion.

Region 3: Towering cumulus clouds in the lowest 1-3 km meet the capping inversion.

Region 4: The air in this subcloud layer (~500m) has relative humidities between 75 and 80%.

The CISK-like driving mechanism is not responsible for the tropical atmosphere's motions. The large circulation is driven by the large temperature differences between Regions 2 and 3 and Region 1 set up by the SST gradient. In other words, the circulation is driven by changes in density because associated with differences in water temperature, which drive the circulation. The latent heat associated with the large cumulus convection has more to do with maintaining the convective motions than maintaining the entire Hadley Circulation.

The idea of cloud clusters, or "organized convection" was originally thought to tap into the reserve of potential energy and so it is mistakenly assumed that this is the cause of hurricanes. The actual energy source for hurricanes lies in the difference between the water and the subcloud layer. Adding heat to this "engine" allows for an increase in entropy and an ability for heat to be converted into work, or mechanical energy. In a hurricane the steady-state is the production of mechanical energy used to balance the frictional dissipation.

The hurricane must then be started by a strong enough disturbance which will amplify in the tropical environment. Tropical cyclones do not develop spontaneously in the tropical atmosphere. Otherwise tropical cyclones would occur frequently. Whatever the mechanisms resulting in tropical cyclone formation, the Carnot heat engine is a good way

to understand how the system maintains itself and strengthens. Work is done to balance frictional dissipation by the acquisition of heat at a high temperature and a deposit of heat at a low temperature.

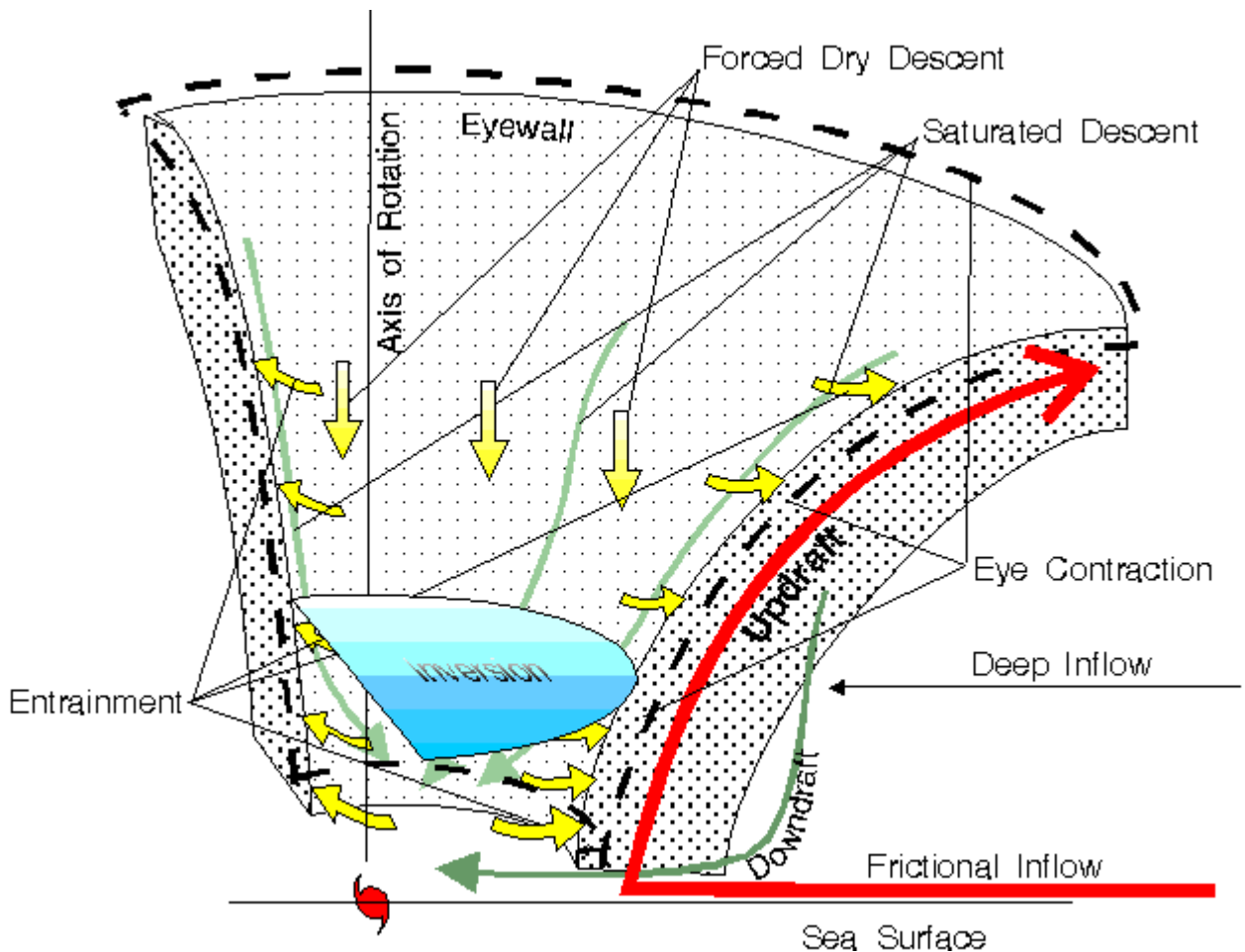
Emanuel posits this hypothesis: *A necessary and sufficient condition for the onset of tropical cyclone intensification is the presence of a mesoscale (order 100 km) region of nearly saturated air through the lower and middle troposphere. If this turns out to be true, then we can define genesis as the ignition point at which the Carnot cycle is turned on, which happens when downdrafts in the core become sufficiently weak.*

The Hurricane's Structure and Eye

The eye of the hurricane is the "calm in the middle of the storm" where skies are relatively clear and winds subside to near calm in its center. Temperatures are often several degrees warmer than the surrounding eye wall, especially at higher levels of the storm. This warmth is explained from the fact that subsidence from storms in the eye wall will result in adiabatic warming which also creates a strong inversion which suppresses convection. Soundings taken within the eye exhibit a layer of warm and moist conditions from the surface to around 1-3 km and beneath the inversion.

The eye typically forms as the intensity of the storm increases. Although the exact method of eye formation is not well-understood, two mechanisms are probably most significant. Keep in mind that strongly rotating fluids may universally result in an eye (e.g. tornadoes, dust devils, hurricanes, etc...) The winds converging and rotating around the center of the storm can no longer be forced toward the center due to the law of the conservation of angular momentum where speeds would quickly rise to supersonic speeds. Consequently, the air will rise before it gets to the exact center. The eye wall which surrounds the eye contains the most turbulent conditions and the most intense thunderstorms. Convection in tropical cyclones is organized into long, narrow rainbands that converge towards the center of the storm, known as spiral bands. Subsidence on both sides of the bands contributes to clearing within the eye. This subsidence, along with that of the centrifuging effect, contributes to the development of the eye, although which of the two predominates is unknown.

Some tropical cyclones intensify and develop two or more concentric eyewalls surrounding the circulation center of the storm. As the inner eyewall forms, convection surrounding the eyewall can organize into distinct rings. With additional subsidence from the outer eyewall, the inner eyewall weakens as the outer eyewall becomes the dominant feature. When the inner eyewall dissipates, pressures rise slightly and are only partially compensated by the more rapid pressure falls associated with the intensification of the outer eyewall. The cyclone itself can weaken for a short period of time before often restrengthening. Eyes range in size from 5 miles to over 120 miles across, but most are approximately 20-40 miles in diameter



Schematic illustration of the secondary flow around the eye of a hurricane. The frictional inflow feeds the buoyancy-driven primary updraft and outflow in the eyewall cloud. Saturated convective downdrafts in the eyewall and the evaporatively driven descent along the inner edge of the eyewall feed moist air into the volume below the inversion surface. Dynamically driven descent of dry air inside the eye warms the air column adiabatically. The descent is forced as entrainment into the eyewall draws mass from the bottom of the eye into the eyewall. Balance between moist-air production and loss by entrainment determines the rate of rise or fall of the inversion. (From Atlantic Oceanographic and Meteorological Laboratory (AOML) web site, <http://www.aoml.noaa.gov/>)

The **storm surge** is the most deadly and destructive part of a hurricane. For every 1 mb drop of atmospheric pressure, the sea level rises 1 cm. Coupled with strong on-shore winds (which dominates storm surge formation), and the "sloshing" effect, the level of the sea can raise several meters, inundating the shore with a wall of water and several meters higher with enormous waves. Coastal flooding is a serious problem which can be exacerbated if a hurricane hits at high tide.

The Dvorak technique is a methodology to get estimates of tropical cyclone intensity from satellite pictures. The scheme utilizes the difference between the temperature of the warm eye and the surrounding cold cloud tops. The larger the difference, the more intense the tropical cyclone is estimated to be. Maximum wind speeds based upon the Dvorak technique alone are prone to some error due to local condition variability. Also, wind speed is not solely a function of the pressure gradient. Since the hurricane is in gradient wind balance, the radius also contributes to the speed of the hurricane's winds.

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. 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.

Conversions

1 mile per hour = 0.864 knot

1 mile per hour = 1.609 kilometers per hour

1 mile per hour = 0.4470 meter per second

1 knot = 1.853 kilometers per hour

1 knot = 0.5148 meter per second

1 meter per second = 3.6 kilometers per hour

1 inch of mercury = 25.4 mm of mercury = 33.86 millibars

1 nautical mile = 1.1515 statute miles = 1.853 kilometers

What will happen with respect to tropical storms if there is global warming?

From <http://www.aoml.noaa.gov/hrd/tcfaq/G3.html>

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.