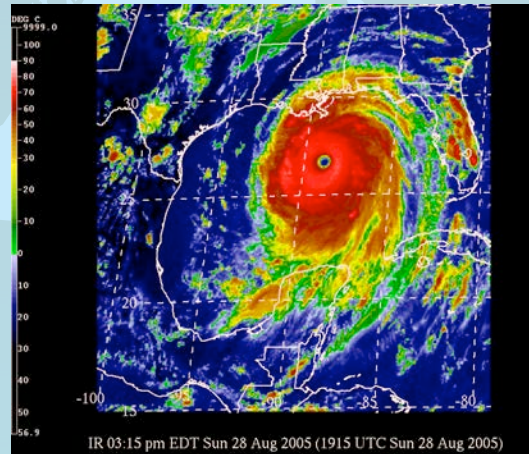


MET 200 Lecture 15 Hurricanes

Structure and Climatology

- What is the structure or anatomy of a hurricane?
- How to build a hurricane?
 - hurricane energy
- Hurricane climatology - when and where



Hurricane Katrina

1

Last Lecture: Atmospheric Optics

The amazing variety of optical phenomena observed in the atmosphere can be explained by four physical mechanisms.



• Scattering • Reflection • Refraction • Diffraction

2

Colorado Flood Damage



3

Hurricanes: Useful Websites

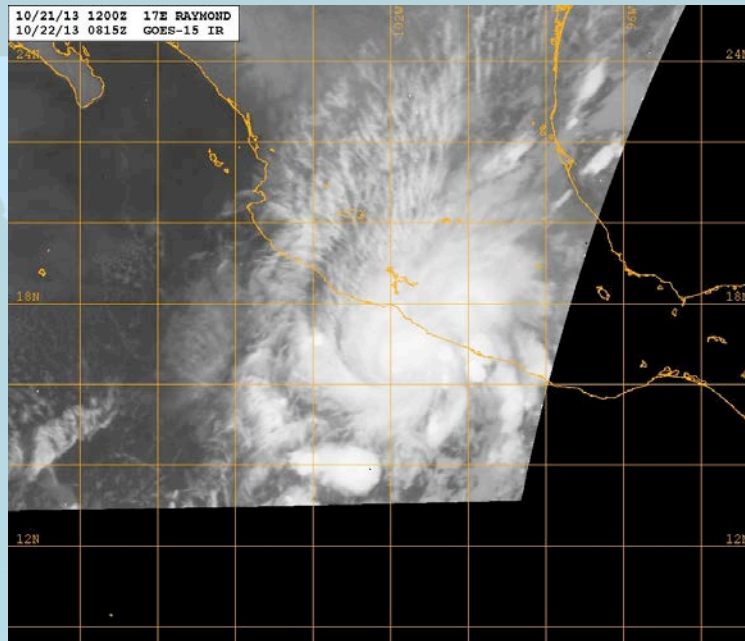
<http://www.wunderground.com/hurricane/>
http://www.nrlmry.navy.mil/tc_pages/tc_home.html
<http://tropic.ssec.wisc.edu>
<http://www.nhc.noaa.gov>



Hurricane Alberto
Hurricanes are much broader than they are tall.

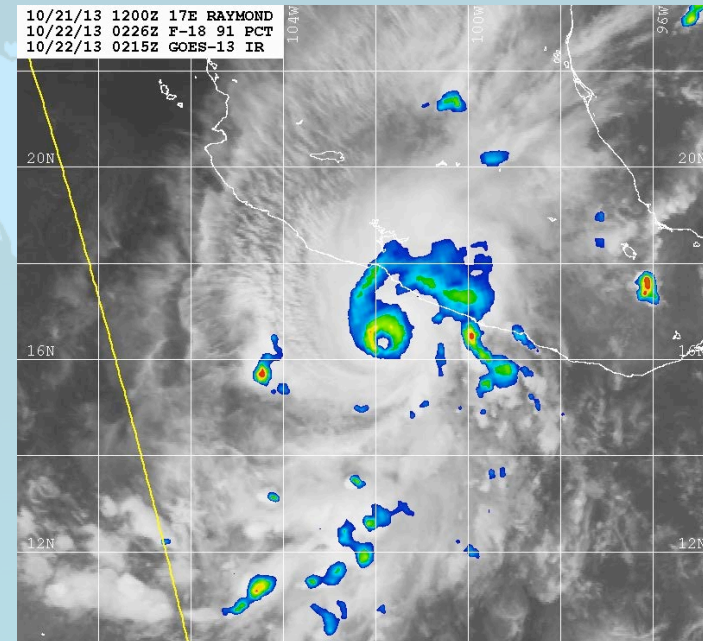
4

Hurricane Raymond



5

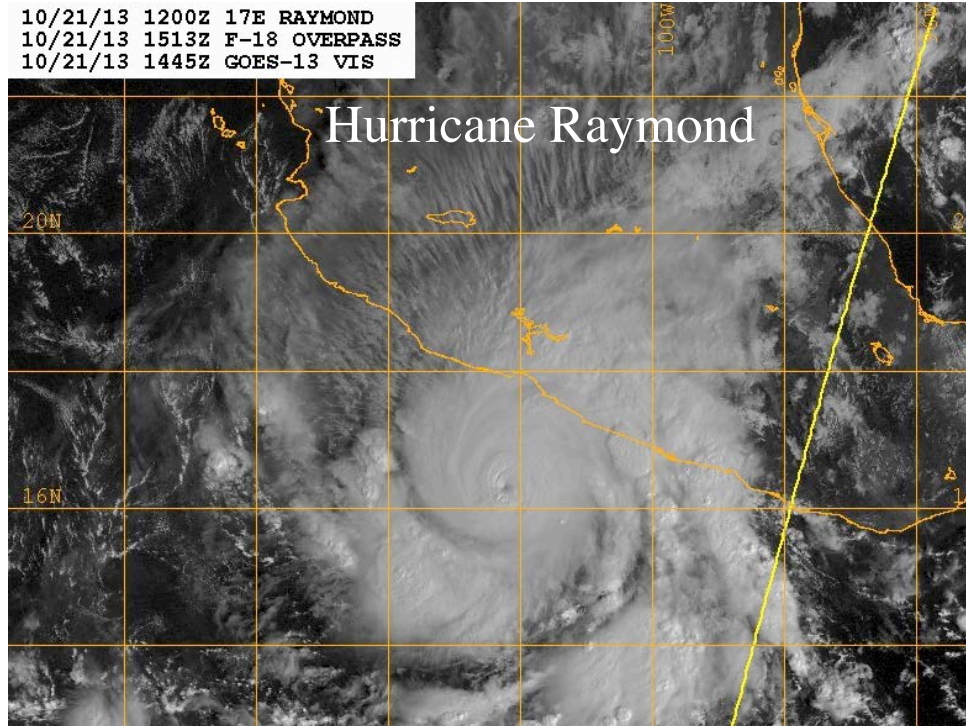
Hurricane Raymond



6

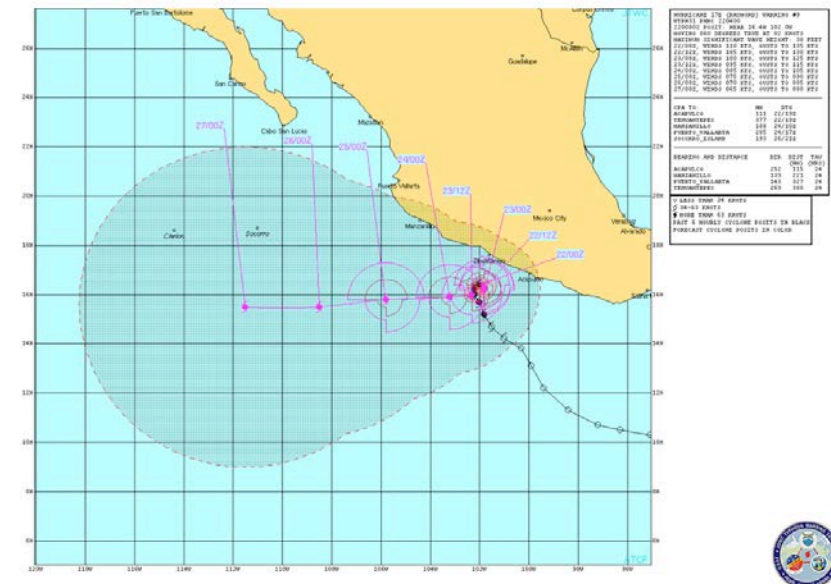
10/21/13 1200Z 17E RAYMOND
10/21/13 1513Z F-18 OVERPASS
10/21/13 1445Z GOES-13 VIS

Hurricane Raymond



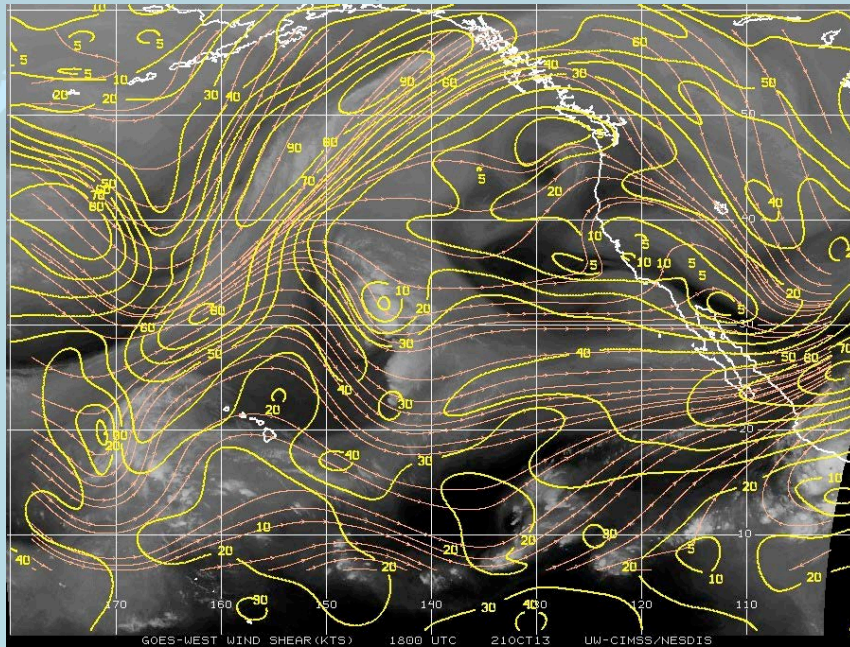
7

Hurricane Raymond



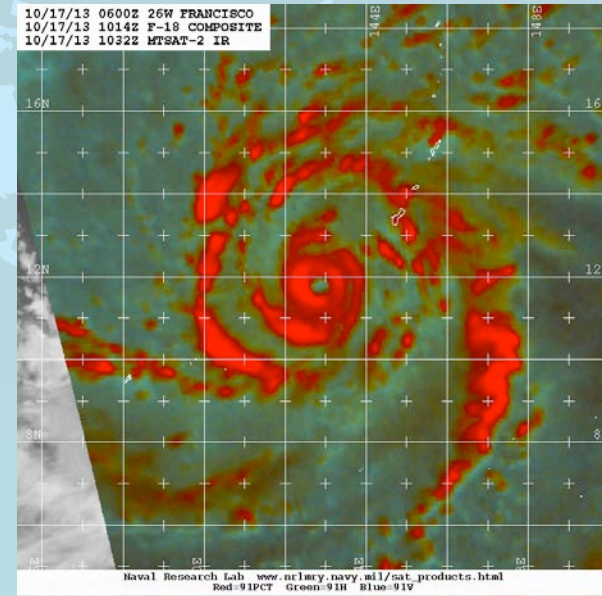
8

Hurricane Raymond: wind shear



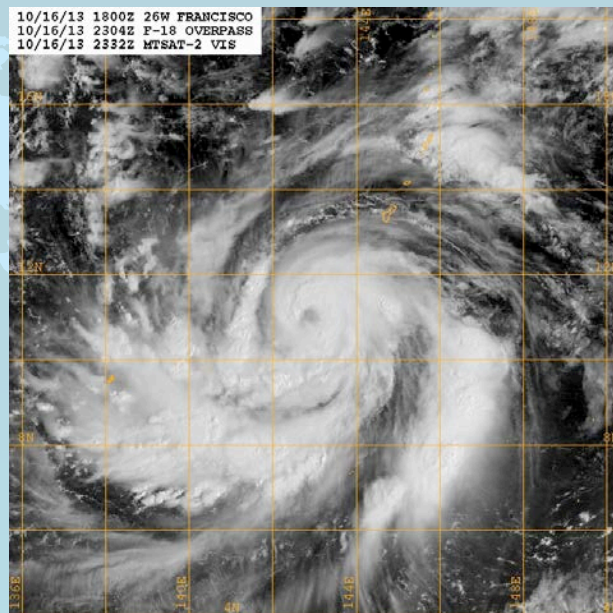
9

Typhoon Francisco



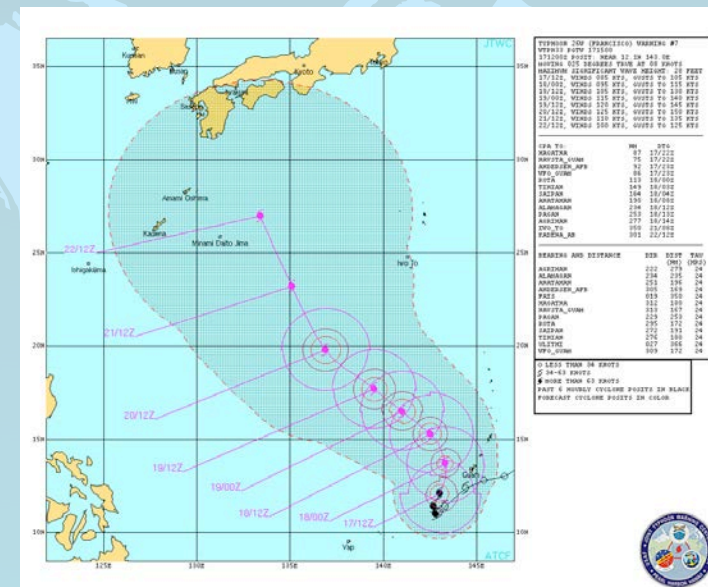
10

Typhoon Francisco



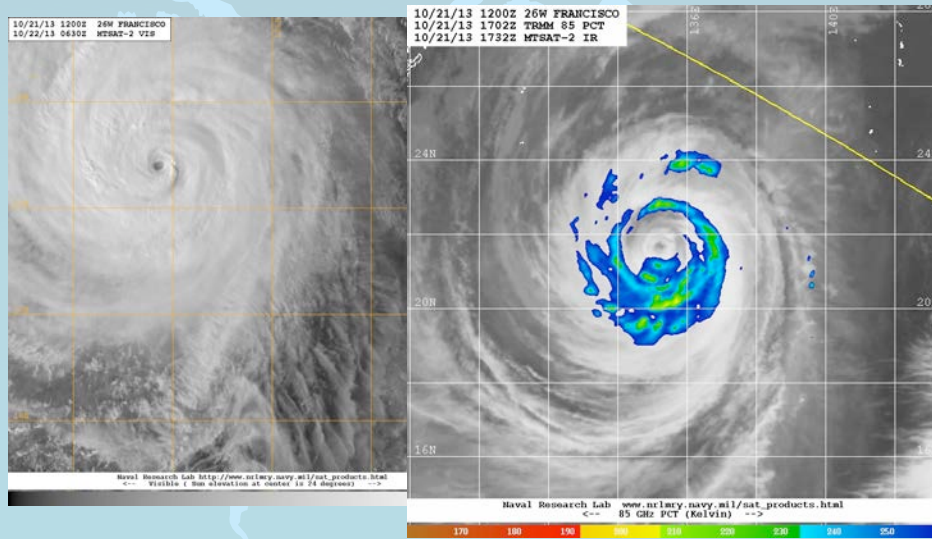
11

Typhoon Francisco



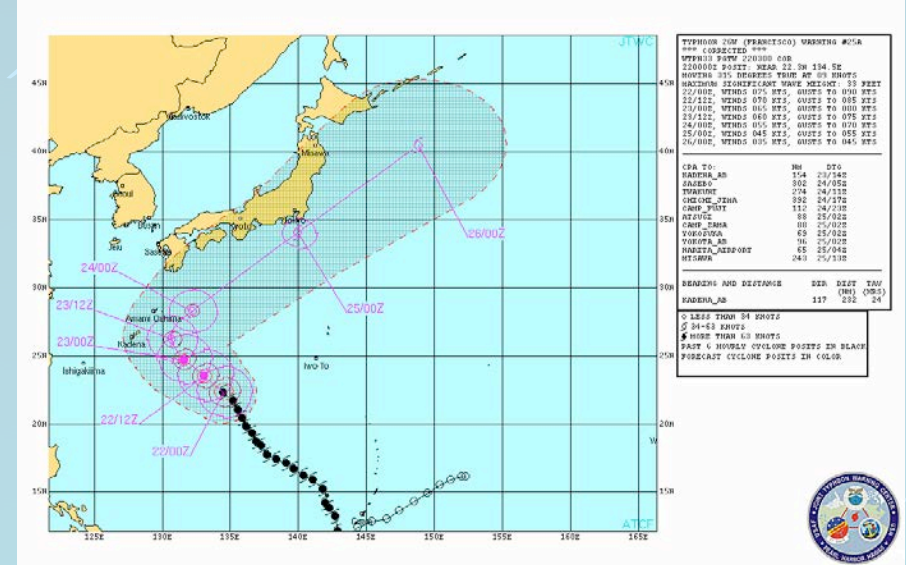
12

Typhoon Francisco



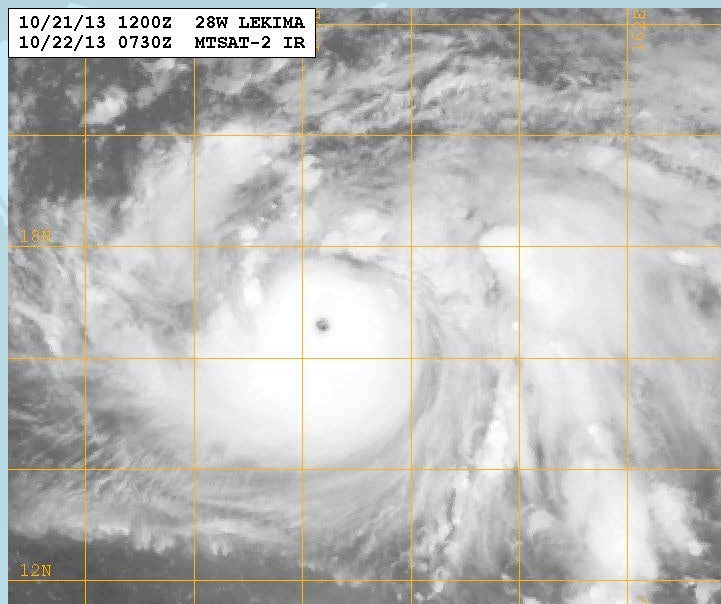
13

Typhoon Francisco



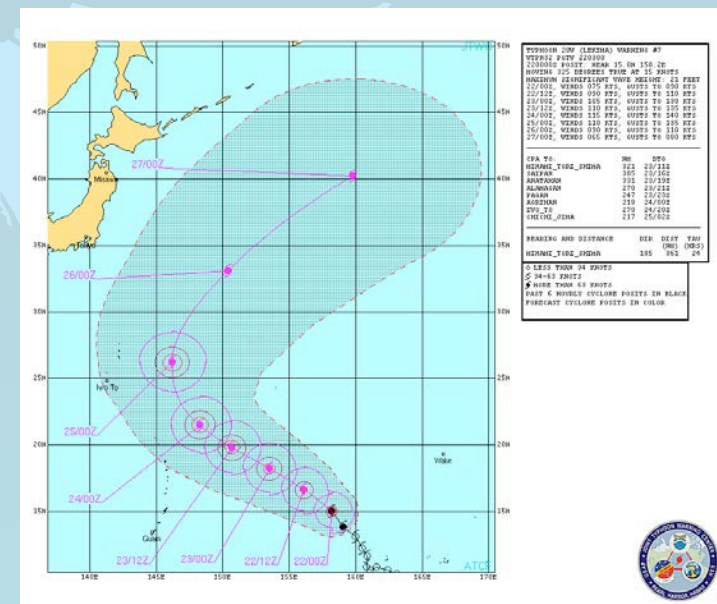
14

Typhoon Lekima



15

Typhoon Lekima

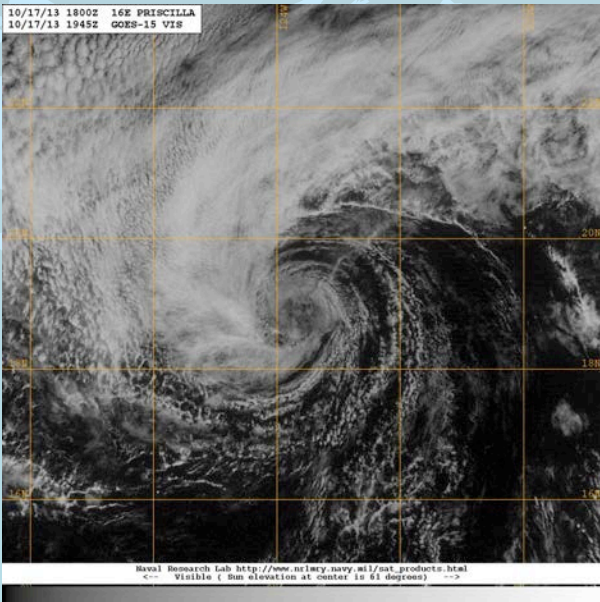


16

Typhoon Lekima

10/21/13 1200Z 28W LKIMA
10/21/13 2202Z F-18 91 PCT
10/21/13 2232Z MTSAT-2 VIS

Hurricane Priscilla



10/17/13 1800Z 16E PRISCILLA
10/17/13 1945Z GOES-15 VIS

Naval Research Lab http://www.nrlmry.navy.mil/mat_products.html
Visible (Sun elevation at center is 51 degrees)

This satellite image shows Hurricane Priscilla as a well-defined cyclone with a clear eye and dense, swirling cloud bands. The image is overlaid with a yellow grid. The background features a light blue map of the Pacific Ocean with the outlines of North and South America visible on the left and right sides, respectively.

Hurricane Priscilla

TROPICAL DEPRESSION TEN (PRISCILLA) WARNING #11
 *** FINAL WARNING ***
 0700Z 19 OCT 1976
 170000Z POSIT WIND 15 7M 120 KM
 MISSING 185 DEGREES TRUE 80 02 HOURS
 MAXIMUM SIGNIFICANT WAVE HEIGHT 6 FEET
 17/00Z WINDS 015 KTS, WAVES TO 015 FTS
 17/12Z WINDS 015 KTS, WAVES TO 015 FTS
 18/00Z WINDS 010 KTS, WAVES TO 010 FTS
 18/12Z WINDS 010 KTS, WAVES TO 010 FTS
 19/00Z WINDS 010 KTS, WAVES TO 010 FTS

○ LESS THAN 34 KNOTS
 ⚡ 34-43 KNOTS
 ● MORE THAN 43 KNOTS
 PART 6 HURRICANE CYCLONE PATHS IN BLACK
 FORECAST CYCLONE PATHS IN COLOR

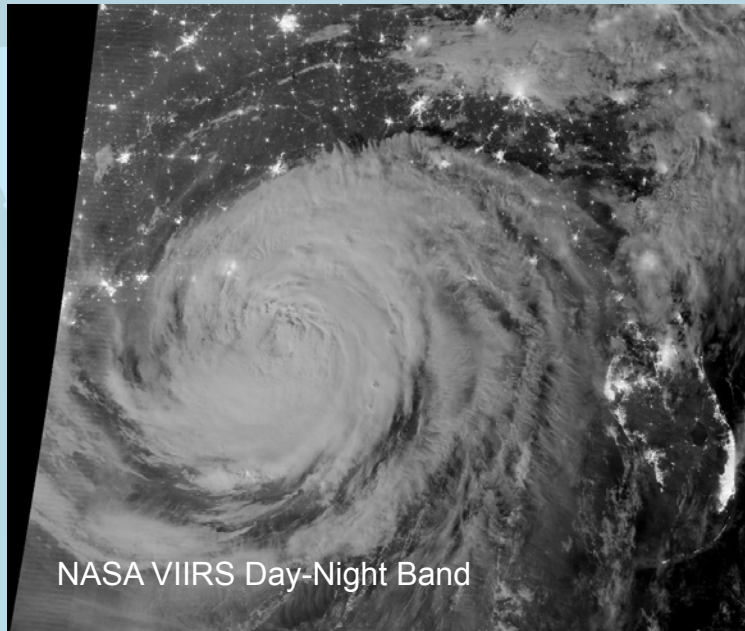
Hurricanes are Tropical Cyclones



Hurricanes are a member of a family of cyclones called **Tropical Cyclones**. West of the dateline these storms are called **Typhoons**. In India and Australia they are called simply **Cyclones**.

20

Hurricane Isaac: August 2012

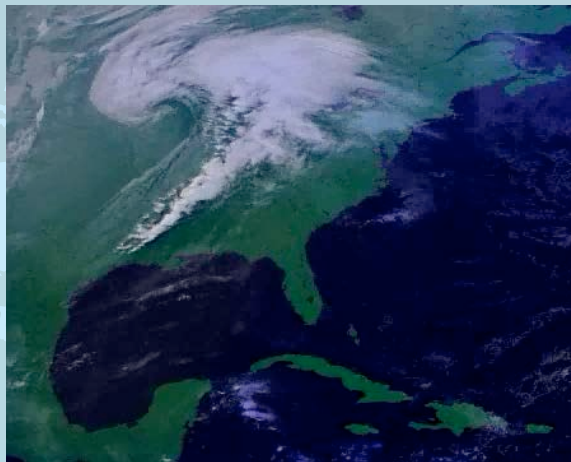


21

Characteristics of Tropical Cyclones

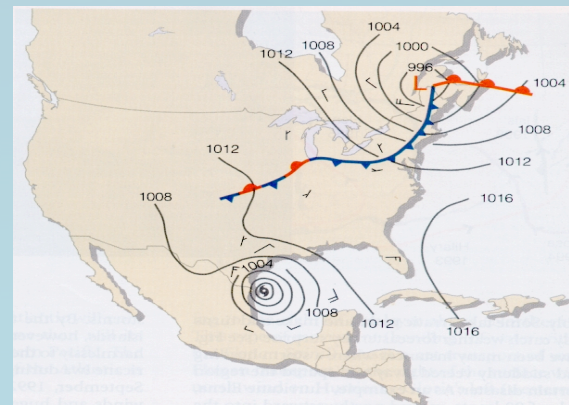
- Low pressure systems that don't have fronts
- Cyclonic winds (counter clockwise in Northern Hemisphere)
- Anticyclonic outflow (clockwise in NH) at upper levels
- Warm at their center or core
- Wind speeds decrease with height
- Symmetric structure about clear "eye"
- Latent heat from condensation in clouds primary energy source
- Form over warm tropical and subtropical oceans

22



- Differences between hurricanes and midlatitude storms:
- Winter storms have cold and warm fronts (asymmetric).
 - Occur in the middle and high latitudes (30° - 60° latitude).
 - Winter storms are generally larger than tropical cyclones.

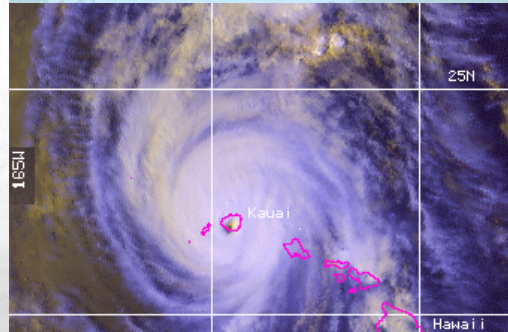
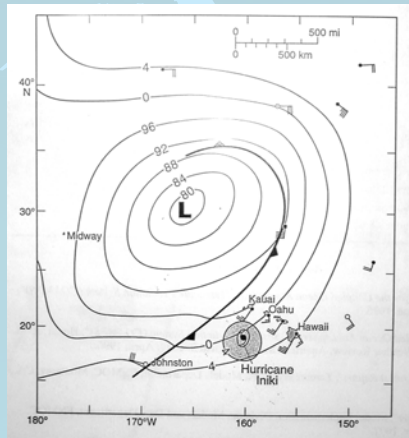
23



- Differences between hurricanes and midlatitude storms:
 - energy source (latent heat vs temperature gradients)
 - vertical structure (warm vs. cold core lows; hurricanes decay with height: no jet stream aloft over hurricanes).
 - horizontal structure (fronts vs. no fronts; horizontal scale)

24

A Question of Size



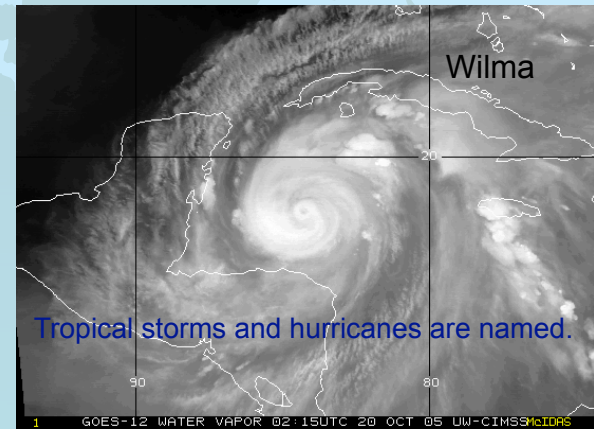
1980 Winter Storm vs. Hurricane Iniki,
2 PM HST on September 12, 1992

25

Tropical Cyclone Life Cycle

Stages of storm development

1. Tropical Depression: surface wind < 39 mph (33 kt)
2. Tropical Storm: $39 \leq$ surface wind \leq 74 mph (64 kt)
3. Hurricane: surface winds > 74 mph (65 kt)

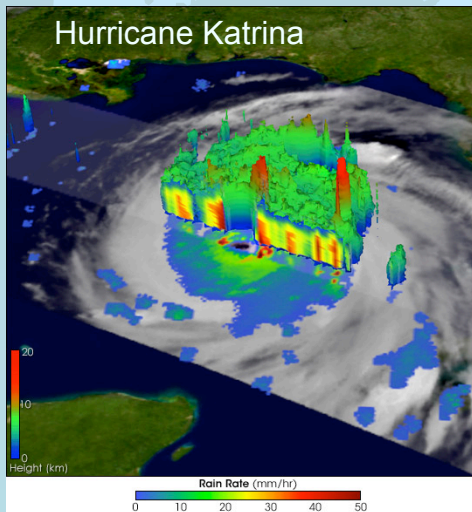


Tropical storms and hurricanes are named.

26

Anatomy or Structure

Basic structure includes spiral rainbands and a concentric eye wall that surrounds a clear eye.



27

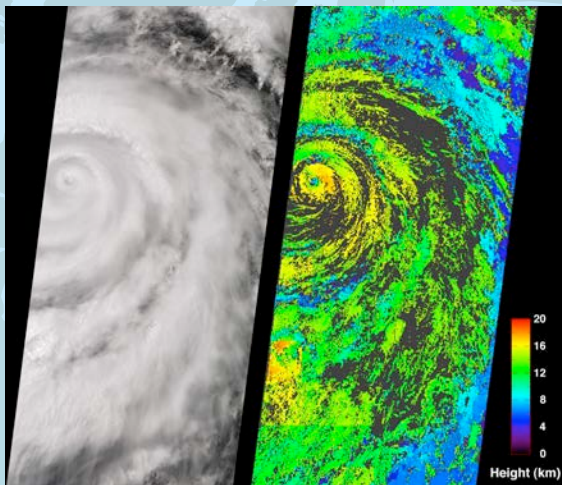
Hurricane Structure



Hurricane Alberto
Hurricanes are much broader than they are tall.

28

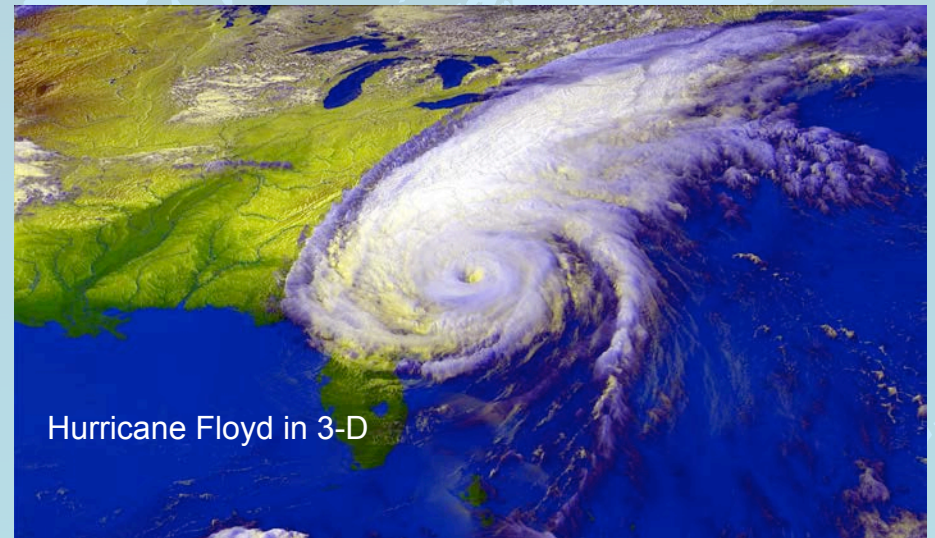
Satellite Derived Cloud Height



Infrared temperature of clouds used to estimate their height.

29

Hurricane Structure



30

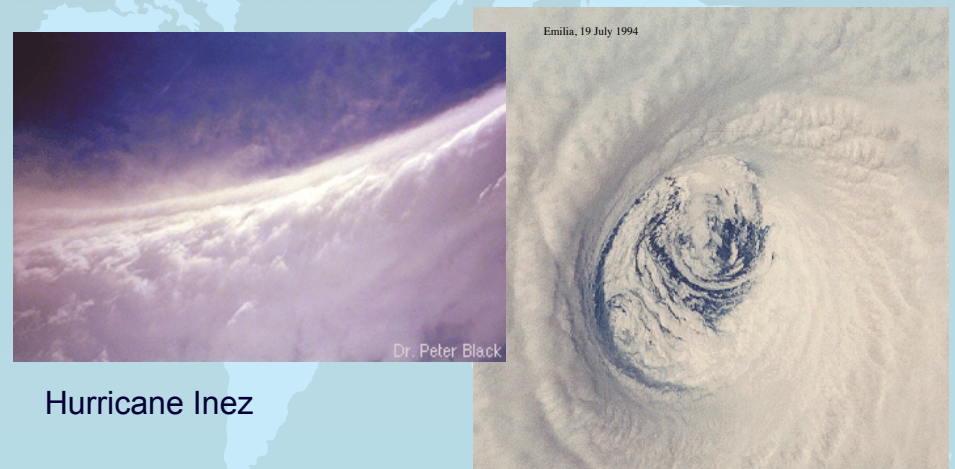
Structure in Hurricane Katrina



Inside the Eye Wall

31

Hurricane Structure

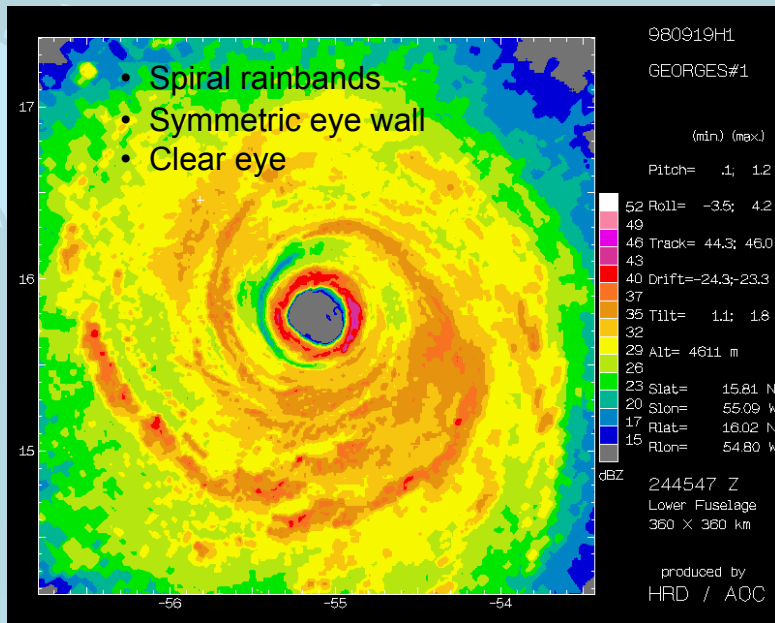


Hurricane Inez

Note the stadium structure of the eye.

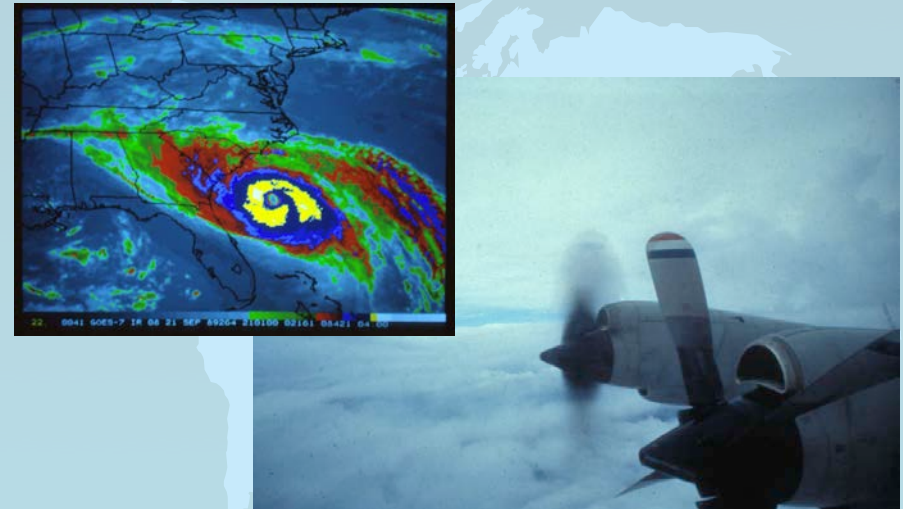
32

Radar Observations



33

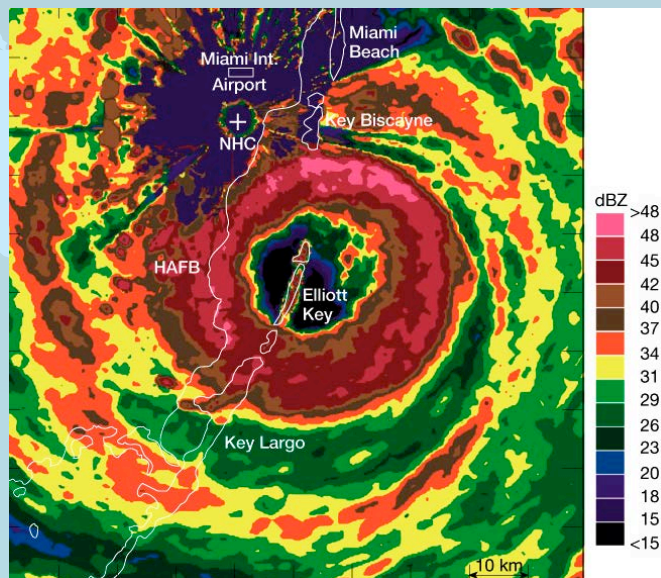
Hurricane Hugo



What's wrong with this photo?

34

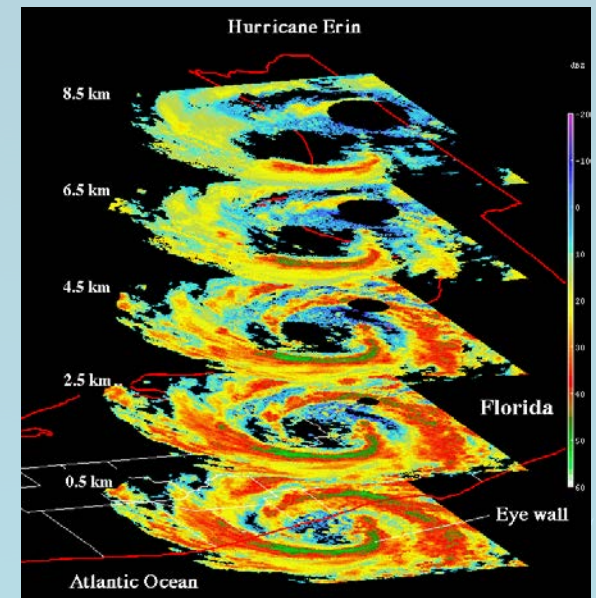
Radar Observations of Andrew



35

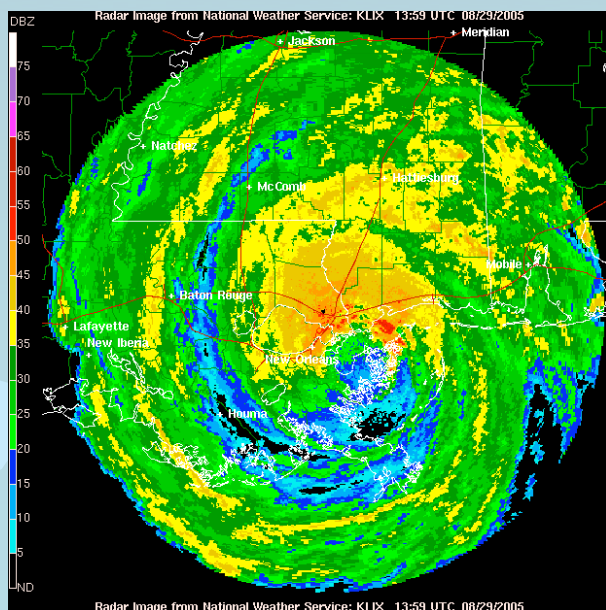
Hurricanes weaken with height

Structure in the rainfall
seen in radar data.



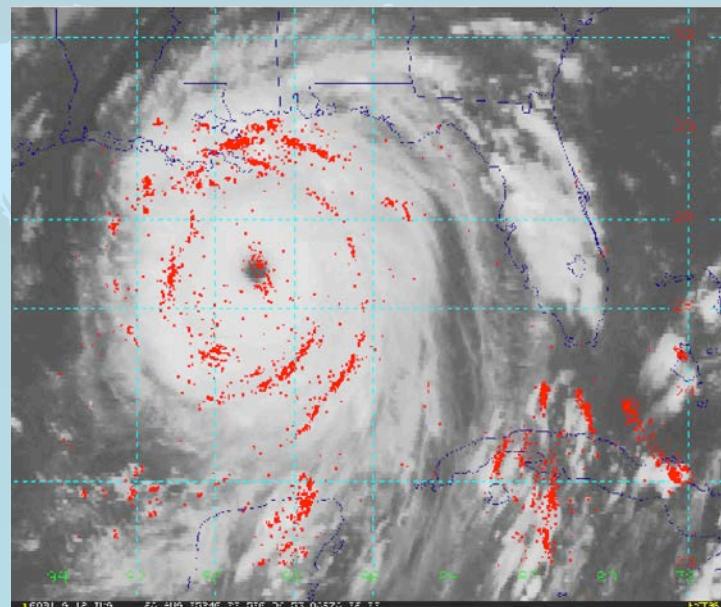
36

Katrina at Landfall



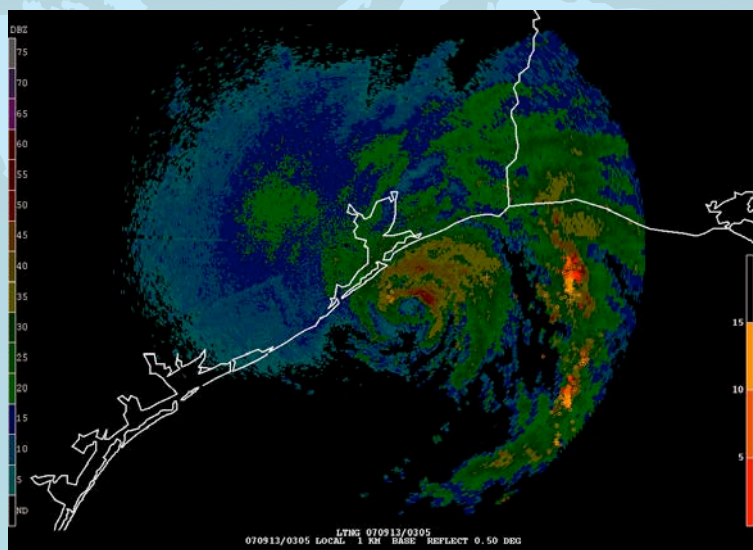
37

Lightning Strikes in Katrina



38

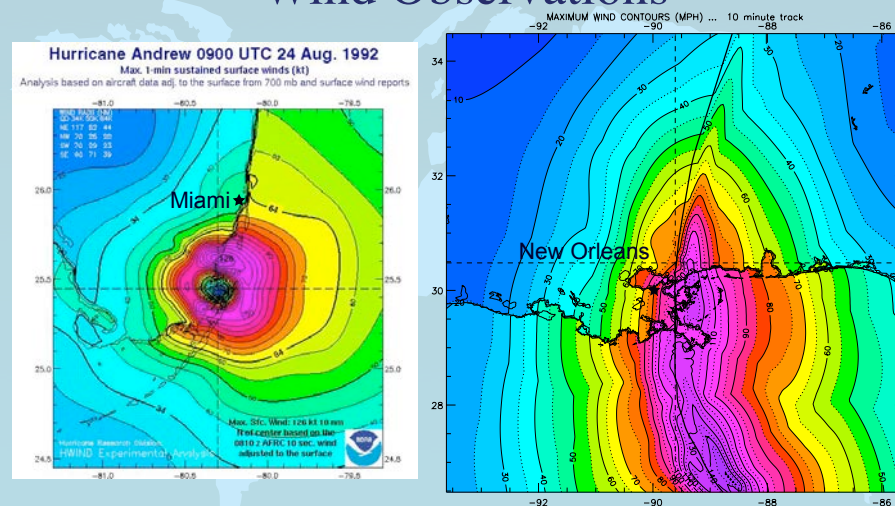
Shedding Light on Storms



Hurricane Humberto – September 2007

39

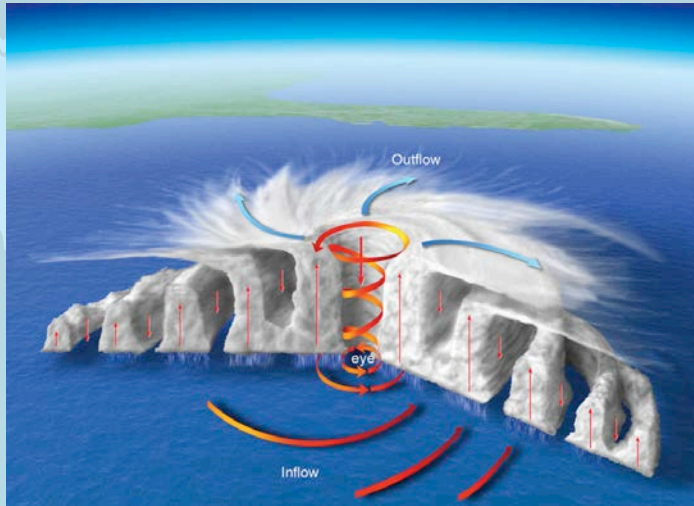
Wind Observations



Wind distributions in Andrew (at single time) and Katrina (wind history - winds weaken inland)

40

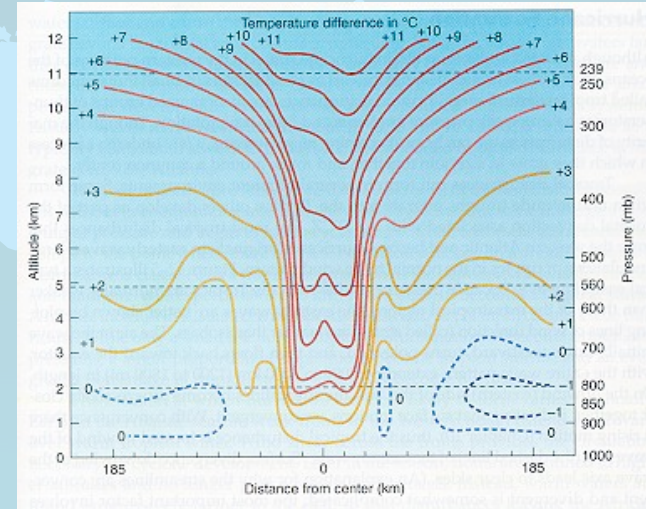
Hurricane Anatomy/Structure



- Hurricanes are “Warm-Core Lows”
Note where rising and sinking motion occurs.

41

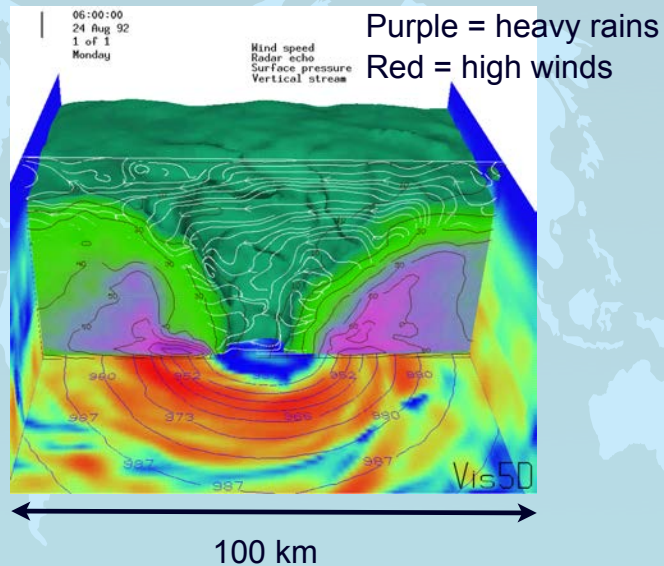
Hurricane Anatomy/Structure



- Hurricanes are “Warm-Core Lows”

42

Model of Hurricane



43

Hurricane Energy Source

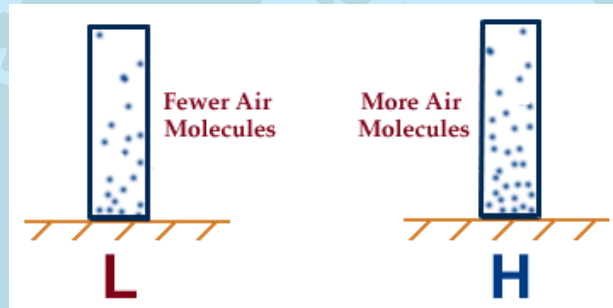
Latent Heat released when Water Vapor condenses in clouds is the Key

- Hurricanes (a.k.a. Typhoons, Tropical cyclones) are giant engines that convert heat into wind energy.
- Consider a rain rate of 2 inches per day over an area of 300 mi radius (typical for tropical depression, tropical storm, and hurricane)
- Over a 7 day lifecycle, the energy released is equal to 50,000 1 MT nuclear explosions!
- This is equivalent to the total explosive yield of the nuclear arsenals of the US and USSR at the height of the Cold War!

44

To Build a Hurricane

Since pressure is the weight of the air, the atmosphere must concentrate warm, moist air over one place to create very low pressure at sea level.



Warm air molecules move faster and take up more space resulting in lower sea-level pressure.

45

Hurricane Energetics

- Tropical cyclones are rare
- Roughly 80 per year worldwide
- Assume a one week life span
- Result – 1-2 storms any day in an area half the surface area of the planet
- Reason – you need to bring 5 prerequisites together to produce a storm

46

How to Build a Hurricane: Five Requirements

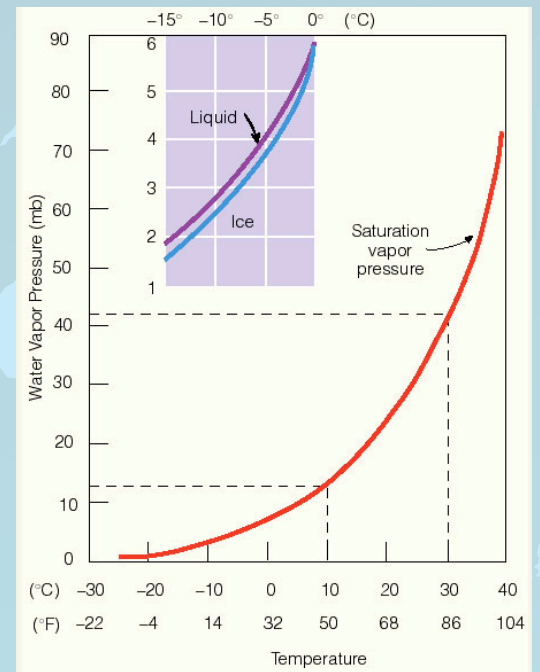
To build a hurricane the atmosphere must concentrate warm, moist air over one place.

1. Warm ocean water with a temperature $> 80^{\circ}\text{F}$.
2. An area of low pressure.
3. Thunderstorms – deep moist unstable air.
4. Little wind shear (change in the wind speed or direction with height).
5. Genesis must occur $\geq 3^{\circ}$ from Equator.

47

Saturation Vapor Pressure

Due to the nonlinearity of the Clausius Clapeyron equation, dw_s/dT increases with T . Only for temperatures above a threshold value of $\sim 26.5^{\circ}\text{C}$ is the rate of increase strong enough to support the development of tropical cyclones.



48

Prerequisites for Hurricane Formation

1. Warm ocean water with a temperature $> 80^{\circ}\text{F}$ (26°C) to a depth of $\sim 50\text{ m}$, so that cooler water cannot easily be mixed to the surface by winds. (Deep thermocline)
2. A pre-existing disturbance with cyclonic circulation (large low-level vorticity) persisting $> 24\text{ hrs}$. As the air in the disturbance converges, angular momentum is conserved and the wind speed increases.
3. Small wind shear or little change in the wind speed or direction with height in the vicinity of the developing storm. ($dv/dz < 10\text{ m/s}$ from 850-200 mb)
4. Unstable troposphere characterized by enhanced thunderstorm activity. $\text{CAPE} > 1000$ (Final CAPE in eyewall rather modest.)
5. Large relative humidity in the middle troposphere (no strong downdrafts). Moist air weighs less than dry air, contributing to lower surface pressures.

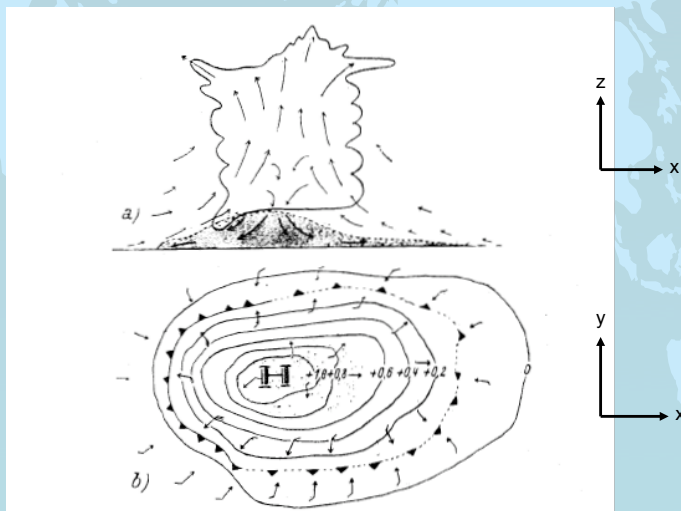
49

Convective Instability of the Second Kind (CISK)

- Convective available potential energy (CAPE) leads to rising motion / increase in moisture content. Rising air condenses, releases lots of latent heat.
- Latent heating aloft leads to high pressure and divergence aloft (organizes the large scale circulation)
- Divergence aloft leads to lower surface pressure.
- Lower surface pressure increases surface convergence.
- Moisture flux leads to larger CAPE.
- Rotation serves to organize flow.
- CISK assumes significant CAPE exists in hurricanes. Analysis of sounding data show this is not the case.

50

Diagram from Bergeron, QJRMS, 1954



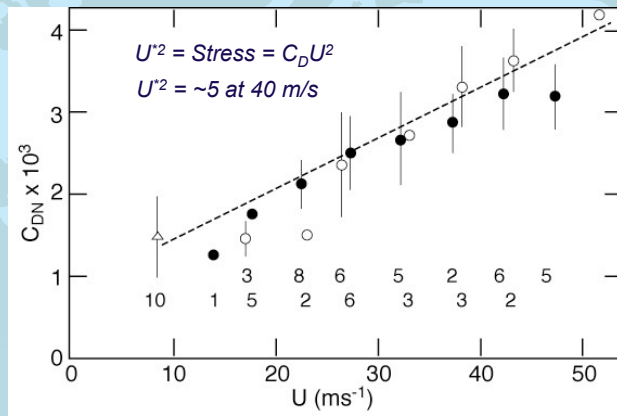
51

Air-sea Interaction Instability

- Surface convergence leads to rising motion / increase in moisture content.
- Rising air condenses, releases lots of latent heat.
- Latent heating aloft leads to high pressure and divergence aloft (organizes the large scale circulation)
- Divergence aloft leads to lower surface pressure.
- Lower surface pressure increases surface convergence.
- Stronger surface winds increase ocean-air moisture flux.
- Rotation serves to organize flow.
- This theory relies on a non-linear increase of surface fluxes associated with increasing surface wind speeds.

52

Estimation of Momentum Flux



Mean values of the neutral drag coefficient as a function of windspeed at a 10-m height. The dashed line refers to Charnock's relation with $n = 0.014$. After Garratt (1977).

53

Elegant Example of Carnot Heat Engine

Total entropy per unit mass of air

- $$s = C_p \ln T + \frac{L_v W}{T} - R \ln p$$

C_p heat capacity
 L_v latent heat of vaporization of water
 R gas const.
 W mixing ratio = mass of vapor/mass of dry air
 $T+P$ temp+press.
 S is conserved except by sfc Fluxes + radiation

In hurricanes entropy gain occurs at relatively high temp (26-30 C), loss occurs at much lower T (-60- -80 C). Carnot theorem- the thermodynamic efficiency of the heat engine is:

- $$\varepsilon = \frac{T_s - T_0}{T_s}$$

T_s = temp at which heat is added (SST)
 T_0 = temp. of loss (T_{strat})

Total mechanical energy available is

- $$E = \varepsilon T_s (S_c - S_a)$$

S_c = entropy at center
 S_a = entropy of far environment

54

Elegant Example of Carnot Heat Engine

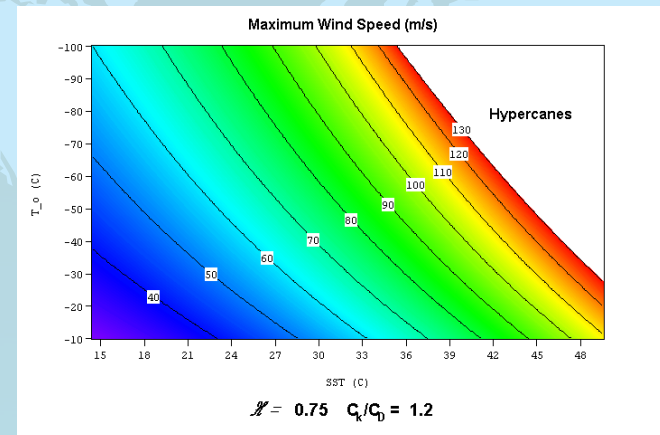
Maximum available energy may be used to calculate the central pressure of the nature of the storm

- $$-\int_c^a \alpha dp = \varepsilon T_s (S_c - S_a) \quad \text{using} \quad \alpha = \frac{RT}{p}$$
- $$RT_s \ln \frac{P_c}{P_a} = -\varepsilon T_s (S_c - S_a)$$

By requiring the surface air at the eye to achieve saturation wrt water, a lower bound on P_c can be determined from (5).

55

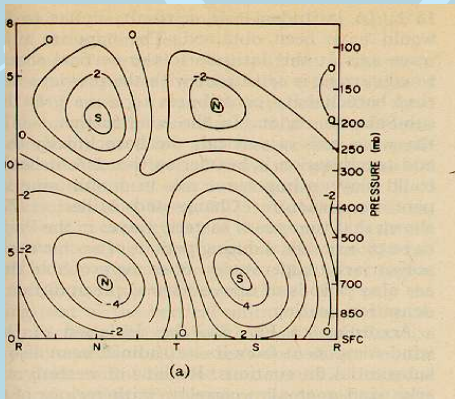
Hurricane Energy Source



Relationship between sea surface temperature, temperature at hurricane anvil outflow and maximum wind speed.

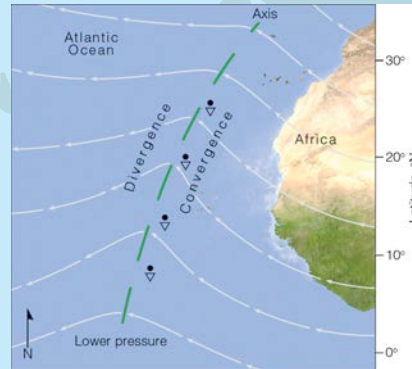
56

Prerequisites for Hurricane Formation



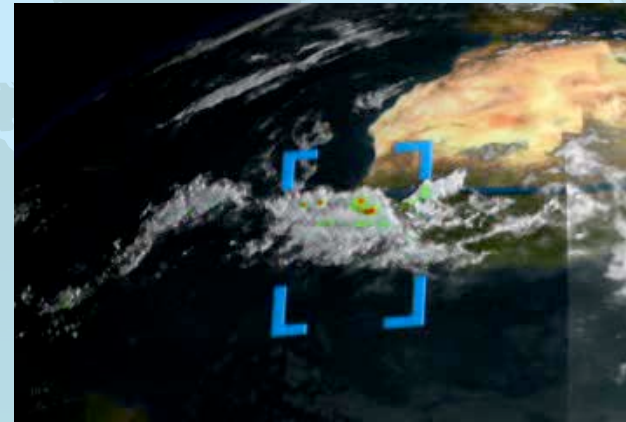
Mean meridional wind from
GATE easterly wave composite
(Reed et al, 1977)

Hurricane development initiated by the passage of a wave disturbance in the subtropics (e.g., easterly waves).



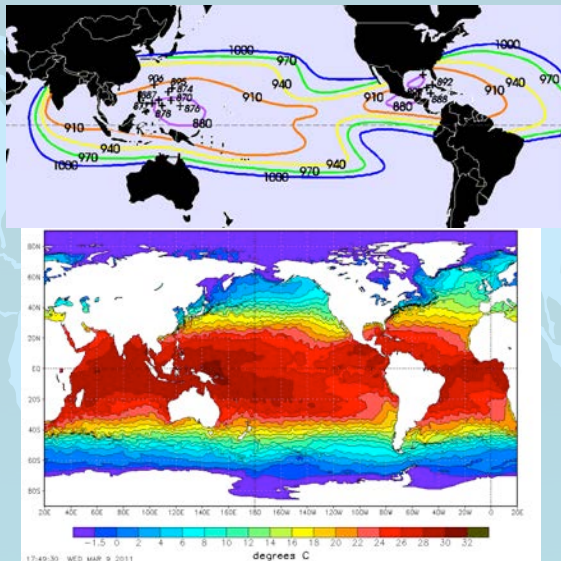
Prerequisites for Hurricane Formation

Easterly waves off coast of Africa provide convergence and rotation of the winds.



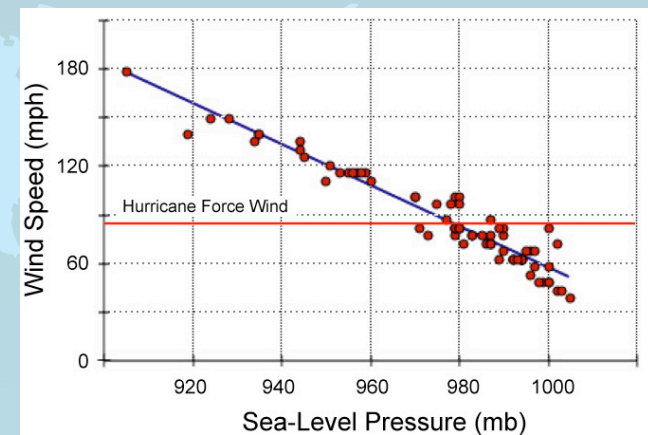
Easterly Waves trigger cyclogenesis over the Atlantic.

Hurricane Energy Source



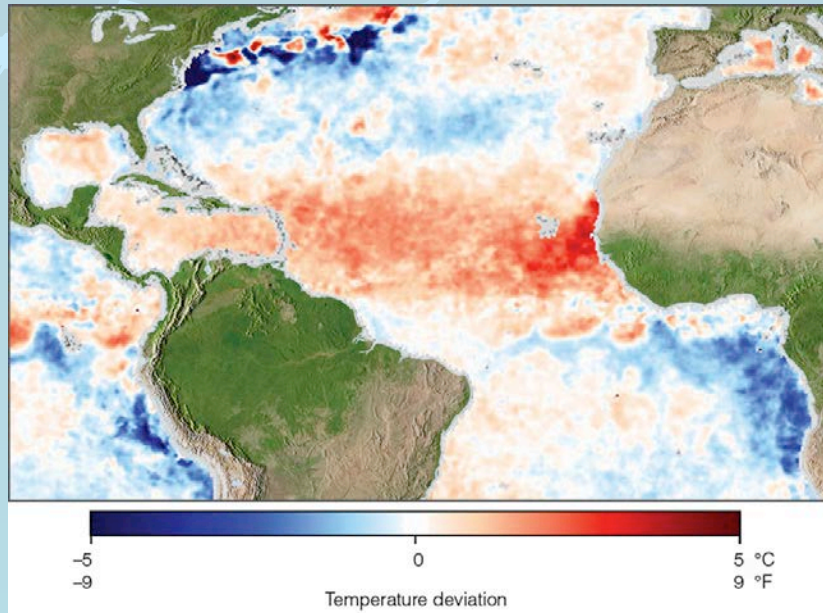
Observed sea surface temperature and predicted and observed minimum central pressure at sea level in tropical cyclones.

Low Sea-level Pressure – Strong Winds



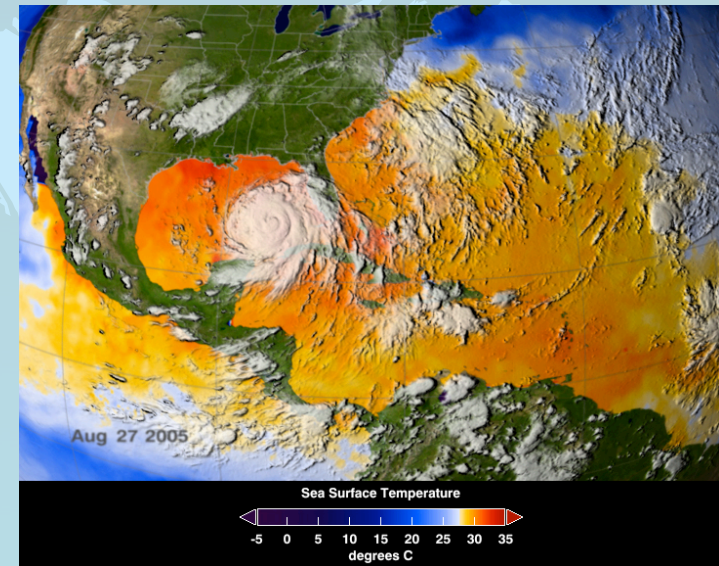
Relationship between surface pressure and wind speed for a number of tropical cyclones. Tropical cyclones are classified as hurricanes when their pressure is 980 millibars or lower, and sustained wind speeds are greater than 74 mph.

SST Anomaly for Summer 2005



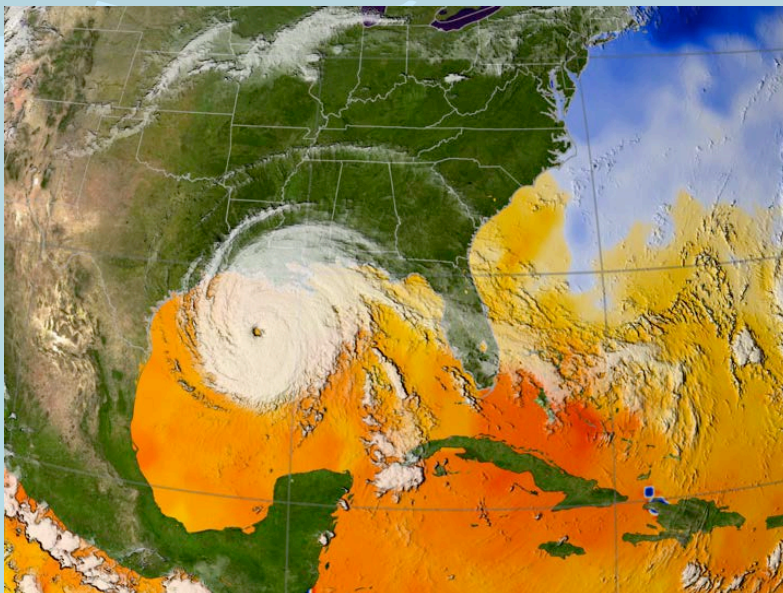
61

Hurricane Katrina and SST



62

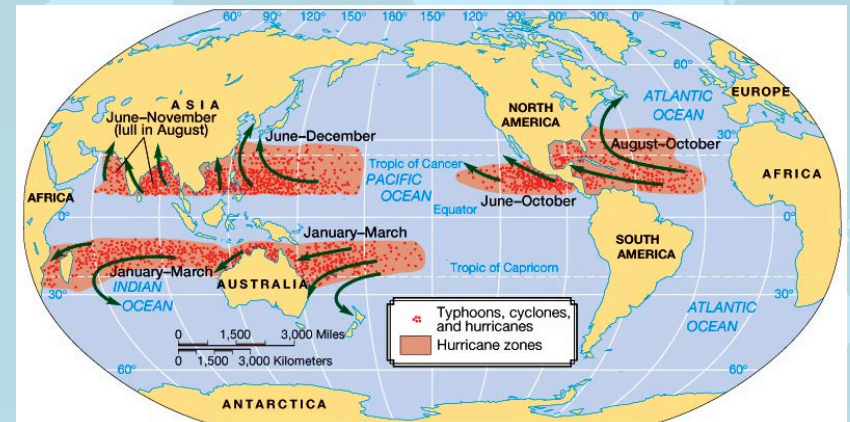
Hurricane Rita and SST



63

Hurricane Climatology

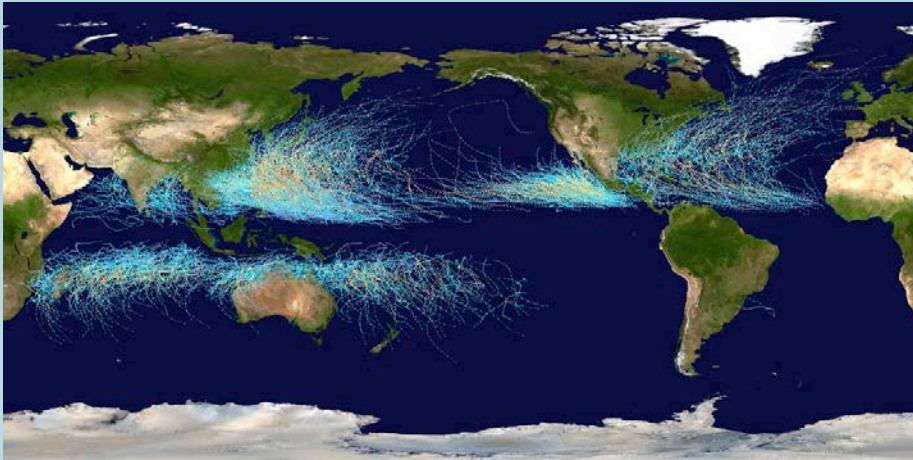
1. Warm Water SST > 26 °C (80 °F)
2. A surface low with unstable air and deep moisture.
3. Low wind shear



Where and when do these conditions exist in the world?

64

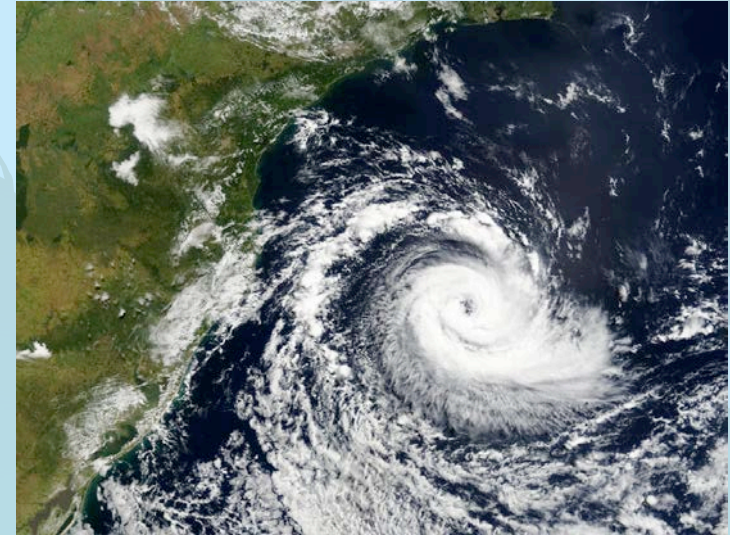
Tracks of Tropical Storms



The strength of the storms is color coded along the tracks, with light blue for weak category one hurricanes and yellow and red for strong storms (cat 3-5)

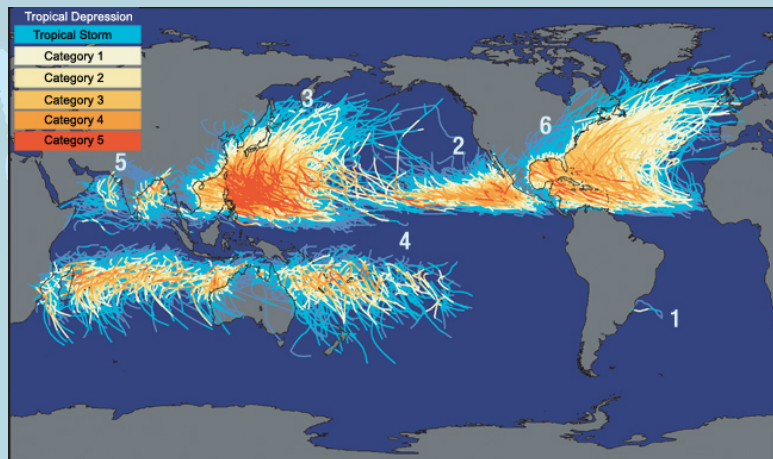
65

First Case of a Brazilian Hurricane



66

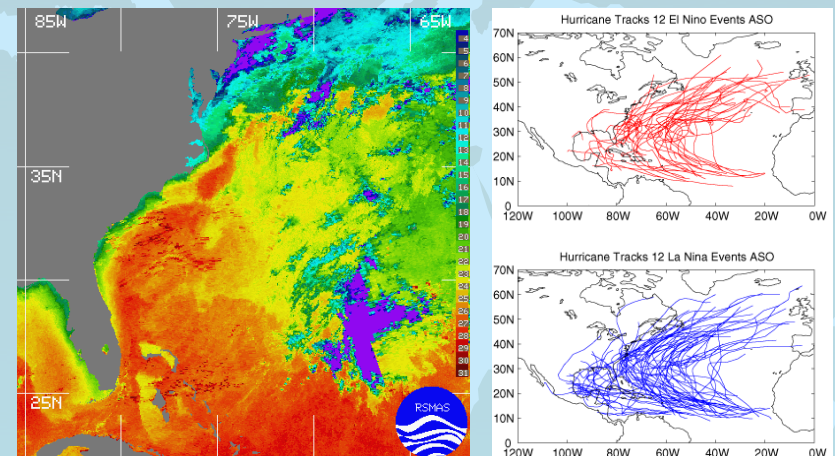
Tracks of Tropical Storms



The strength of the storms is color coded along the tracks, with light blue for weak tropical storms and orange and red for strong hurricanes (cat 3-5)

67

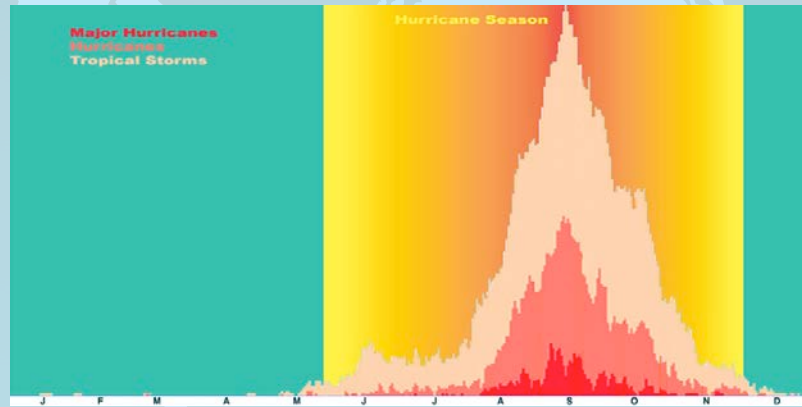
Hurricane Climatology



Hurricanes travel the warm Gulf Stream

68

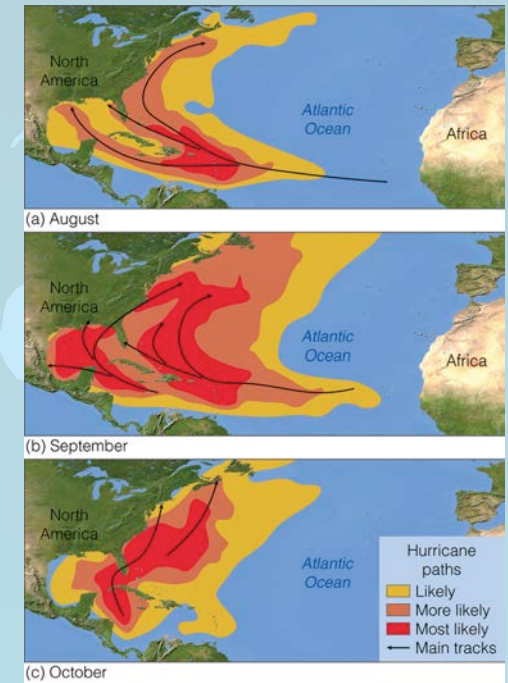
Atlantic Hurricane Climatology



Number of hurricanes per month in the Atlantic Basin.

69

Likely Tracks



70

US Hurricane Climatology



- Category of US hurricanes at the time of landfall.

71

Questions?



72