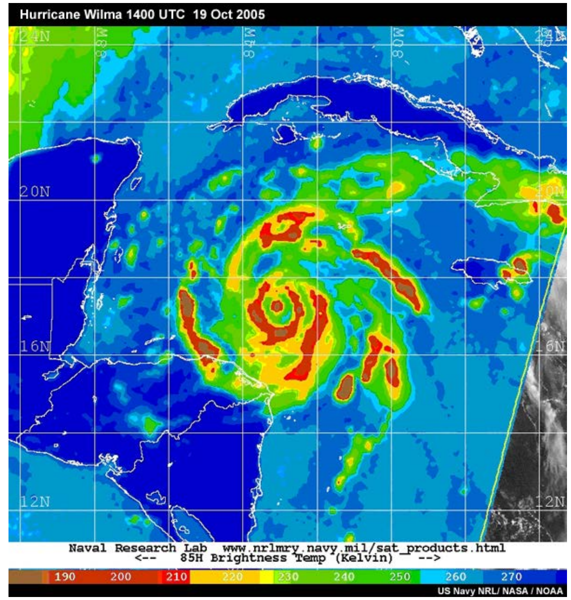
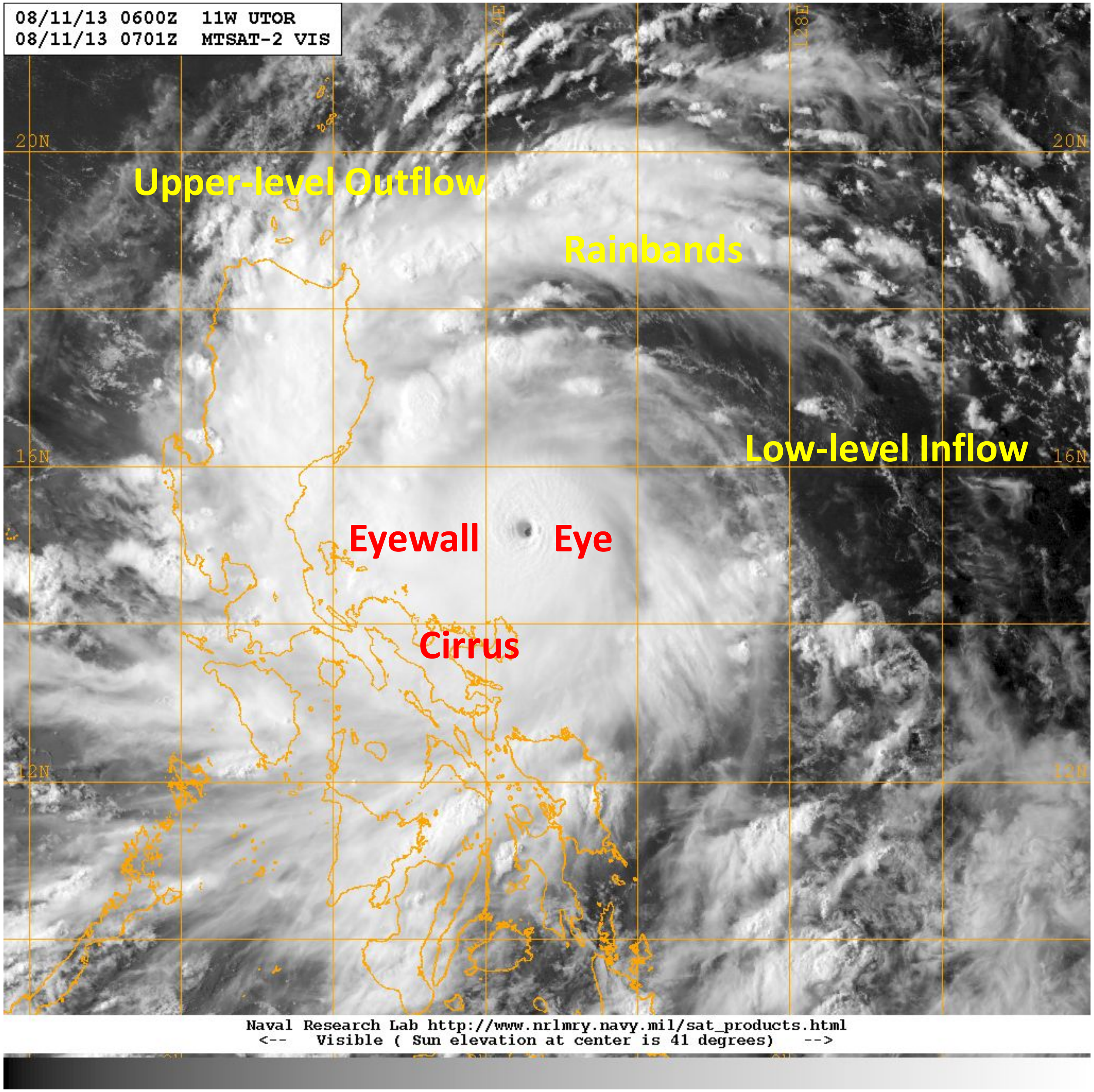


Lecture 4. Inner Core Dynamics

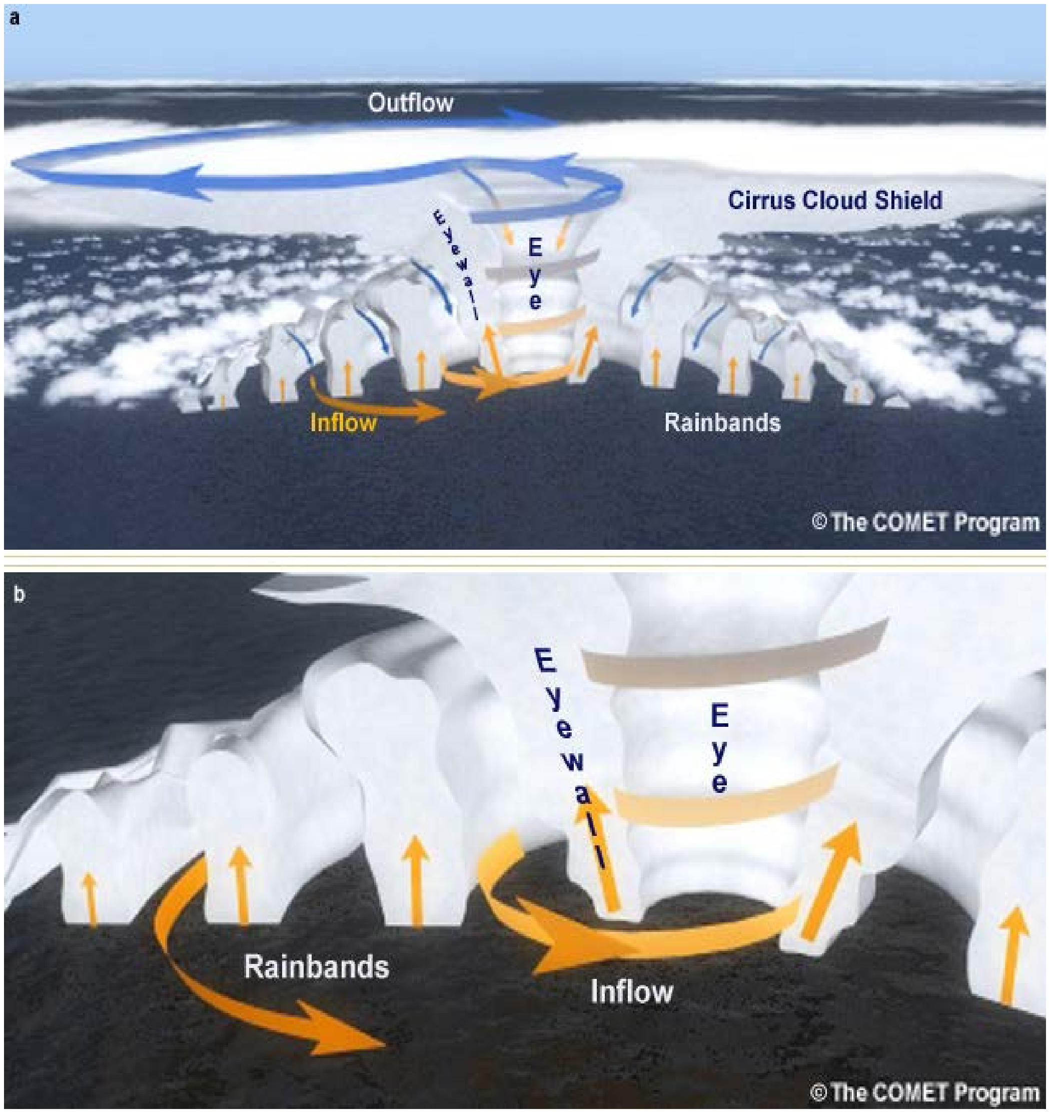
FIU HRSSERP Internship

August 16, 2013

Typhoon UTOR

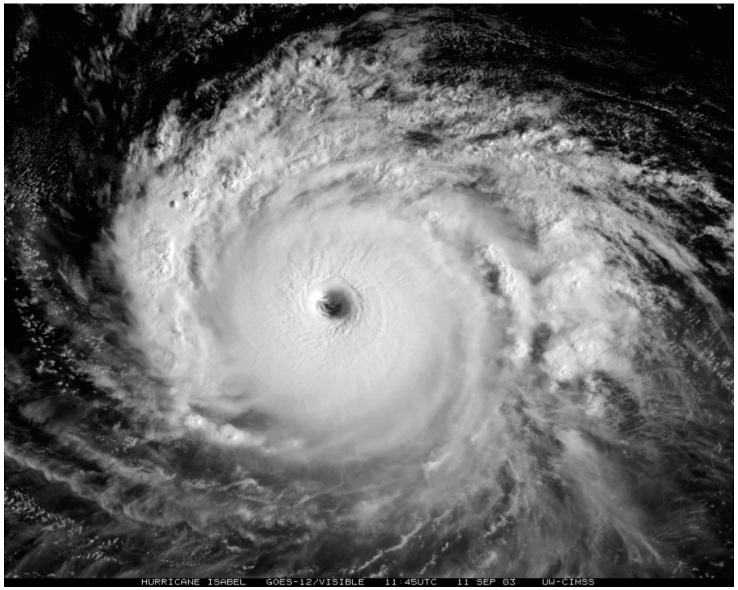


Three-Dimensional Structure



- The boundary layer inflow
- Eyewall
- Cirrus Cloud Shield
- Rainbands
- Upper tropospheric outflow
- For storms that are more intense, a clear central eye

Three-Dimensional Structure: Eye, Eyewall, and Rainbands

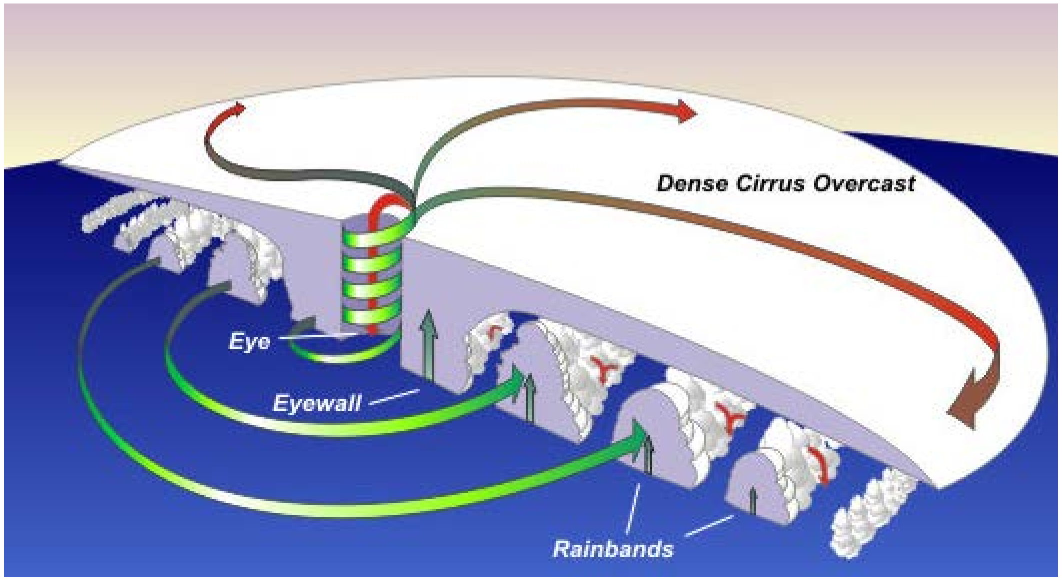


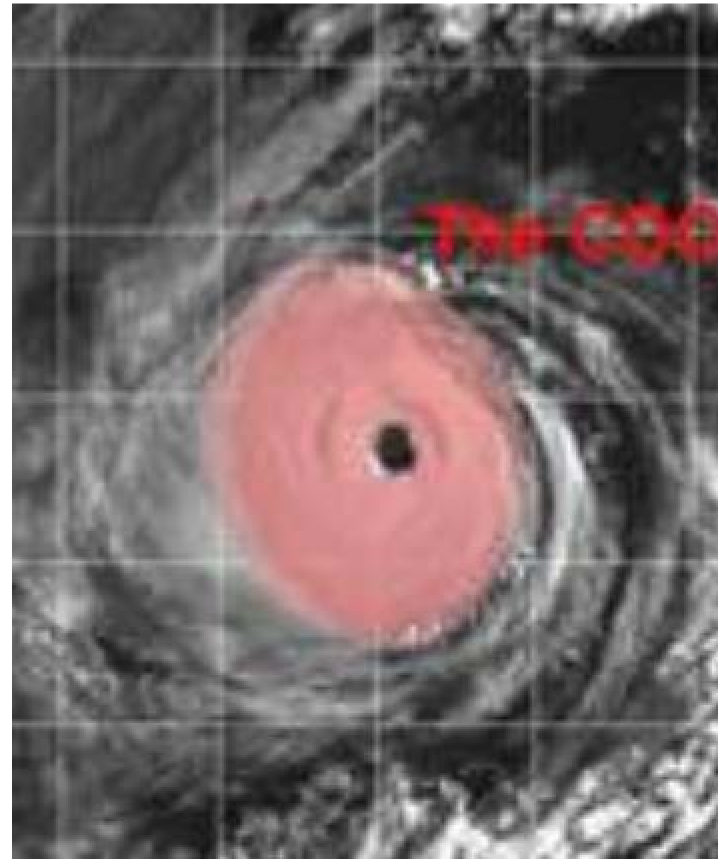
- Eye
  - A clear region in the center of a mature tropical storm
  - Relatively calm with light winds
  - The lowest surface pressure

- Eyewall
  - Organized thunderstorms surrounding the eye
  - The strongest winds

- Rainbands
  - Rings of clouds and thunderstorms that spiral out from the eye
  - Responsible for rain and tornadoes

Three-Dimensional Structure: CDO

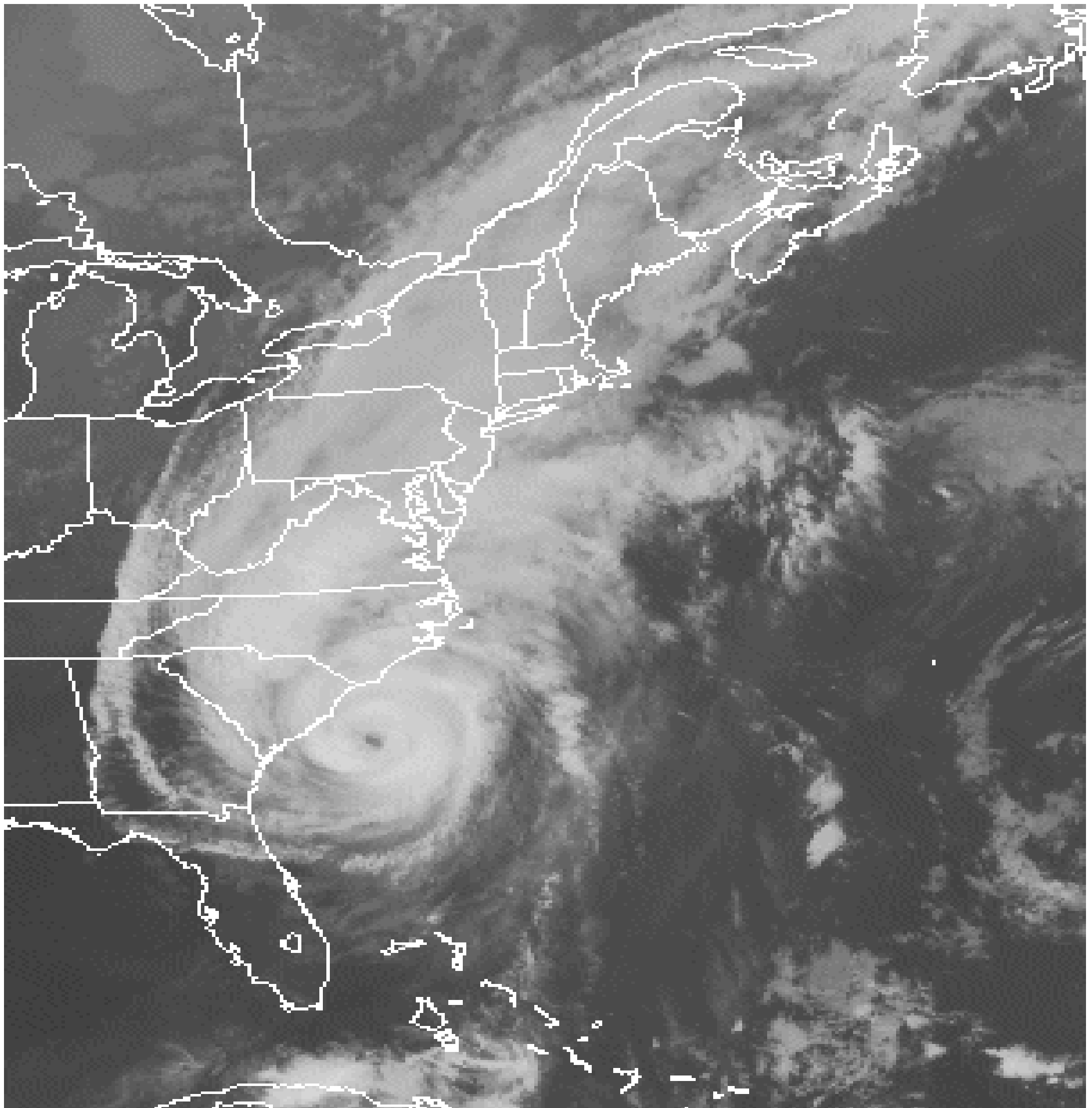




- The central dense overcast

(CDO– Dense Cirrus Overcast)

Three-Dimensional Structure: Outflow Jet



- Many hurricanes contain an “outflow jet”
- Spinning off anti-cyclonically
- Formed due to strong pressure gradient

Atmospheric Forces

- Pressure Gradient Force (PGF)

  - Wind blows from high to low pressure

- Coriolis Force (CF)

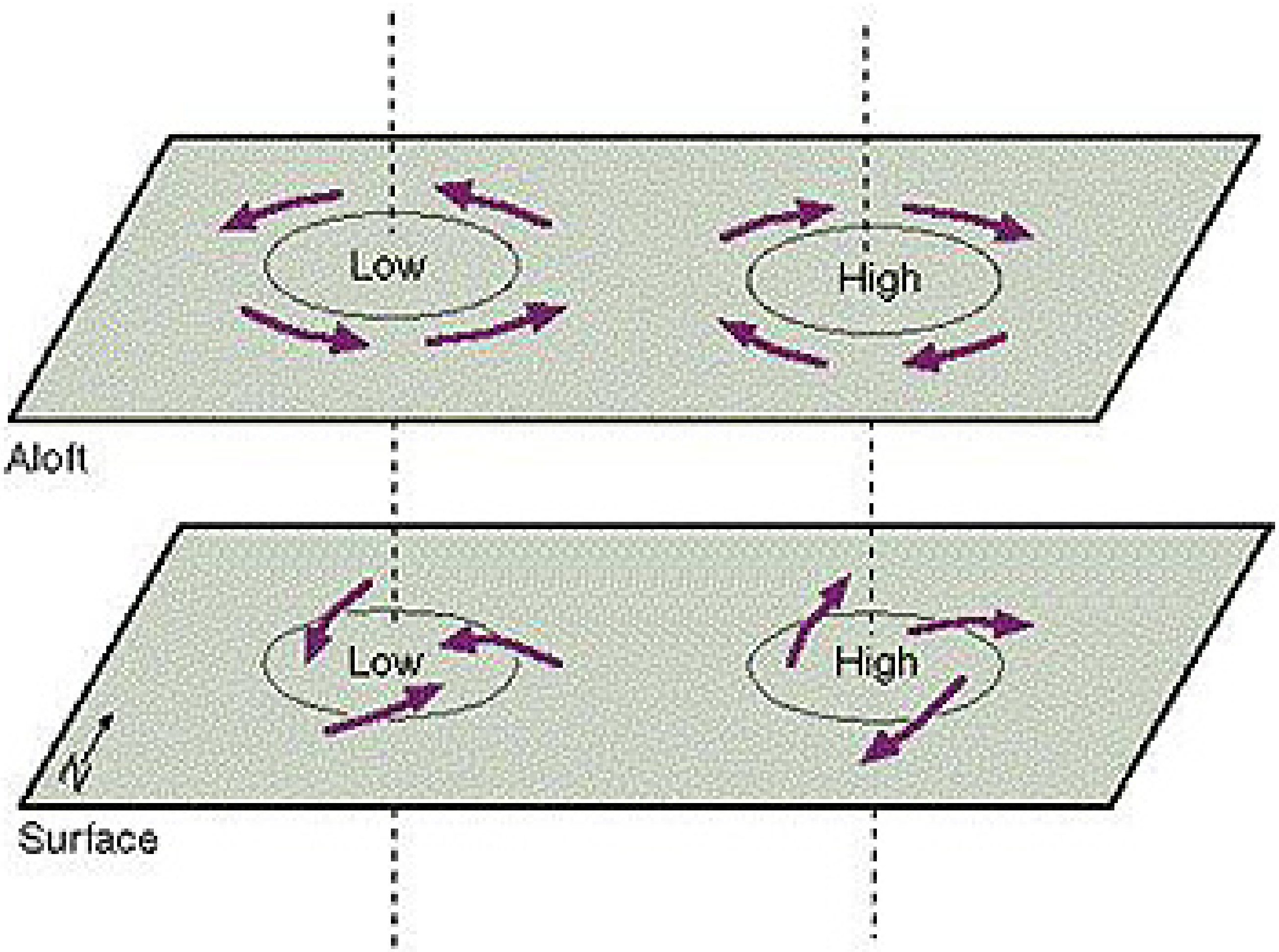
  - “Apparent” deflection of wind to right in Northern Hemisphere (Left in Southern Hemisphere)

  - Reverse direction at Equator, too low near equator for low pressure systems to “spin up”

- Friction (F)

  - Slow speed of wind

Frictionless vs. Friction Flow

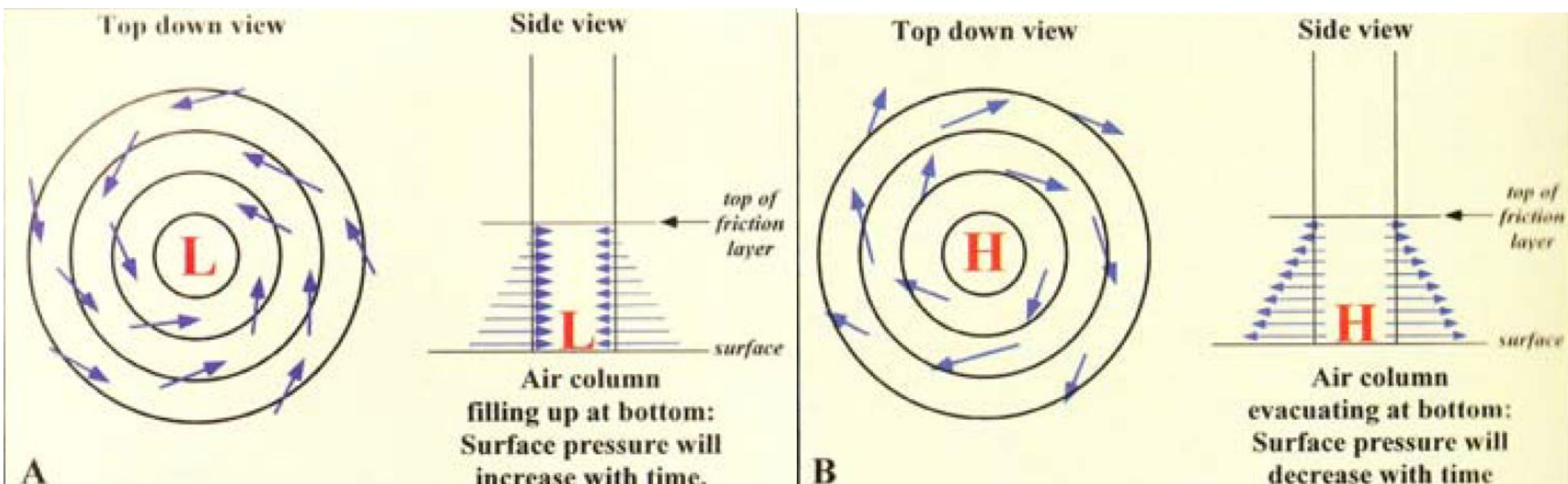


Ideal "Frictionless" Flow

Flow with Friction

Effect of Friction on TCs

- Friction causes wind to cross isobars
- Result is that both low and high pressure systems are weakened over time
- Friction over land > Friction over water, so a landfalling hurricane "fills in" quickly



TC Intensity

Will it hit me?

How intense is it?

How will it affect me?

……

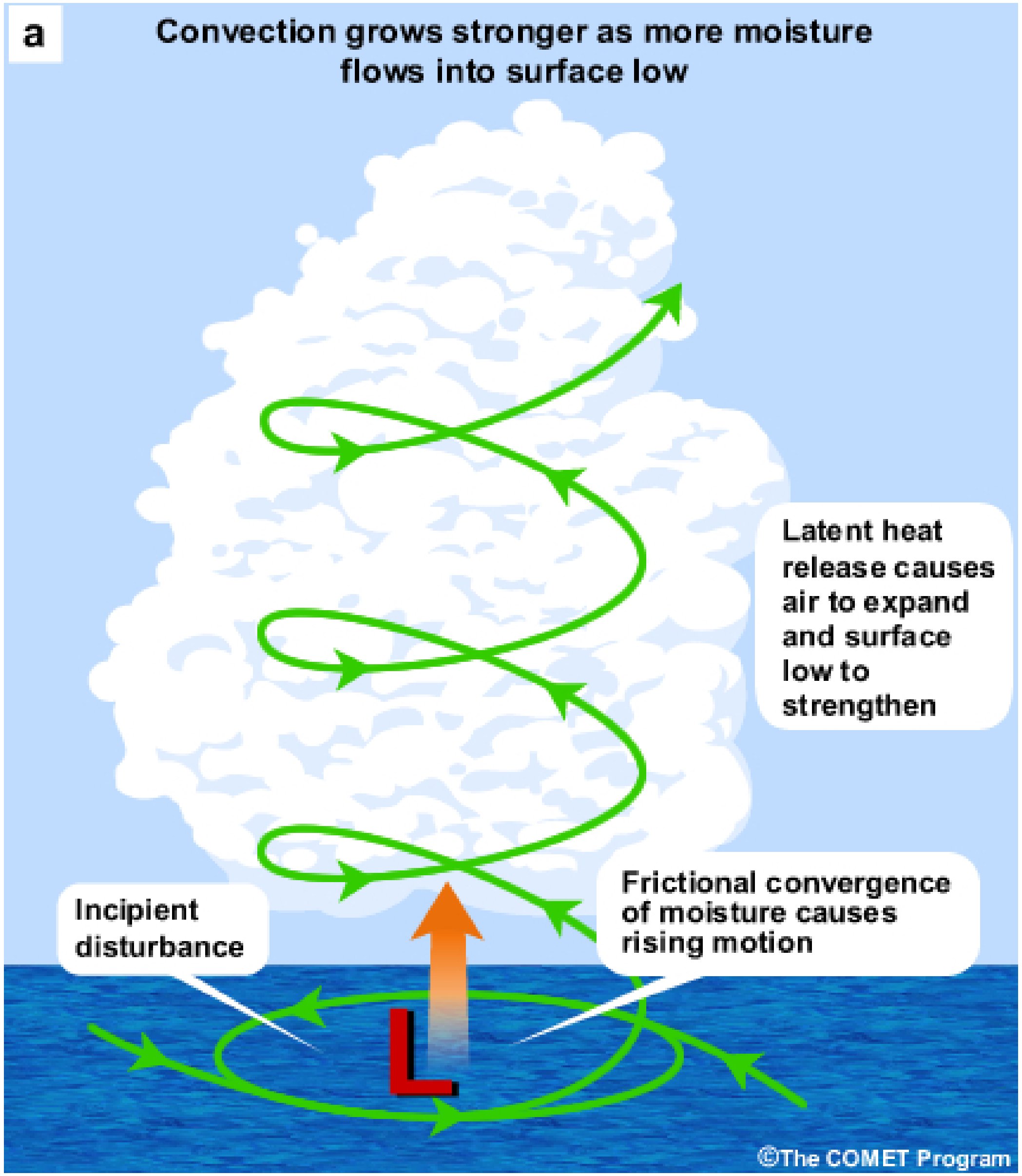
Potential Intensity (PI)

- Potential Intensity (PI): the maximum possible surface wind speed/ the minimum central pressure attainable by an individual storm.
- Two dominant alternative theories compete to explain the limits on tropical cyclone intensity ---- its PI.

  - Conditional Instability of the Second Kind (CISK)

  - Wind-induced surface heat exchange (WISHE)

Early Theories of PI: CISK



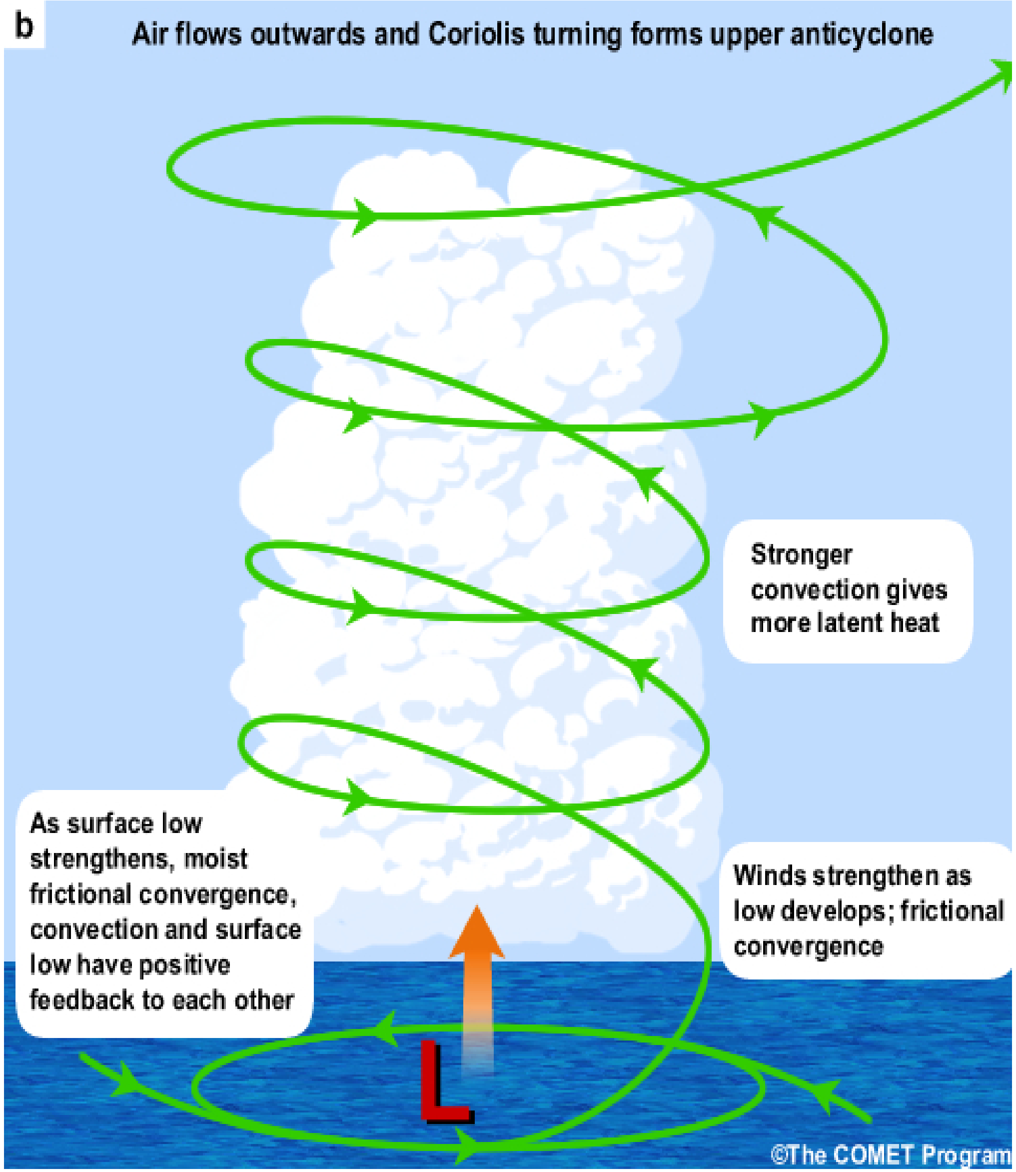
- Friction decelerates the surface winds
- Frictional convergence of moisture causes rising motion
- The moisture ascend into the convection and condense as rain
- Latent heat release
- The air expands and the surface low strengthen

Kinds of heat

- Latent heat ---- the heat released or absorbed by a chemical substance or a thermodynamic system during a change of state that occurs *without a change in temperature*, meaning a phase transition such as the melting of ice or the boiling of water.

- Sensible heat ---- the energy exchanged by a thermodynamic system that has as its *sole effect change of temperature*.

Early Theories of PI: CISK



- As surface low strengthens, continuous heat and moisture are provided by the frictional convergence
- Providing more latent heat release that is converted to mechanical energy
- Positive feedback

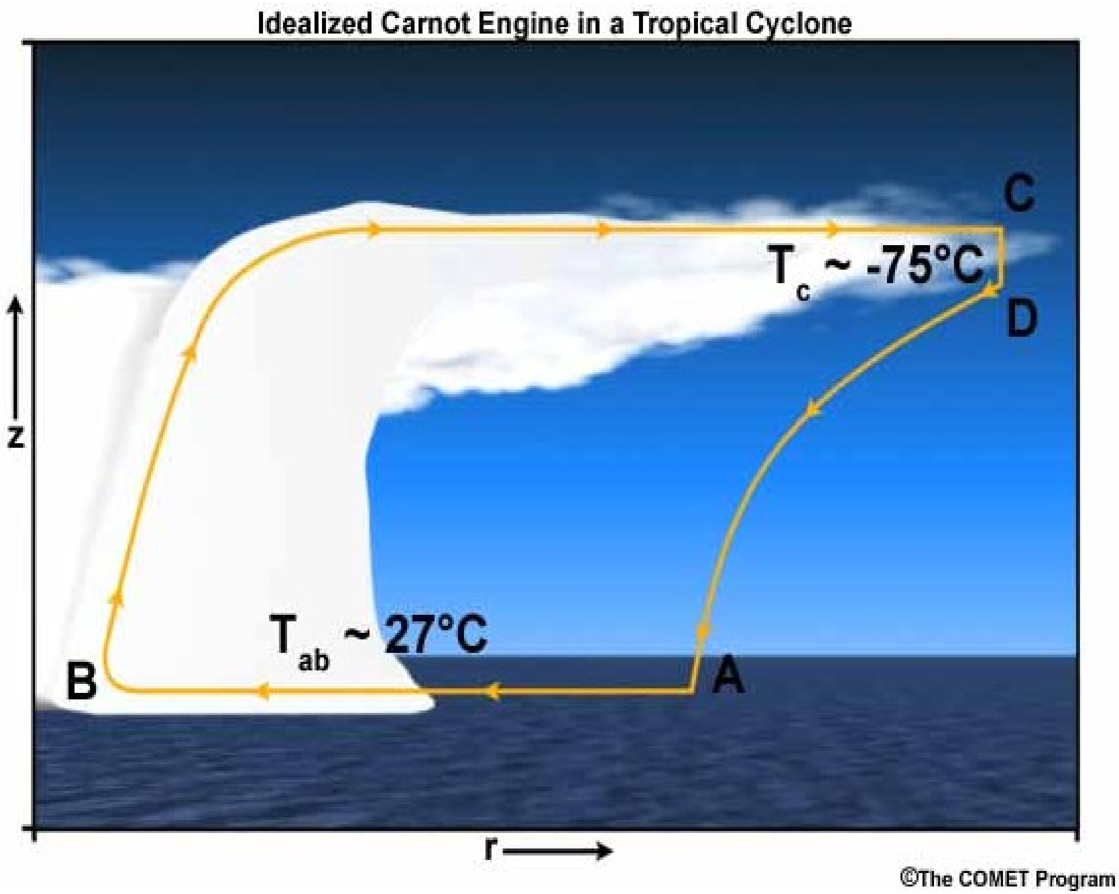
Early Theories of PI: CISK

- Friction has two roles in CISK:
  - deceleration of surface winds
  - frictional convergence
- If the energy from the latent heat release *balances* the energy lost to surface friction, the storm will *maintain* its intensity
- If the energy from the latent heat release *exceeds* the energy lost to surface friction, the storm will *intensify*

Early Theories of PI: CISK

- The CISK theory relies on the existence of an incipient disturbance.
- However, many tropical disturbances exist, only a few develop into tropical cyclones.
- The success of an individual disturbance depends upon its environment.

A Carnot Cycle Theory of PI: WISHE



- Isothermal inflow of near-surface air (A-B)
- Moist adiabatic ascent in the eyewall, and outflow just below the tropopause (B-C)
- Sinking of cooled air far from the center (C-D)
- The cooled air returns to the TC environment adiabatically (D-A)

- Also relies on the presence of a finite amplitude incipient disturbance

A Carnot Cycle Theory of PI: WISHE

- The source of energy is the underlying ocean.
- Evaporation, sensible heat flux and heat from friction combine to feed the deep convection of the eyewall.
- The temperature difference between the ocean surface and the tropopause provides the thermodynamic energy to drive the whole system.
- "Carnot engine efficiency" ξ

$$\varepsilon = \frac{T_{IN} - T_{OUT}}{T_{IN}} = \frac{(SST - T_{trop})}{SST} = \frac{300-200}{300} = \frac{1}{3}$$

Approximately one third of the available heat energy can be converted into mechanical energy.

Application of PI

- Inference of maximum possible intensity for an observed tropical cyclone anywhere on the globe;
- Providing a reality check upper bound on SHIPS forecasts of actual storm intensity by comparing them against the PI;
- Studying the "rebound" of the environment back to earlier conditions after a tropical cyclone passage

Environmental Factors limiting TC Intensity

- Warm ocean waters, much cooler outflow temperatures, boundary layer convergence, and high relative humidity and convection all present for every Tropical Storms.

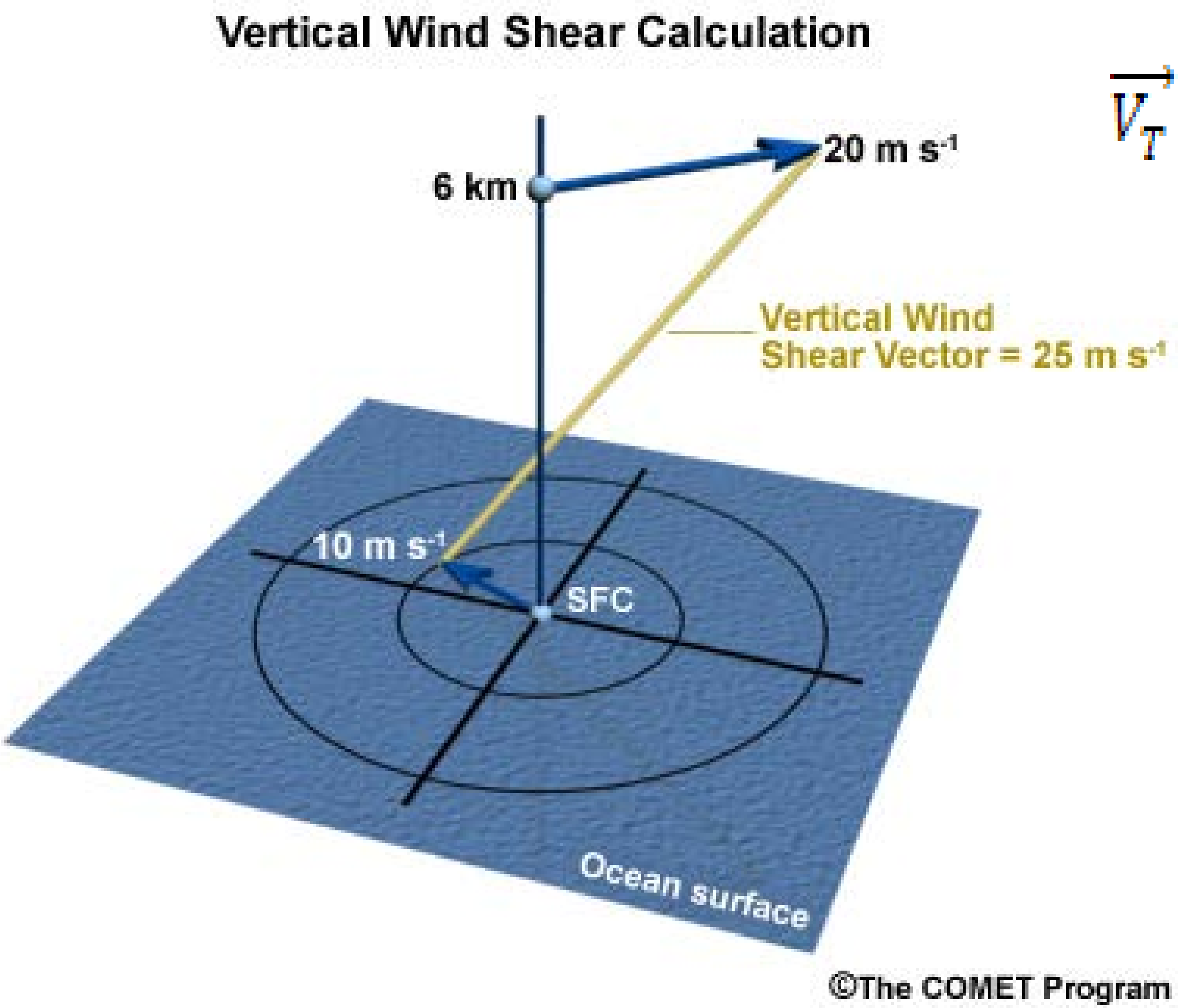
⇨ Why does every TC not intensity to 100 m/s?

Reality is no the IDEAL !!

Environmental Factors limiting TC Intensity

- Inhibitors of intensification:
  - Insufficient humidity
  - Cooler SST or warmer tropopause
  - Dry air intrusion
  - A region of strong baroclinicity
  - Eyewall Replacement Cycle
  - Vertical wind shear and more……
- “Potential” intensity is only achievable when these factors combine favorably.

The vertical wind shear



$$\overrightarrow{V_T} = \overrightarrow{V_g}(p_A) - \overrightarrow{V_g}(p_B)$$

- Vertical wind shear: the difference between the geostrophic wind at two vertical levels

Environmental Wind Shear

- The environmental wind shear will cause the storm to reorganize.
- Convection generates on the downshear side, creating an asymmetry
- Ultimately the storm will either

  - re-intensify as a tropical system

  - become extratropical and re-intensify

  - decay.

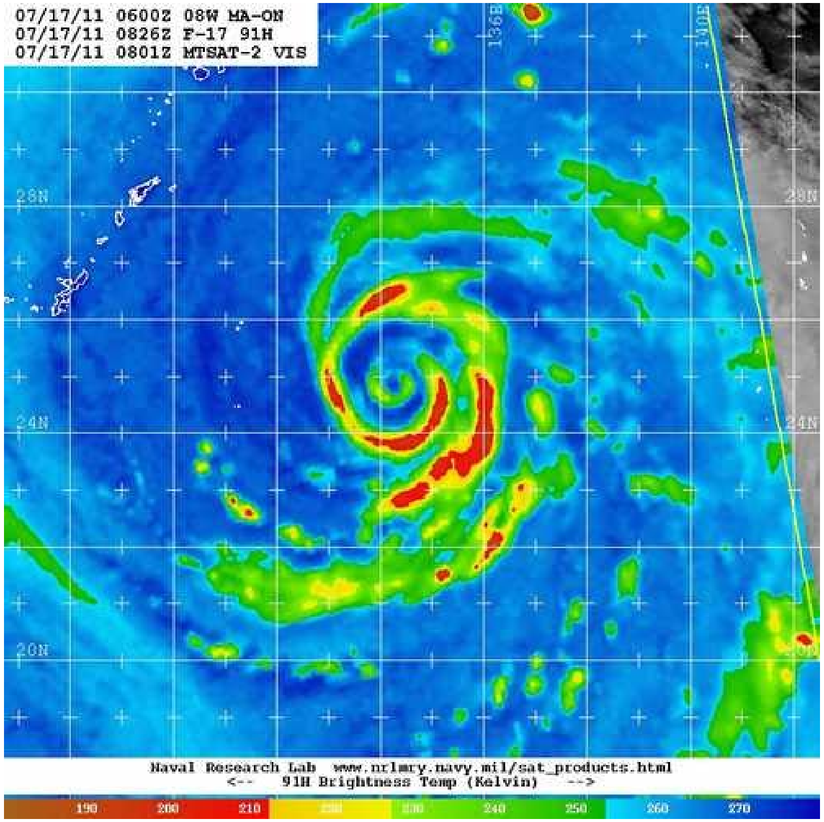
Environmental Wind Shear

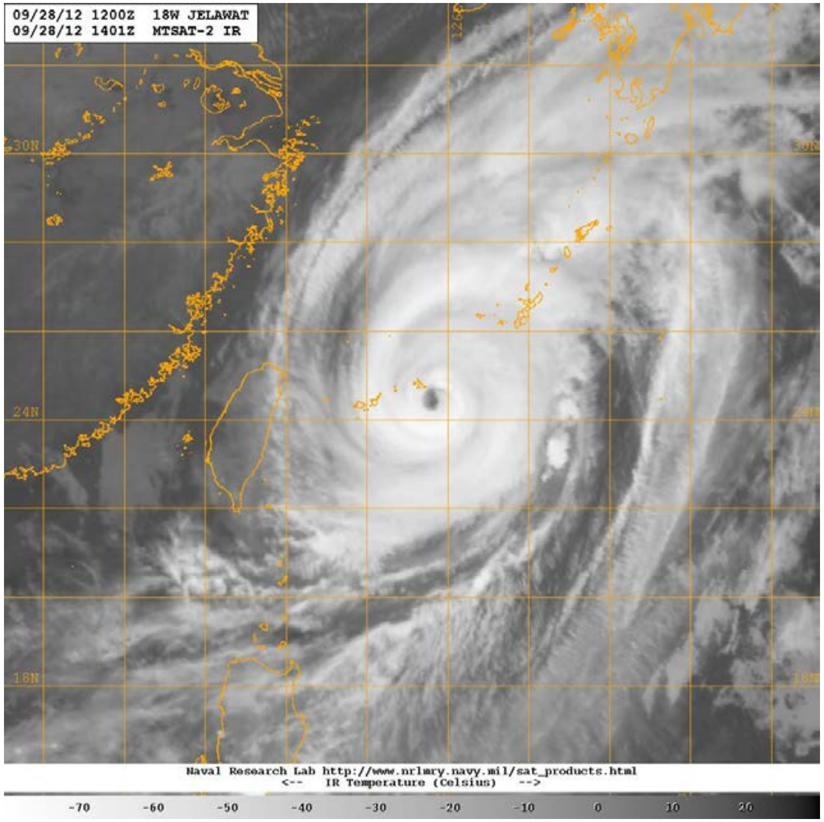
- Strong vertical wind shear can cause storms to weaken

- *How about very low or even no vertical wind shear?*

  - A minimum level of vertical wind shear is necessary for a storm to maintain its intensity or to intensify further

Eyewall Replacement Cycles: Video





- http://www.youtube.com/watch?v=LIRLn2CZQwA

Eyewall Replacement Cycles: Definition

- Often observed during periods of intensification or weakening of intense TCs (winds > 115 mph).
- The whole process includes (*Willoughby et al. 1982*):

  - Genesis of a secondary eyewall

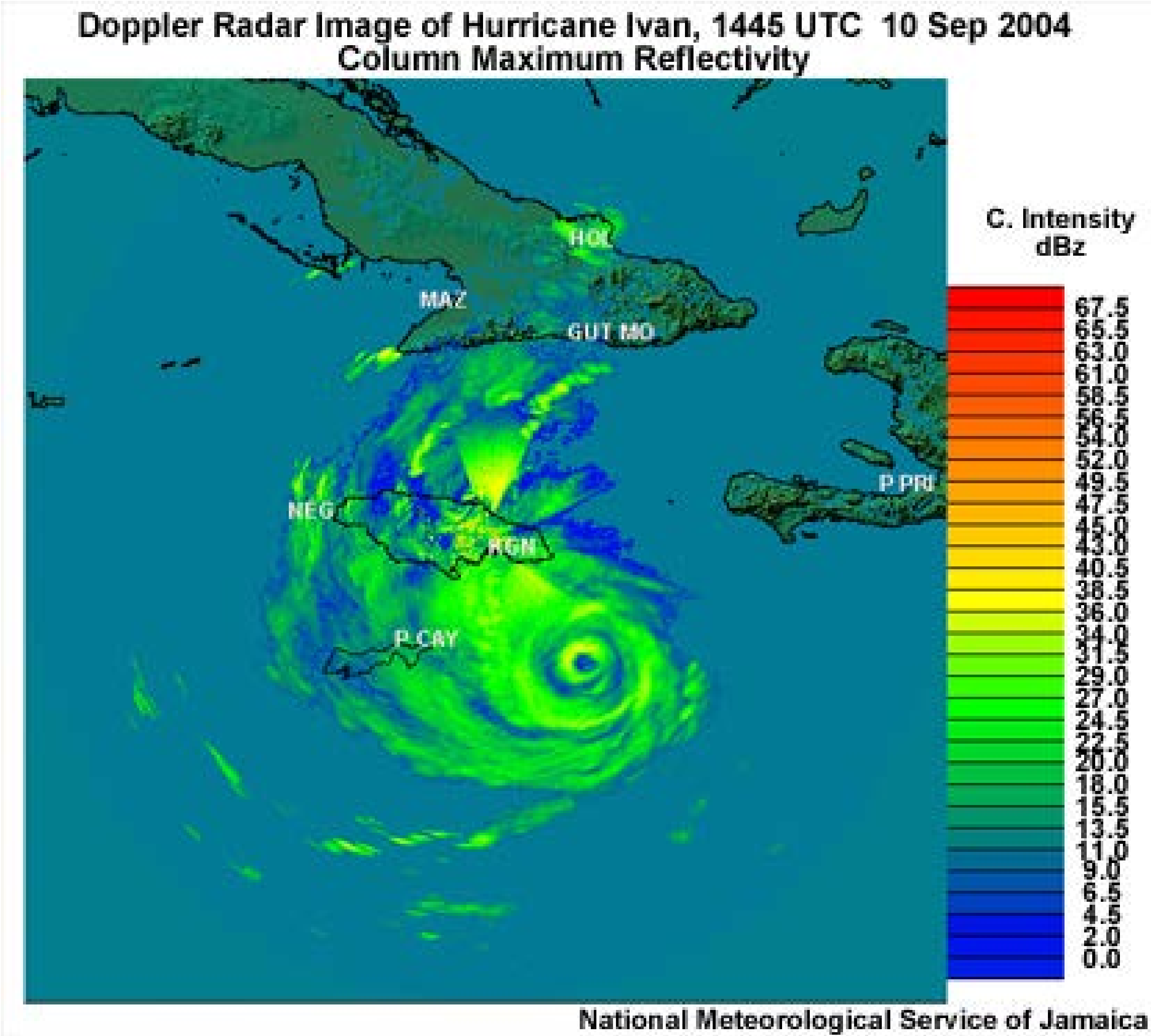
  - Dissipation of the inner eyewall

  - Organization of the new eyewall

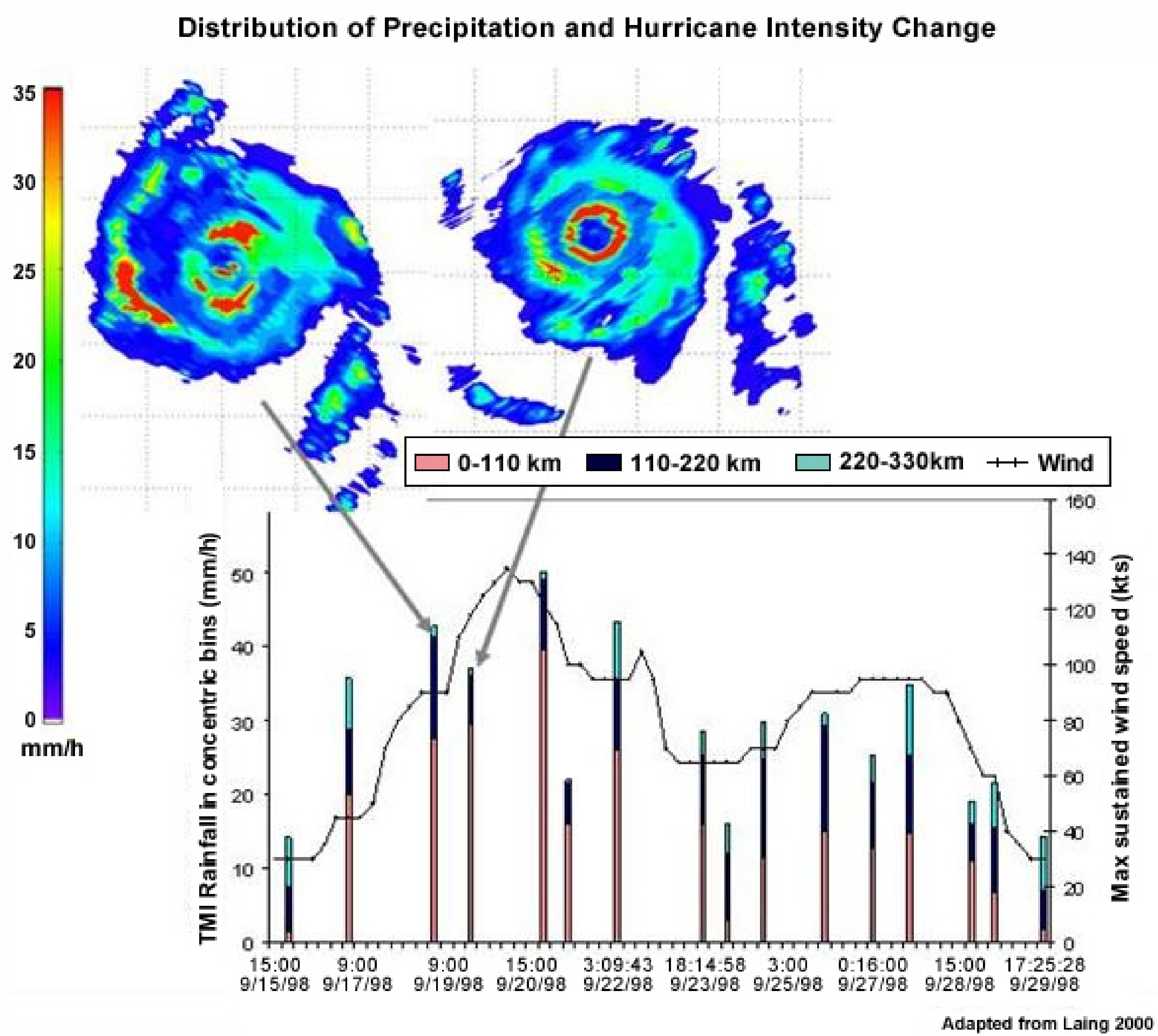
Eyewall Replacement Cycles and TC intensity

- TC eyewall contract when reaching higher intensity
- When the eyewall reaching its minimum size, the TC begins to weaken
- Other things being equal, the TC weakens when an outer eyewall forms
- The outer eyewall contracts gradually and the TC begins to intensify

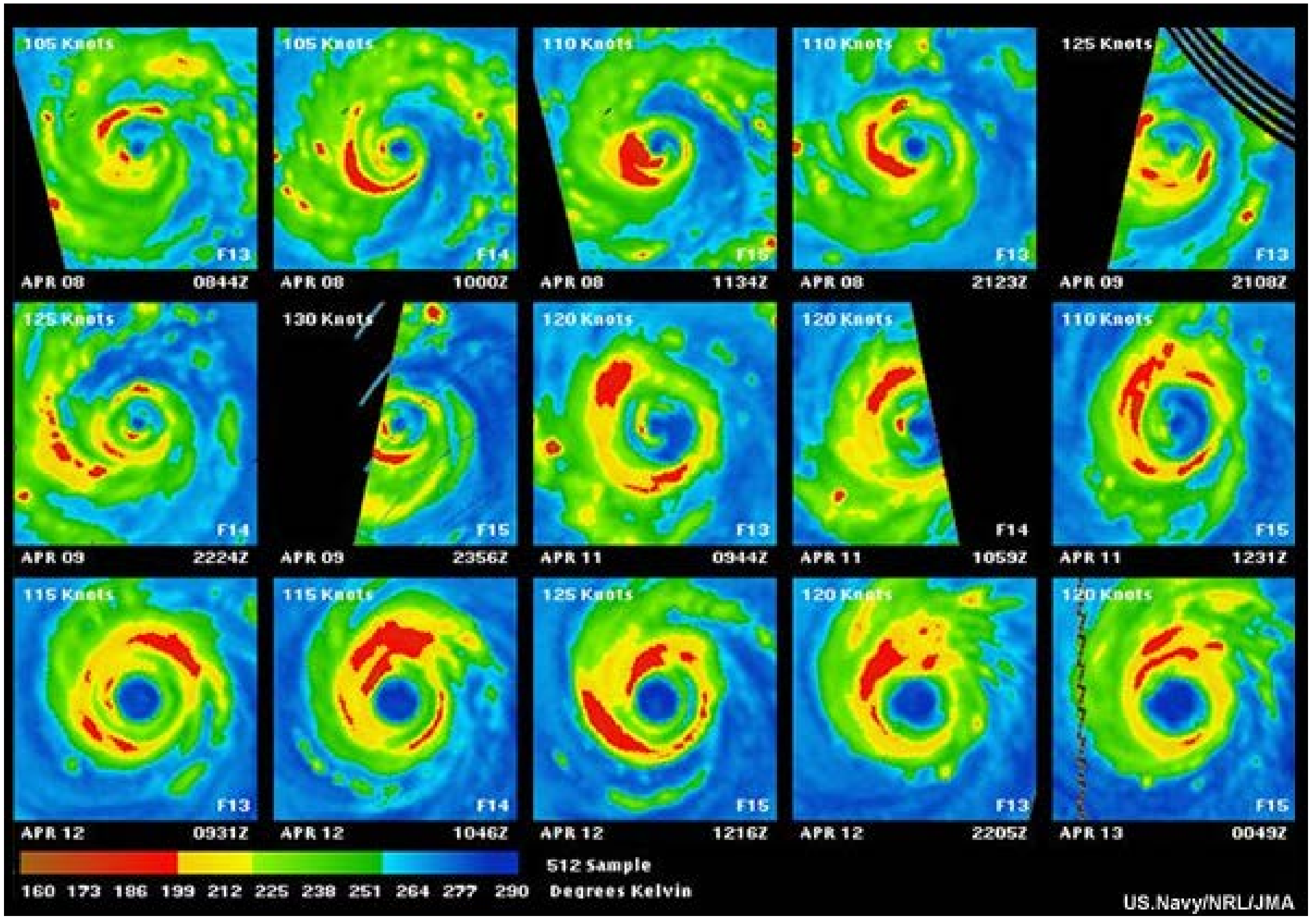
Example 1: Hurricane Ivan (2004)



Example 2: Hurricane Georges (1998)



Eyewall Replacement Cycle: Summary

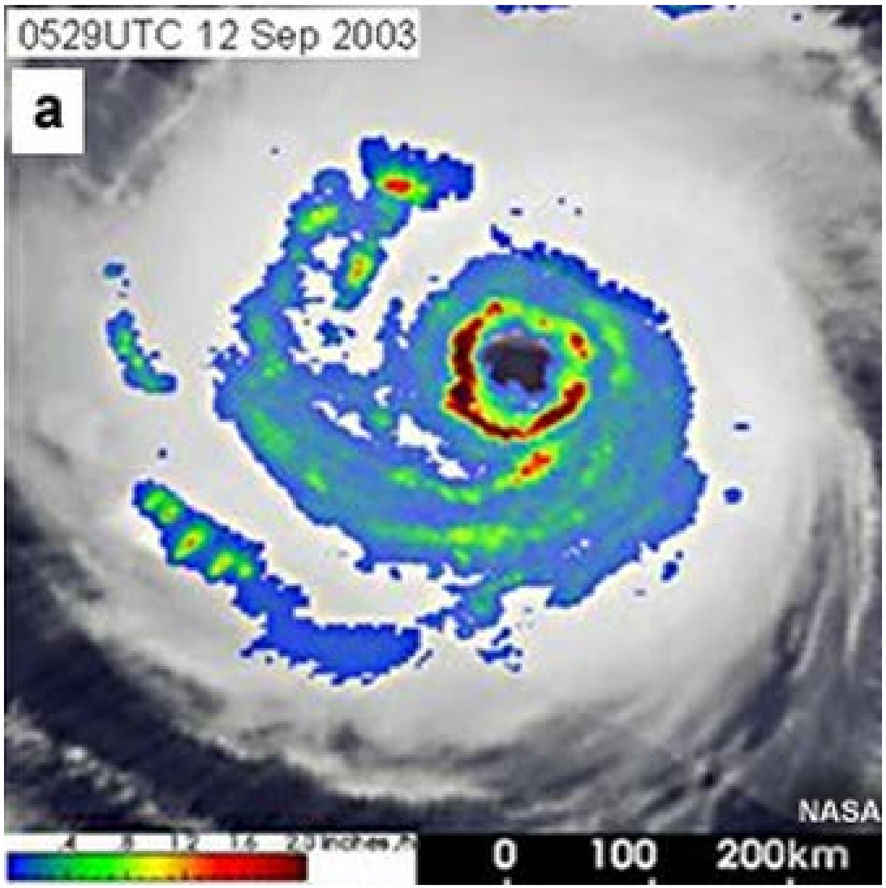


- Can last from 12-18 h to 2-3 days
- Some intense TCs undergo multiple ERC
- The West Pacific has the largest percentage of storms exhibiting double eyewall structure

Satellite-derived Winds

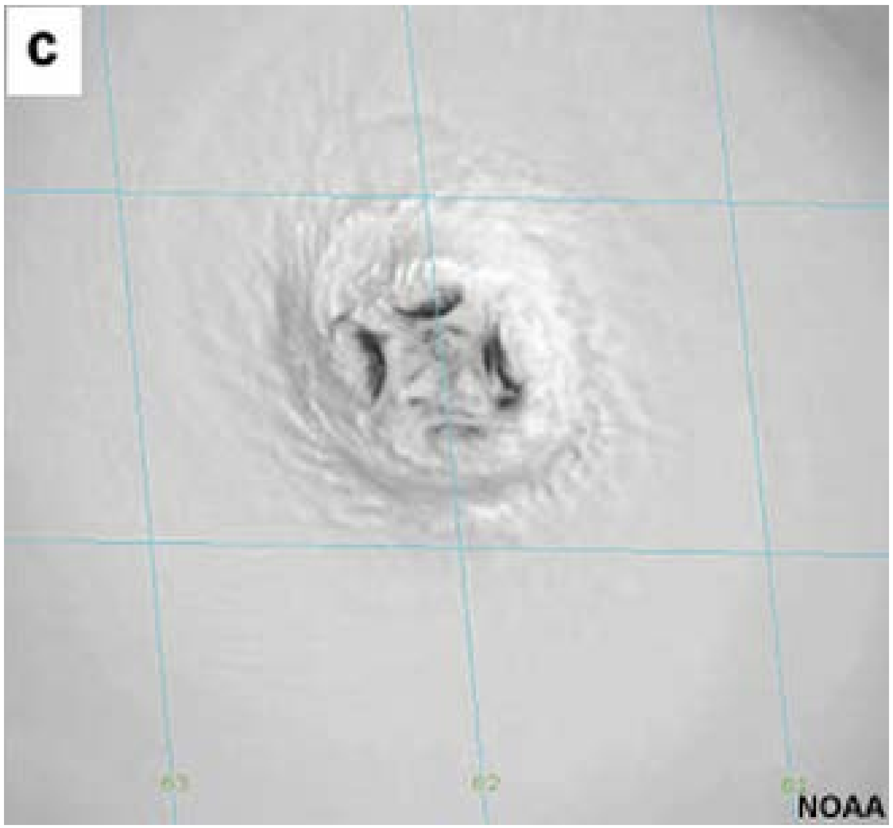
- It's important to consider TC intensity in terms of wind speed radii. For example, the width of evacuation zones is based on thresholds such as the radius of gale force winds (1min winds 34-47 knots)
- Studies indicate that the radius of 34 knot winds could be used to estimate TC intensity (*Weissman, D.E. et al. 2002*).

Remote Sensing of Inner Core Dynamical Features: Eyewall Mesovortices



- Eyewalls are occasionally observed to adopt polygonal shapes which were hypothesized to be associated with mesovortices (*Kossin, J. P et al. 2000; Montgomery, M. T., et al. 2002*).
- These eyewall mesovortices are deep vortex structures in the eyewall convection.
- Wind speed in eyewall vortices can be 10% greater than the rest of the eyewall

Eyewall Mesovortices and TC Intensity



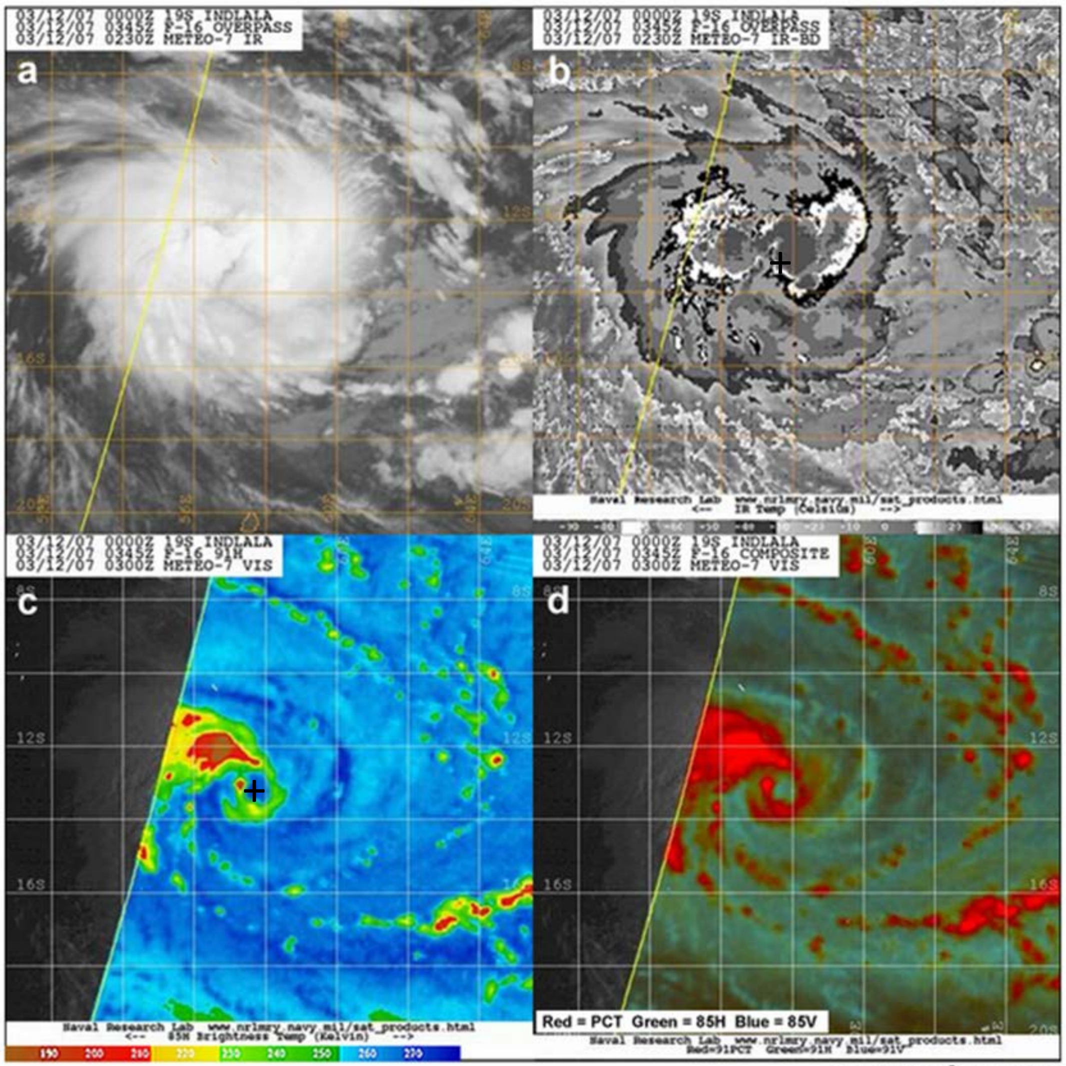
- Contribute cyclonic vorticity which is mixed into the eye
- This increase in the local vorticity spins up the eye
- The low-level mesovortices create a secondary circulation---- transfer air from the eye to the eyewall

Estimation of TC Intensity by Remote Sensing: IR

- The standard method of estimating TC intensity is by analyzing IR images.
- The Dvorak Enhanced IR technique uses a special enhancement to identify intense convection and changes in the cloud top pattern around the eye. It identifies four basic TC pattern types, the:

  - Eye pattern
  - Curved band pattern
  - Shear pattern
  - Central dense overcast (CDO) pattern

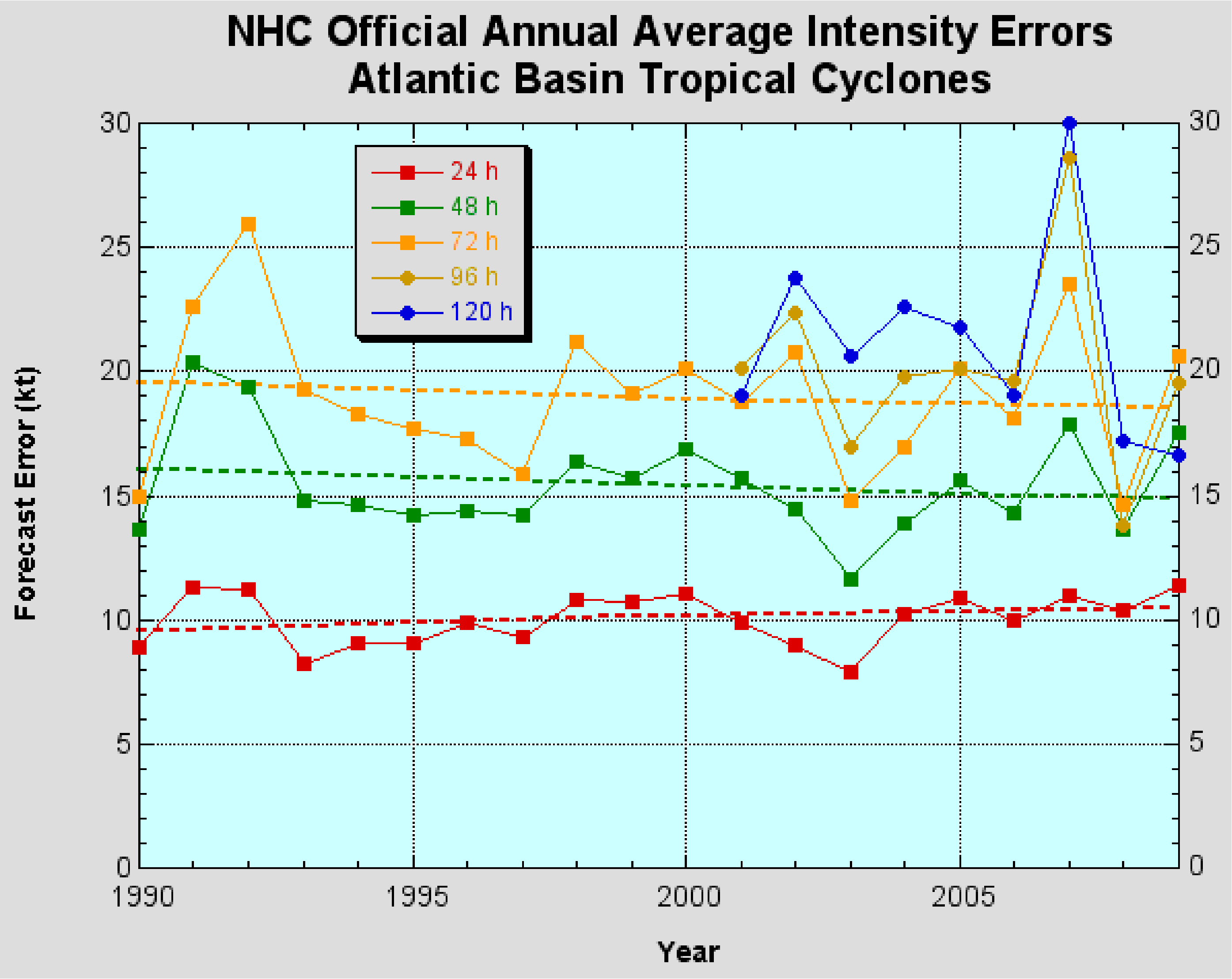
Estimation of TC Intensity by Remote Sensing: Microwave



US Navy/NRL/ ©EUMETSAT 2007

- Can detect the internal cyclone structure
- In the 85GHz microwave images, the eye is prominent
- The 85GHz channel has higher resolution, and is preferred channel for observing TC structure and intensity changes.

Intensity Forecast



Intensity Forecast

- Much more complicated problem than track
- Depends critically on wind, temperature and moisture patterns in the core of the storm and in the near environment.
- Also governed by internal processes, such as eyewall replacement cycles
- Involves complex interactions between thunderstorms in the TC core and the TC environment, as well as air-sea interactions.

Rapid Intensification (RI)

- Rapid Intensification (RI) is the explosive deepening of a tropical cyclone.
- RI---- The maximum sustained surface wind speed increase of 15.4 m/s (or 30 kt) over a 24-hour period (*Kaplan and DeMaria, 2003*).
- All CAT 4 and 5 hurricanes, 83% of all major hurricanes (CAT 3-5), 60% of all hurricanes, and 31% of all TCs experienced at least one RI period during their lifetime.

Forecast of RI

- RI probability can be estimated through the analysis of five predictors:
  - Previous 12-hour intensity change
  - SST
  - Low-level relative humidity
  - Vertical shear
  - Difference between current intensity and PI

Hot Towers

- “…neither a gradual mass circulation nor simple convective diffusion can transport heat upward to balance losses aloft and postulate a mechanism of selective buoyancy with undilute cloud towers…”
- “…considering the ascent of narrow warm towers through an environment…”

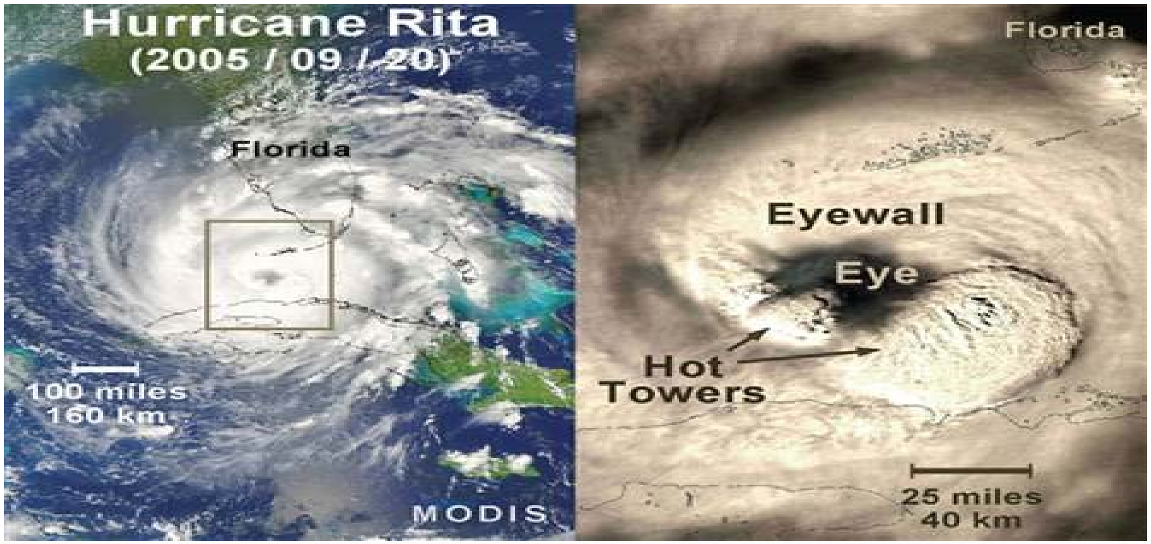
----- *H. Riehl and J. Malkus, 1958*

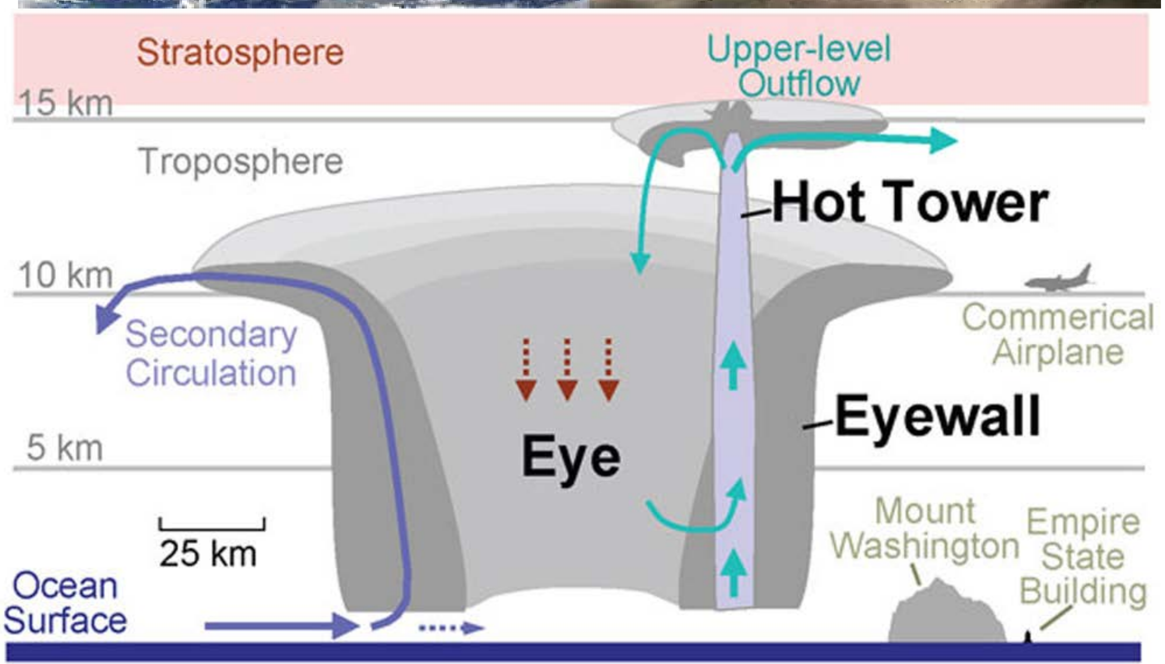
Hot Towers and Hurricanes

- "…Radar photographs since the early 1940's have demonstrated abundantly that the latent heat is not released uniformly through the rain area, but is concentrated in spiral convective bands of narrow width, especially in a ring surrounding the eye…"
- "…The models envisage that the ascent in the core occurs in extremely restricted regions of undilute, rapidly rising cumulonimbus towers, which come to occupy a significant fraction of the rain area as the eye wall is approached…"

----- *Joanne S. Malkus, 1961*

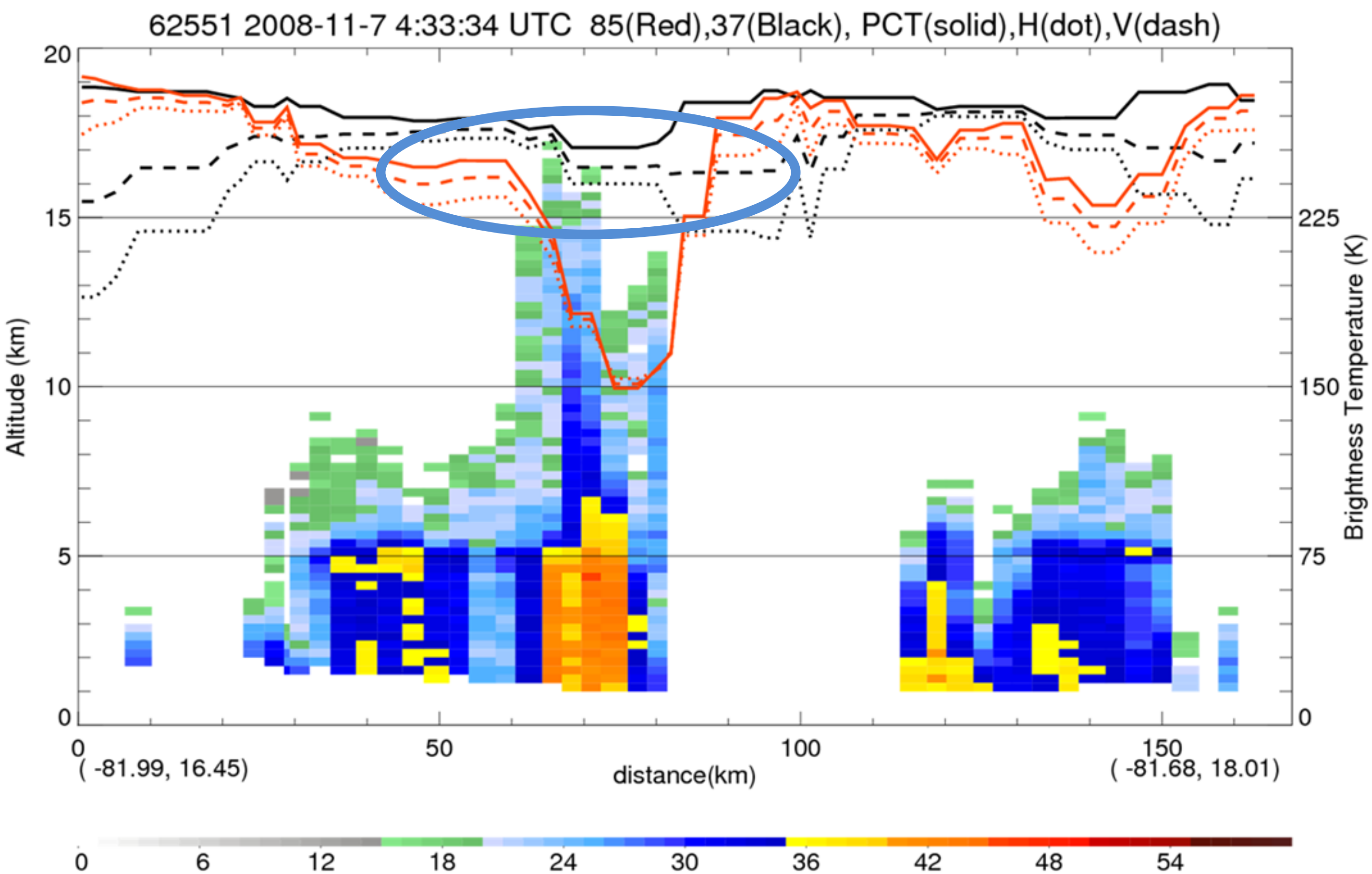
Hot Towers and Hurricanes: Definition





- A "hot tower" is a tropical cumulonimbus cloud that penetrates the tropopause.
- Hot towers can rise up through the eyewall of a hurricane and protrude from the storm top.

Hot Towers Viewed by TRMM



- Minimum Sea Level Pressure: 985.5 hPa
- Maximum Wind Speed: 65.0 kts

- 200816 PALOMA (orbit:62551) from TRMM TCPF database

Hot Towers and Hurricanes

- "…If hot towers are active at least 33 percent of the time during a three-hour period, surface winds have an 82 percent chance of intensifying…"
- "…The trick is to keep an eye on the height of rain that radars see when a hurricane approaches within 200 miles of the coast…"

----*Owen Kelley, 2004, 2005*

Review Questions

1. Name environmental factors that would limit TC’s intensity.
2. Why could weak vertical wind shear limit storm intensity?
3. Usually, at what intensity stage can you observe the eyewall replacement cycles?