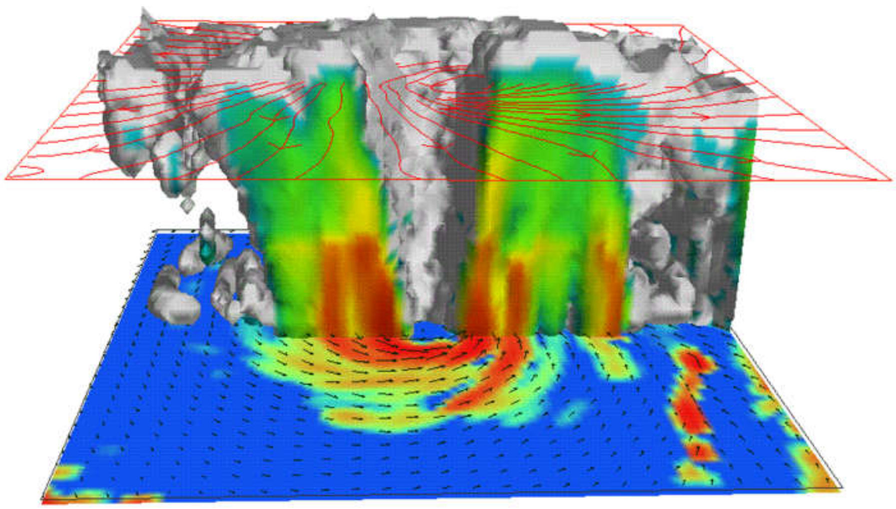
# Tropical Cyclone Structure



MM5 Simulation of Hurricane Andrew        Courtesy of Da-Lin Zhang at Univ. Maryland

# Outline

**Basic Circulations and Structure**

- Primary Circulation
- Secondary Circulation
- Thermal Structure

**Basic Components of a Mature Hurricane**

- Eye
- Eyewall
- Rainbands
- Low-Level Inflow
- Upper-Level Outflow

**Tropical Cyclones as a Carnot Cycle**

**Differences between Tropical and Mid-Latitude Cyclones**

**Fun Facts about Tropical Cyclones**

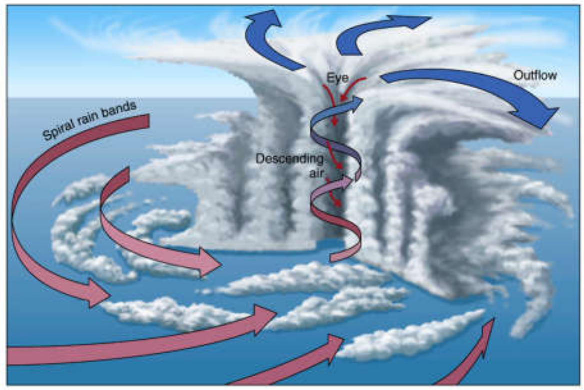
# TC Circulations

**Primary Circulation:**

The horizontal (or tangential) circulation that results from horizontal pressure gradients

**Secondary Circulation:**

The radial and vertical (or transverse) circulation that results from friction, low-level convergence, and buoyancy in the eyewall and rainbands

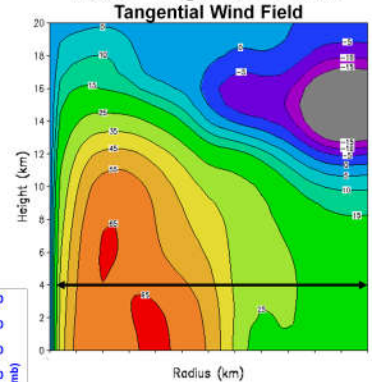


# TC Primary Circulation

**Tangential Wind Field:**

- Maximum is near the surface in the eyewall
- Magnitude is a function of the local horizontal pressure gradient (i.e. cyclostrophic balance)
- Cyclonic flow throughout most of the troposphere
- Anticyclonic flow aloft at larger radii (>100 km)
- In thermal wind balance with the storm's temperature field

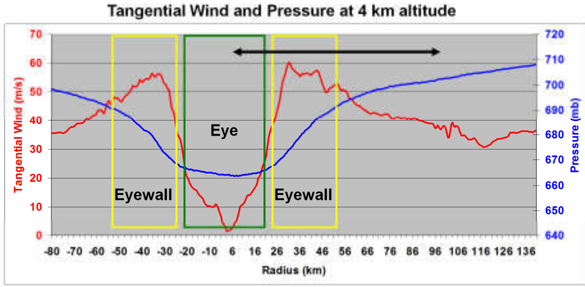
**Radius – Height Cross Section**
**Tangential Wind Field**




**Positive values are cyclonic (or counter-clockwise)**

**Negative values are anticyclonic (or clockwise)**

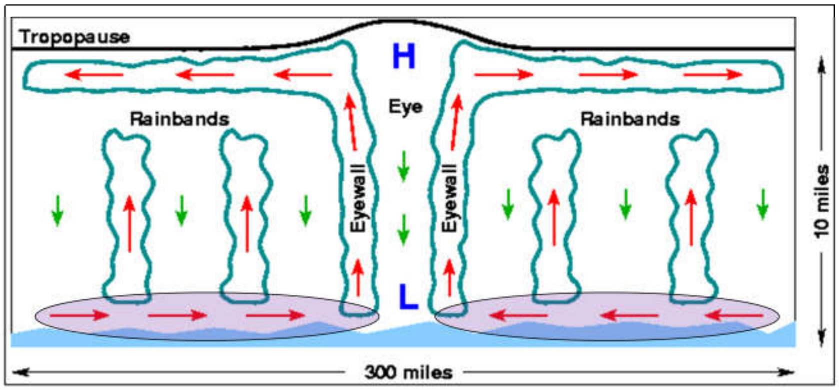
**Tangential Wind and Pressure at 4 km altitude**



# TC Secondary Circulation

**Radial Wind Field at Low-levels:**

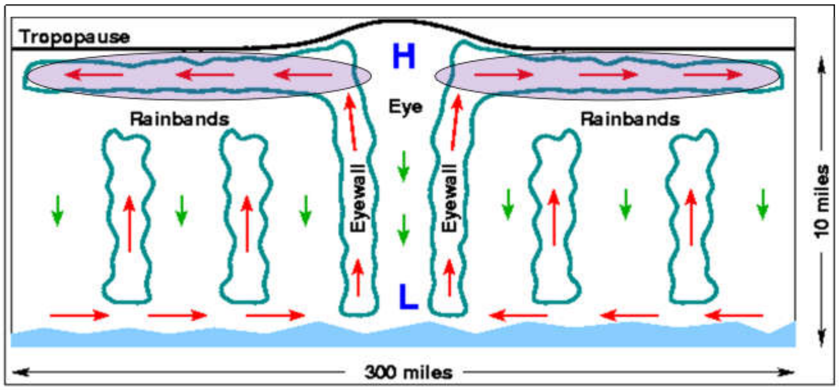
- **Inflow** driven by friction in the boundary layer
- Maximum found near the eyewall where the pressure gradient is maximum
- Supplies the rainbands and eyewall with warm moist air



# TC Secondary Circulation

**Radial Wind Field at Upper-levels:**

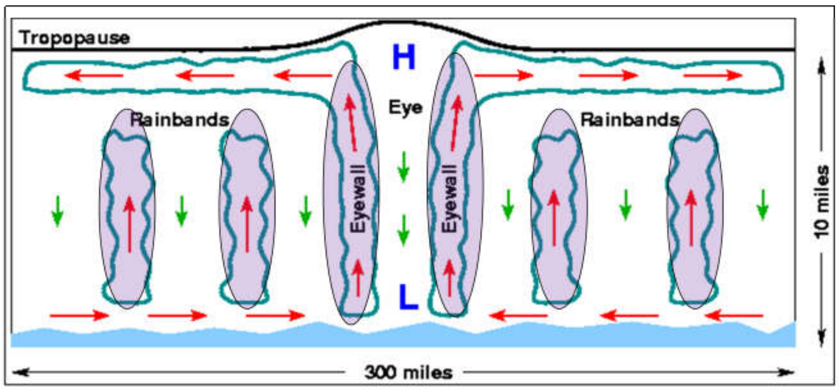
- **Outflow** driven by forced ascent from below and the pressure gradient associated with the upper-level anticyclone
- Maximum found at large radii (> 200 km)



# TC Secondary Circulation

**Vertical Wind Field:**

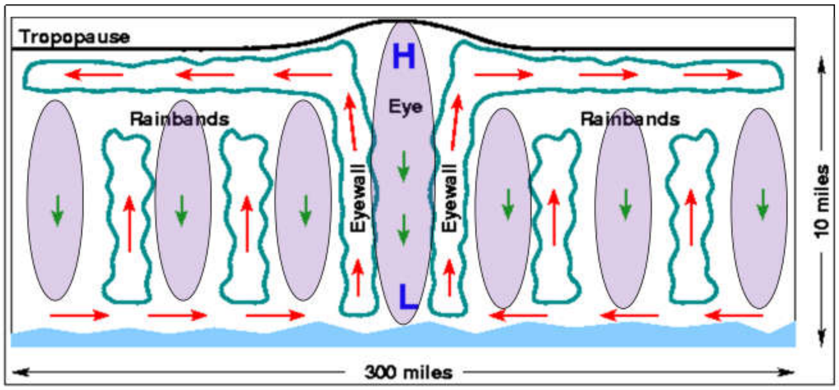
- **Ascent** driven by low-level convergence and local buoyancy
- Primarily focused in narrow channels (the eyewall and rainbands)
- Maximum frequently observed in the upper-level eyewall (~10-20 m/s)
- Resulting latent heat release contributes to the “warm core”



# TC Secondary Circulation

**Vertical Wind Field:**

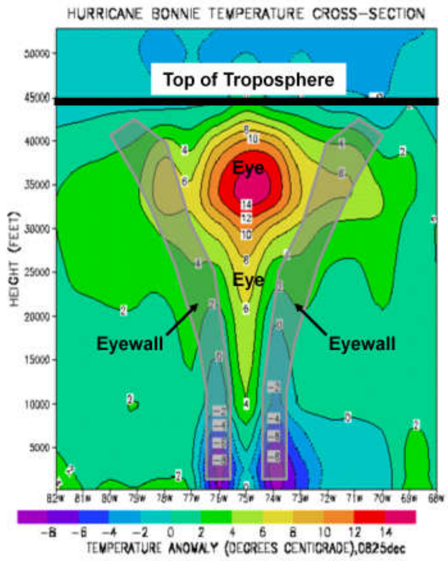
- **Descent** driven by mass balance and convergence aloft.
- Frequently spread over wide regions (the eye) and bands (“moats”).
- Magnitudes are much weaker (~0.1-0.2 m/s)
- Resulting adiabatic warming contributes to the warm core



# Tropical Cyclone Thermal Structure

**Temperature Field:**

- Tropical cyclones are "warm core"
- Air near the center of circulation (in the eye) is much warmer than air in the large-scale environment
- Maximum temperature anomalies located in the upper-level eye
- Anomalies result from eye subsidence and eyewall latent heat release
- The warm core is responsible for the extremely low surface pressures in the eye and large pressure gradients across the eyewall
- Warm core is in thermal wind balance with the primary circulation

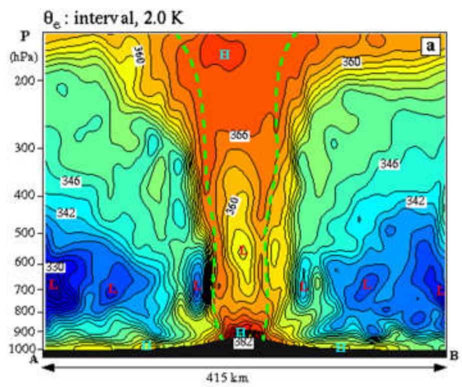


# Tropical Cyclone Thermal Structure

**Equivalent Potential Temperature:**

- A rough measure of the total thermodynamic energy (includes both temperature and moisture)
- Nearly conserved for both dry and moist adiabatic processes
- Maxima are frequently located in both the upper and lower eye.
  - Upper maximum caused by very warm temperatures and low pressures
  - Lower maximum caused by very moist air, moderately warm temperatures, and low pressures

**MM5 Simulation: Hurricane Andrew**
**Equivalent Potential Temperature**



# Tropical Cyclone Eyes

**Typical Conditions**

- Light winds
- Clear or partly cloudy skies
- Little or no precipitation
- Stratocumulus layer near surface
- Range in diameter from 8 - 200 km
- Size is not correlated with intensity

**Origin**

- Formed by air sinking from upper levels to lower levels

**Role**

- Home to the warm core
- "Buoyancy reservoir" for eyewall convection

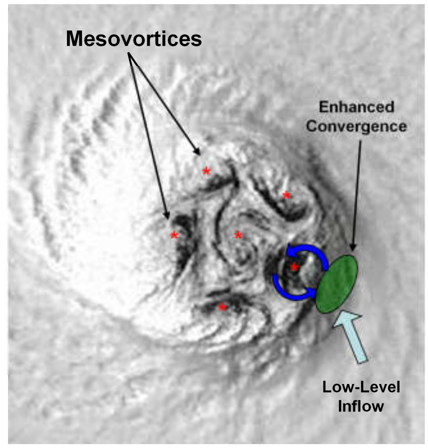
**Photograph from the NOAA WP-3D**
**The Eye and Eyewall of Hurricane Olivia (1994)**

**Photo courtesy of Mike Black at NOAA HRD**

# Tropical Cyclone Eyes

**Eye Mesovortices**

- Distinct cyclonic and anti-cyclonic features in the low-level clouds
- 5-20 km in diameter
- May play a significant role in tropical cyclone evolution
    - Generate buoyant convection in the eyewall by ejecting the warm, moist air from the low-level eye
    - Generate enhanced convergence at the eyewall cloud base

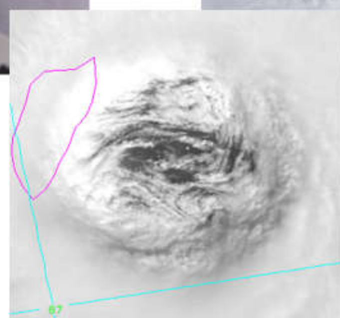



Hurricane Isabel (2003) SSMI Visible

# Tropical Cyclone Eyes

**Hurricane France (2004) ISS**

**Hurricane Isabel (2003) ISS**



**Hurricane Wilma (2005) GOES**

# Tropical Cyclone Eyewalls

**Basic Statistics**

- "Ring" of convection around the eye
- Strongest winds near the surface
- Strongest updrafts (up to 25 m/s)
- Highest clouds (up to 15 km)
- Maximum pressure gradient
- Maximum temperature gradient

**Roles**

- Primary upward branch of the secondary circulation
- Contributes to the warm core via latent heat release

Photograph from the NOAA WP-3D
The Eye and Eyewall of Hurricane Olivia (1994)

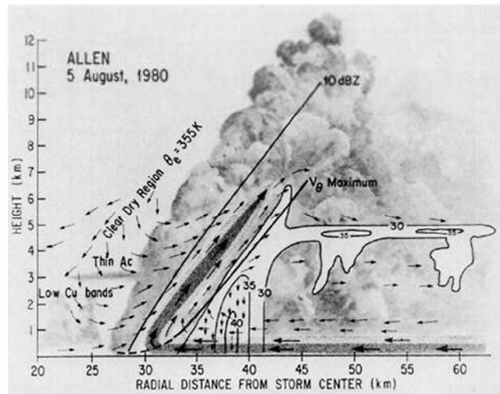
Photo courtesy of Mike Black at NOAA HRD

# Tropical Cyclone Eyewalls

**Typical Detailed Structure**

- Convection slopes outward with height (30°-45° from vertical)
- Primary updraft located 2-5 km **inside** the tangential wind and radar reflectivity (precipitation) maxima
- Median (50% level) updraft magnitude is ~2.0 m/s
- 90% of convective updrafts are less than 8.0 m/s in magnitude
- Local eyewall "environment" contains CAPE < 500 J/kg
- Buoyant convection is common, but the observed local buoyancies within updrafts are often < 0.2°C

**Aircraft Observation Composite of Eyewall Structure**



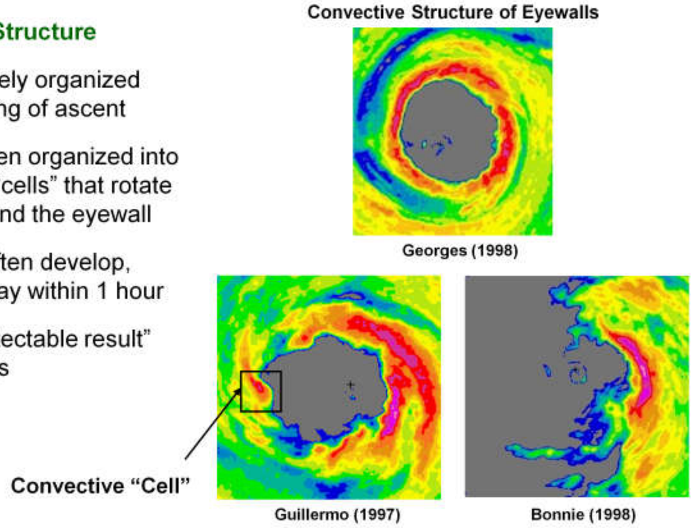

From Jorgensen (1984)

# Tropical Cyclone Eyewalls

**Typical Detailed Structure**

- Convection is rarely organized into a uniform ring of ascent
- Convection is often organized into multiple distinct "cells" that rotate cyclonically around the eyewall
- Individual cells often develop, mature, and decay within 1 hour
- Cells are the "detectable result" of strong updrafts

**Convective Structure of Eyewalls**

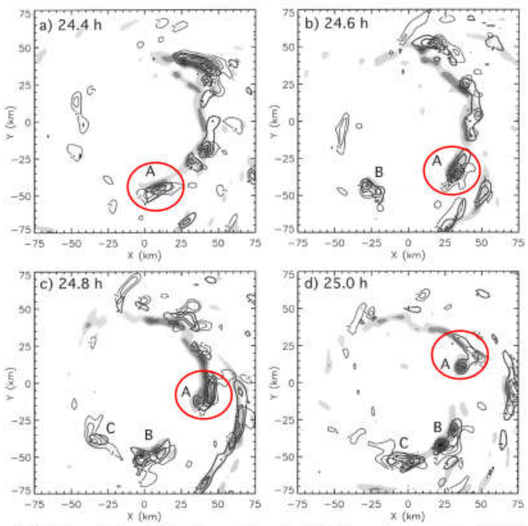


# Tropical Cyclone Eyewalls

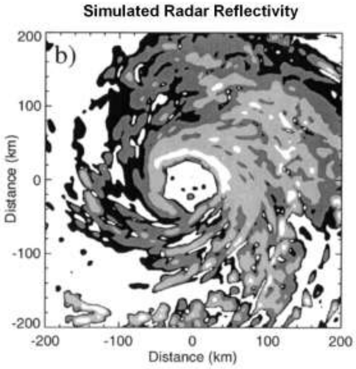
## Typical Detailed Structure

• Radar reflectivity maxima are often "downwind" of their parent updrafts

Upward Vertical Velocity




Simulated Radar Reflectivity

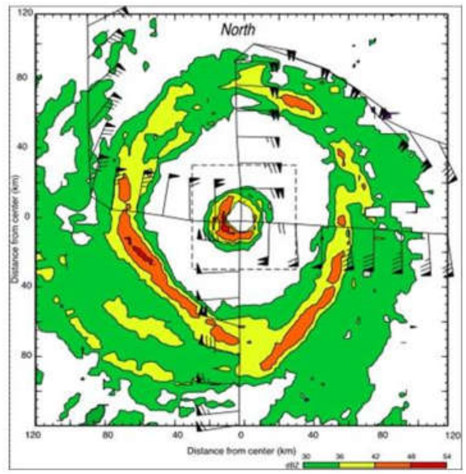



MM5 Simulation of Hurricane Bonnie (1998)    Braun et al . (2006)

# Tropical Cyclone Eyewalls

**Multiple Eyewalls**

- More then 50% of tropical cyclones have multiple eyewalls at some point in their life
- Most common in major tropical cyclones (e.g. Cat 3-4-5)
- Eyewall Replacement Cycles
    - Major influence on storm intensity
    - Outer eyewall forms and begins to contract
    - Inner eyewall collapses
    - Outer eyewall continues to contract and replaces the inner eyewall

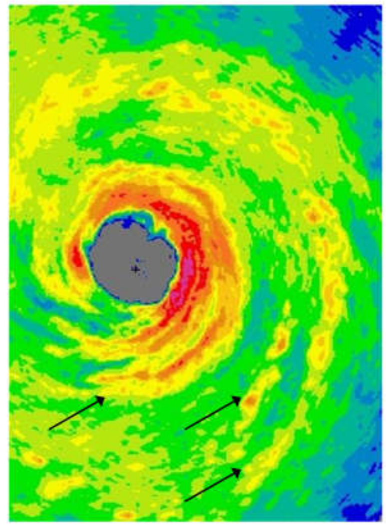



**Hurricane Gilbert (1988)**

# Tropical Cyclone Rainbands

**Basic Statistics**

- Localized bands of precipitation outside the eyewall
- Often spiral inward
- Convection is shallower (up to 10 km)
- Weaker updrafts (up to 20 m/s)
- Local rainband "environment" contains CAPE ~500 to 2000 J/kg
- Often contain prominent wind and temperature maxima



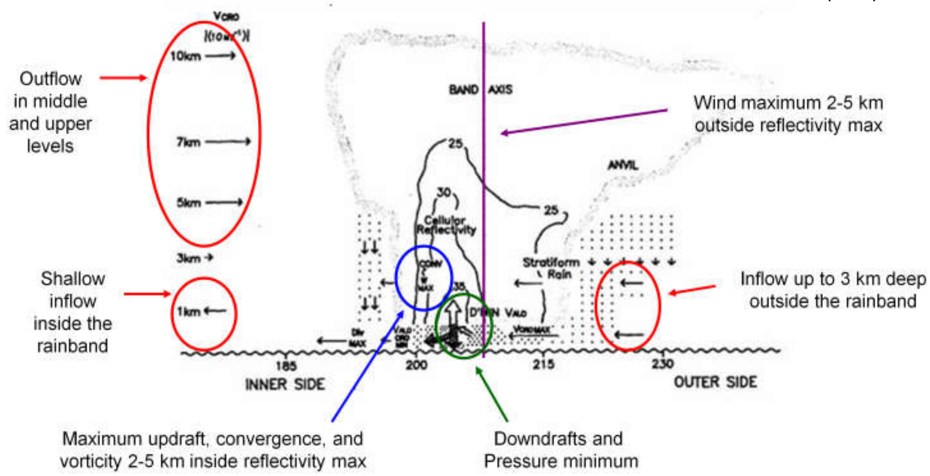
**Roles**

- Contribute to the warm core via latent heat release
- Moisten the atmosphere beyond the eyewall (help protect the eyewall)

# Tropical Cyclone Rainbands

**Typical Cross-Band Kinematic and Precipitation Structure**

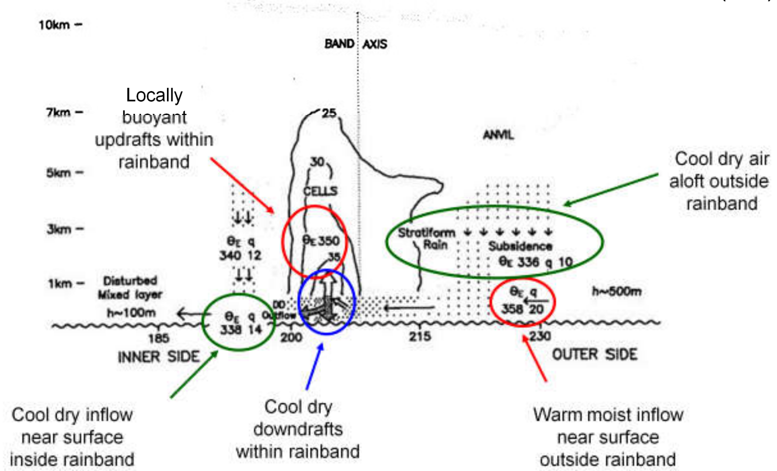
**From Powell (1990)**



# Tropical Cyclone Rainbands

**Typical Cross-Band Thermodynamic Structure**

From Powell (1990)

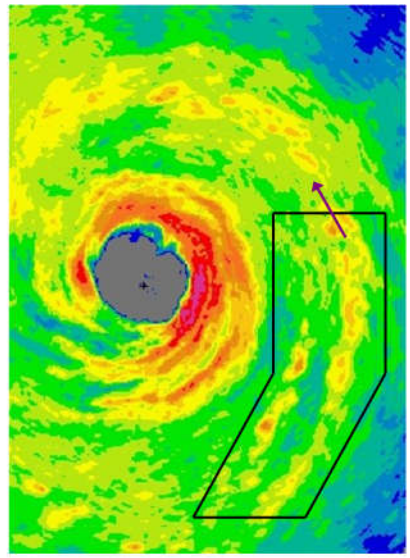


# Tropical Cyclone Rainbands

### Typical Along-Band Structure

**Upwind Segments**

- Cellular structures dominant
- Convergence maximum
- Updrafts are frequent, buoyant, and relatively strong (2-5 m/s)
- Downdrafts are rare and often weak (~ -1 m/s)
- Inflow warm and moist

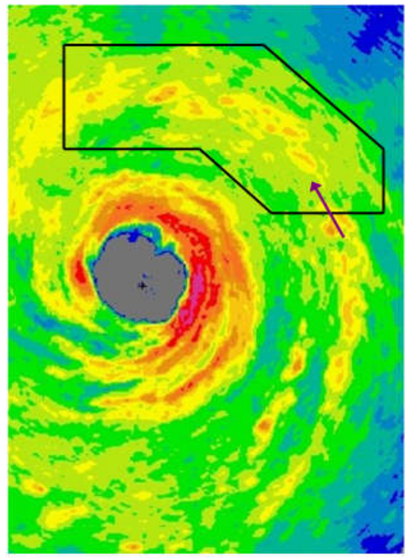


# Tropical Cyclone Rainbands

**Typical Along-Band Structure**

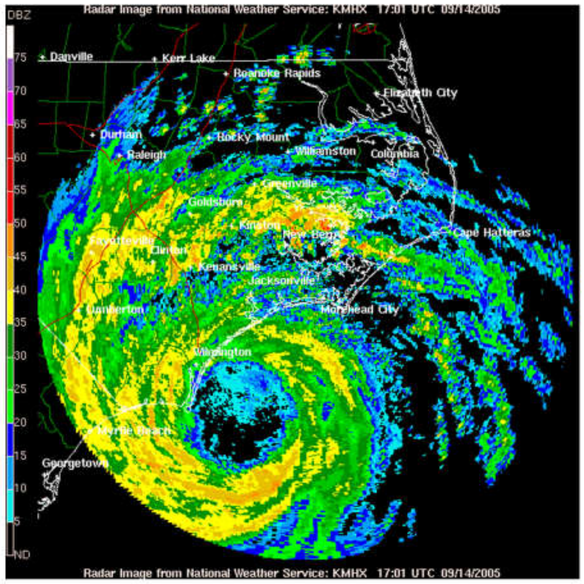
Downwind Segments

- Stratiform precipitation dominant
- Updrafts are less frequent, less buoyant and relatively weak (1-3 m/s)
- Downdrafts are more common, often contain cool/dry air, and are stronger (up to -3 m/s)
- Occasional "cold pools" near surface



## Tropical Cyclone Rainbands

**Hurricane Ophelia (2005)**

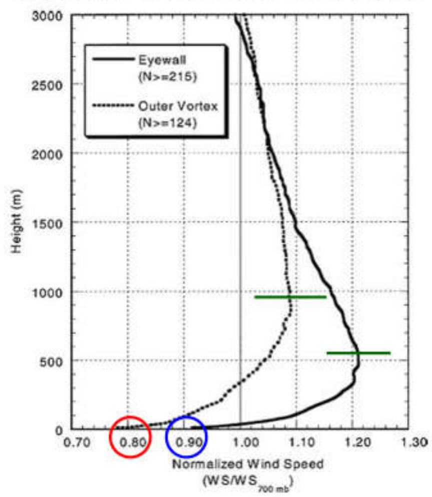


# Tropical Cyclone Inflow Layer

**Kinematic Structure**

- Total wind increases with height in the boundary layer
- Winds must be "reduced to the surface"
  - Eyewall: ~90% of observed wind
  - Outer: ~80% of observed wind
- Tangential wind maximum located at the top of the frictional boundary layer
- Radial wind maximum located near the surface
- The **depth** of the inflow layer decreases upon approach to the eyewall
  - ~1.0 to 2.0 km at r > 150 km
  - ~0.5 km at r = 50 km

**Mean Wind Profile from GPS Dropwindsondes**



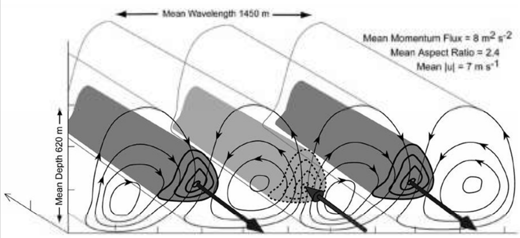

From Franklin et al. (2003)

# Tropical Cyclone Inflow Layer

## Kinematic Structure

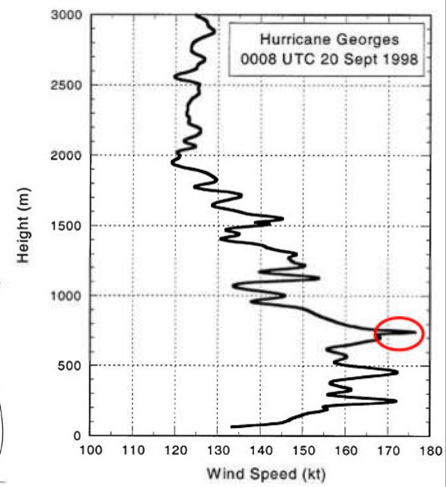
- Inflow near the eyewall often contains low-level jets
- The jets may be associated with boundary layer rolls

**Hurricane Boundary Layer Rolls**




From Morrison et al. (2005)

**Wind Profile from one GPS Dropwindsonde**




From Franklin et al. (2003)

# Tropical Cyclone Inflow Layer

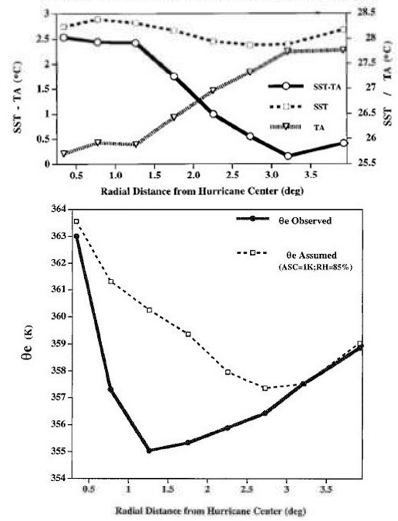
**Thermodynamic Structure**

- Sensible and latent heat fluxes from the ocean continuously act to increase the temperature and humidity of the air

- Adiabatic cooling (from the decrease in pressure) acts on the inflow
- Rainbands tap the warm moist air to supply their convection and often inject cold dry air
- Evaporation of sea spray acts to cool, but moisten the air (net $\theta_e$ decrease)
- Dissipative heating helps to offset

- The livelihood of eyewall convection relies on the surface fluxes to dominate

**Composite BL profile from 738 buoys**




**From Cione et al. (2000)**

# Tropical Cyclone Inflow Layer

Sea State in Hurricane Isabel (2003)

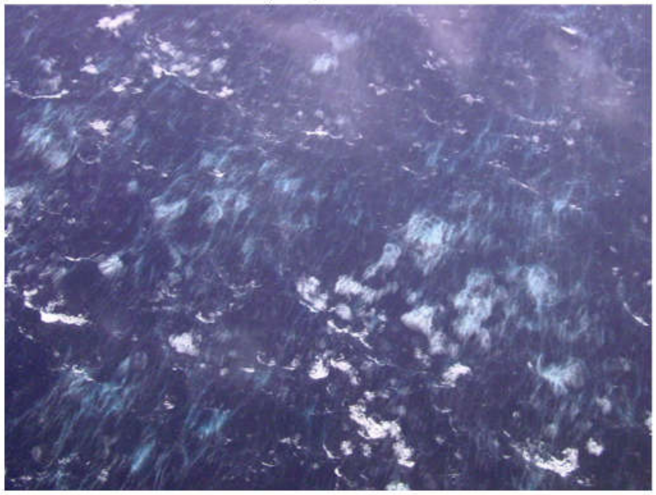


Photo courtesy of Mike black at NOAA HRD

# Tropical Cyclone Inflow Layer

**Thermodynamic Structure**

• Budget analyses suggest hurricane rainbands can be a significant inhibitor to eyewall convection (and TC intensification)

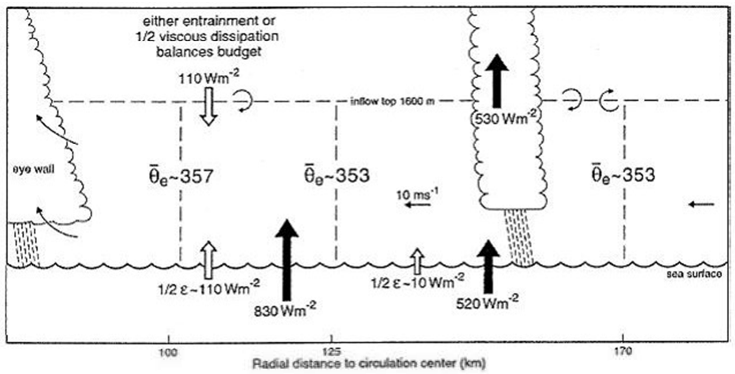



FIG. 15. A height–radius schematic of the inflow to Hurricane Bonnie. From 170 to 125 km,

From Wroe and Barnes (2003)

# Tropical Cyclone Outflow Layer

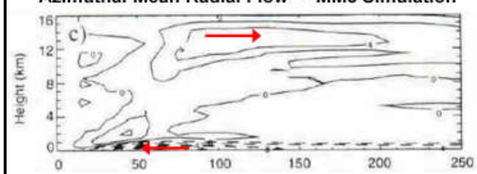
**Basic Structure**

- Cyclonic at small radii (r < 200 km)
- Anti-cyclonic at larger radii

- Maximum channel near tropopause
- Outflow often observed through significant depths (~5-8 km)

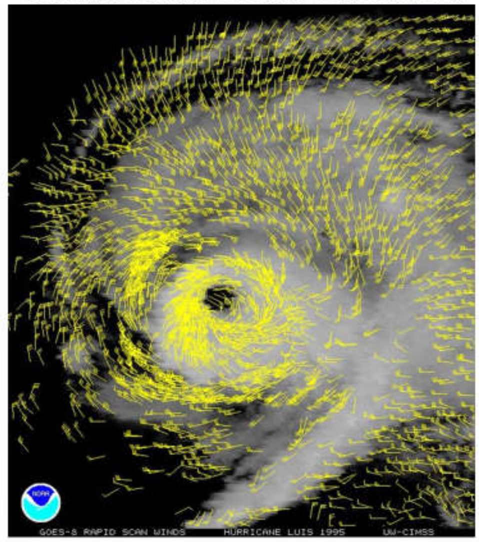
- Can be enhanced by approaching synoptic-scale troughs

**Azimuthal Mean Radial Flow - MM5 Simulation**




From Braun and Tao (2000)

**Cloud-tracked wind vectors from GOES rapid scan**



# Tropical Cyclones and the Carnot Cycle

The **Carnot Cycle** describes an idealized (reversible) heat engine and can be approximately applied to tropical cyclones as a theoretical model of the secondary circulation

In 1824, Sadi Carnot proposed an "Idealized Heat Engine"

- A heat engine converts input energy (maybe from a fire) into work (like a steam engine)
- Each heat engine has an efficiency (E):

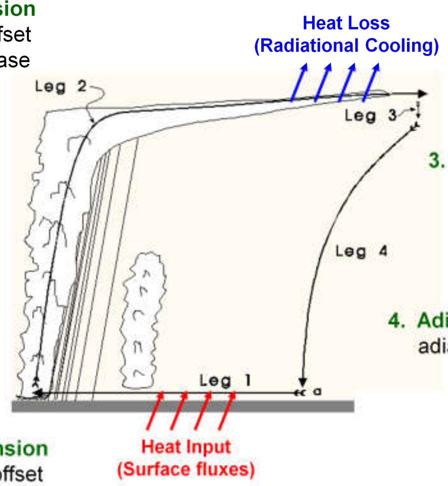
Temperature of "Hot" Reservoir (SST)

Temperature of "Cold" Reservoir (outflow level)

$$E = \frac{T_H - T_C}{T_H}$$

# The Tropical Cyclone Carnot Cycle

**2. Adiabatic Expansion**
cooling partially offset by latent heat release




**3. Isothermal Compression**
adiabatic warming offset by radiational cooling

**4. Adiabatic Compression**
adiabatic warming

**1. Isothermal Expansion**
adiabatic cooling offset by surface fluxes

# The Tropical Cyclone Carnot Cycle

How **efficient** is a tropical cyclone as a Carnot cycle?

Temperature of "Hot" Reservoir (SST) → $T_H$

Temperature of "Cold" Reservoir (outflow level) → $T_C$

$$E = \frac{T_H - T_C}{T_H}$$

| | |
|---|---|
| Sea Surface Temperatures (SSTs): | 26° to 30°C |
| Outflow Temperatures: | -60° to -80°C |
| Efficiency (tropical cyclones): | 30 to 35% |
| Efficiency (automobiles): | ~25% |

In **reality**, a tropical cyclone is not a true Carnot cycle. Why?

- Inflow is not isothermal (Leg 1)
- Ascent is not reversible due of rainfall (Leg 2)

# Tropical vs. Mid-Latitude Cyclones

| | Tropical Cyclone | Mid-Latitude Cyclone |
|---|---|---|
| Size (diameter) | ~1000 km | ~4000 km |
| Lifetime | ~4 days | ~6 days |
| Minimum Surface Pressure | 1000-880 mb | 1005-970 mb |
| Level of Maximum Winds | Near Surface (Warm Core) | Near Tropopause (Cold Core) |
| Warm/Cold Fronts? | No | Yes |
| Primary Energy Source | Warm Oceans | Horizontal Temperature Gradients |

# Tropical Cyclone Fun Facts

The **Latent Energy Release** in a strong tropical cyclone is enormous

- Roughly 1.5 x $10^{14}$ Watts

- Greater than the global electrical power consumption (~1.0 x $10^{13}$ W)
- Greater than ten times (10x) than the energy released by the atomic bomb dropped on Hiroshima (~6.3 x $10^{12}$ W)

Where does this energy go?

- Roughly 99.75% is used to simply raise the air parcels from the surface to the upper levels

- The other 0.25% is used to maintain the warm core and drive the primary circulation

# Tropical Cyclone Structure

**Summary**

• Primary Circulation (structure and origin)
• Secondary Circulation (structure and origin)
• Thermodynamic Structure (structure and origin)

• Eye (structure, origin, role)
• Eyewall (structure, origin, role)
• Rainbands (variety, structure, origin, role)
• Inflow Layer (structure, role, impacts)
• Outflow Layer (structure)

• TCs as Carnot Heat Engines (basic concept, efficiency, reality)

• Differences between Tropical and Mid-latitude Cyclones

# References


Braun, S. A., M. T. Montgomery, and Z. Pu, 2006: High resolution simulation of Hurricane Bonnie (1998), *J. Atmos. Sci.*, **63**, 19-42

Braun, S. A., and W.-K. Tao, 2000: Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.,* **128**, 3941-3961.

Cione, J. J., P. G. Black, and S. H. Houston, 2000: Surface observations in the hurricane environment. *Mon. Wea. Rev.,* **128**, 1550-1561.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting*, **18**, 32-44.

Jorgensen, D. P., 1984: Mesoscale and convective-scale characteristics of mature hurricanes. Part I: General Observations by research aircraft. *J. Atmos. Sci.*, **41**, 1268-1285.

Jorgensen, D. P., 1984: Mesoscale and convective-scale characteristics of mature hurricanes. Part II: Inner-core structure of Hurricane Allen (1980). *J. Atmos. Sci.*, **41**, 1287-1311.

Morrison, I., S. Businger, F. Marks, P. Dodge, and J. A. Businger, 2005: An observational case for prevalence of roll vortices in the hurricane boundary layer., *J. Atmos. Sci.*, **62**, 2662-2673.

Powell, M, D, 1990: Boundary layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale rainfall and kinematic structure. *Mon. Wea. Rev.,* **118**, 891-917.

Powell, M, D, 1990: Boundary layer structure and dynamics in outer hurricane rainbands. Part II: Downdraft modification and mixed layer recovery. *Mon. Wea. Rev.,* **118**, 918-938.

Wroe, D. R., and G. M. Barnes, 2003: Inflow layer energetics of Hurricane Bonnie (1998) near landfall. *Mon. Wea. Rev.,* **131**, 1600-1612.