地球系统科学前沿讲座

台风研究现状和问题

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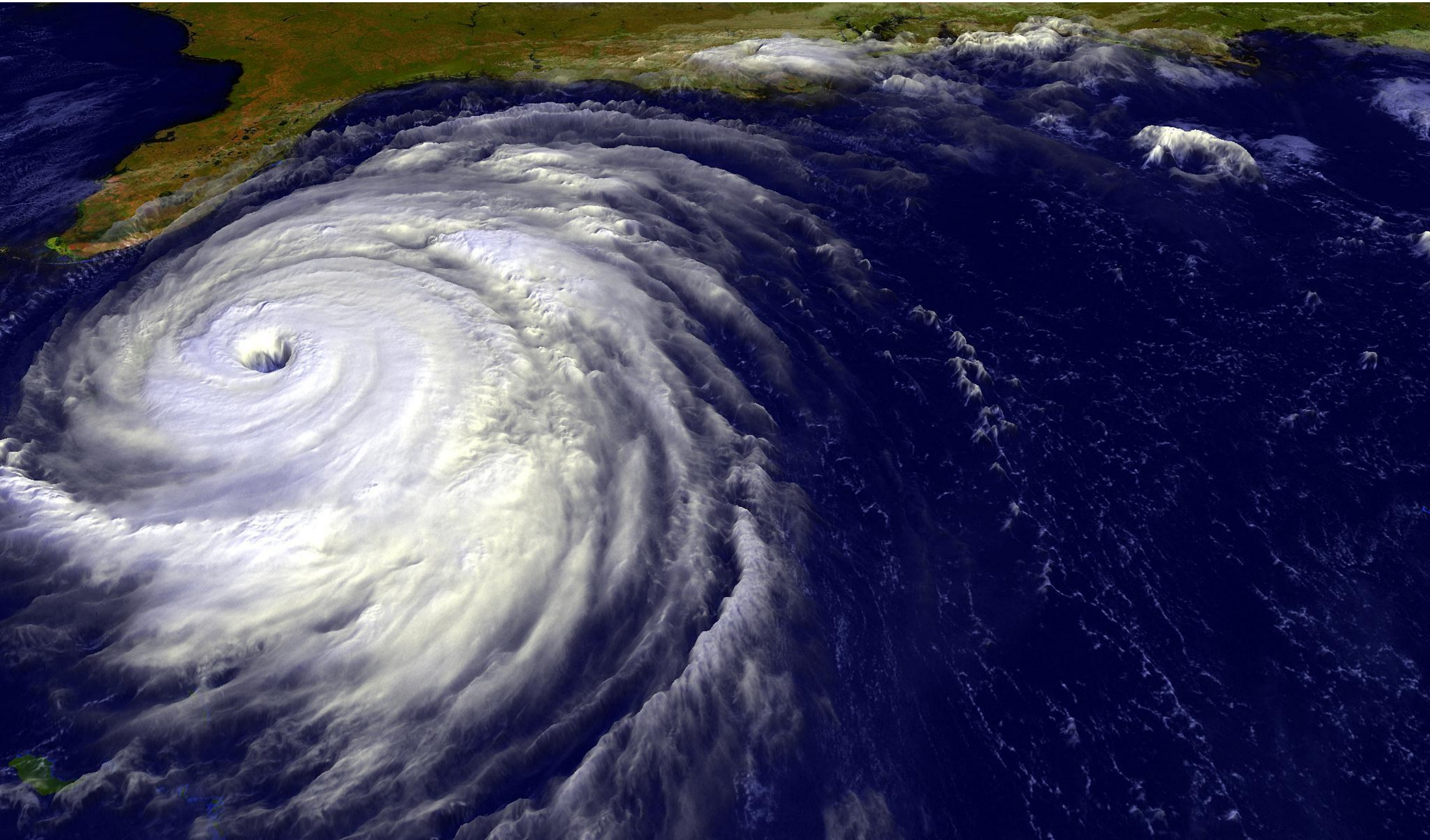
2013.3.18

Satellite image of Hurricane Floyd approaching the east coast of Florida in 1999. The image has been digitally enhanced to lend a three-dimensional perspective.
Credit: NASA/Goddard Space Flight Center.



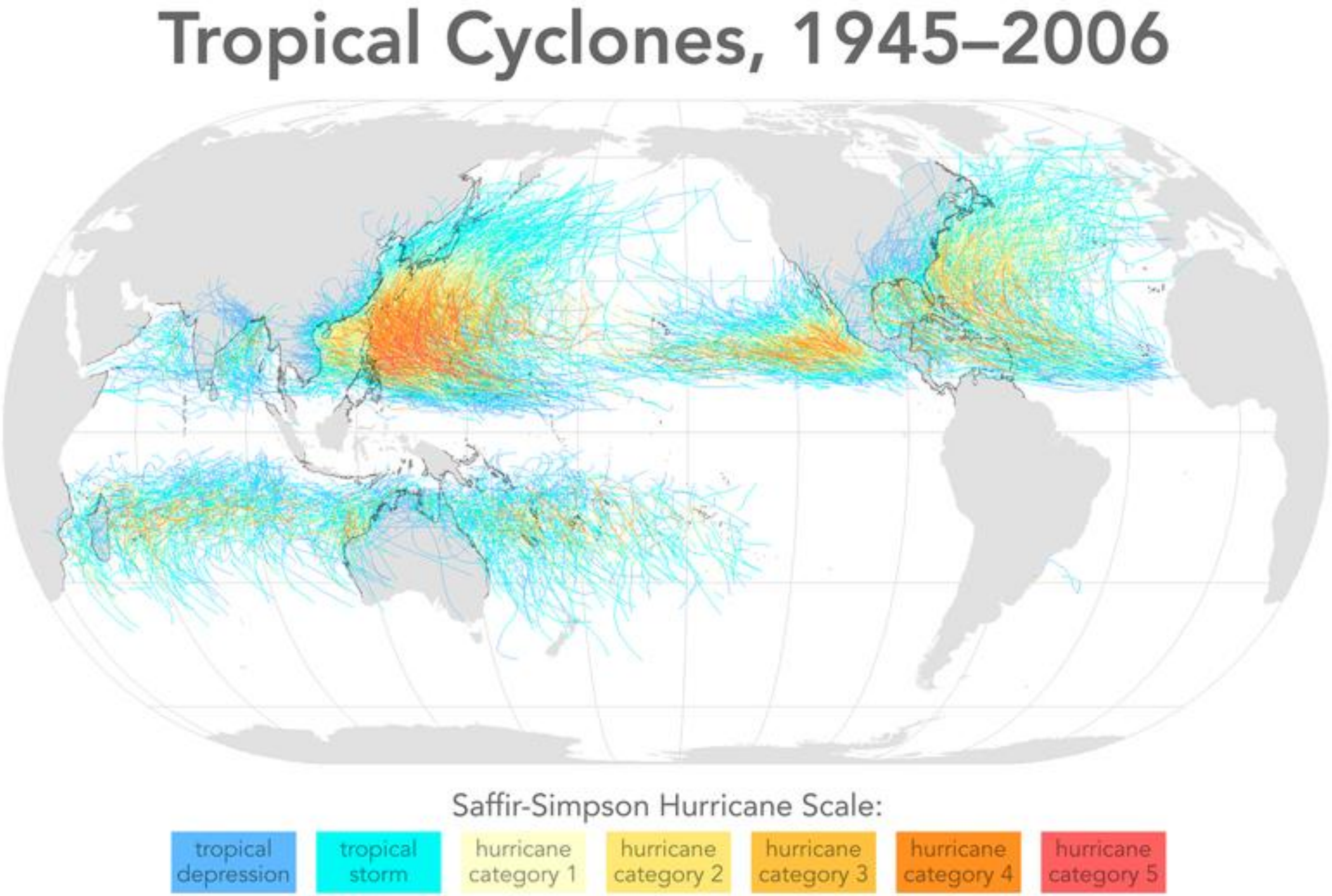
Some questions

- How many TC each year on the earth and why?
- What fuels TC?
- How TC spins up?
- What controls TC genesis?
- What is the basic structure of TC?
- How TC impacts ocean and climate?
- What is the current status of TC forecast?
- What controls a TC size?

Outline

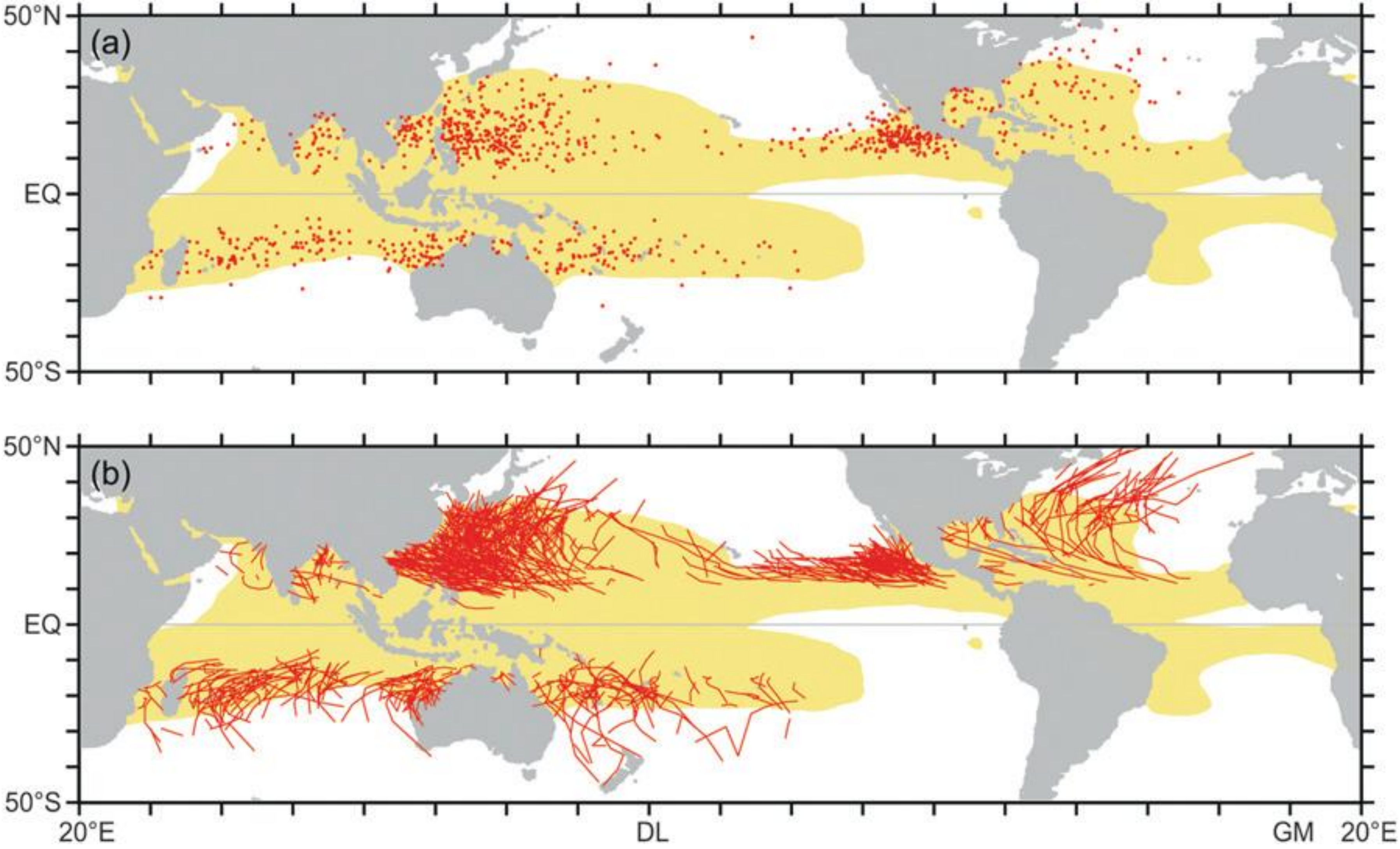
- TC climatology
- TC structure
- TC maintenance and intensification
- TC genesis
- TC size
- TC and climate

1. Climatology

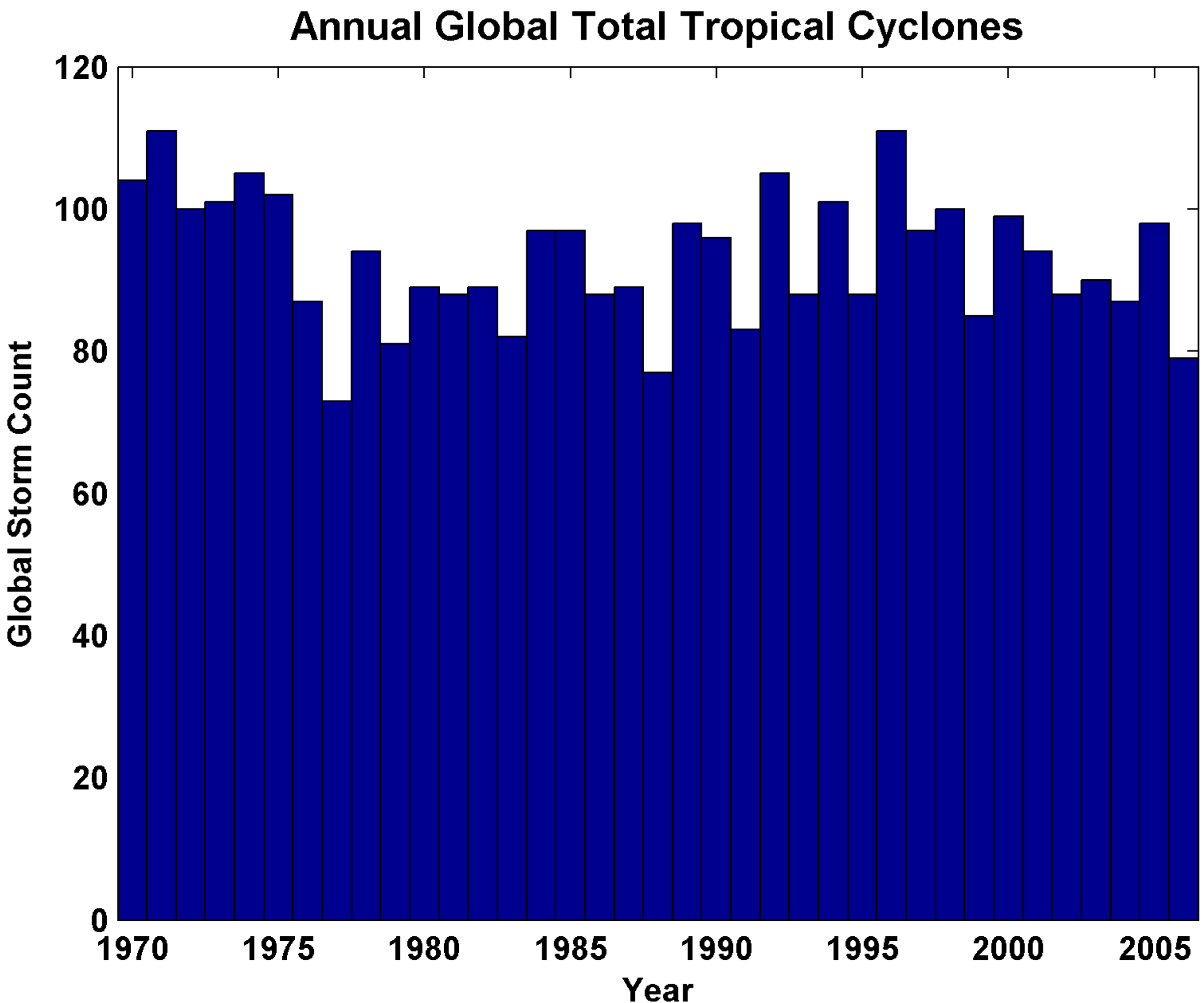


Tropical Cyclones, 1945–2006

Current climatology (1970-1989)

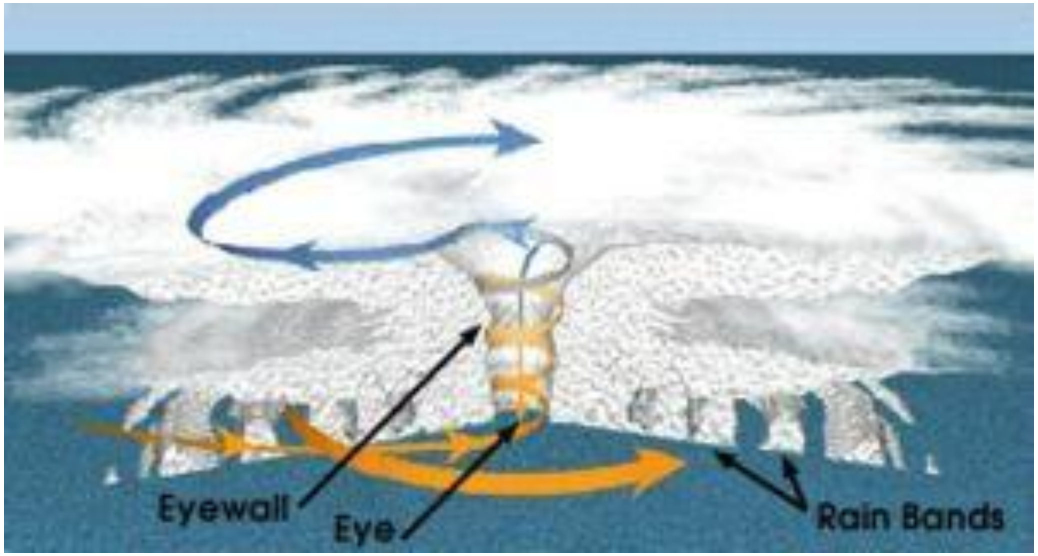


Global total number



2. TC structure

- Eye, eyewall
- Rain band
- Primary and secondary circulation
- Eyewall mesovortex
- Annular hurricanes



Katrina

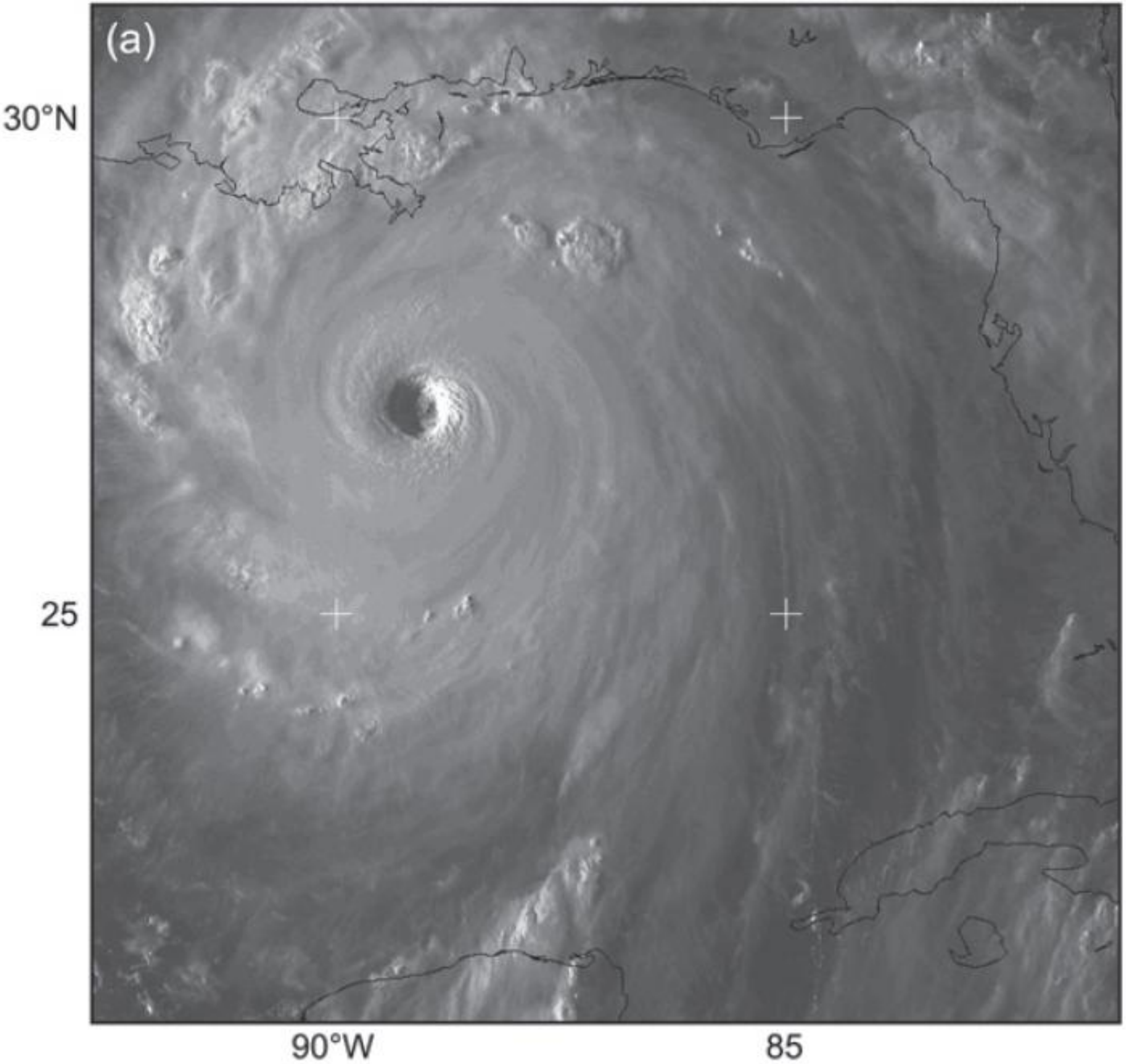
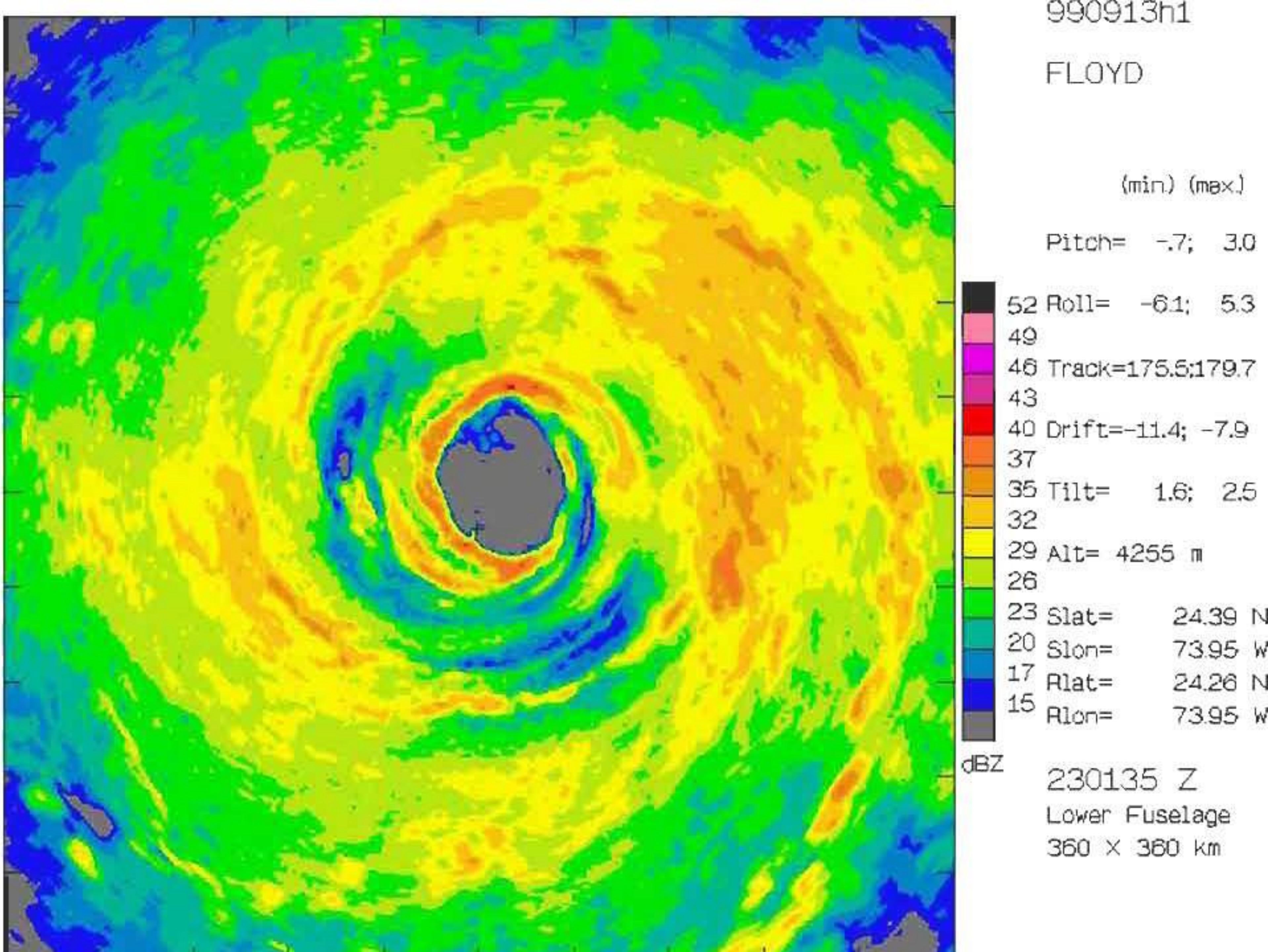
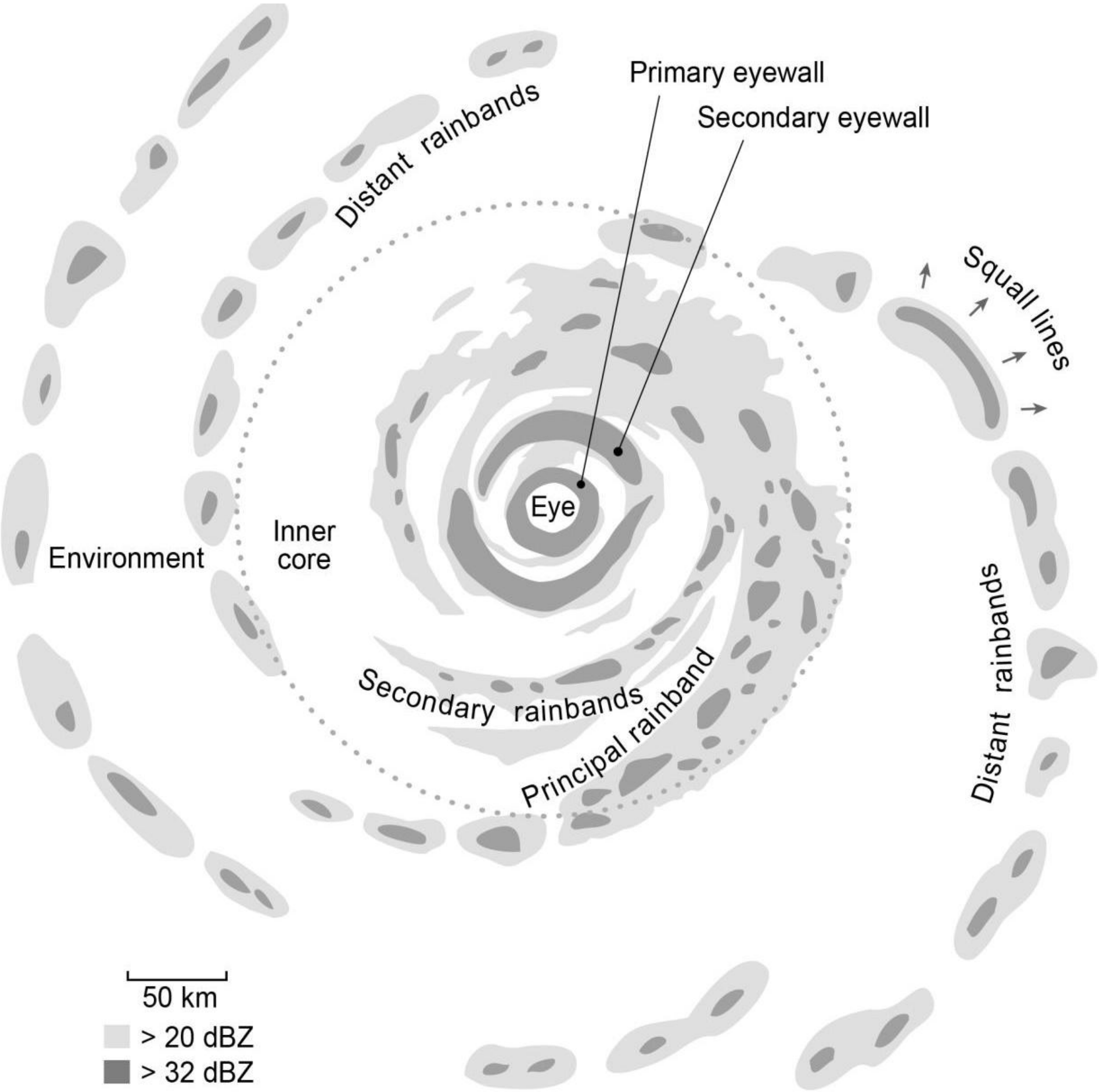


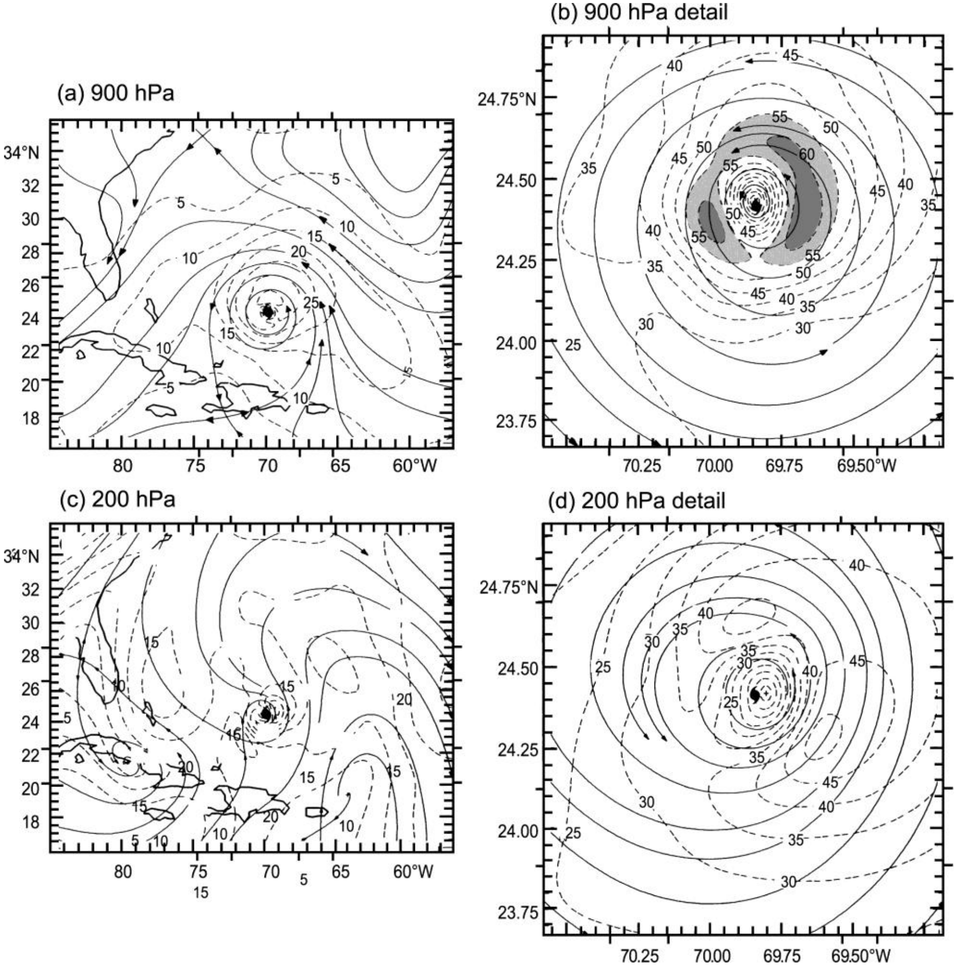
Figure 11 Photograph inside the eye of Hurricane Olivia at 2136 UTC on 25 September 1993, showing the downward cascade of moist air along the inner edge of the eyewall. The moist boundary layer is most clearly visible along the border between the eyewall and the sky that runs from the left center to the upper right. The eyewall slopes away from the camera so that the line of sight is tangent to it along the border. This geometry renders the cascade more visible because it provides a long optical path in the moist air. The mist visible against the sky derives from cloud and precipitation particles mixed a kilometer or two into the eye. (From Willoughby 1998. Photograph by James Franklin.)


990913h1
FLOYD
(min.) (max.)
Pitch= -.7; 3.0
Roll= -6.1; 5.3
Track=175.5;179.7
Drift=-11.4; -7.9
Tilt= 1.6; 2.5
Alt= 4255 m
Slat= 24.39 N
Slon= 73.95 W
Rlat= 24.26 N
Rlon= 73.95 W
52
49
46
43
40
37
35
32
29
26
23
20
17
15
dBZ
230135 Z
Lower Fuselage
360 X 360 km


Primary eyewall
Secondary eyewall
Distant rainbands
Squall lines
Eye
Inner core
Environment
Secondary rainbands
Principal rainband
Distant rainbands
50 km
> 20 dBZ
> 32 dBZ

Houze 2010

Primary Circulation Structure



(Figure obtained from Houze (2010), © 2010 American Meteorological Society.)

Vertical Schematic

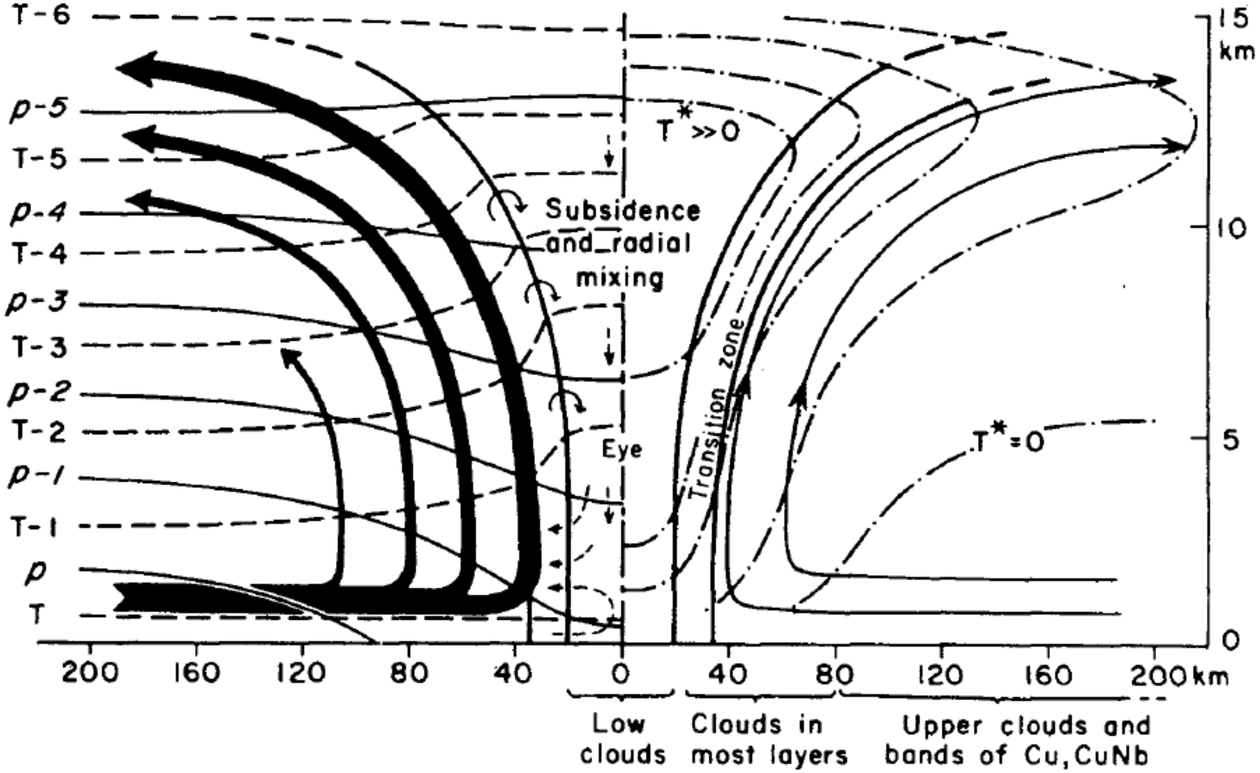


Fig. 2.1 Schematic cross section through the core of a tropical cyclone, showing the warm core, low pressure anomaly, and secondary circulation (Palmen and Newton 1969). Pressure (solid) and temperature (dashed) surfaces are shown on the left side, and temperature deviations from a standard atmosphere (dashed-dotted) are shown on the right side.

(Figure obtained from Willoughby (1995), © 1995 World Meteorological Organization.)

Mature Hurricane: Vertical Structure

tangential wind (kt)

temperature anomaly (K)

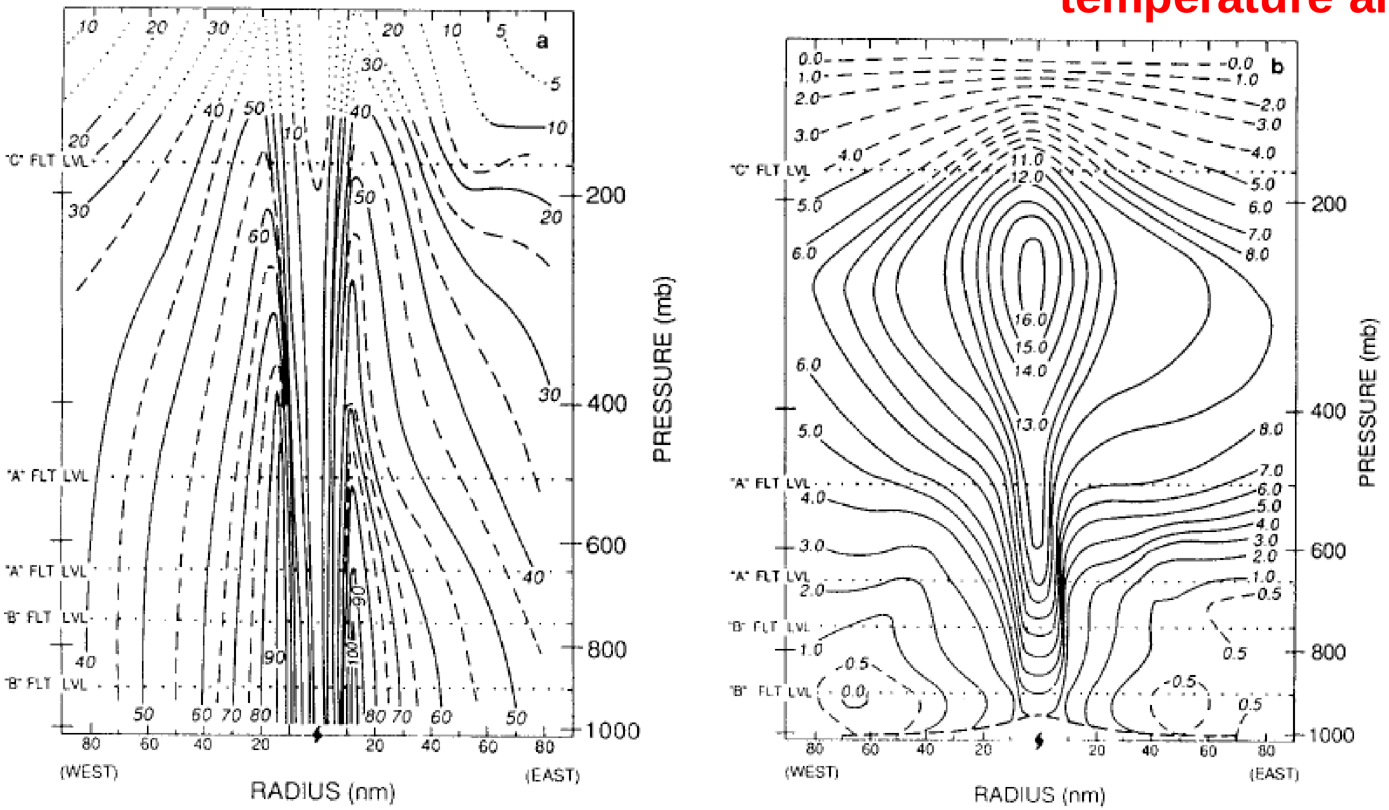
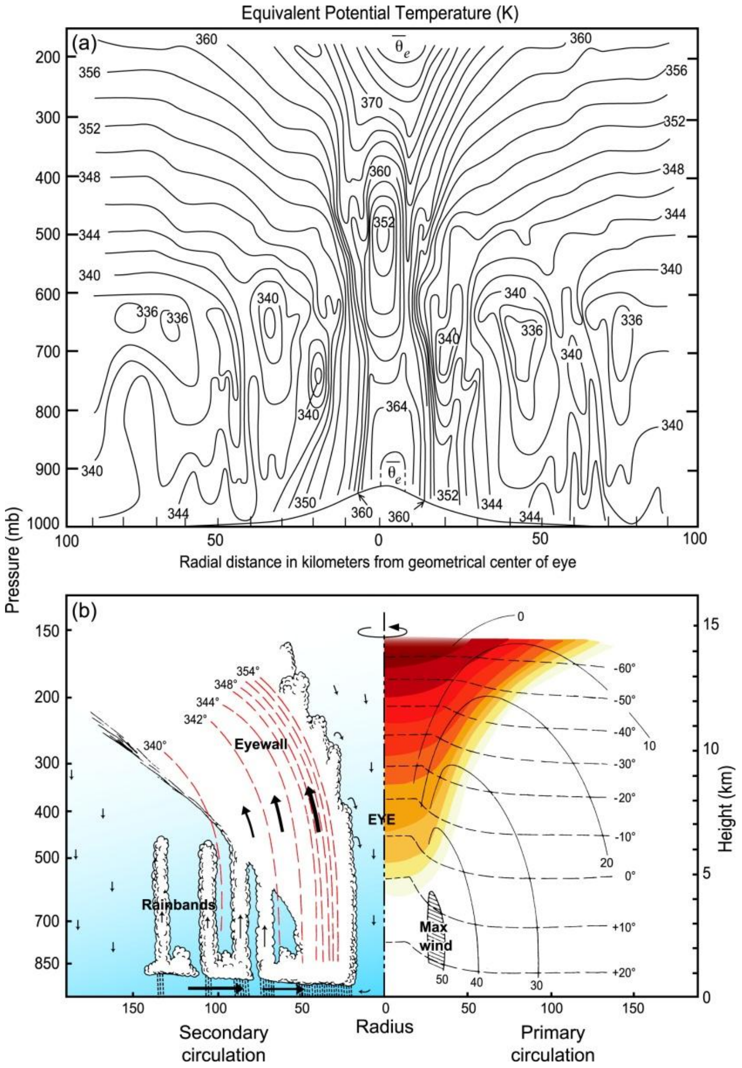


Fig. 2.6 Vertical cross sections of (*a*) azimuthal wind (kt), and (*b*) temperature anomaly (°K) in Hurricane Hilda of 1964 (Hawkins and Rubsam 1968).

(Figure obtained from Willoughby (1995), © 1995 World Meteorological Organization.)

Thermodynamic Structure



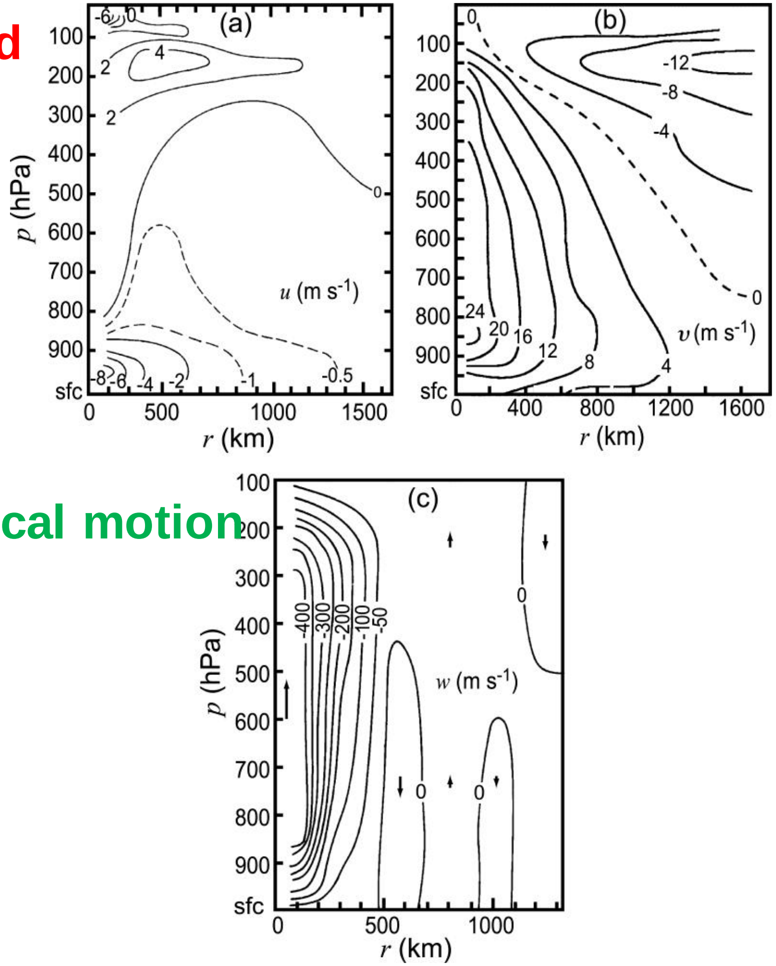
(Figure obtained from Houze (2010), © 2010 American Meteorological Society.)

Composites of Vertical Structure

radial wind

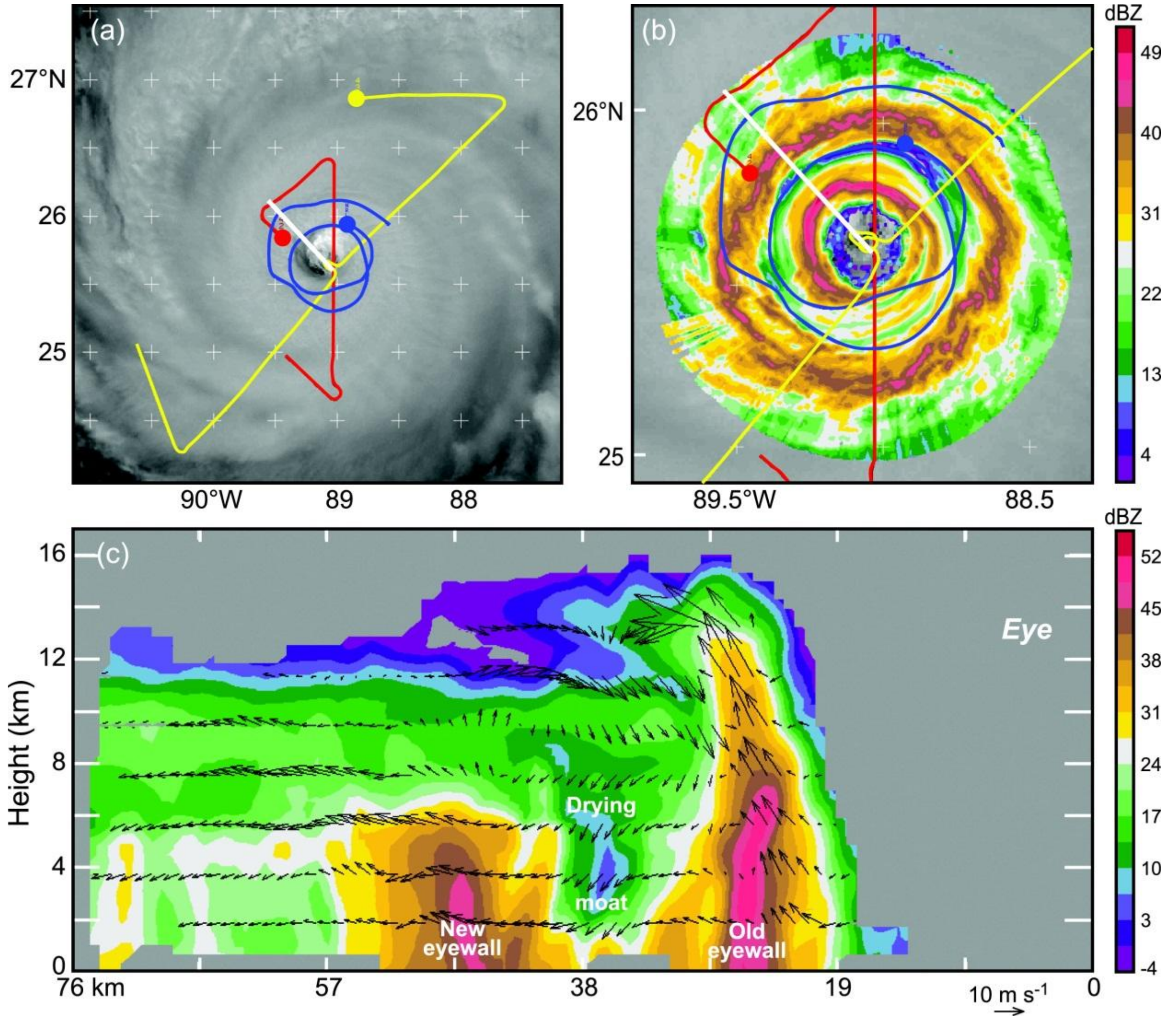
tangential wind

vertical motion



(Figure obtained from Houze (2010), © 2010 American Meteorological Society.)

Primary and Secondary Eyewalls



(Figure obtained from Houze (2010), © 2010 American Meteorological Society.)

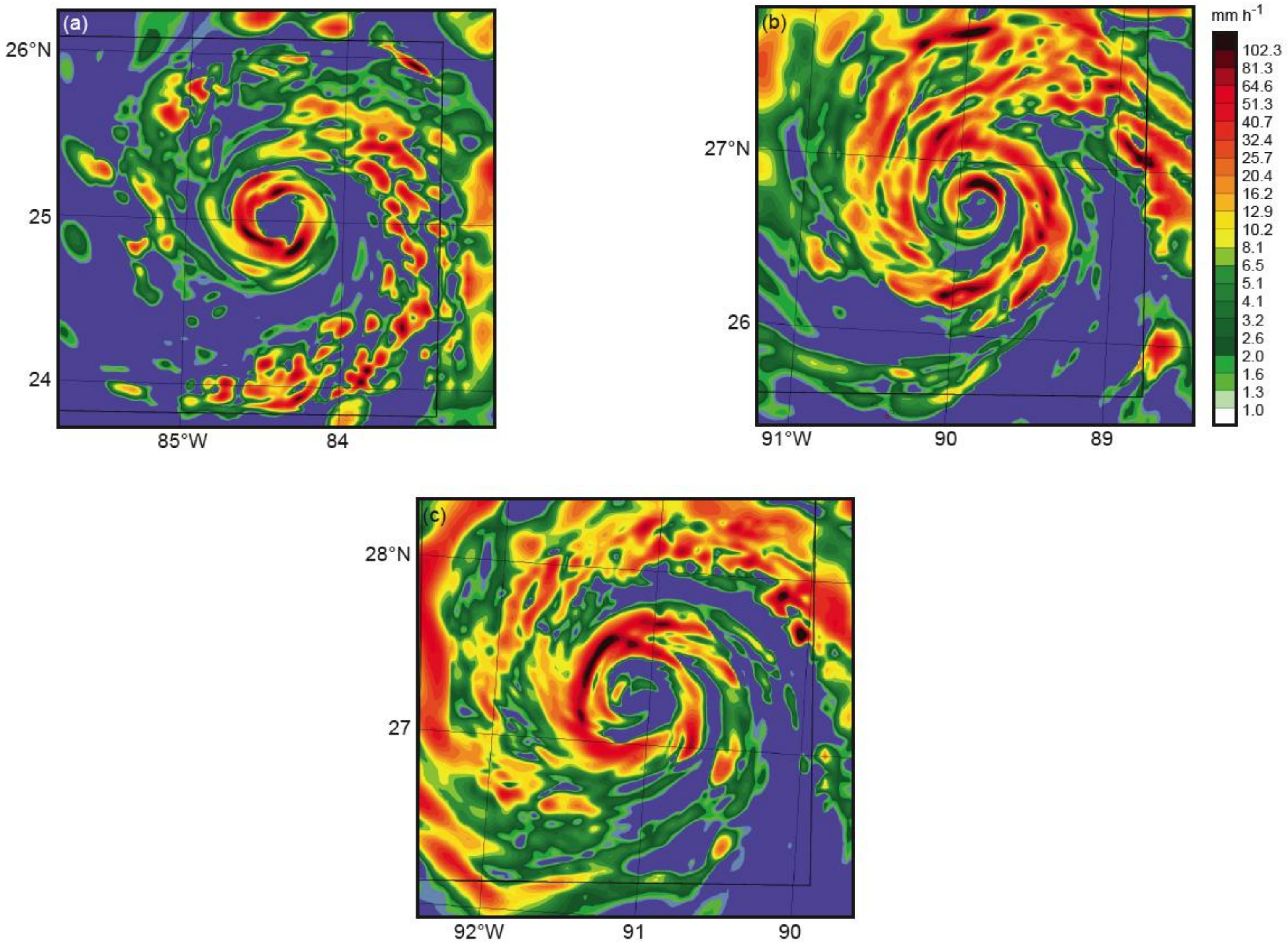
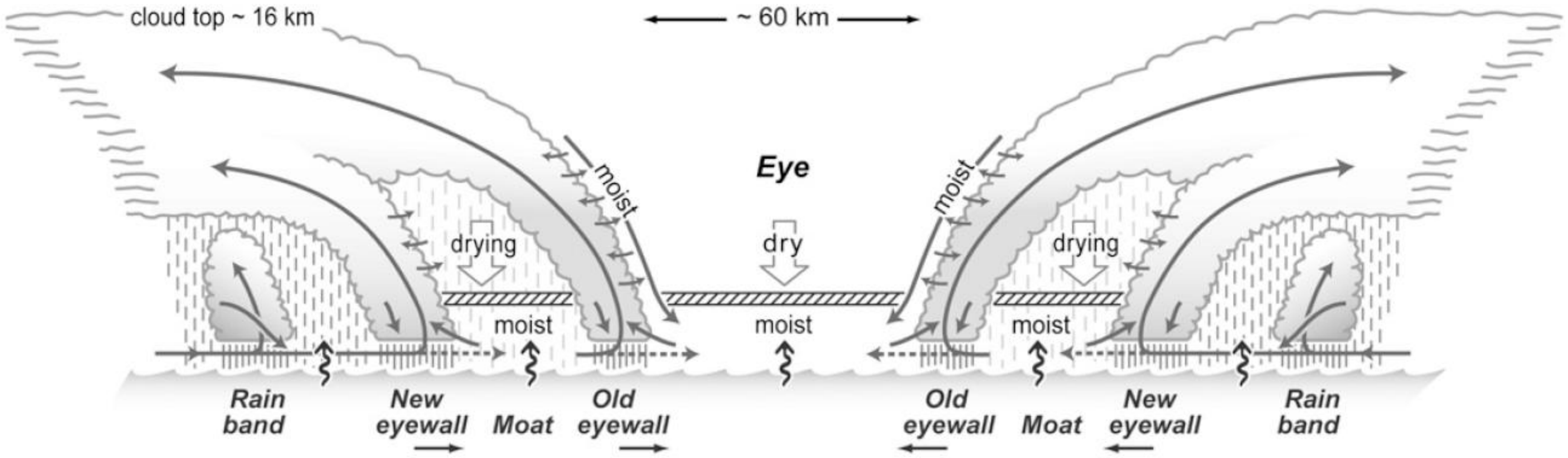
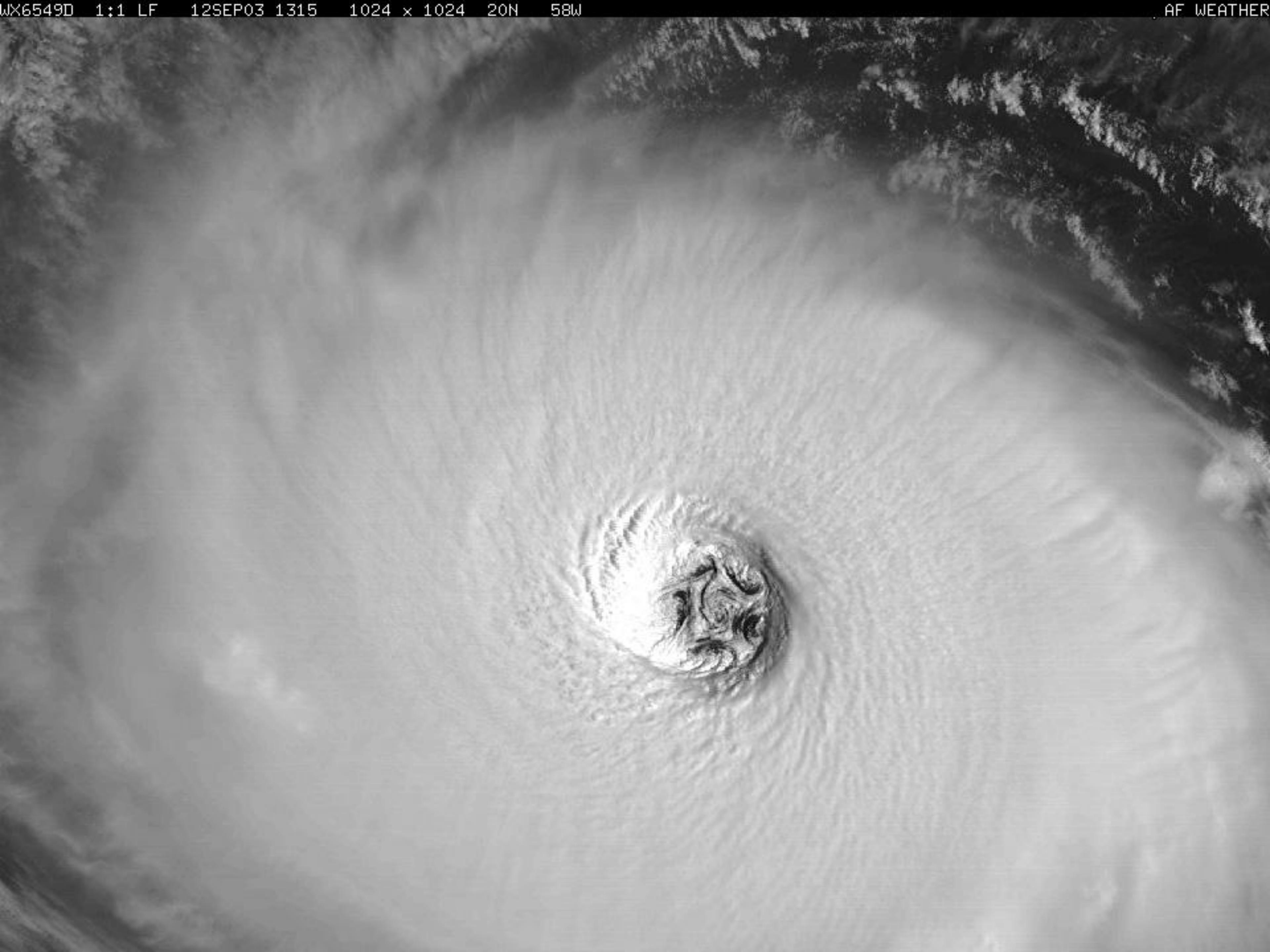


Figure 38. Forecast of surface rainfall intensity in Hurricane Rita (2005). (a) 0715 UTC 21 September, (b) 1115 UTC 22 September, (c) 1715 UTC 22 September. Colors show the rainfall rate (mm h^{-1}) at the sea surface generated by a high resolution numerical model. (From Houze et al. 2007. Reproduced with permission from the American Association for the Advancement of Science.)

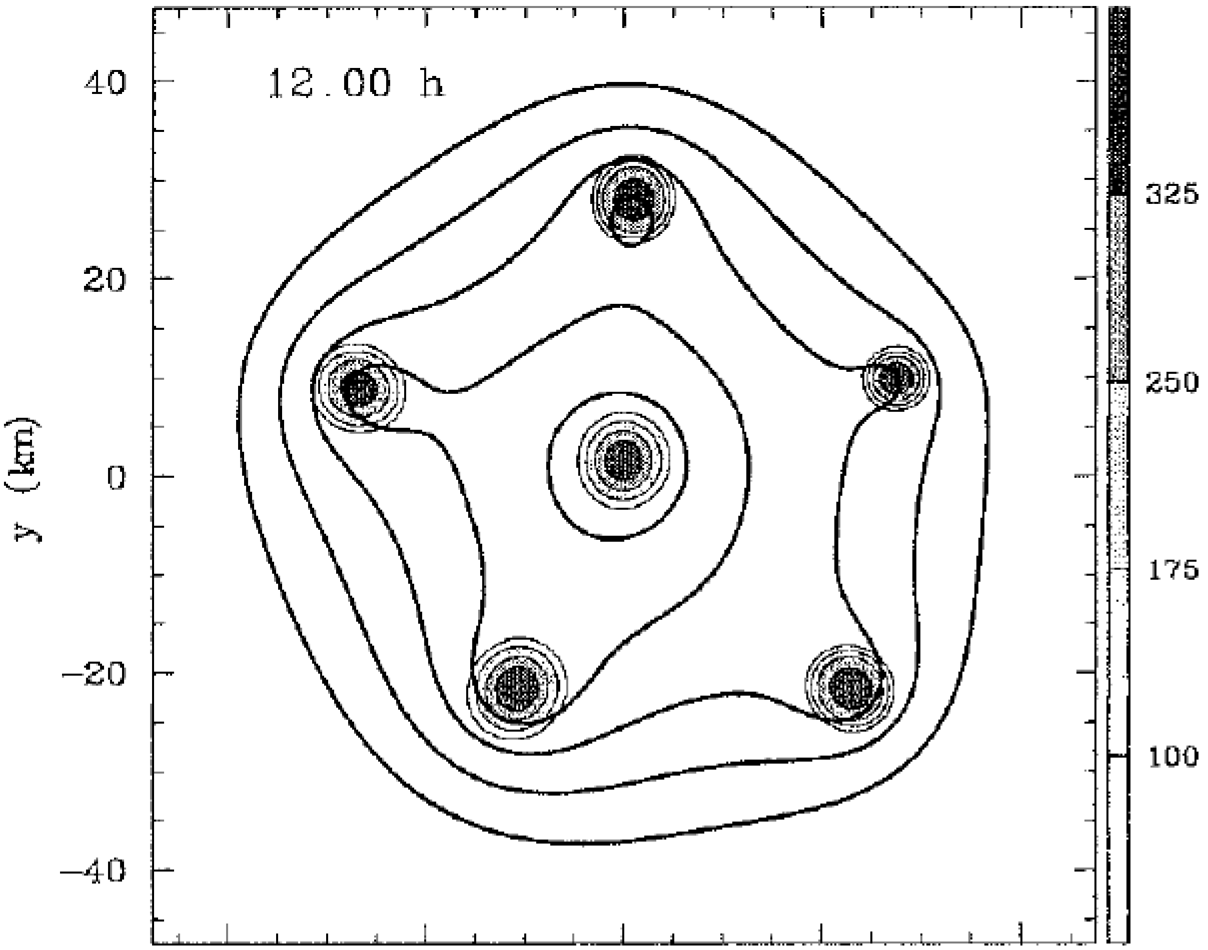
A detailed cross section



Houze 2010


WX6549D 1:1 LF 12SEP03 1315 1024 x 1024 20N 58W
AF WEATHER

Model simulation
(Kossin and Schubert 2001)



3. TC maintenance and intensification

- Axisymmetric balanced vortex
- CISK (Charney and Eliassen 1964)
- The Cooperative-intensification paradigm (Ooyama 1963, 1964, 1969, 1982)
- WISHE (Emanuel 1986,1988, 1989,1995,1997)
- VHT Boundary layer path (Montgomery, Smith, and many others from their group)

Primary circulation

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g,$$ Hydrostatic balance

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{v^2}{r} + fv,$$ Gradient wind balance

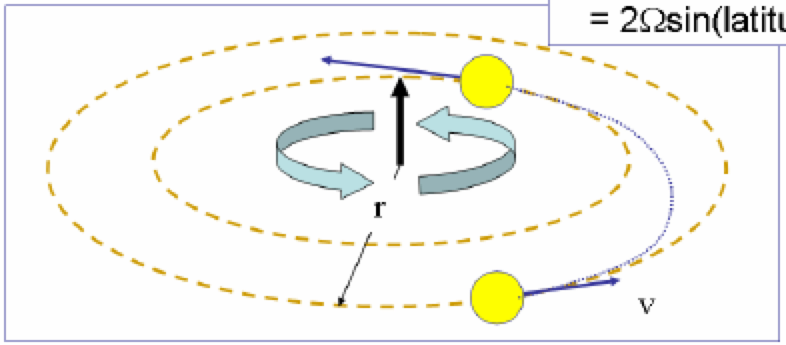
$$g\frac{\partial \ln \rho}{\partial r} + C\frac{\partial \ln \rho}{\partial z} = -\frac{\partial C}{\partial z},$$ Thermal wind balance

$$C = \frac{v^2}{r} + fv$$

- Conservation of absolute angular momentum:

M = rv + r^2f/2

f = Coriolis parameter
= 2Ωsin(latitude)



v = M/r - rf/2 → If r decreases, v increases!

→ Spin up requires radial convergence

Secondary circulation

$$N^2 = \frac{g}{\theta_0}\frac{\partial\theta}{\partial z}$$

$$B = -\frac{g}{\theta_0}\frac{\partial\theta}{\partial r} = -\frac{1}{r^3}\frac{\partial m^2}{\partial z}$$

$$I = \frac{1}{r^3}\frac{\partial m^2}{\partial r} = \left(f + \frac{1}{r}\frac{\partial(rv)}{\partial r}\right)\left(f + \frac{2v}{r}\right)$$

$$\frac{\partial}{\partial t}(-B) + \frac{\partial}{\partial z}(Iu - Bw) = \frac{1}{r^3}\frac{\partial F}{\partial z}$$

$$\frac{\partial}{\partial t}(-B) + \frac{\partial}{\partial r}\left(-Bu + N^2 w\right) = \frac{g}{\theta_0}\frac{\partial Q}{\partial r}$$

$$\Downarrow$$

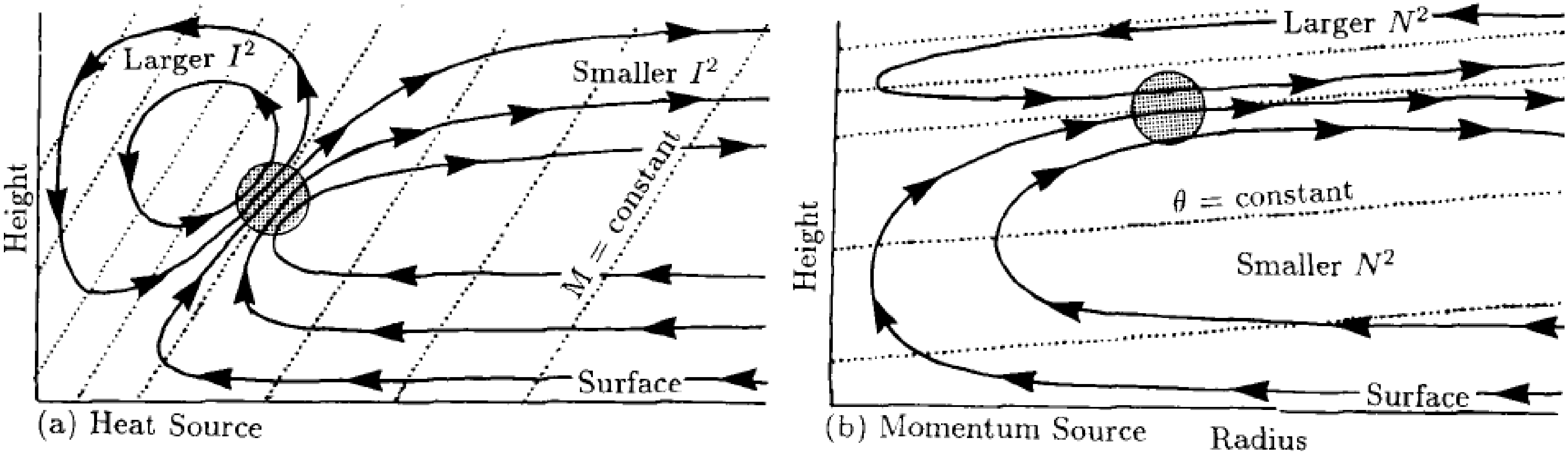
$$\frac{\partial}{\partial r}\left(N^2 w - Bu\right) + \frac{\partial}{\partial z}(Bw - Iu) = \frac{g}{\theta_0}\frac{\partial Q}{\partial r} - \frac{1}{r^3}\frac{\partial F}{\partial z}$$

$$\Downarrow$$

$$\frac{\partial}{\partial r}\left(N^2\frac{1}{r}\frac{\partial(r\psi)}{\partial r} + B\frac{\partial\psi}{\partial z}\right) + \frac{\partial}{\partial z}\left(B\frac{1}{r}\frac{\partial(r\psi)}{\partial r} + I\frac{\partial\psi}{\partial z}\right) = \frac{g}{\theta_0}\frac{\partial Q}{\partial r} - \frac{1}{r^3}\frac{\partial F}{\partial z}$$

Sawyer-Eliassen secondary circulation diagnostic equation

Secondary Circulation



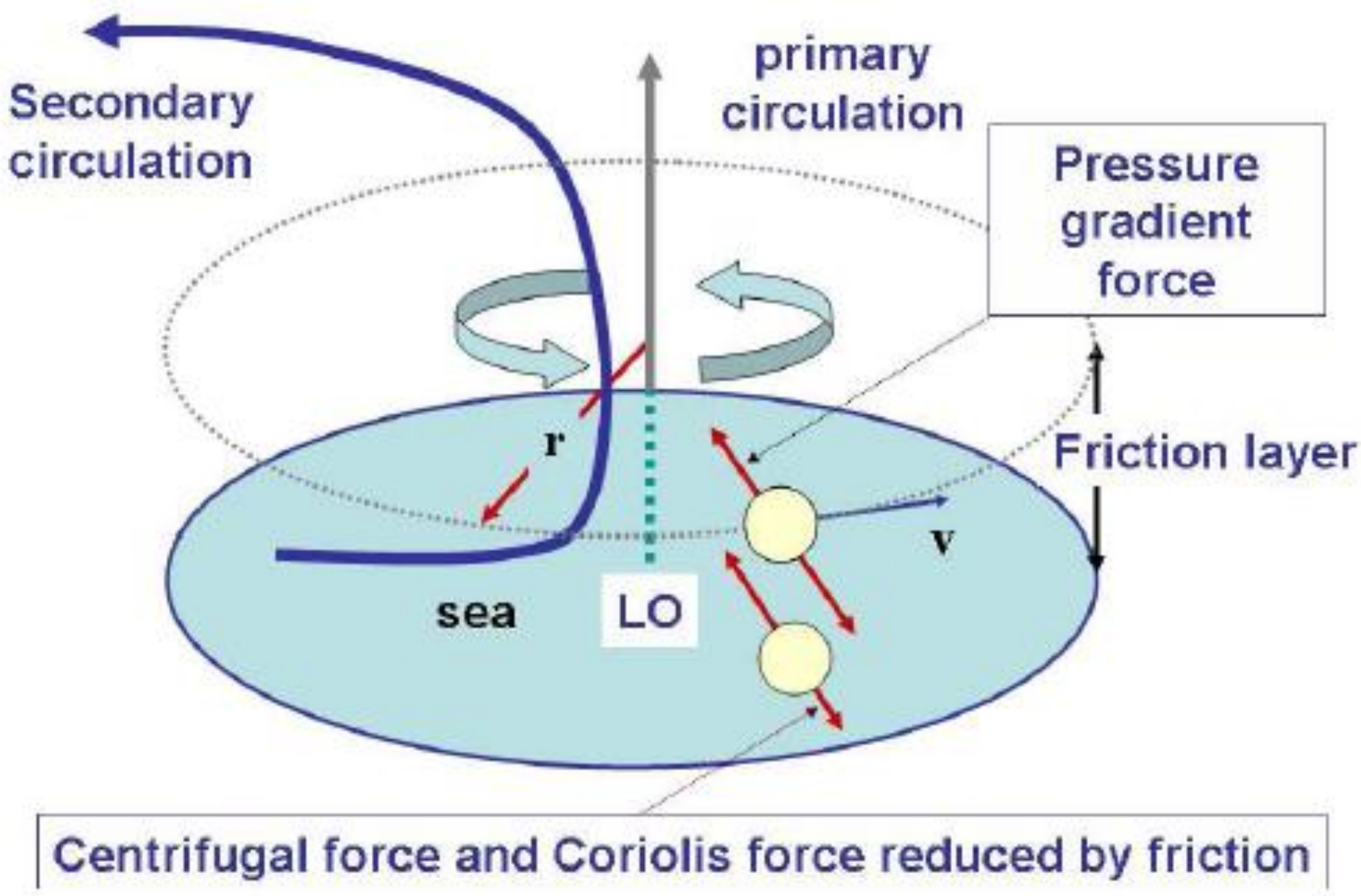
(a) Heat Source

(b) Momentum Source

Fig. 2.3 Secondary circulation induced in a balanced vortex by (a) a heat source and (b) a cyclonic momentum source, showing the distortion induced by variation in inertial stability, I^2, and thermodynamic stability, N^2, and baroclinity, B^2. The strong motions through the source follow lines of constant angular momentum for a heat source and of constant potential temperature for a momentum source.

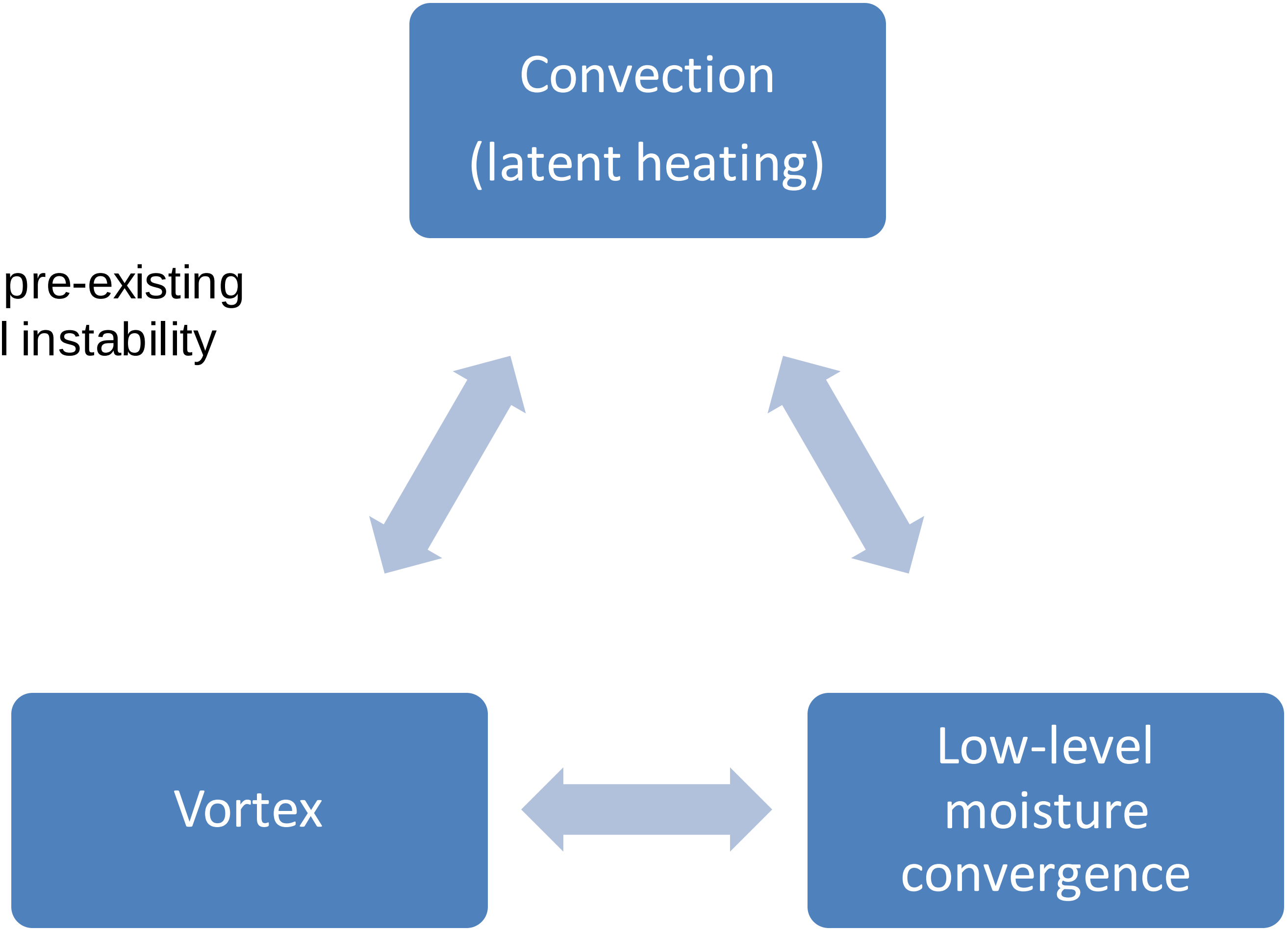
(Figure obtained from Willoughby (1995), © 1995 World Meteorological Organization.)

Consider friction (TC boundary layer)



CISK (Charney and Eliassen 1964)

(conditional instability of the second kind)



Convection

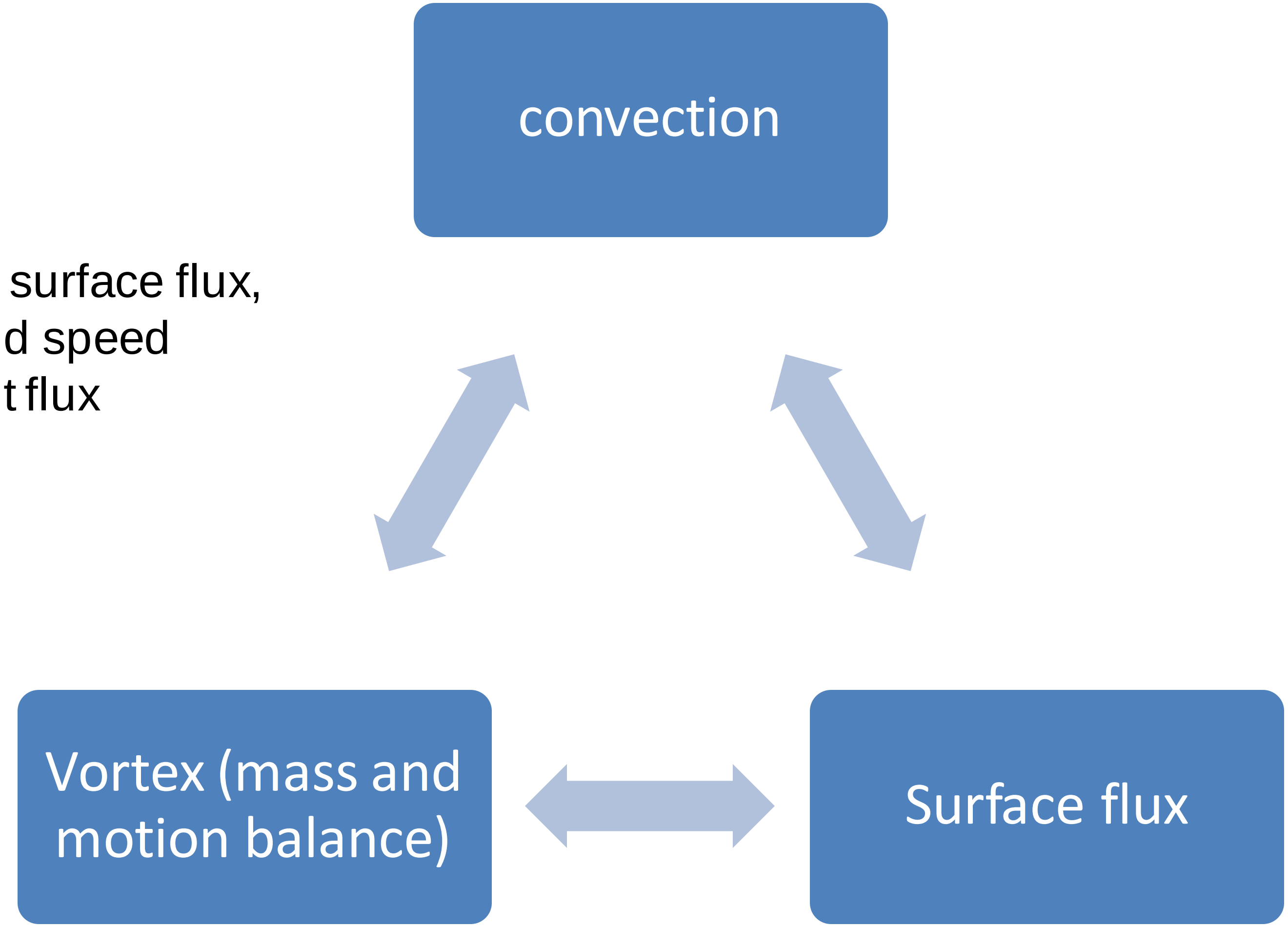
(latent heating)

Vortex

Low-level moisture convergence

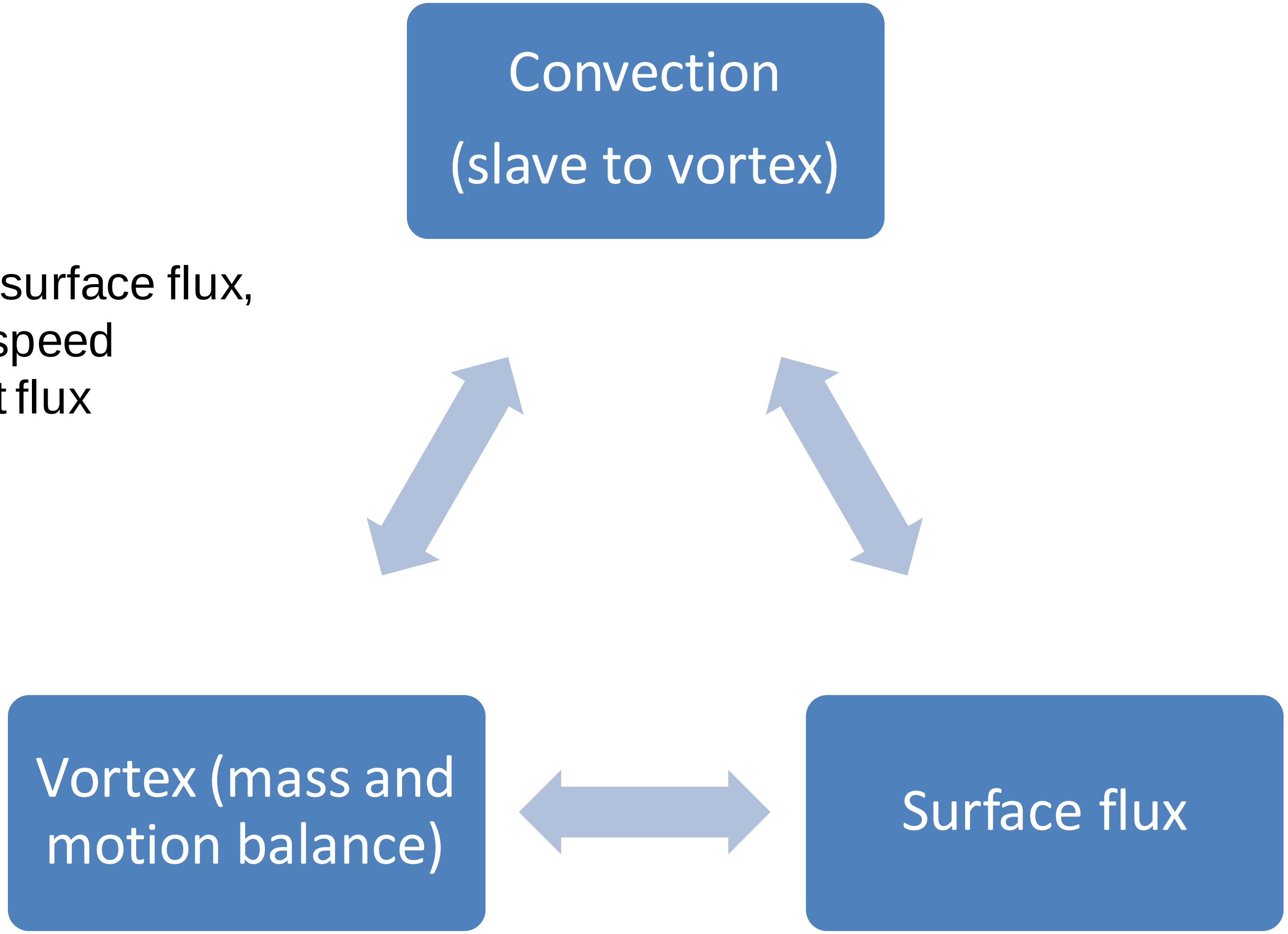
Fueled by pre-existing conditional instability

Cooperative-intensification (Ooyama 1963,1964,1969,1982)



Fueled by surface flux,
but no wind speed
dependent flux

WISHE
(Emanuel 1986,1988,1995,1997)



Convection

(slave to vortex)

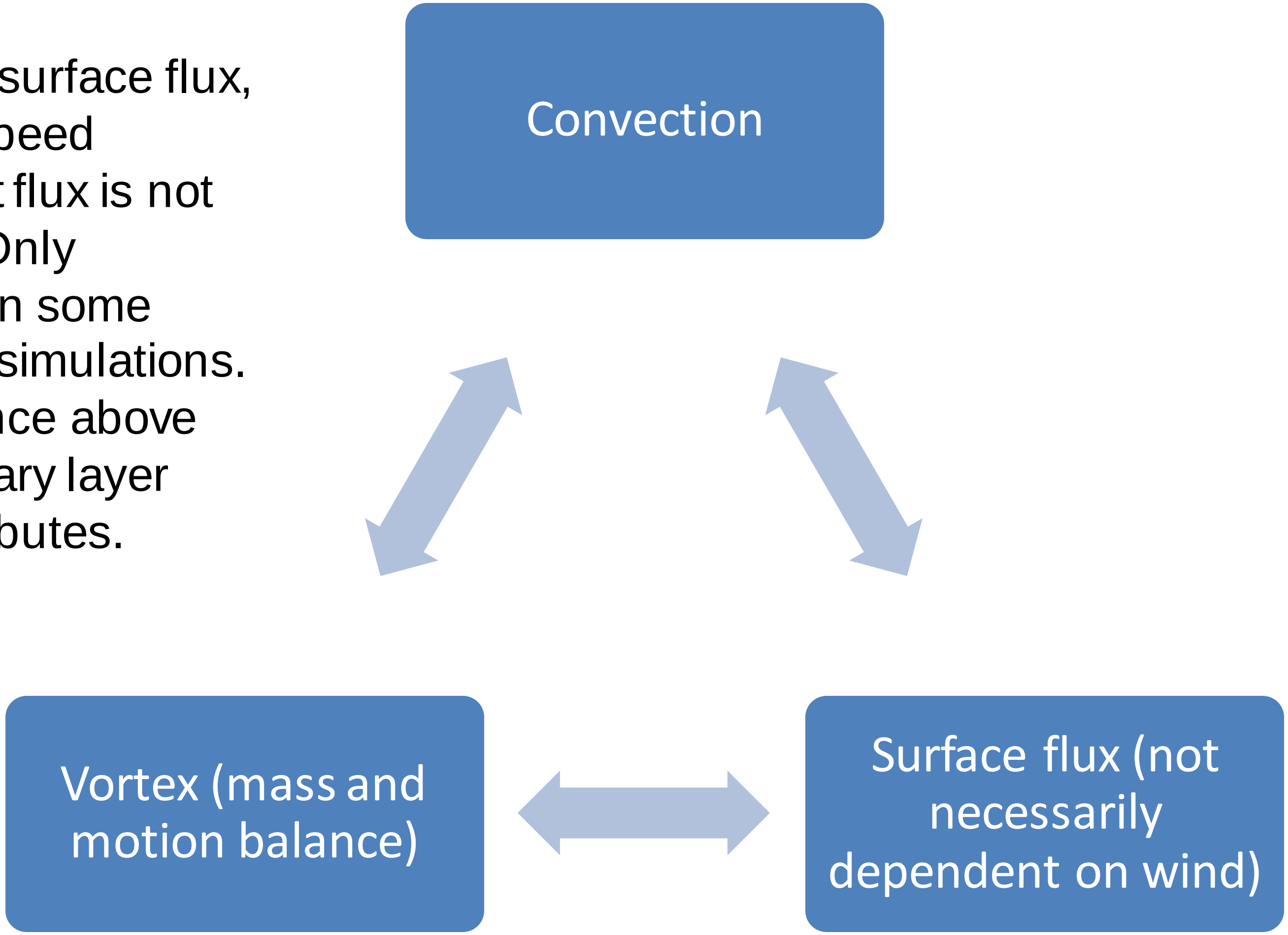
Vortex (mass and motion balance)

Surface flux

Fueled by surface flux,
with wind speed
dependent flux

VHT and boundary layer (Smith, Montgomery)

Fueled by surface flux, but wind speed dependent flux is not required. Only depends on some numerical simulations. Convergence above the boundary layer also contributes.



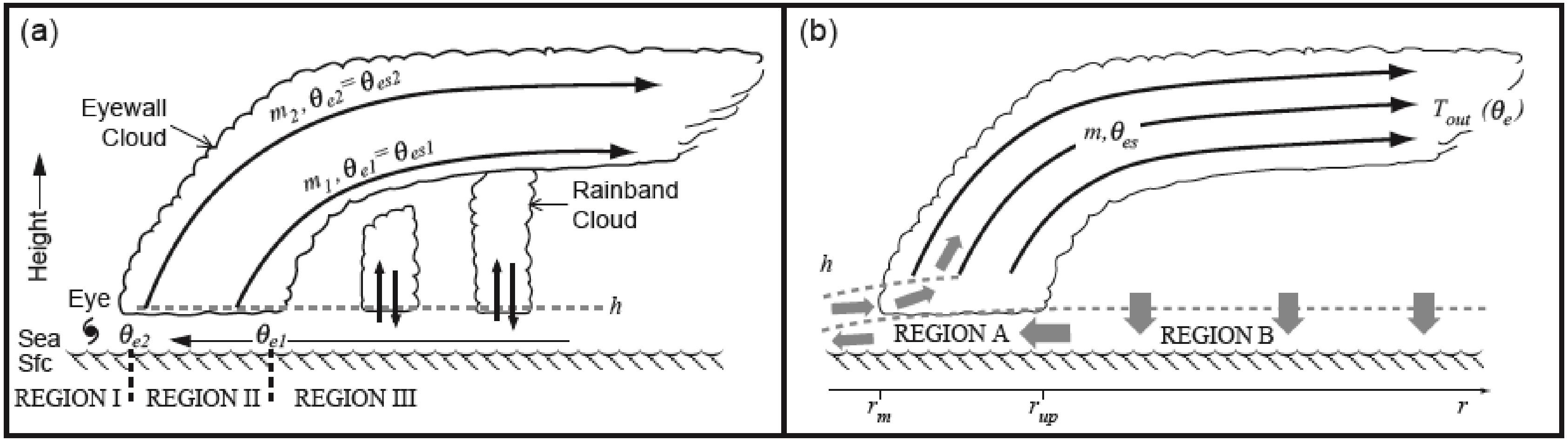
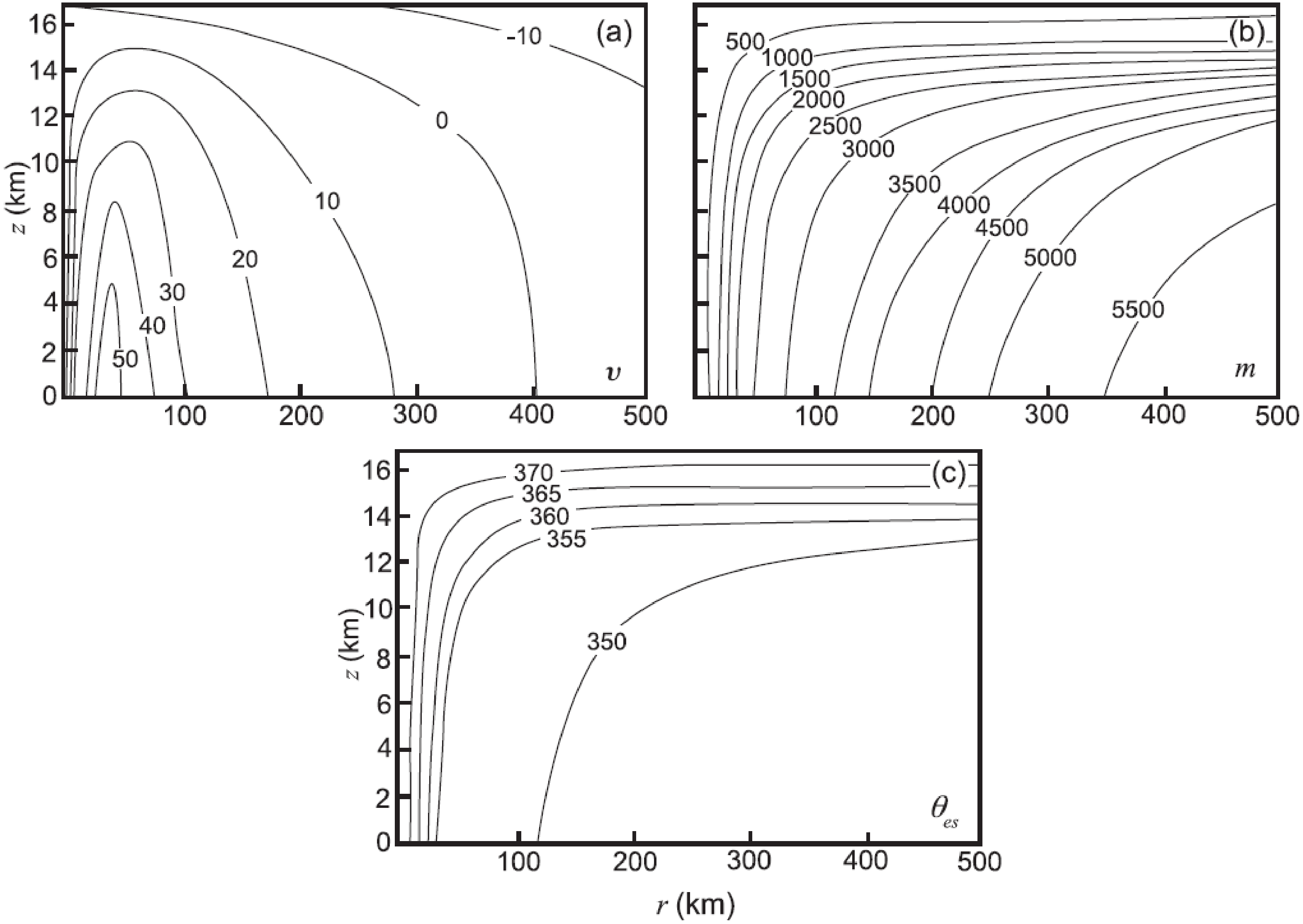
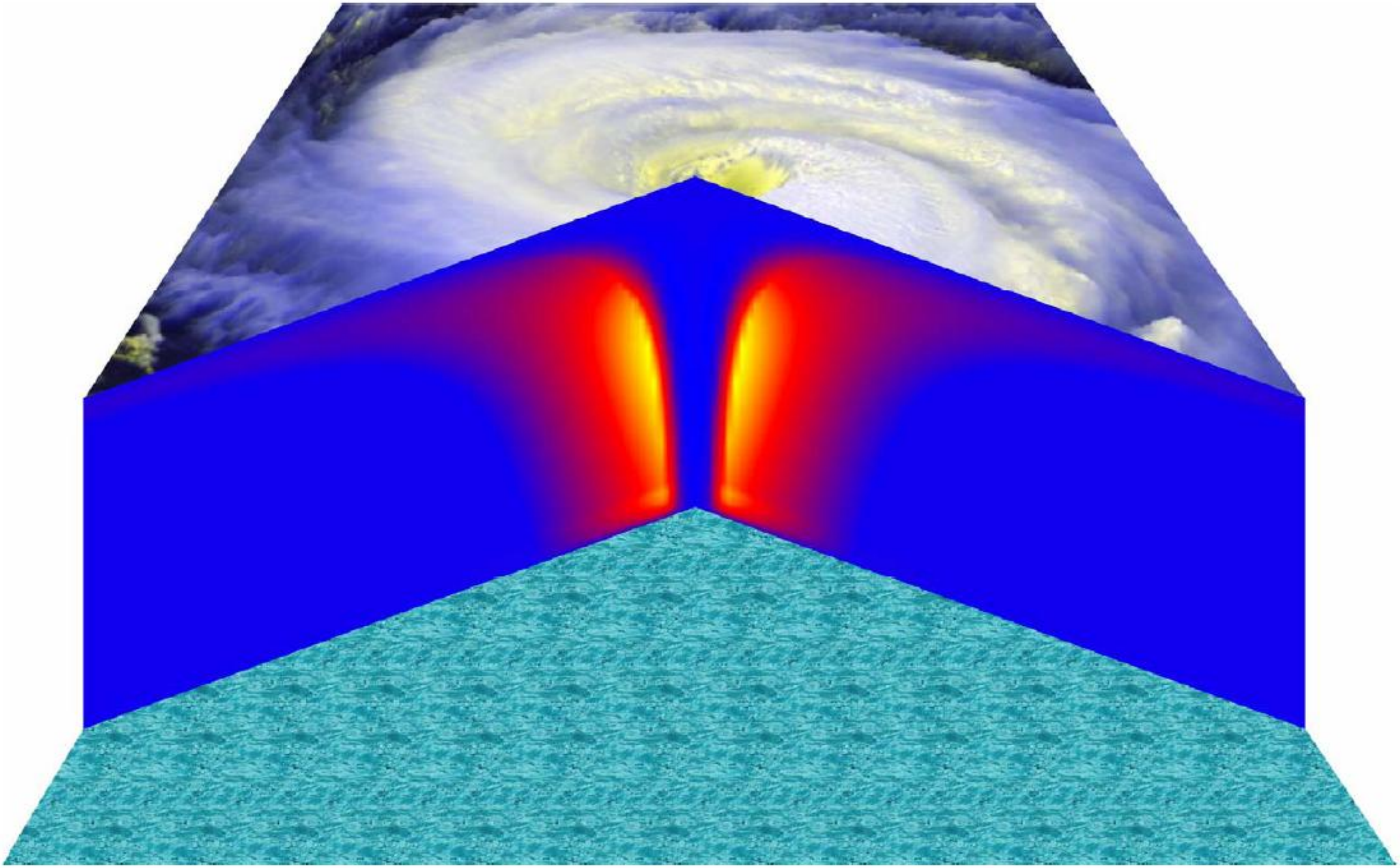


Figure 12 (a) Idealized air-sea interaction model of a tropical cyclone adapted from Emanuel (1986). Arrows indicate direction of airflow at selected locations. Dashed line represents the top of the boundary layer at height h. (b) Modification by Smith et al. (2008) of Emanuel's conceptual model. Air subsides into the boundary layer for $r > r_{up}$ and ascends out of the boundary layer for $r < r_{up}$. The frictionally induced net inward force in the outer region produces a radially inward jet at $r = r_{up}$. The subsequent evolution of this jet depends on the bulk radial pressure gradient that can be sustained by the mass distribution at the top of the boundary layer. The jet eventually generates supergradient tangential winds whereupon the radial flow rapidly decelerates and turns upwards and outwards. When the outflow has adjusted to the radial pressure gradient that is sustained by the mass field, the flow turns upwards into the eyewall clouds. (Second panel reprinted with permission from the Royal Meteorological Society.)

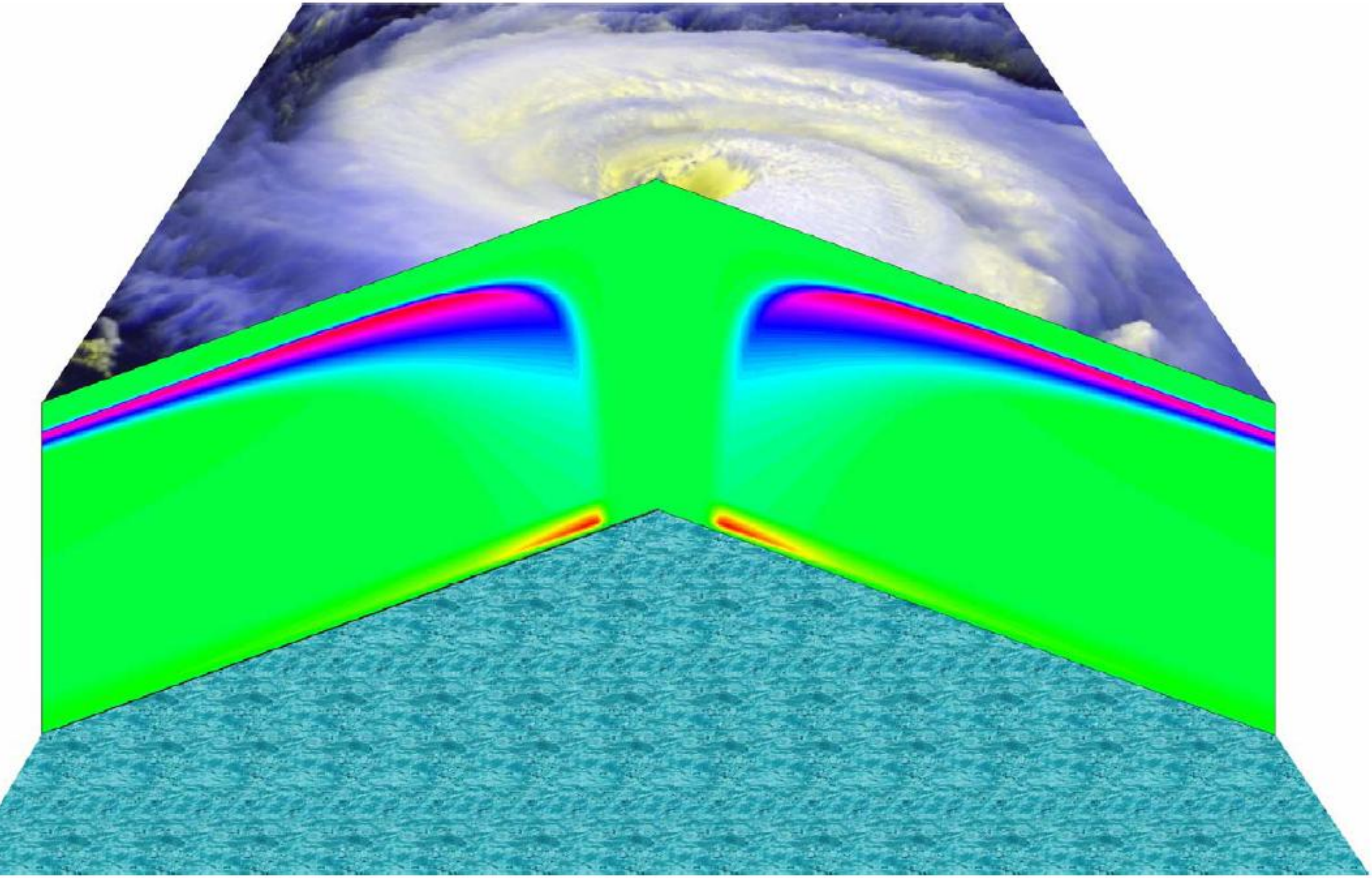
The solution of E86



Vertical winds



Radial wind



Maximum potential intensity (MPI)

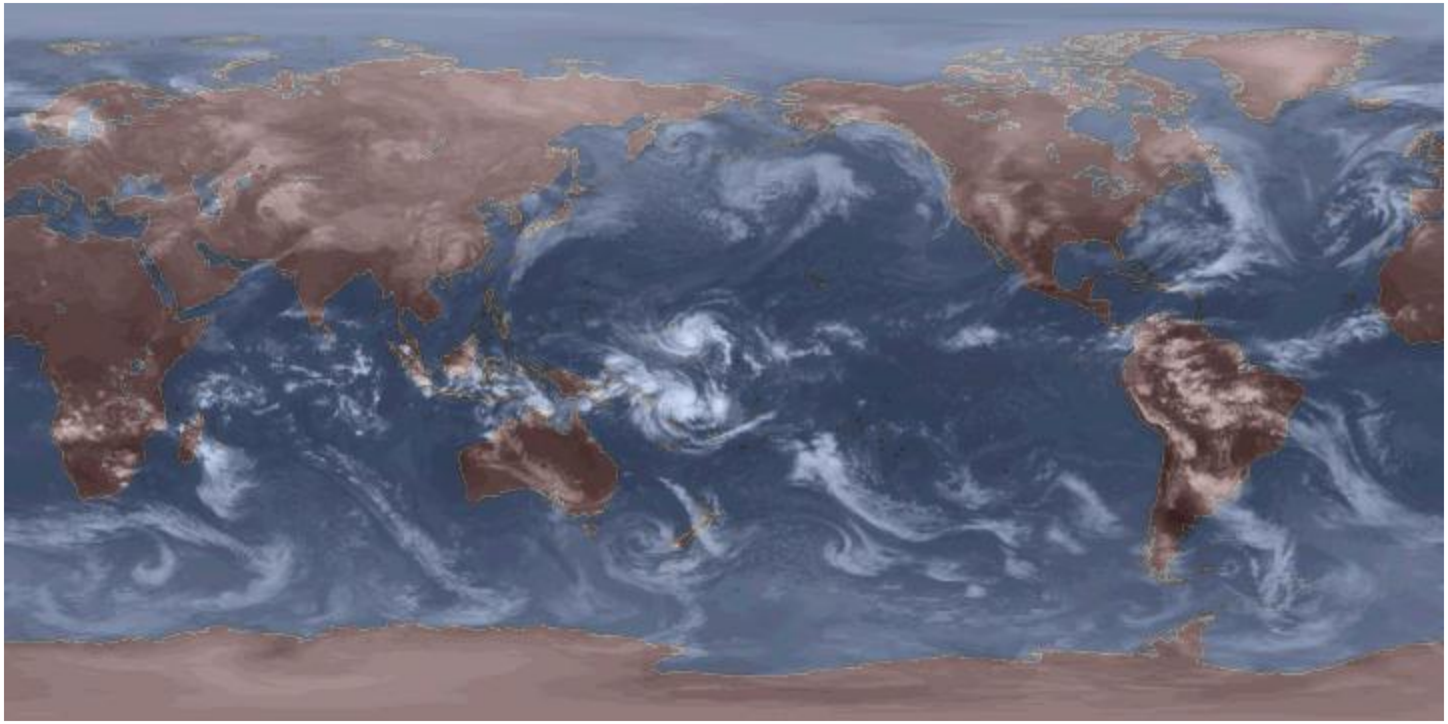
- An analogue to Carnot cycle (Emanuel 1988)

$$G = \varepsilon C_k \rho V_s \left(k_o^* - k_a \right)$$

$$D = C_d \rho V_s^3$$

$$|V_{\max}|^2 \approx \frac{C_k}{C_D} \frac{T_s - T_0}{T_0} (k_0^* - k).$$

4. TC genesis (number)



What is cyclogenesis?

- The central problem in genesis is the transformation of an existing disturbance

  into a system operating on the feedback between surface enthalpy fluxes and surface wind.

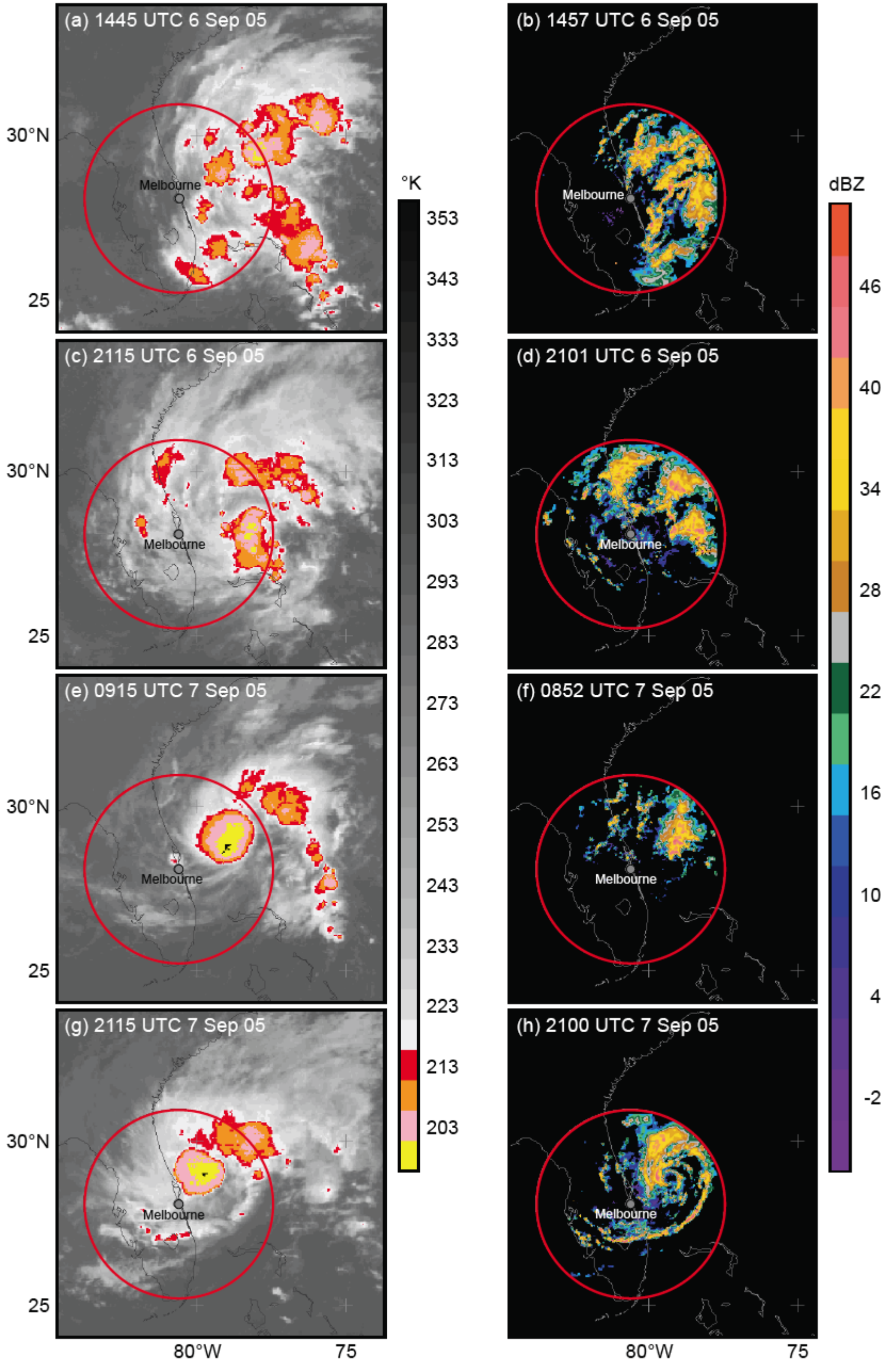


Figure 4. Satellite and radar overview of the genesis of Ophelia. Circle shows maximum range. Satellite imagery shows infrared temperature from GOES-12. Radar data are from the Melbourne, FL, WSR-88D. (From Houze et al. 2009)

TC development

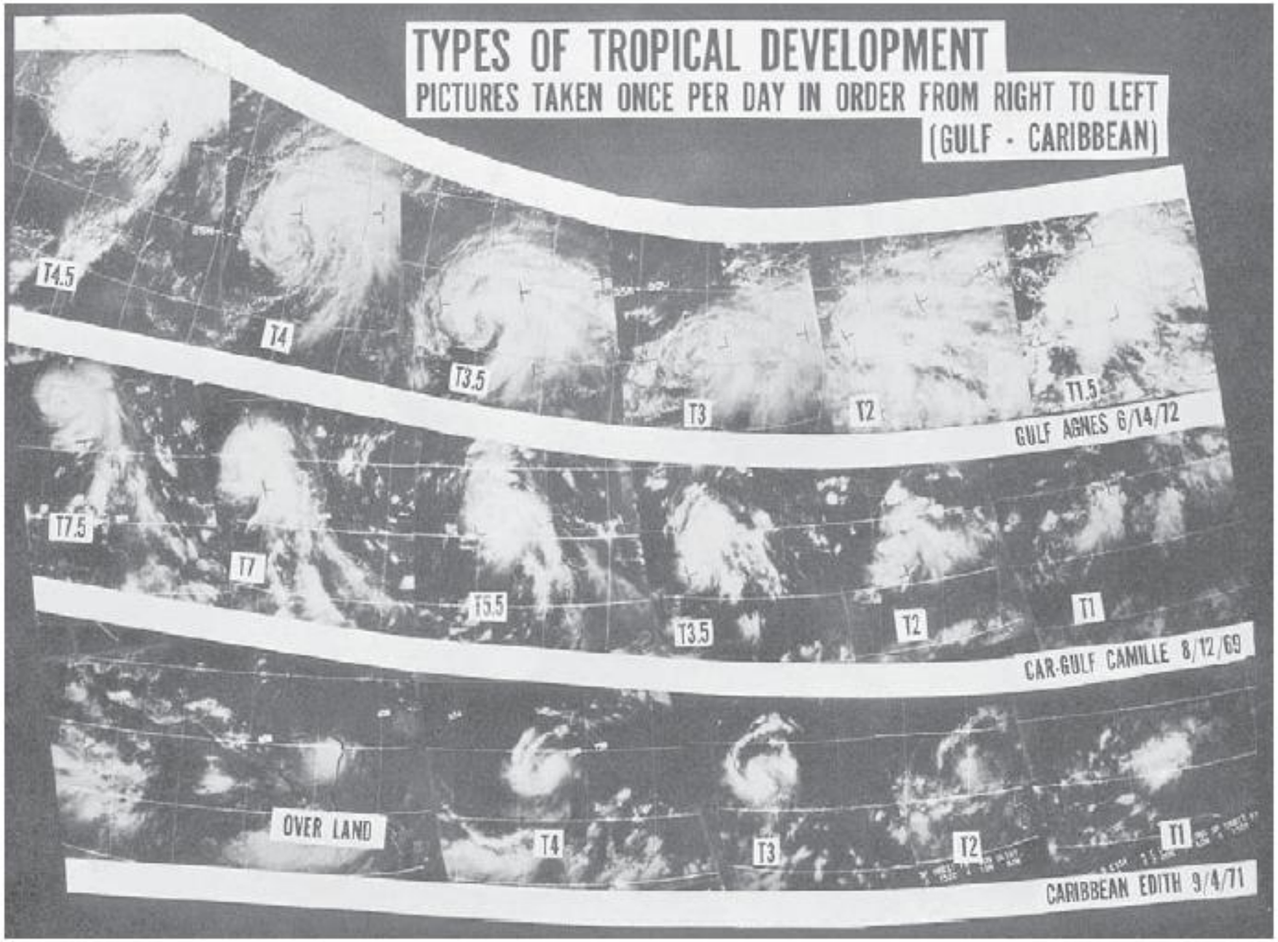


FIG. 2. Examples of characteristic cloud patterns of developing TCs (from Dvorak 1973).

(Figure obtained from Velden et al. (2006). © 2006, American Meteorological Society.)

Genesis Potential – Gray (1979)

Thermal potential

- ocean thermal energy (to 60 m depth)
- potential instability between surface and 500mb
- mid-tropospheric relative humidity

Dynamic potential

- low-level relative vorticity
- Coriolis parameter
- the inverse of the vertical wind shear

Finite amplitude disturbance (seed)

- Easterly wave (Atlantic TC)
- Tropical wave (Equatorial Rossby wave)
- Mesoscale convective system
- Midlatitude system (front, trough)
- ITCZ
- Monsoon trough
- …

Bister and Emanuel (1997) Schematic

Downward MCV penetration

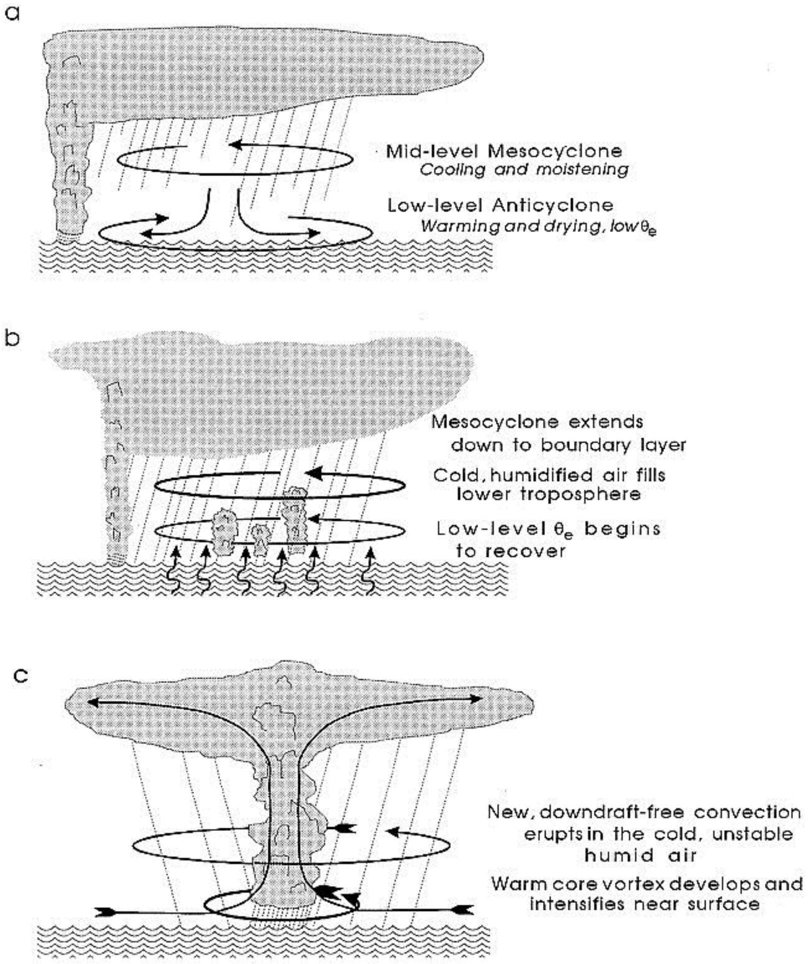
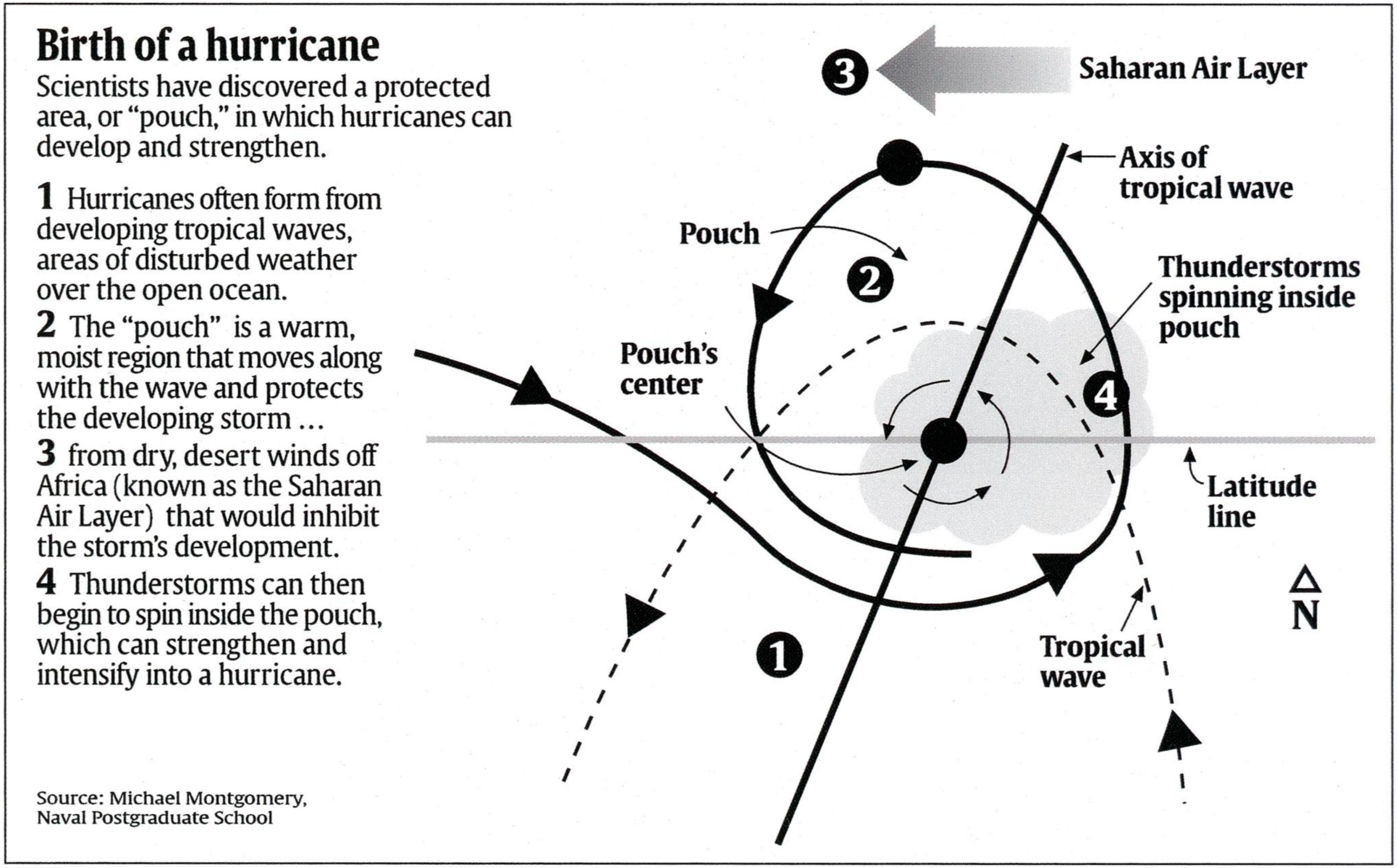


Figure obtained from Bister and Emanuel (1997, *MWR*), their Fig. 13. © 1997 American Meteorological Societ

Marsupial theory (Dunkerton et al. 2009)



Birth of a hurricane

Scientists have discovered a protected area, or "pouch," in which hurricanes can develop and strengthen.

1 Hurricanes often form from developing tropical waves, areas of disturbed weather over the open ocean.

2 The "pouch" is a warm, moist region that moves along with the wave and protects the developing storm …

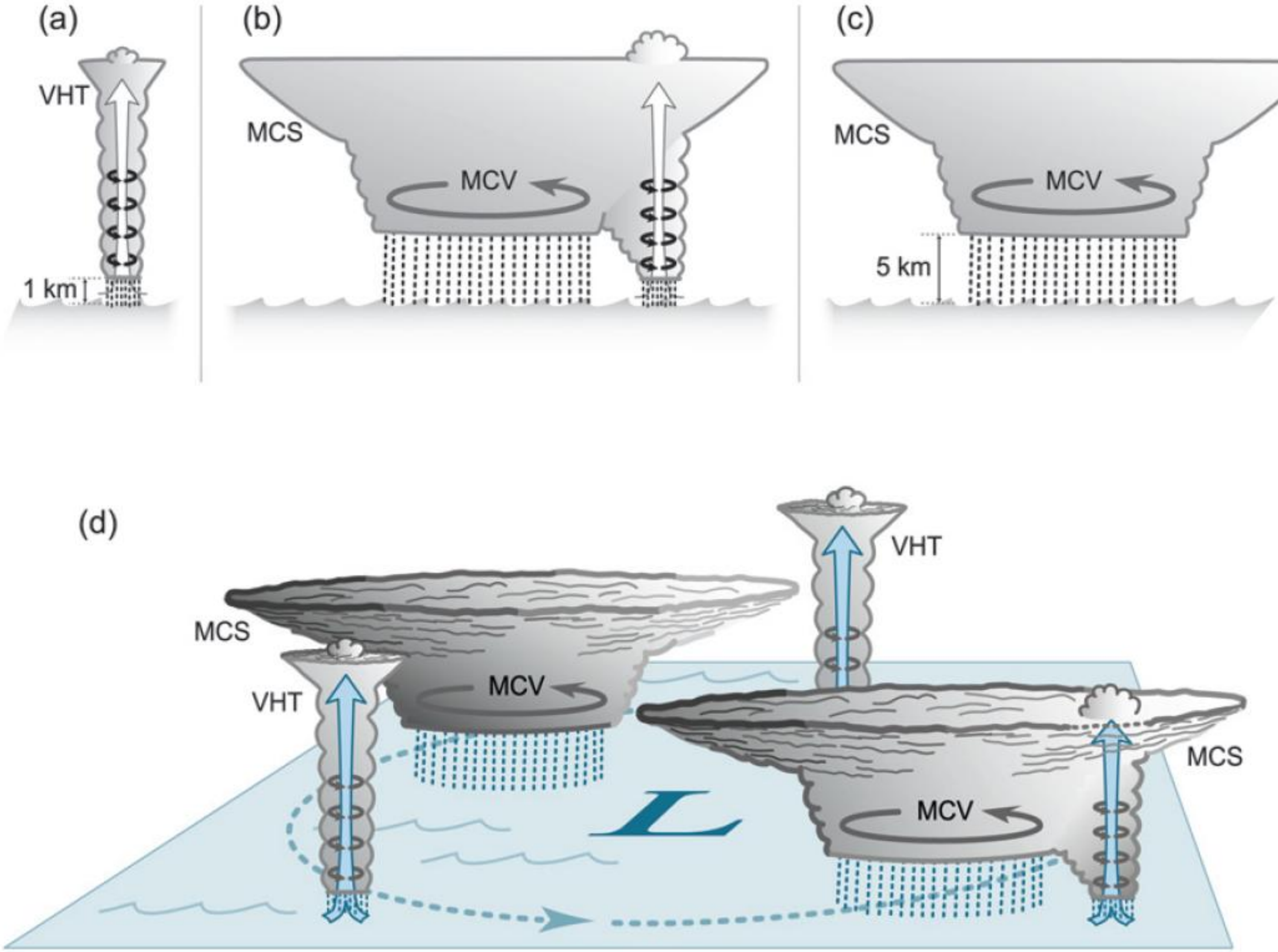
3 from dry, desert winds off Africa (known as the Saharan Air Layer) that would inhibit the storm's development.

4 Thunderstorms can then begin to spin inside the pouch, which can strengthen and intensify into a hurricane.

Source: Michael Montgomery, Naval Postgraduate School

By Doyle Rice and Adrienne Lewis, USA TODAY

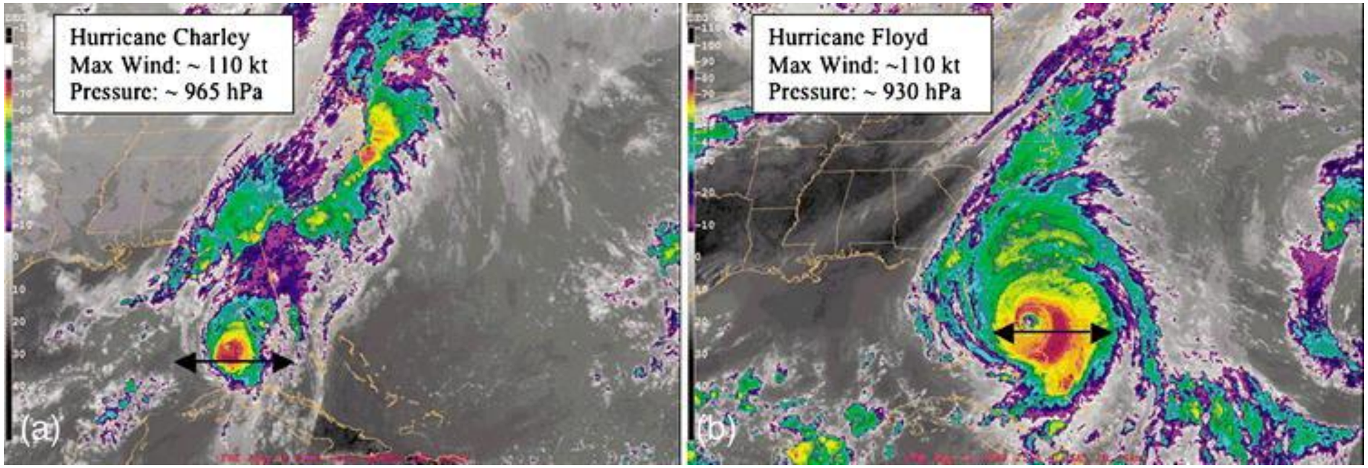
MCS and VHT (vortical hot tower)



Houze 2010

5. TC size

- No theory for TC size yet



Hill and Lackmann 2009

Another example

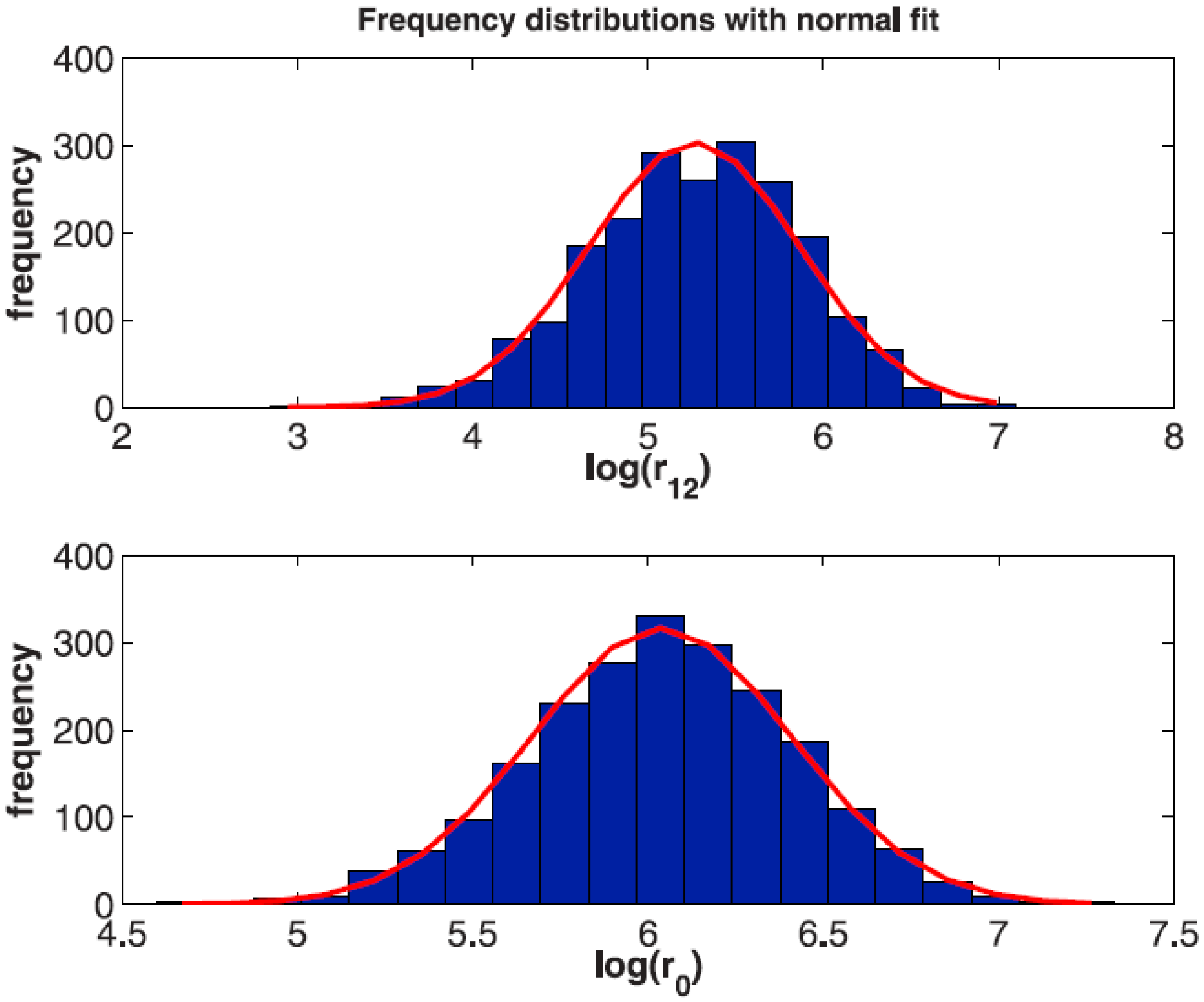
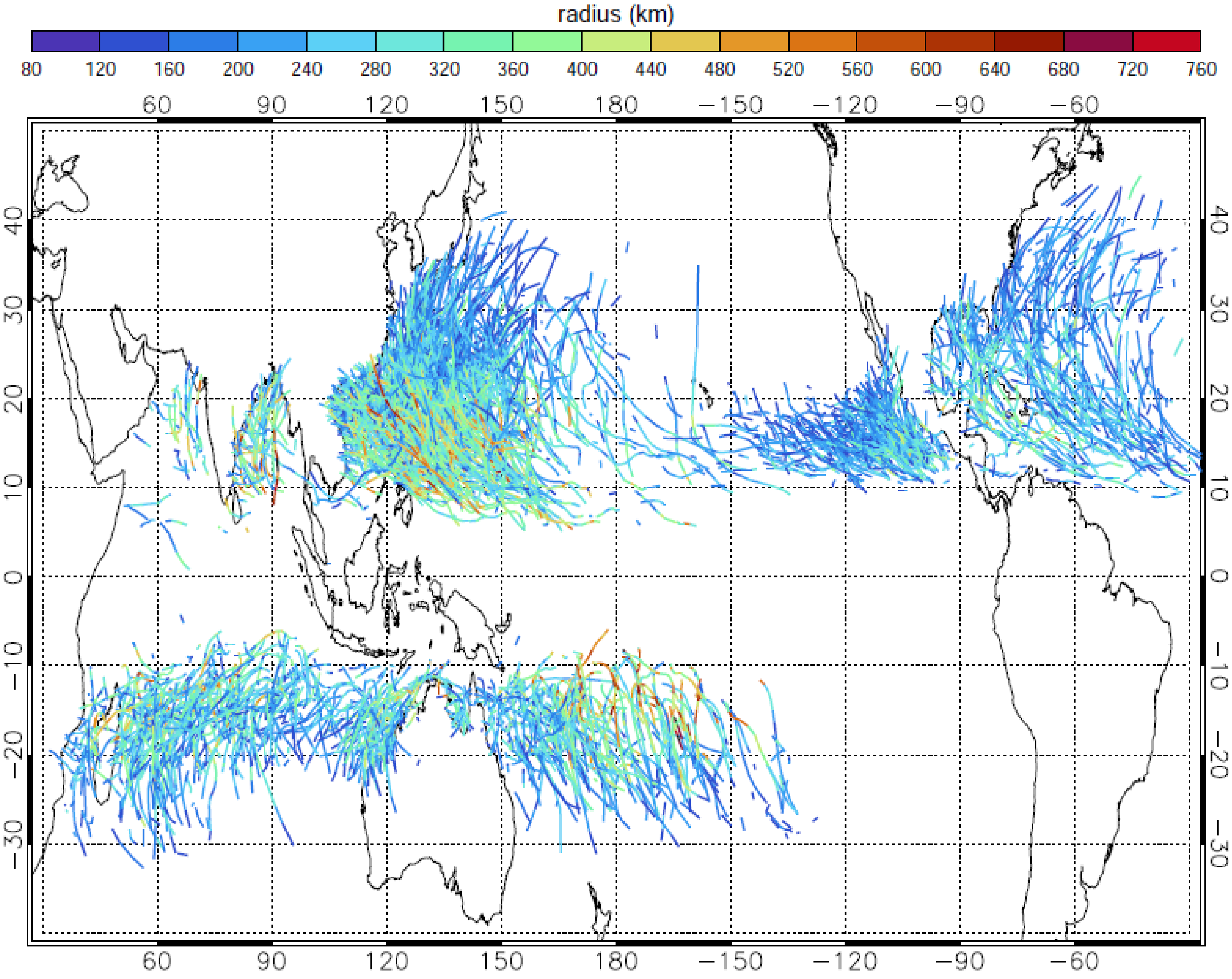


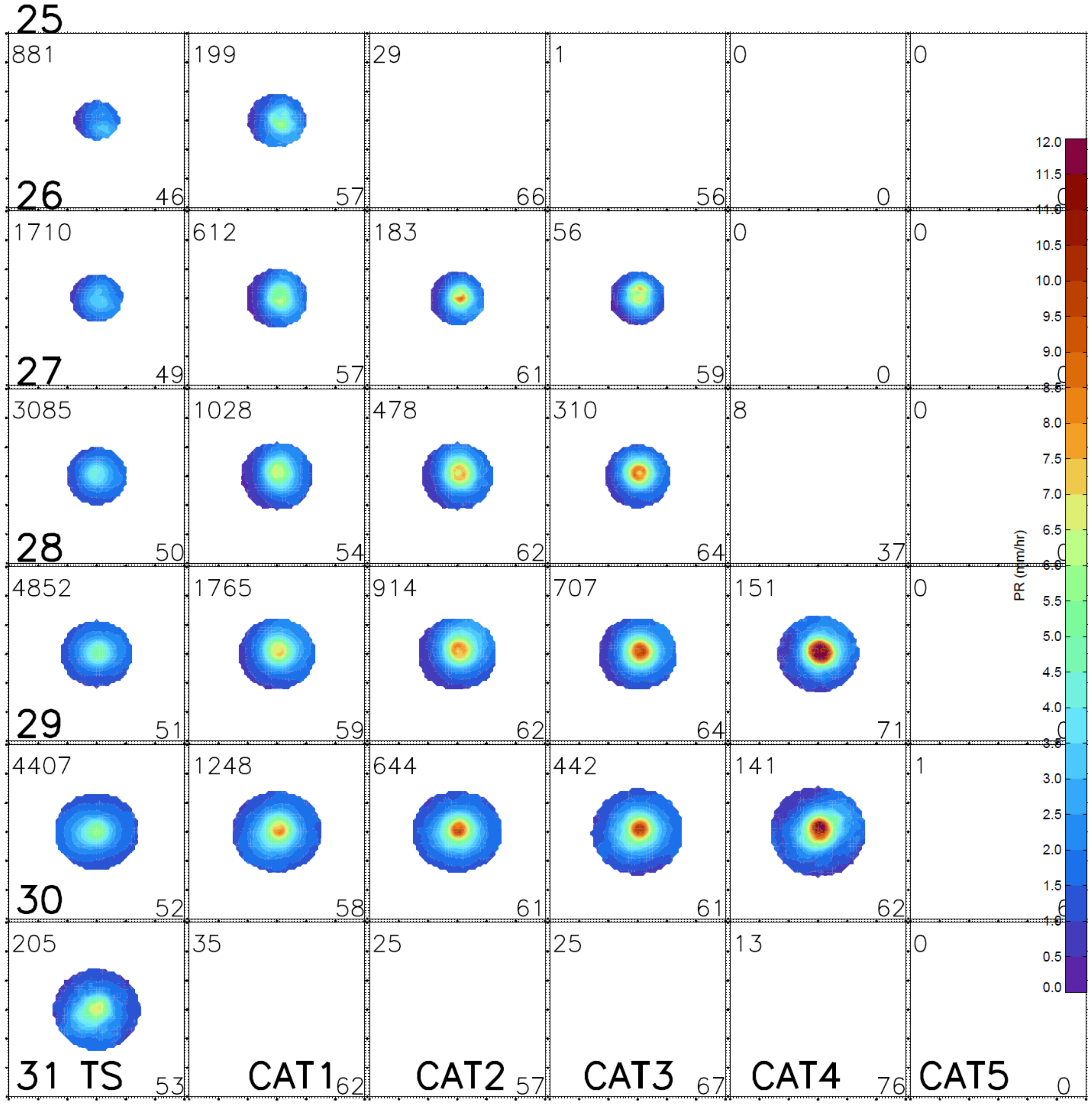
Figure 2. Global frequency distribution with Gaussian fit (red line). (top) $\log(r_{12})$; (bottom) $\log(r_0)$.

Chavas and Emanuel 2010

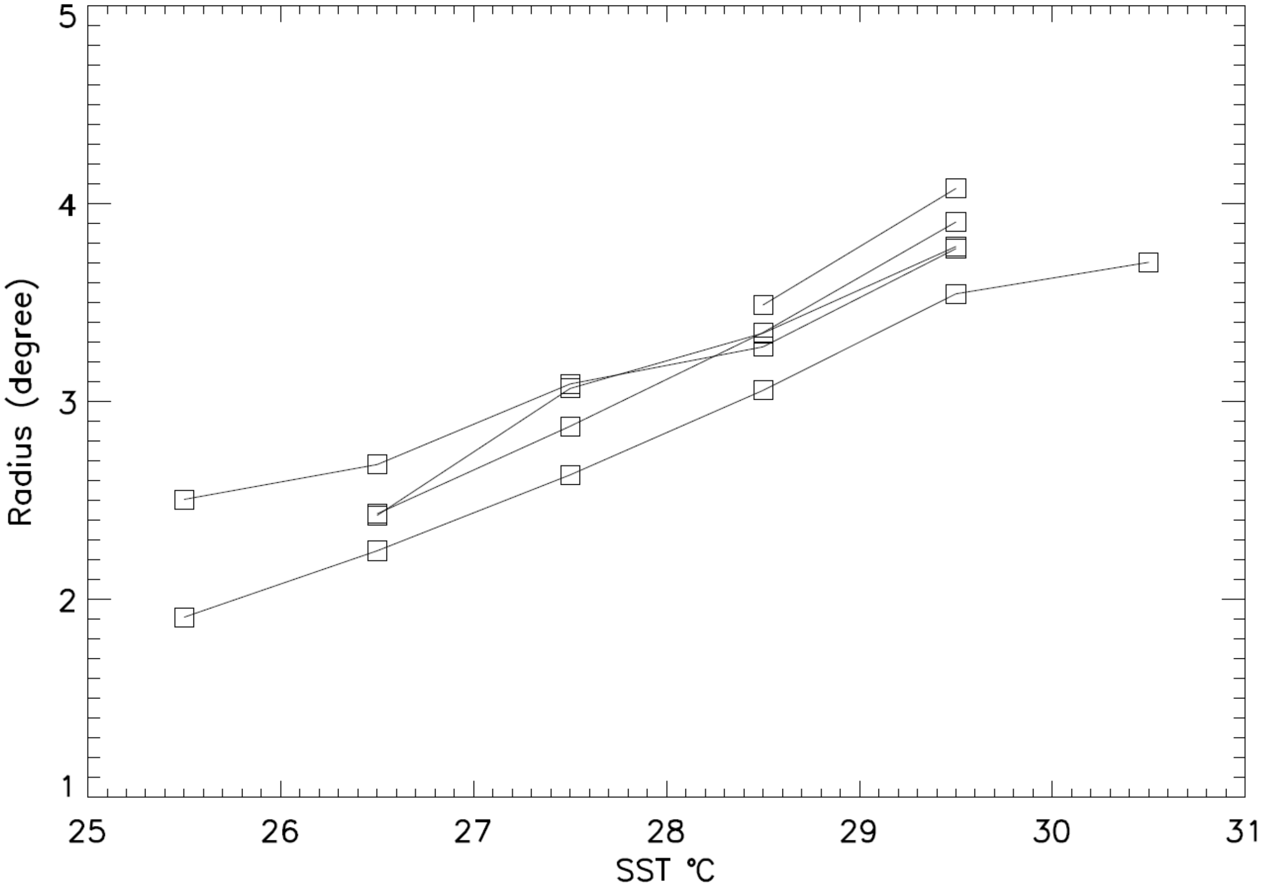
Global TC size distribution



TC precipitation area



Mean TC precipitating radius

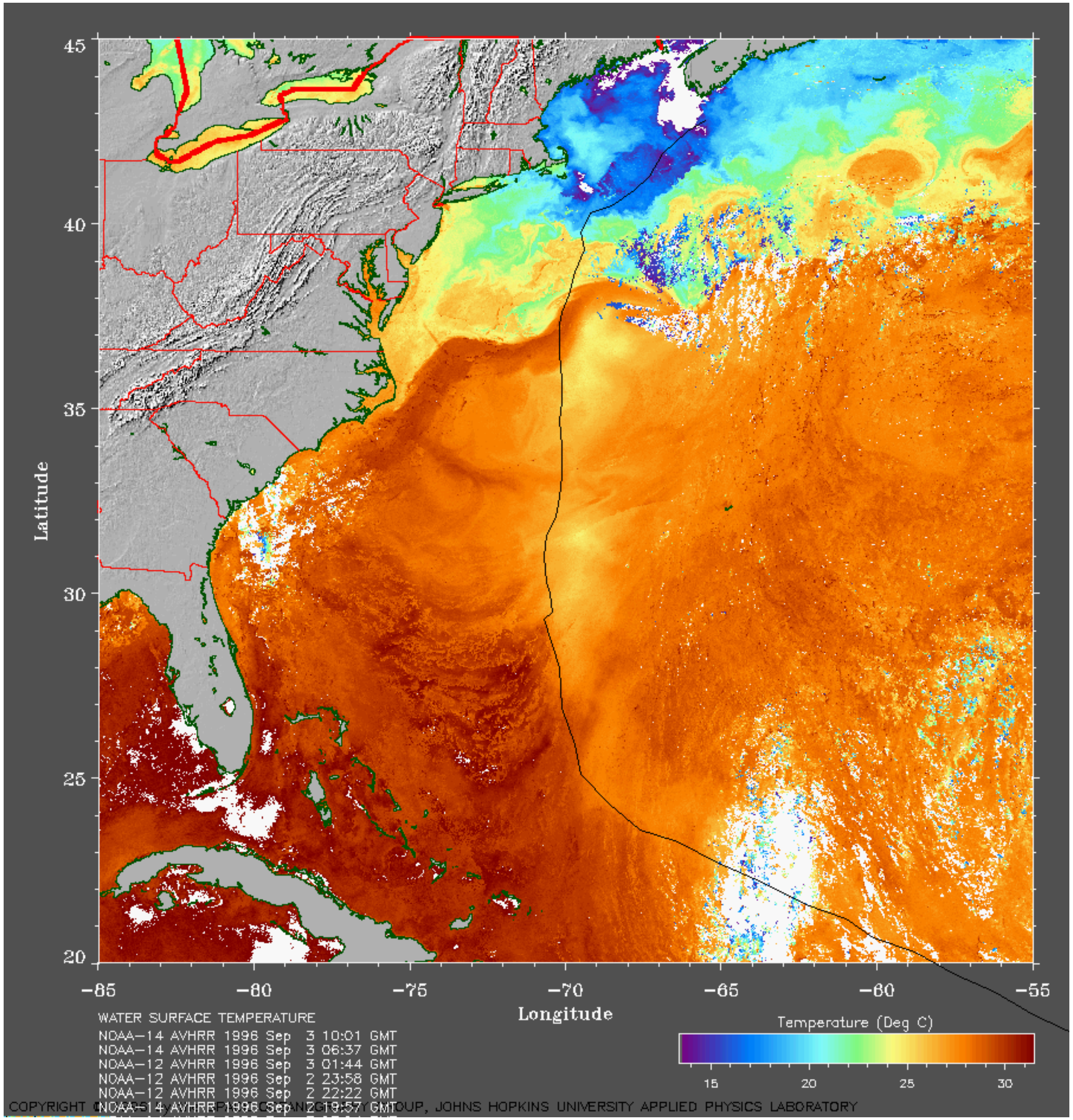


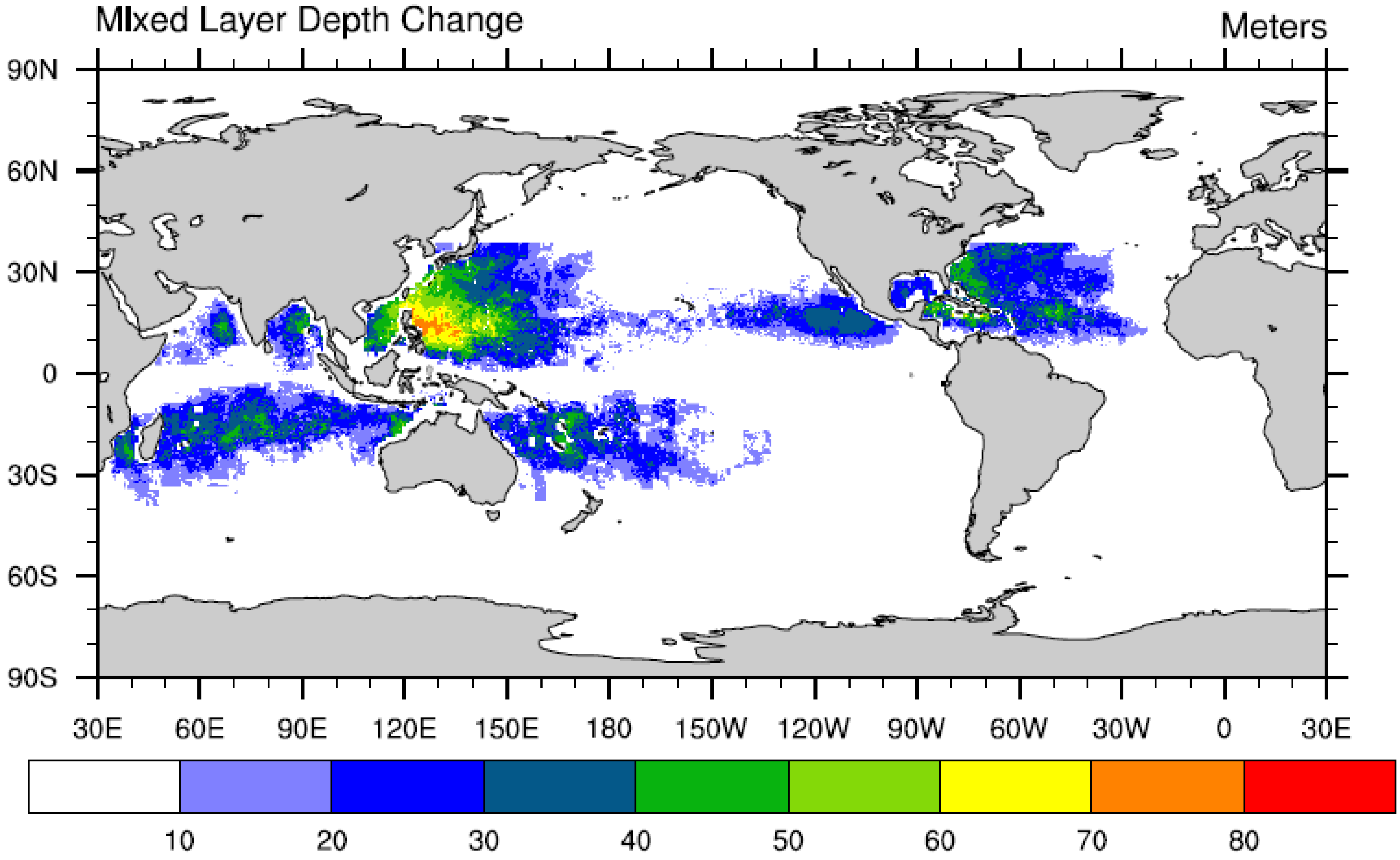
How to explain such a dependence using a balanced vortex model is currently undergoing.

6. TC and climate

- Is TC a passive ingredient of a climate system?
- How is TC characteristics (number, intensity, size, etc.) going to change in a warming climate?

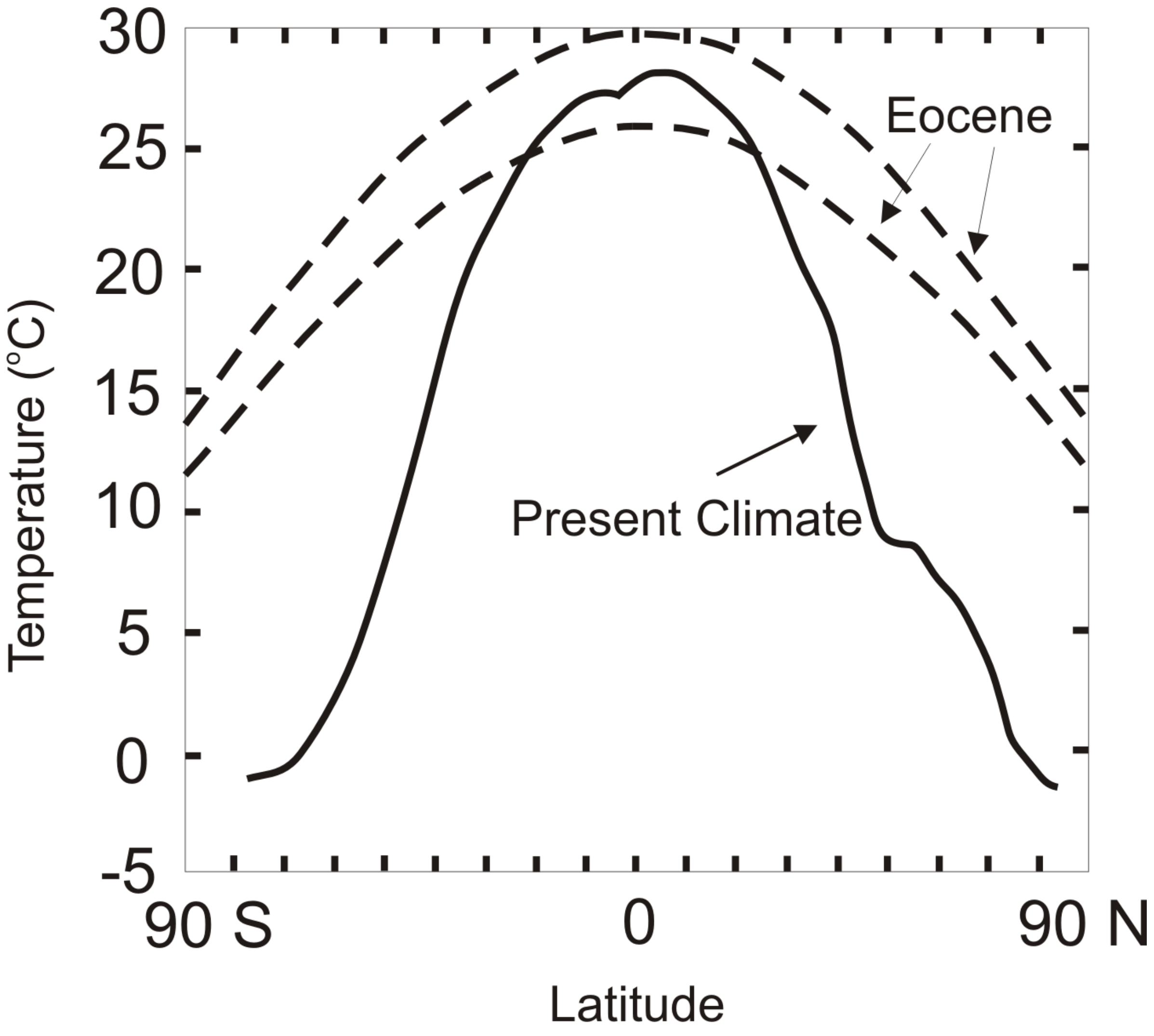
Strong Mixing of Upper Ocean





Sriver and Huber, Nature, 2007, TC induced mixing can contributes to 15% of the total ocean heat transport

TC-Mixing may be Crucial for High-Latitude Warmth and Low-Latitude Moderation During Warm Climates, such as that of the Eocene

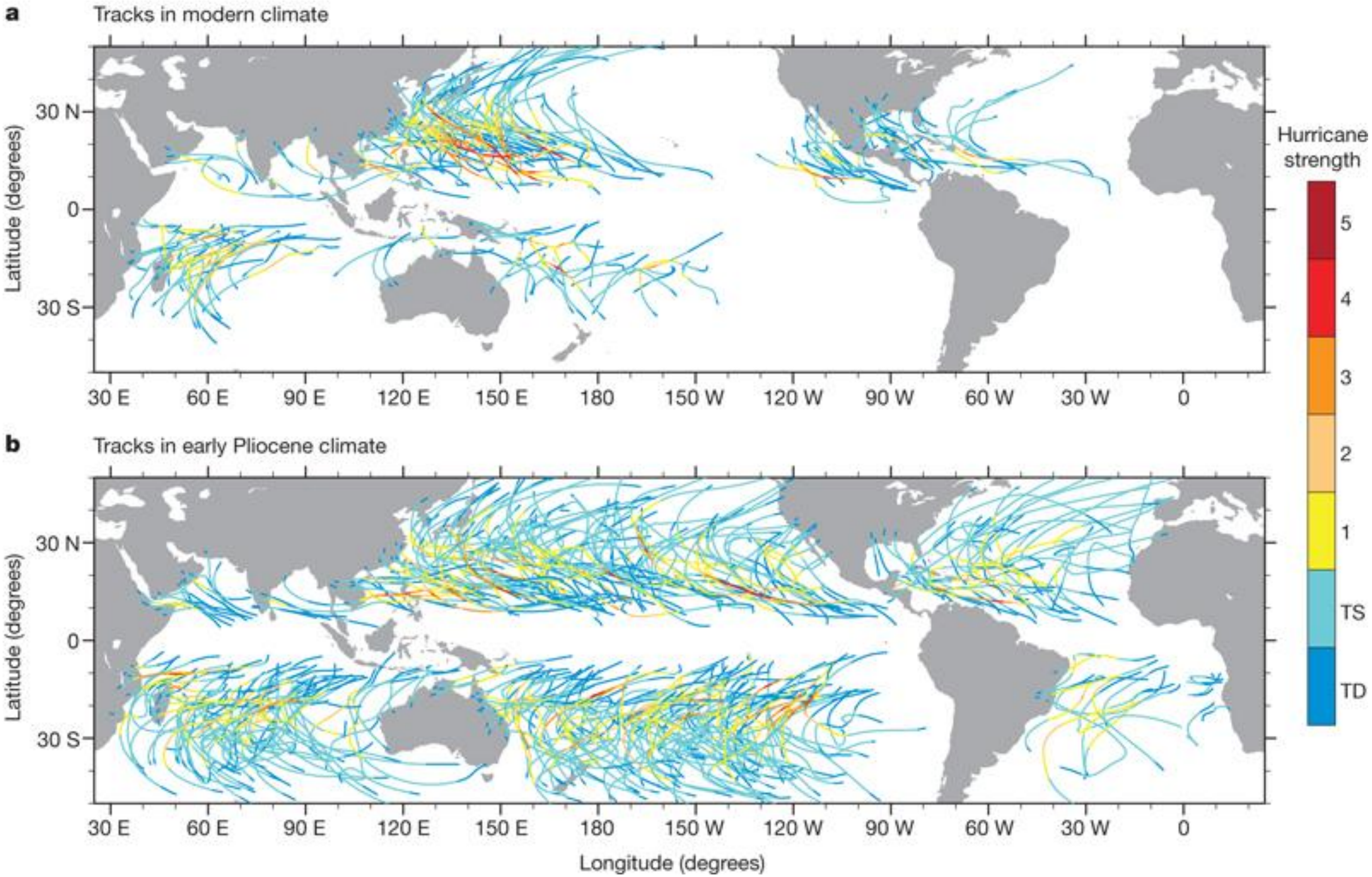


Most on ocean

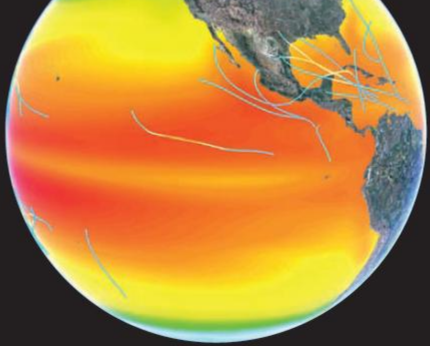
- **Storm-induced mixing of the upper tropical ocean may be an important driver of the ocean's thermohaline circulation**

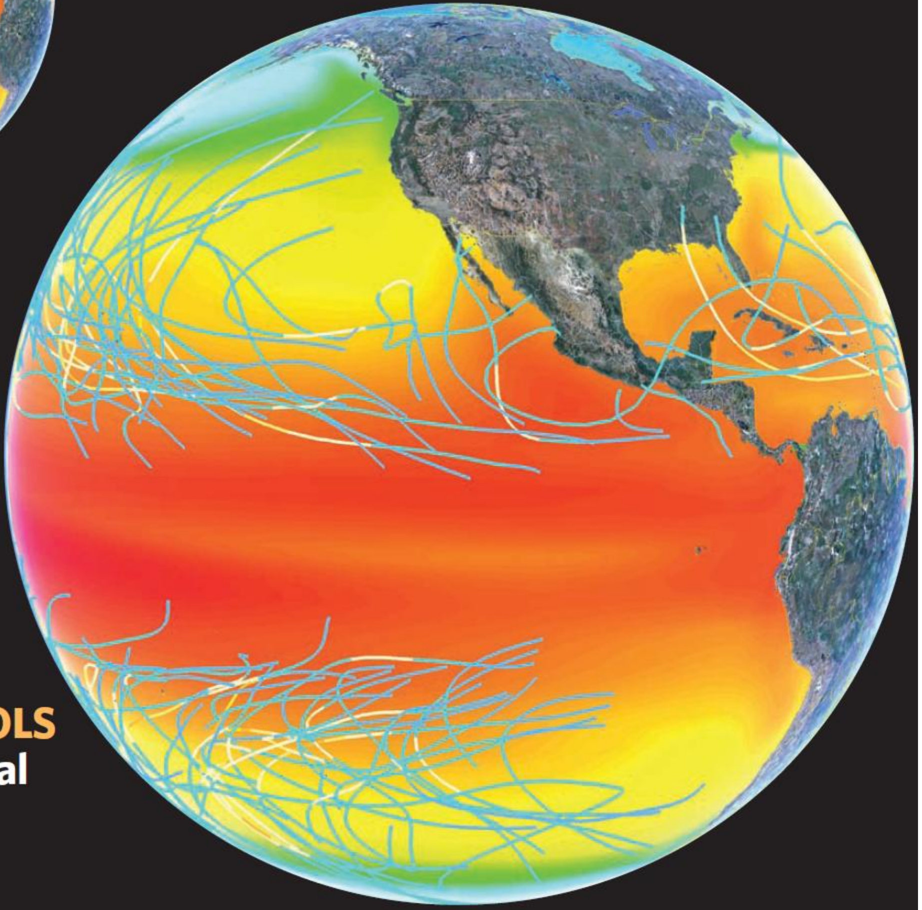
- **Increased TC power dissipation in a warming climate will drive a larger poleward heat flux by the oceans, tempering tropical warming but amplifying the warming of middle and high latitudes**

The tracks of tropical cyclones simulated by the SDSM.



AV Fedorov *et al. Nature* **463**, 1066-1070 (2010) doi:10.1038/nature08831





A SENSE OF FAIRNESS
Neural aversion to inequality

EXOPLANETS
The disappearing hot Jupiter

TOBACCO CONTROLS
WHO's treaty on trial

WINDS OF CLIMATE CHANGE

Tropical cyclones maintained permanent El Niño-like conditions in the early Pliocene

NATUREJOBS
How to ask for a pay rise

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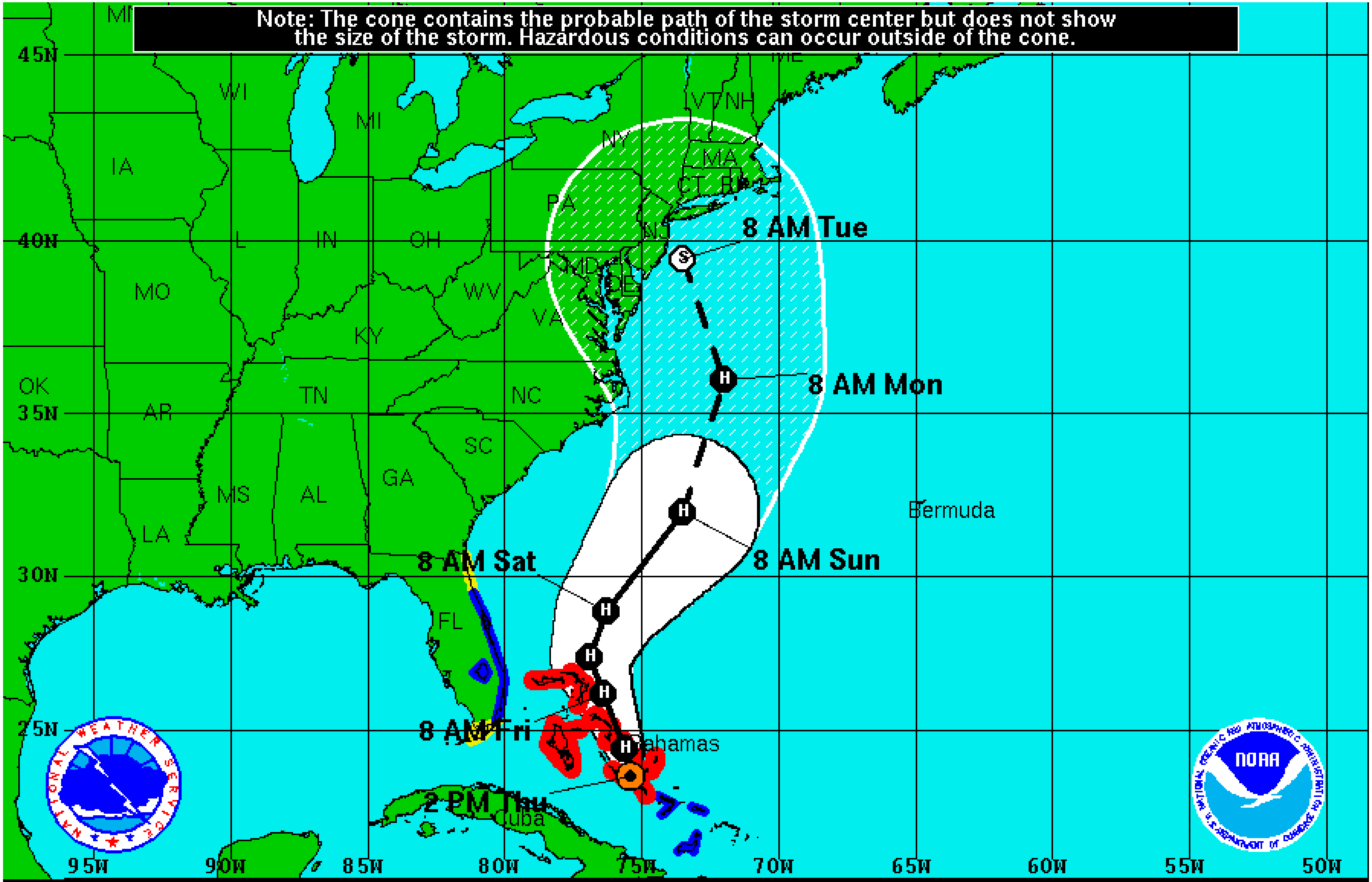
9 770028 083095

TC modeling

- Idealized modeling (Ooyama 1969, Rotunno and Emanuel 1987, Nolan, etc.)
- Statistical modeling
- Regional mesoscale modeling (GFDL hurricane model (1980s), HWRF (operational 2007))
- Global model (GFDL HiRAM, NOGAPS, etc.)
- The challenge: Track is OK, but intensity



Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.

Hurricane Sandy

Thursday October 25, 2012

2 PM EDT Intermediate Advisory 13A

NWS National Hurricane Center

Current Information: ◉

Center Location 23.5 N 75.4 W

Max Sustained Wind 105 mph

Movement N at 20 mph

Forecast Positions:

● Tropical Cyclone ○ Post-Tropical

Sustained Winds: D < 39 mph

S 39-73 mph H 74-110 mph M > 110mph

Potential Track Area:

Day 1-3 Day 4-5

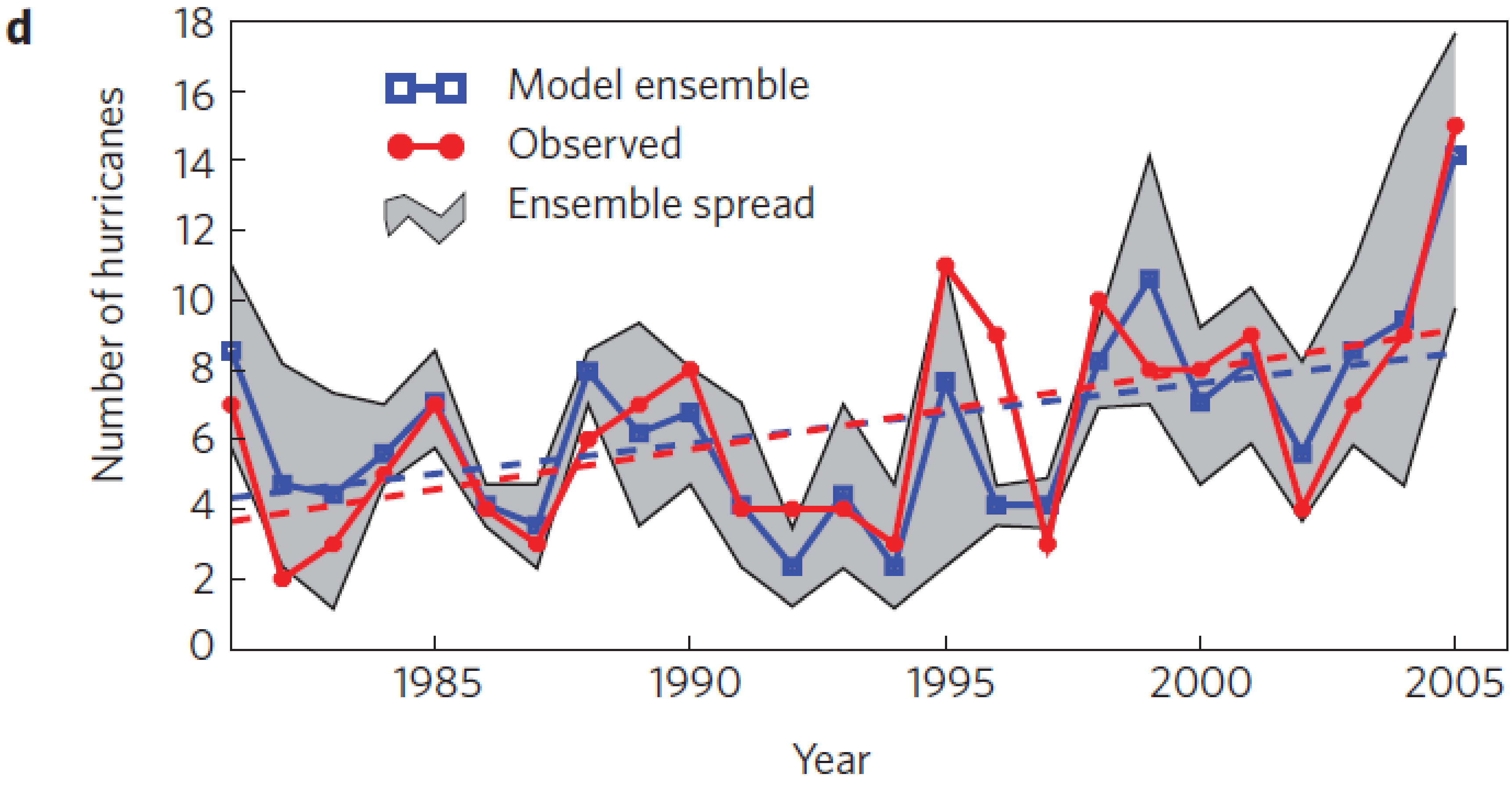
Watches:

▭ Hurricane 🟨 Trop.Storm

Warnings:

🟥 Hurricane 🟦 Trop.Storm

50-km GFDL HiRAM model



Zhao et al. 2009

TC projection

1. Frequency: Current models project changes ranging from −6 to −34% globally, and up to ±50% or more in individual basins by the late twenty-first century.
2. Intensity: Some increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally) with projected twenty-first-century warming
3. Rainfall: Rainfall rates are likely to increase. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone centre.

Knutson et al. 2010 Nature Geo.

Question list by Emanuel

- How do Tropical Cyclones, once initiated, intensify? (Emanuel, 1997, Smith and Montgomery, 2009)
- How do tropical cyclones form? This is one of the great, largely unsolved problems of tropical meteorology. While empirical necessary conditions for tropical cyclone formation have been known for many decades (e.g., Palmen 1948; Gray 1979), a fundamental understanding of genesis remains elusive.
- What controls the sizes of tropical cyclones? While there have been recent advances in empirical knowledge of storm size distributions (e.g. Chavas and Emanuel, 2010), there is almost no theoretical understanding of storm size.
- What determines the level of tropical cyclone activity in a given climate state?

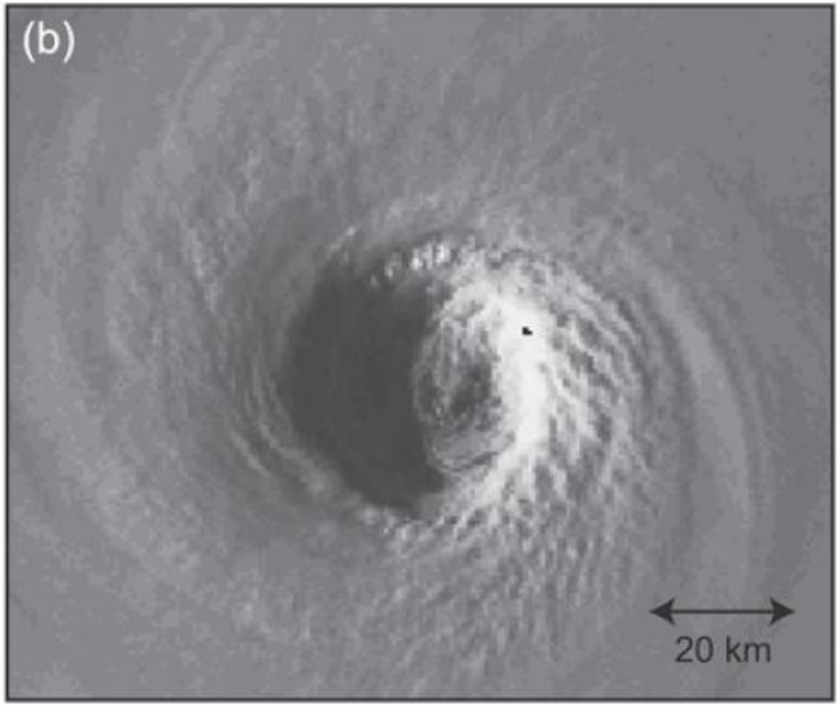
continued

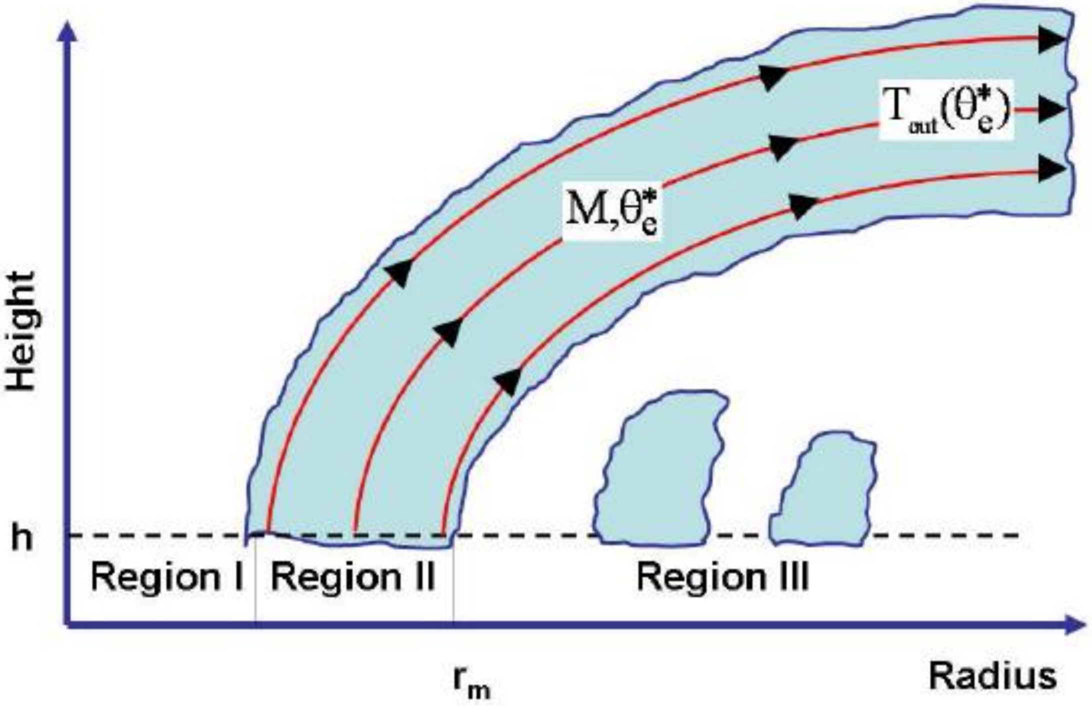
- What environmental factors control the actual (as opposed to potential) intensity of tropical cyclones? Answering this question involves such issues as
  - Response of the upper ocean to tropical cyclones; especially, cooling of the sea surface by vertical mixing in the ocean (Khain and Ginis, 1991)
  - Interaction of tropical cyclones with environmental winds, which may serve to import low entropy air into the storm core (Tang and Emanuel, 2010)
  - The time it takes for storms to intensify, as they are more likely to reach their maximum potential intensities if they have time to do so before reaching land or colder ocean surfaces.

continued

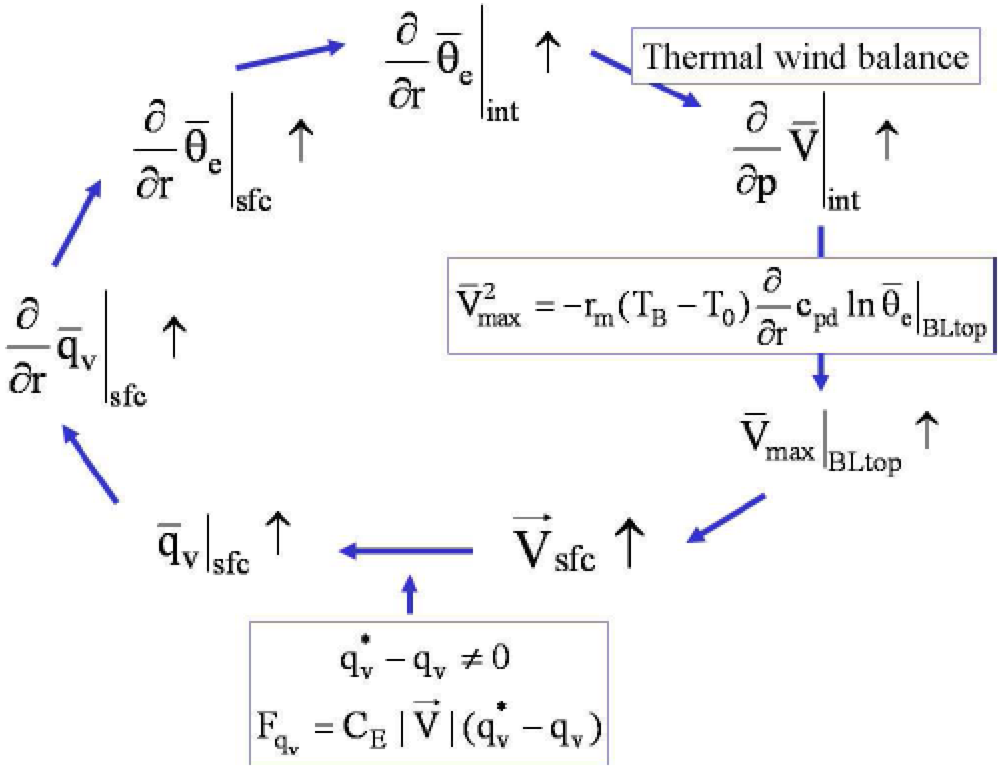
- What environmental and physical parameters determine the maximum achievable intensity of tropical cyclones? There are many related issues that must be resolved to answer this question. These include, but may not be limited to
  - The physics of air-sea enthalpy and momentum transport at high wind speeds, including such factors as waves and sea spray (Fairall et al., 1994, Edson et al., 1996, Andreas and Emanuel, 2001)
  - The existence and magnitude of supergradient winds in the boundary layer (Smith et al., 2008, Bryan and Rotunno, 2009a)
  - Horizontal mixing by atmospheric eddies (Bryan and Rotunno, 2009b)
  - Radial structure of the “outflow temperature” (Emanuel and Rotunno 2011)

Hurricane Katrina




$T_{out}(\theta_e^*)$
M,θ_e^*
Height
h
Region I
Region II
Region III
r_m
Radius

A schematic of WISHE



$\frac{\partial}{\partial r}\overline{\theta}_e\Big|_{int} \uparrow$

Thermal wind balance

$\frac{\partial}{\partial p}\overline{V}\Big|_{int} \uparrow$

$$\overline{V}^2_{max} = -r_m(T_B - T_0)\frac{\partial}{\partial r}c_{pd}\ln\overline{\theta}_e\Big|_{BLtop}$$

$\overline{V}_{max}\Big|_{BLtop} \uparrow$

$\vec{V}_{sfc} \uparrow$

$$q_v^* - q_v \neq 0$$

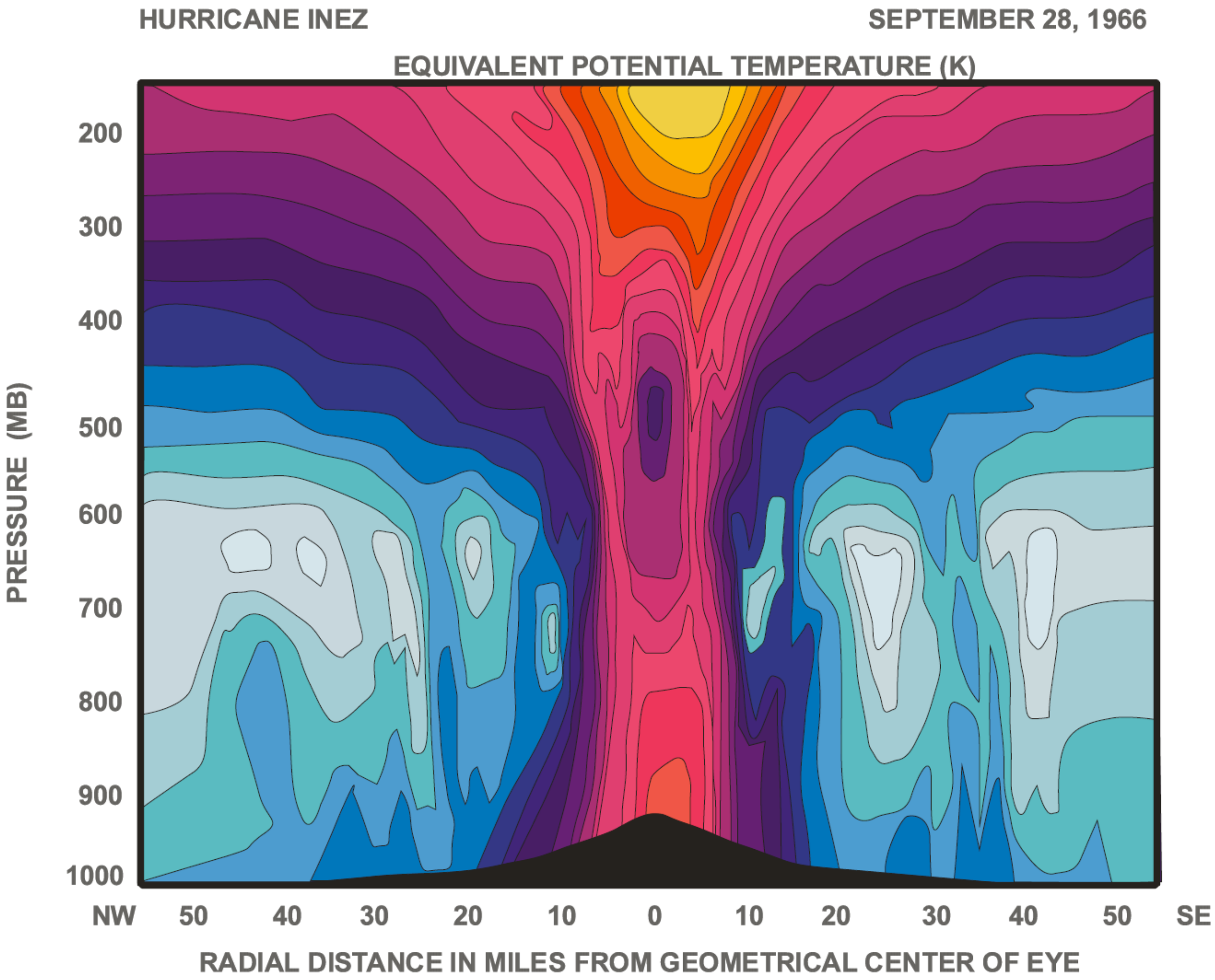
$$F_{q_v} = C_E|\vec{V}|(q_v^* - q_v)$$

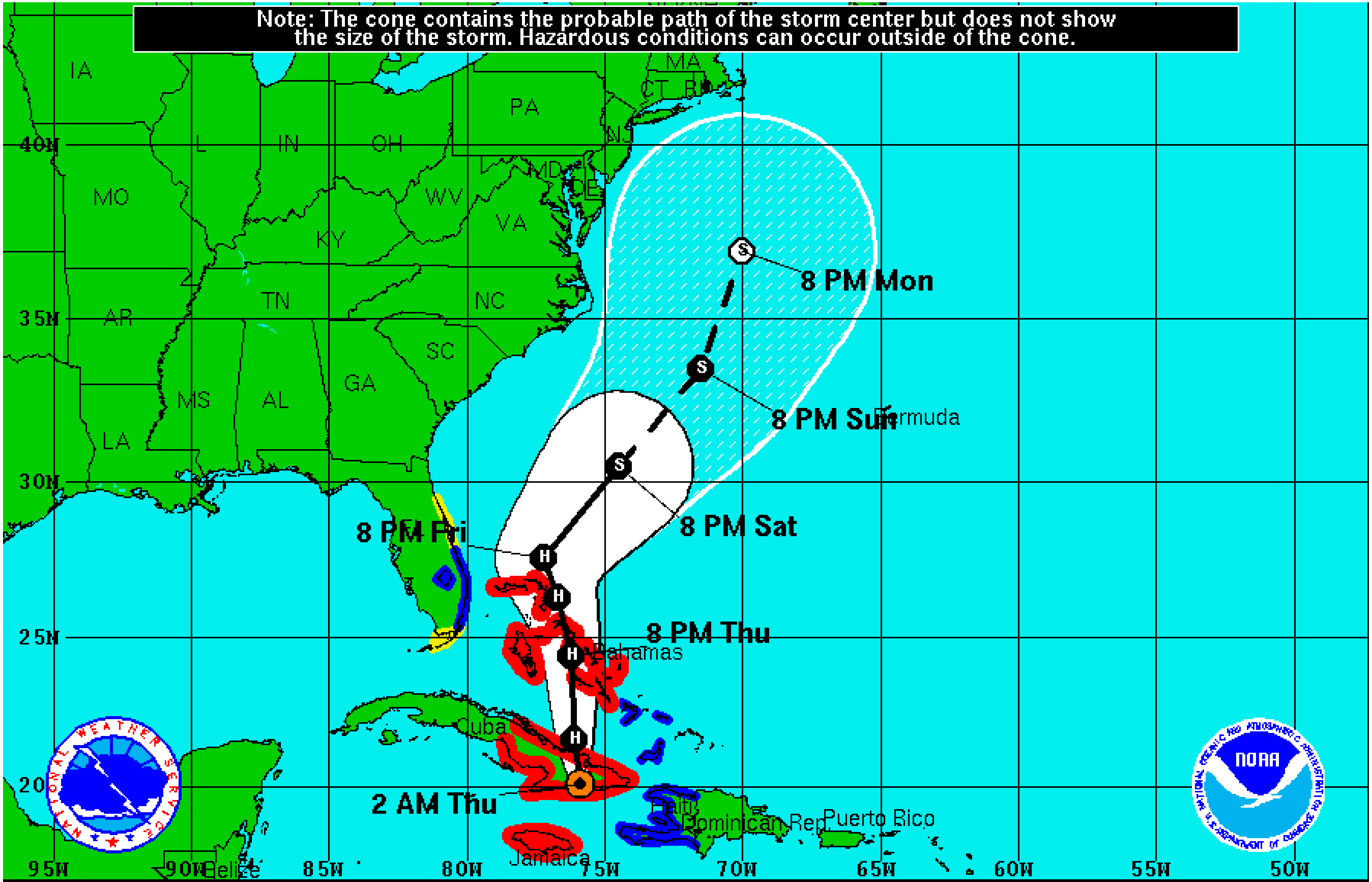
$\overline{q}_v\Big|_{sfc} \uparrow$

$\frac{\partial}{\partial r}\overline{q}_v\Big|_{sfc} \uparrow$

$\frac{\partial}{\partial r}\overline{\theta}_e\Big|_{sfc} \uparrow$

Thetae distribution





Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.

Hurricane Sandy
Thursday October 25, 2012
2 AM EDT Intermediate Advisory 11A
NWS National Hurricane Center

Current Information: ◉
Center Location 20.1 N 75.9 W
Max Sustained Wind 110 mph
Movement NNE at 15 mph

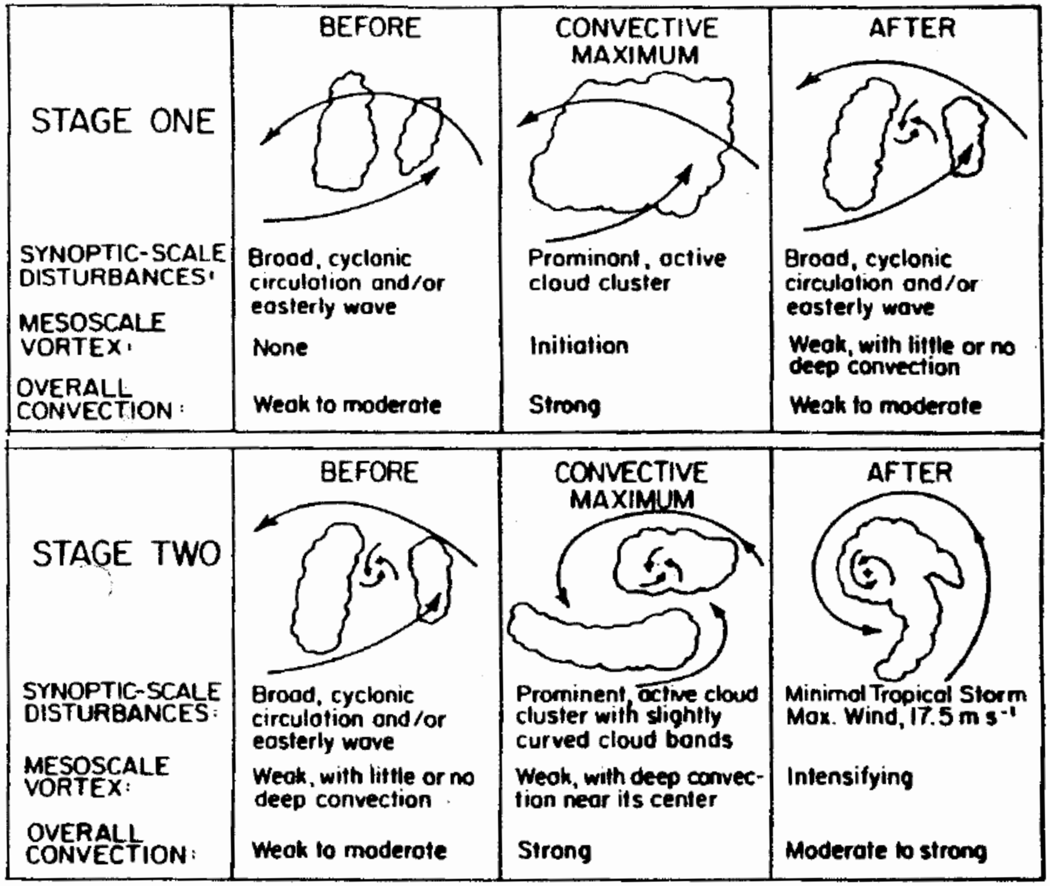
Forecast Positions:
● Tropical Cyclone ○ Post-Tropical
Sustained Winds: D < 39 mph
S 39-73 mph H 74-110 mph M > 110mph

Potential Track Area:
Day 1-3 Day 4-5

Watches:
Hurricane Trop.Storm

Warnings:
🟥 Hurricane 🟦 Trop.Storm

Zehr (1992) Model of Formation

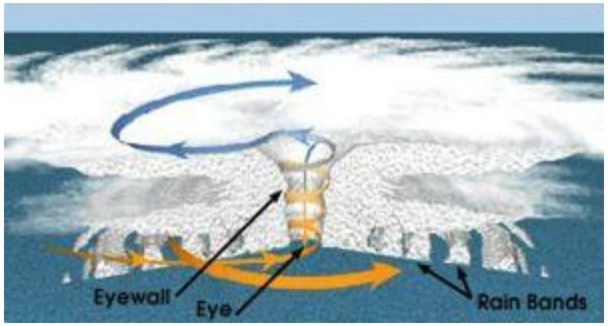


STAGE ONE	BEFORE	CONVECTIVE MAXIMUM	AFTER
SYNOPTIC-SCALE DISTURBANCES:	Broad, cyclonic circulation and/or easterly wave	Prominent, active cloud cluster	Broad, cyclonic circulation and/or easterly wave
MESOSCALE VORTEX:	None	Initiation	Weak, with little or no deep convection
OVERALL CONVECTION:	Weak to moderate	Strong	Weak to moderate

STAGE TWO	BEFORE	CONVECTIVE MAXIMUM	AFTER
SYNOPTIC-SCALE DISTURBANCES:	Broad, cyclonic circulation and/or easterly wave	Prominent, active cloud cluster with slightly curved cloud bands	Minimal Tropical Storm Max. Wind, 17.5 m s⁻¹
MESOSCALE VORTEX:	Weak, with little or no deep convection	Weak, with deep convection near its center	Intensifying
OVERALL CONVECTION:	Weak to moderate	Strong	Moderate to strong

Fig. 3.21 Conceptual model of two stages in tropical cyclone formation based on case studies with visual and infrared satellite images in the western North Pacific (Zehr 1992).

(Figure obtained from *Global Perspectives on Tropical Cyclones*, Ch. 3, © 1995 WMO.)


Eyewall
Eye
Rain Bands