# Hurricane Physics

Kerry Emanuel

Massachusetts Institute of Technology

# Program

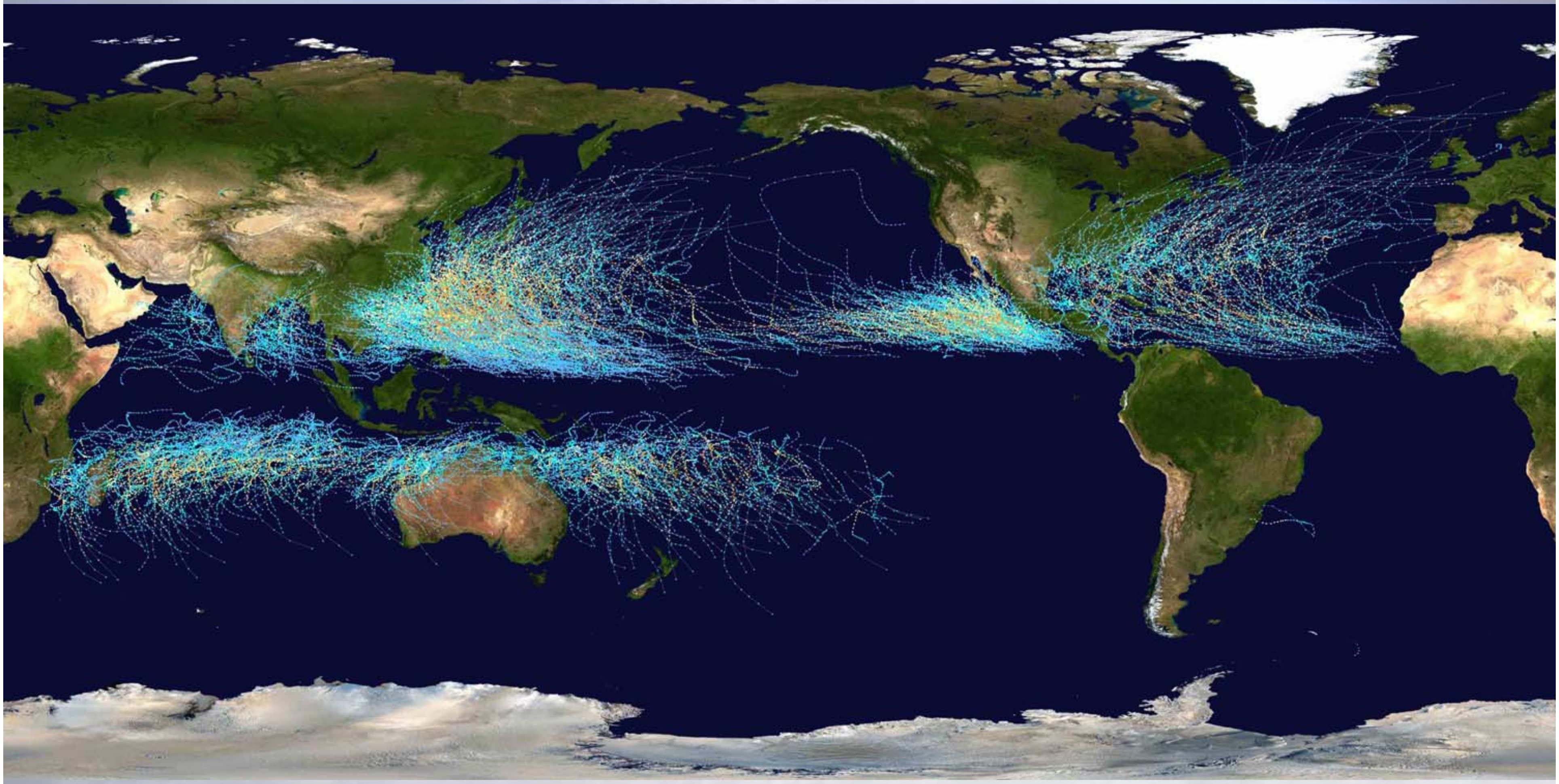
- **Overview of hurricanes**
- **Physics of mature, steady hurricanes**
- **The genesis problem**

# 1. Overview: What is a Hurricane?

**Formal definition**: A *tropical cyclone* with 1-min average winds at 10 m altitude in excess of 32 m/s (64 knots or 74 MPH) occurring over the North Atlantic or eastern North Pacific

A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface

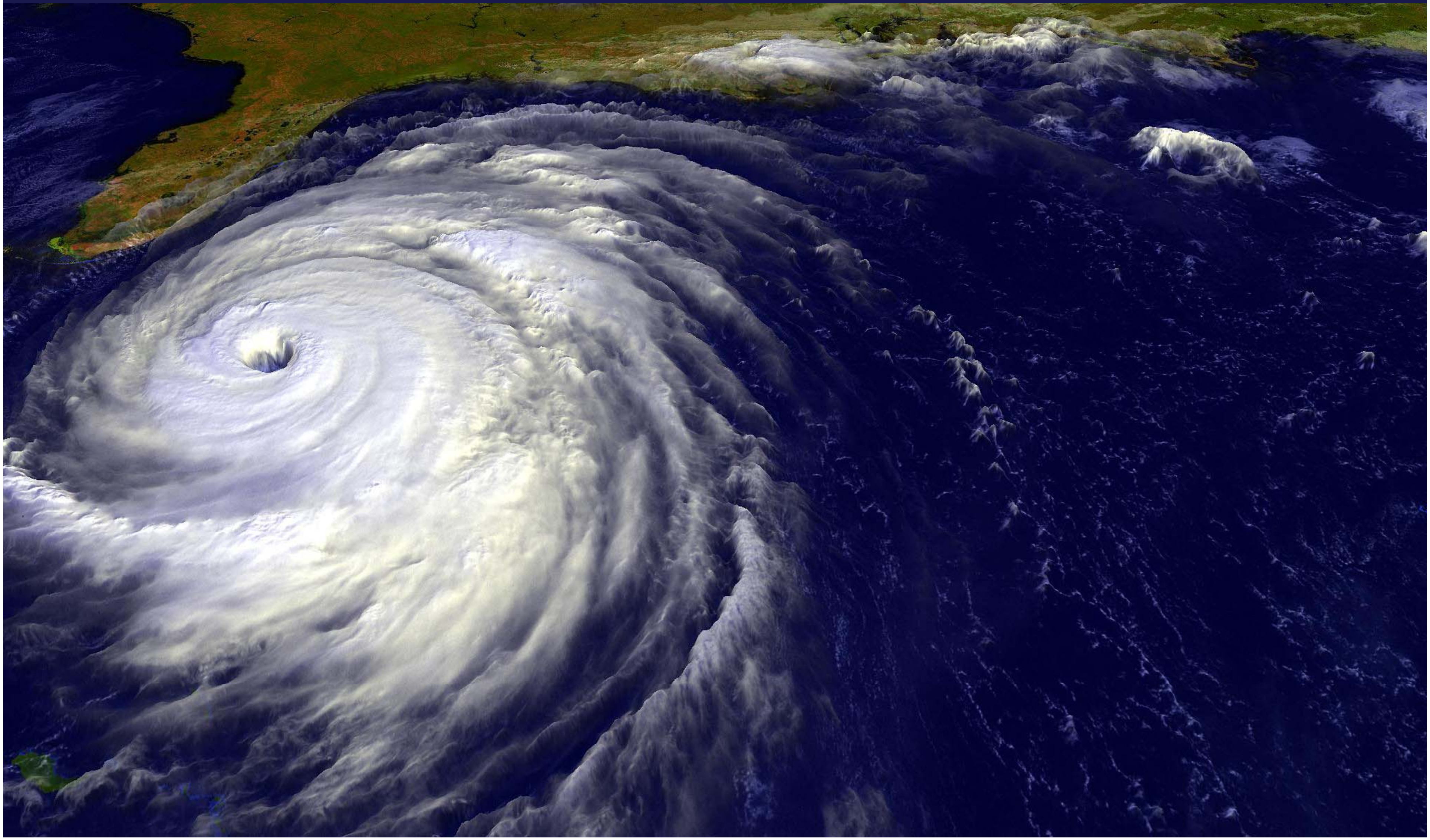
# Tracks of all tropical cyclones, 1985-2005



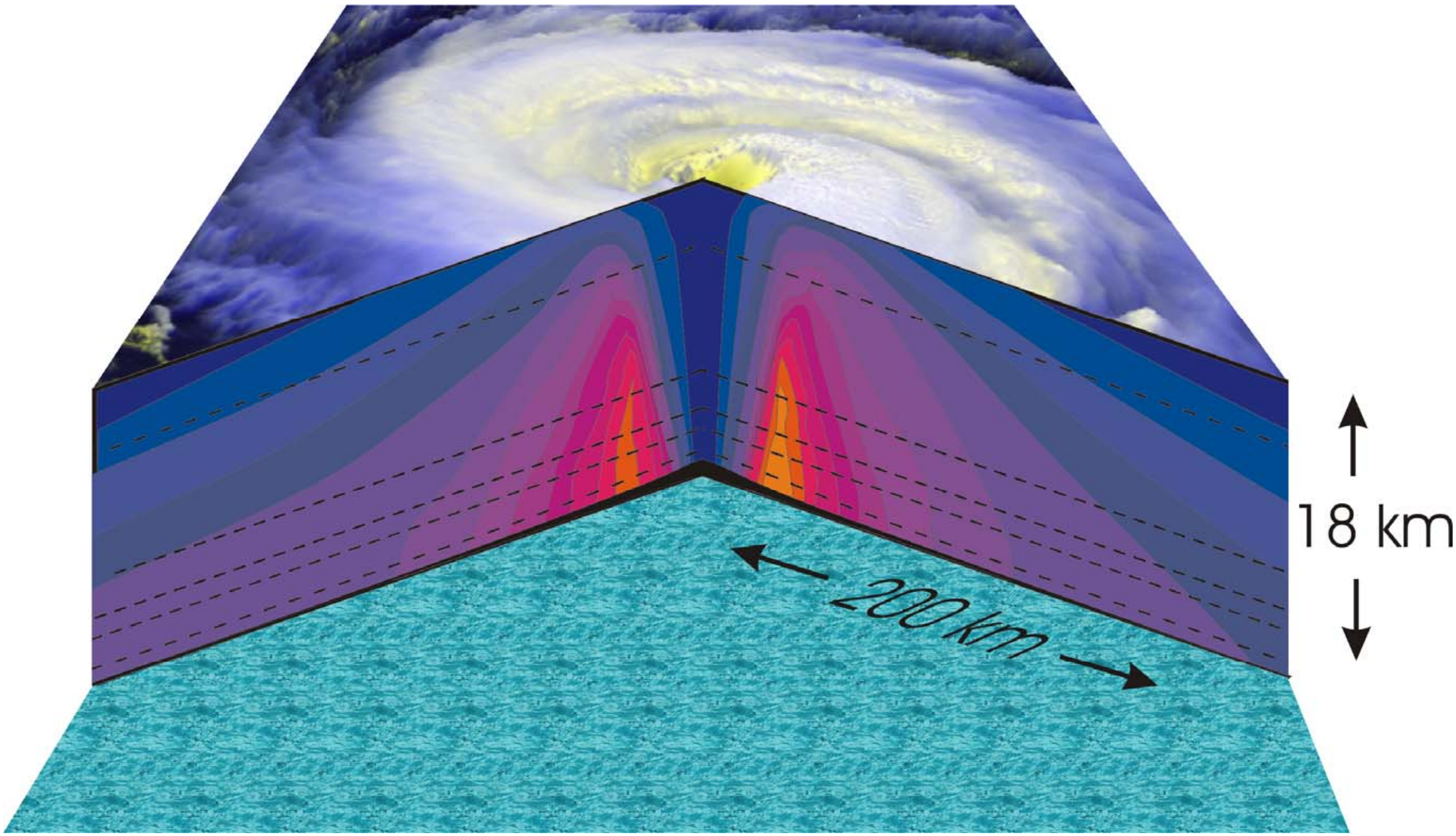
Source:  Wikipedia


Hurricane Structure

# The View from Space



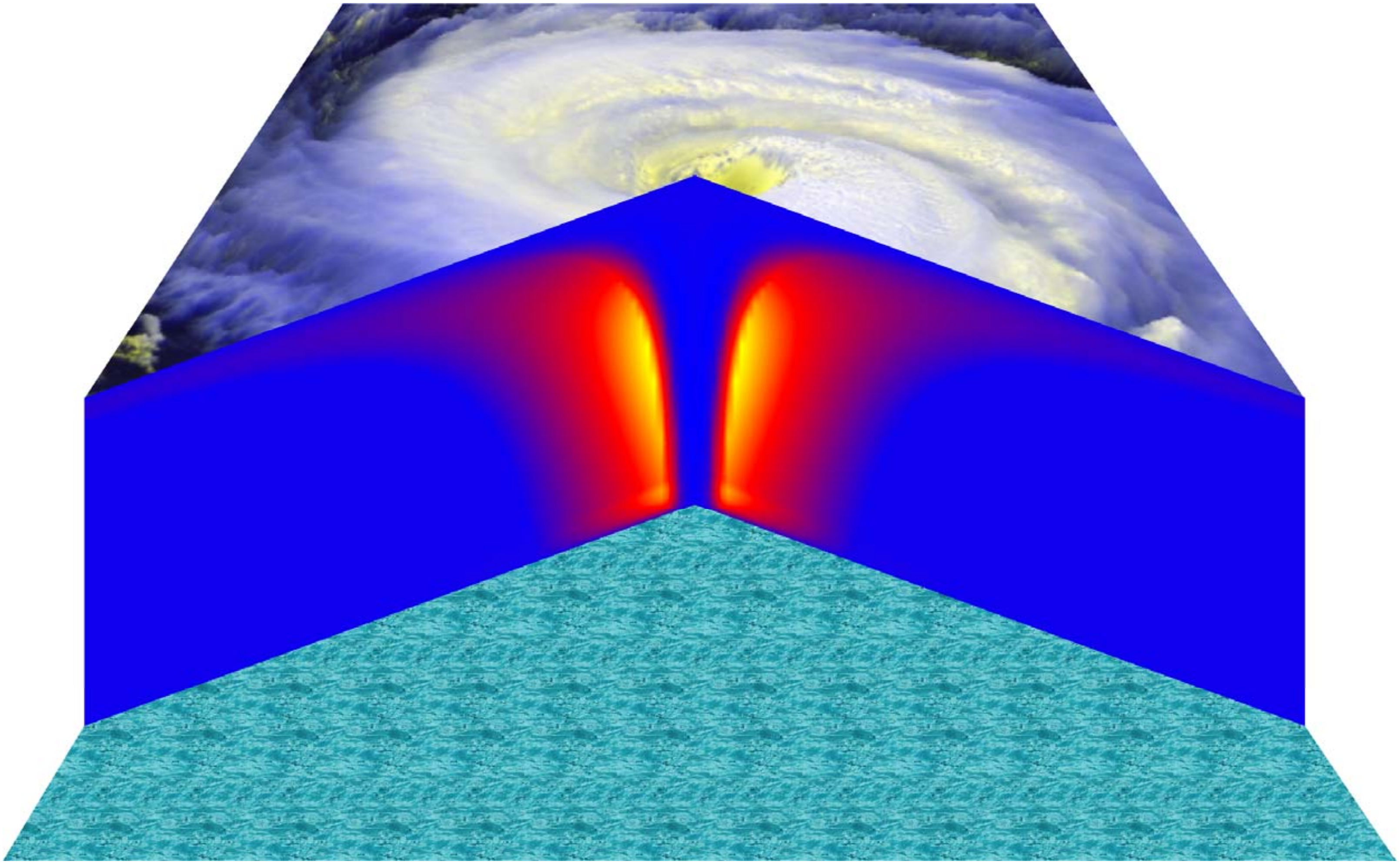
# Hurricane Structure: Wind Speed




**Azimuthal component of wind**

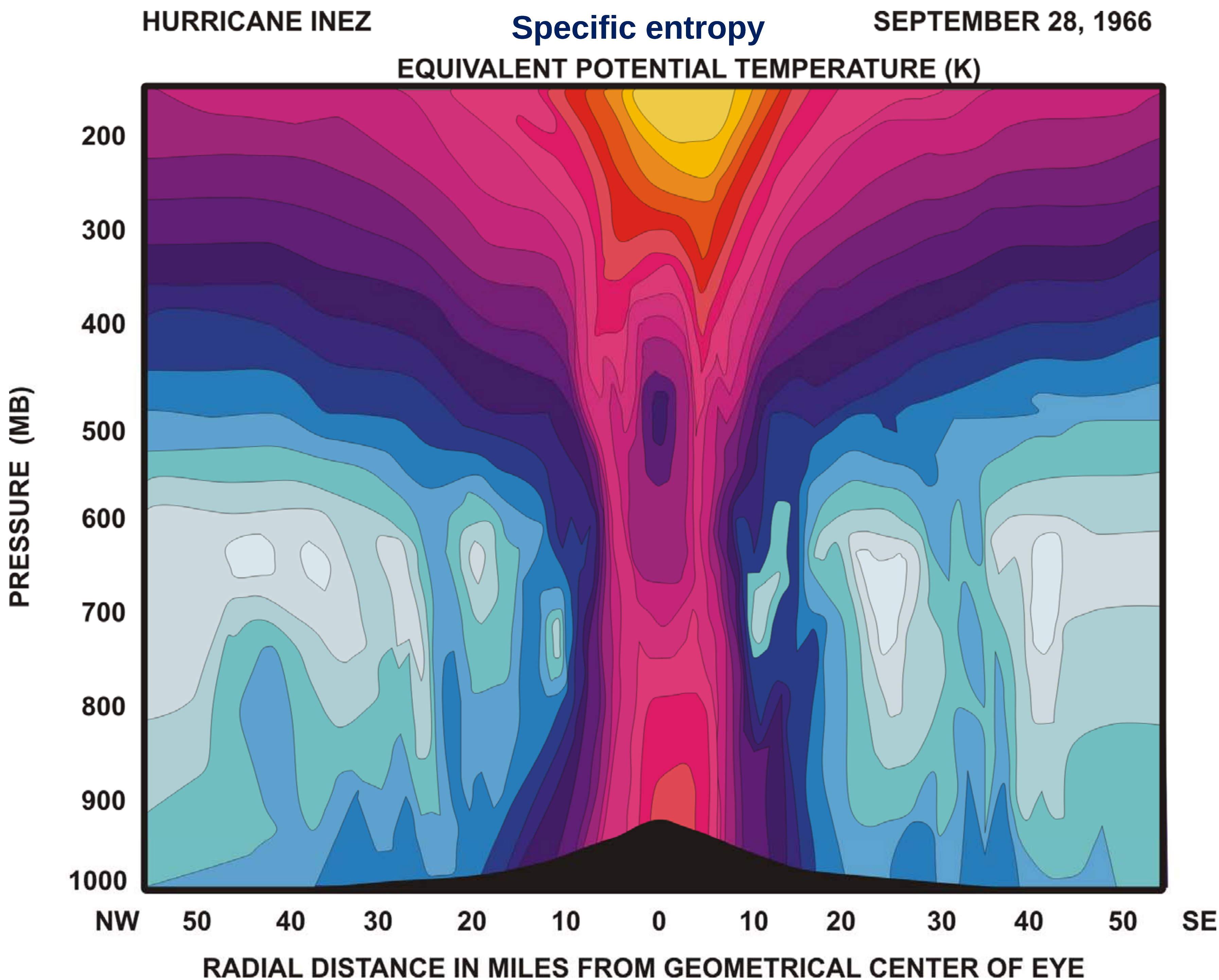
**< 11 5 $ms^{-1}$ - > 60 $ms^{-1}$**

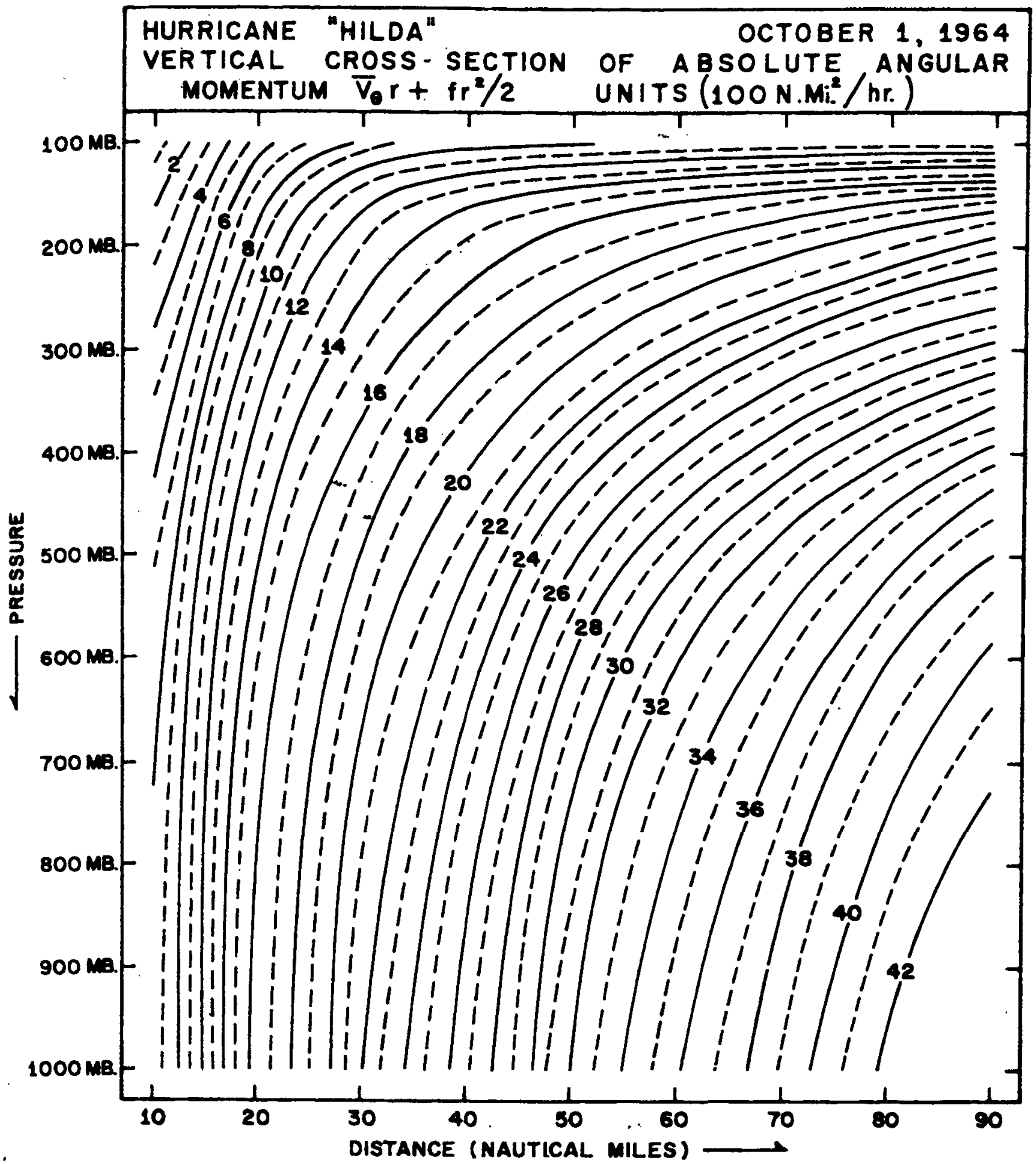
# Vertical Air Motion



**Updraft Speed**

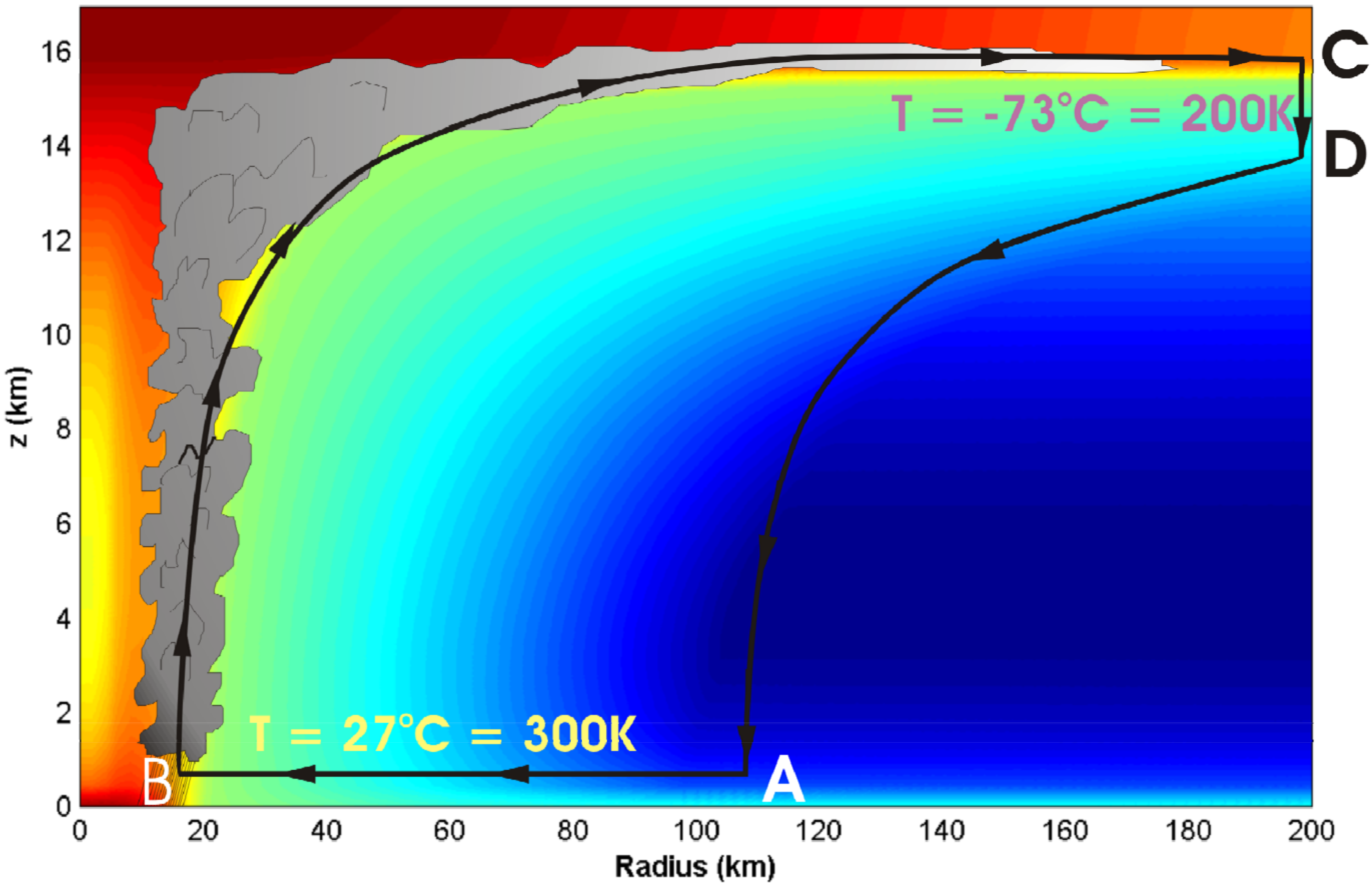
**Strong upward motion in the eyewall**


HURRICANE INEZ
Specific entropy
SEPTEMBER 28, 1966
EQUIVALENT POTENTIAL TEMPERATURE (K)
PRESSURE (MB)
200
300
400
500
600
700
800
900
1000
NW
50
40
30
20
10
0
10
20
30
40
50
SE
RADIAL DISTANCE IN MILES FROM GEOMETRICAL CENTER OF EYE


HURRICANE "HILDA"
OCTOBER 1, 1964
VERTICAL CROSS-SECTION OF ABSOLUTE ANGULAR MOMENTUM $\overline{V}_\theta r + fr^2/2$ UNITS (100 N.Mi.$^2$/hr.)
PRESSURE
100 MB.
200 MB.
300 MB.
400 MB.
500 MB.
600 MB.
700 MB.
800 MB.
900 MB.
1000 MB.
DISTANCE (NAUTICAL MILES)
10
20
30
40
50
60
70
80
90
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42

# Physics of Mature Hurricanes

# Energy Production



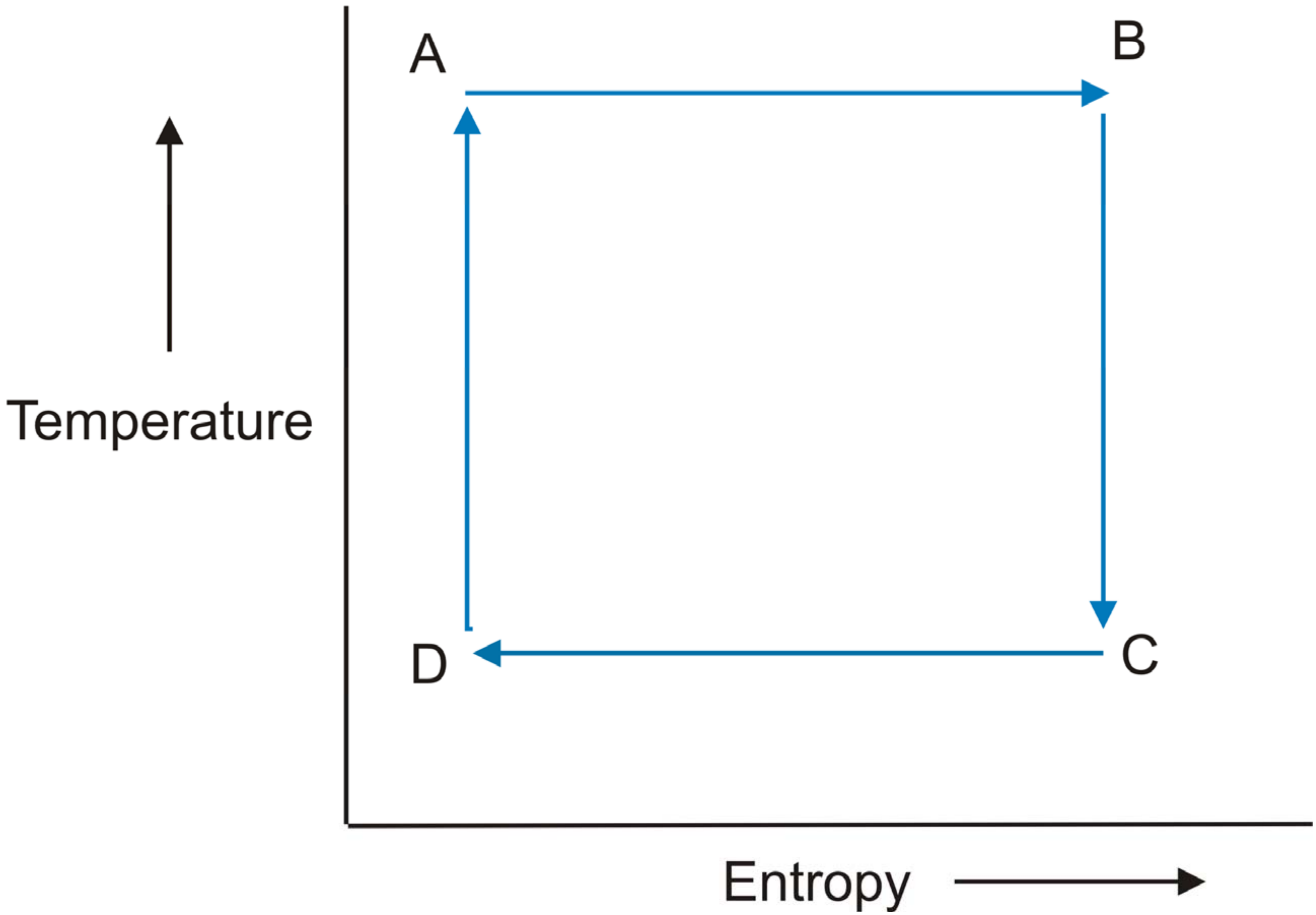
# Carnot Theorem: Maximum efficiency results from a particular energy cycle:

- Isothermal expansion
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

Note: Last leg is not adiabatic in hurricane: Air cools radiatively. But since environmental temperature profile is moist adiabatic, the amount of radiative cooling is the same as if air were saturated and descending moist adiabatically.

Maximum rate of energy production:

$$P = \frac{T_s - T_o}{T_s} \dot{Q}$$


A
B
C
D
Temperature
Entropy

Total rate of heat input to hurricane:

$$\dot{Q} = 2\pi \int_0^{r_0} \rho \left[ C_k \, |\mathbf{V}| \left( k_0^* - k \right) + C_D \, |\mathbf{V}|^3 \right] r\,dr$$

Surface enthalpy flux

Dissipative heating

In steady state, energy production is used to balance frictional dissipation:

$$D = 2\pi \int_0^{r_0} \rho \left[ C_D \, |\mathbf{V}|^3 \right] r\,dr$$

Plug into Carnot equation:

$$\int_0^{r_0} \rho \left[ C_D |\mathbf{V}|^3 \right] r dr = \frac{T_s - T_o}{T_o} \int_0^{r_0} \rho \left[ C_k |\mathbf{V}| \left( k_0^* - k \right) \right] r dr$$

If integrals dominated by values of integrands near radius of maximum winds,

$$\rightarrow \quad |V_{\max}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left( k_0{}^* - k \right)$$

Note: This equation can be derived exactly from the governing equations

# Theoretical Upper Bound on Hurricane Maximum Wind Speed:

$$|V_{pot}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left( k_0^* - k \right)$$

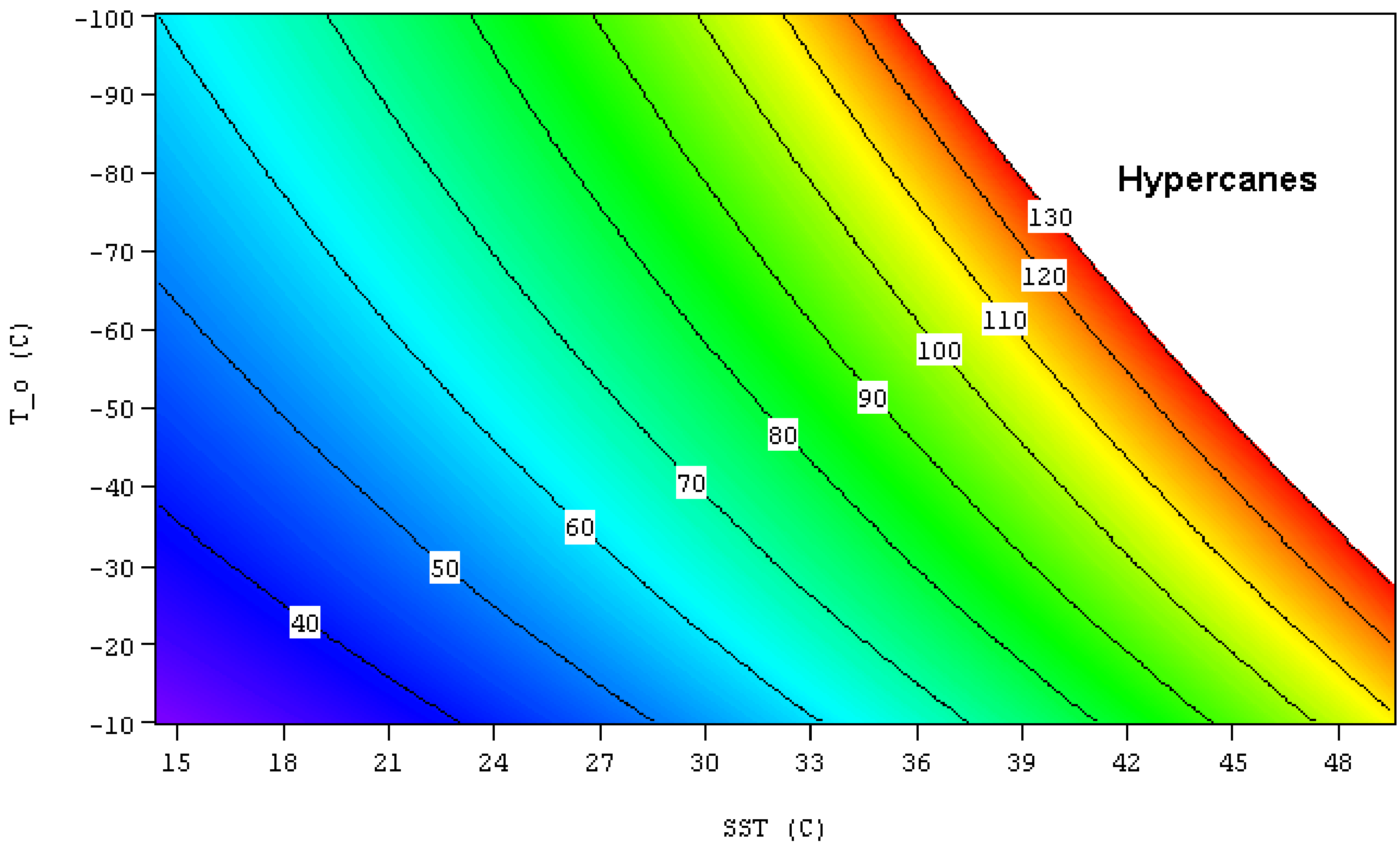
**Surface temperature**

**Ratio of exchange coefficients of enthalpy and momentum**

**Outflow temperature**

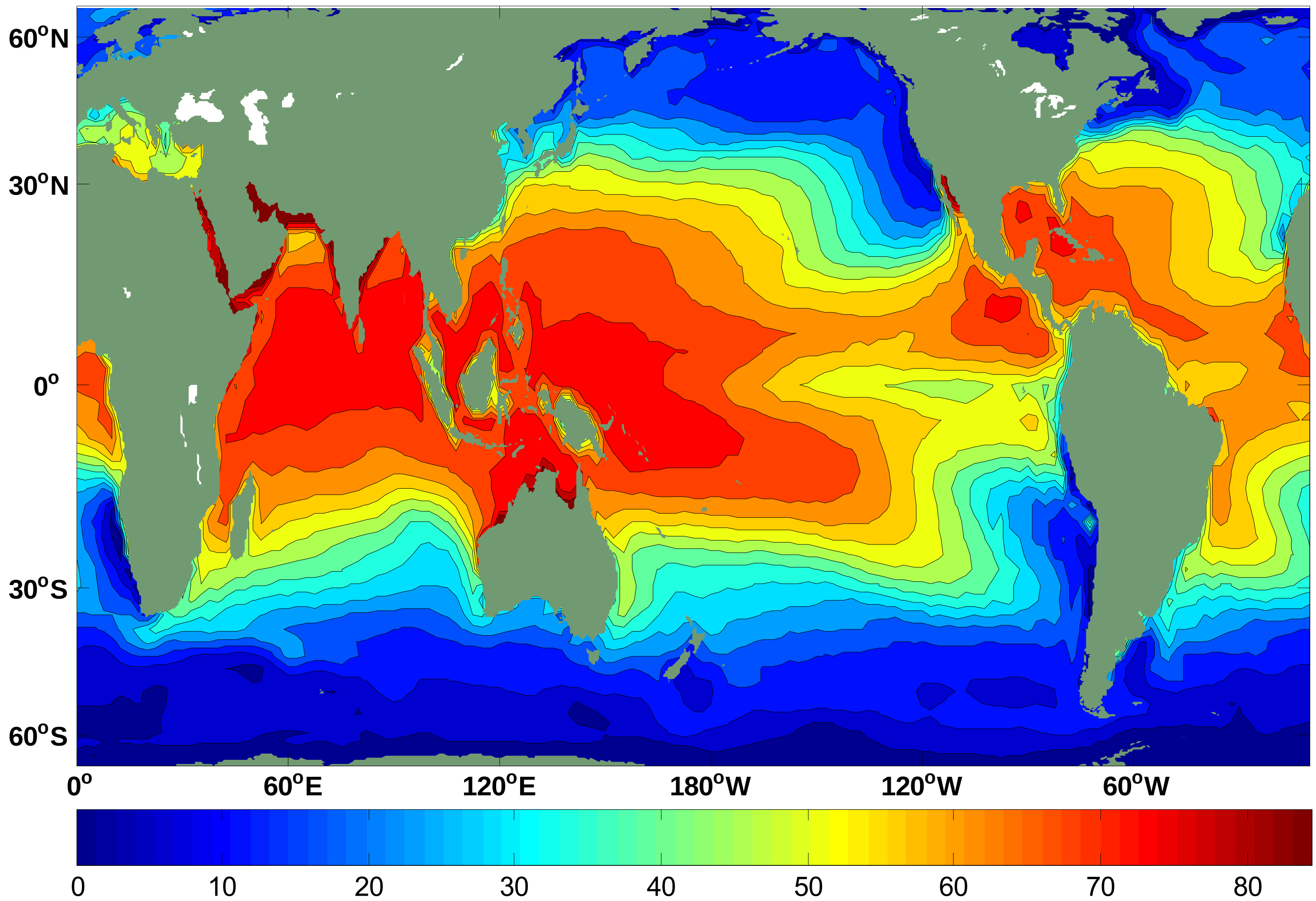
**Air-sea enthalpy disequilibrium**

Maximum Wind Speed (m/s)




$\mathscr{H} = 0.75 \quad C_k/C_D = 1.2$

# Annual Maximum Potential Intensity (m/s)



# Thermodynamic disequilibrium necessary to maintain ocean heat balance:

**Ocean mixed layer Energy Balance** (neglecting lateral heat transport):

$$C_k \rho |\mathbf{V_s}| \left( k_0^* - k \right) = F_\downarrow - F_\uparrow - F_{entrain}$$

Ocean mixed layer entrainment

$$\rightarrow$$

Greenhouse effect

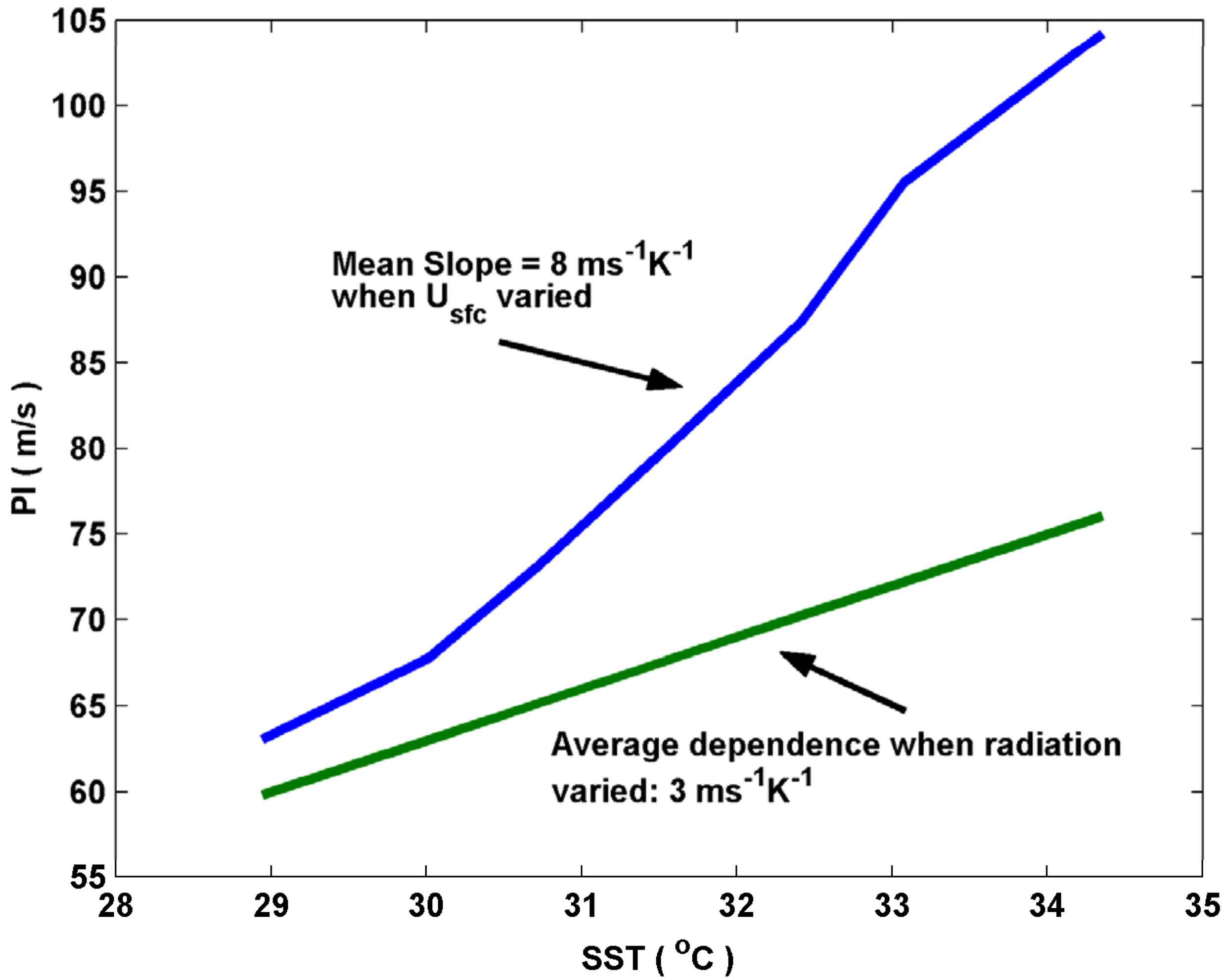
Ocean mixed layer entrainment

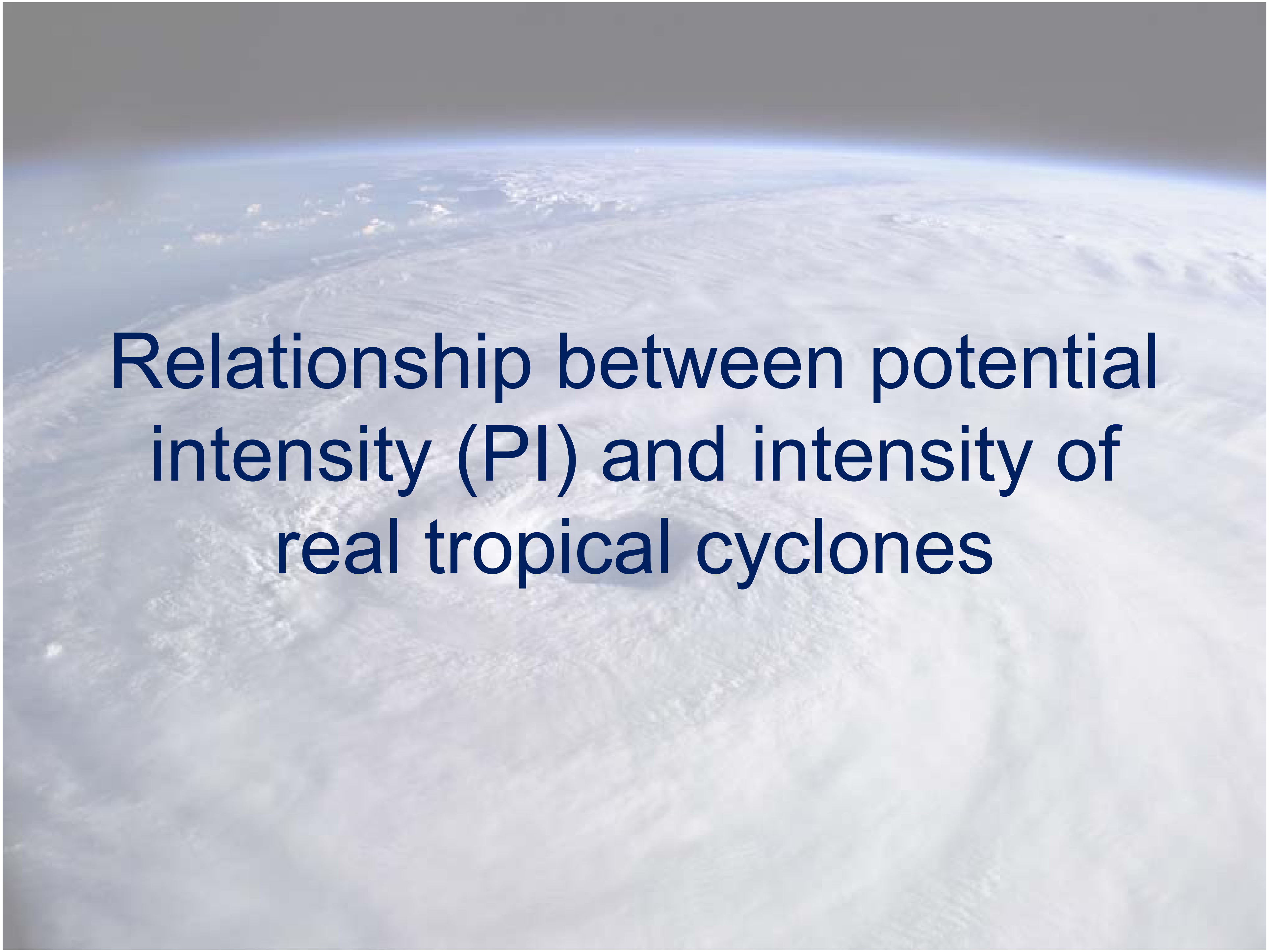
$$V_{pot}^2 = \frac{T_s - T_o}{T_o} \frac{F_\downarrow - F_\uparrow - F_{entrain}}{C_D \rho |\mathbf{V}_s|}$$

Weak explicit dependence on $T_s$

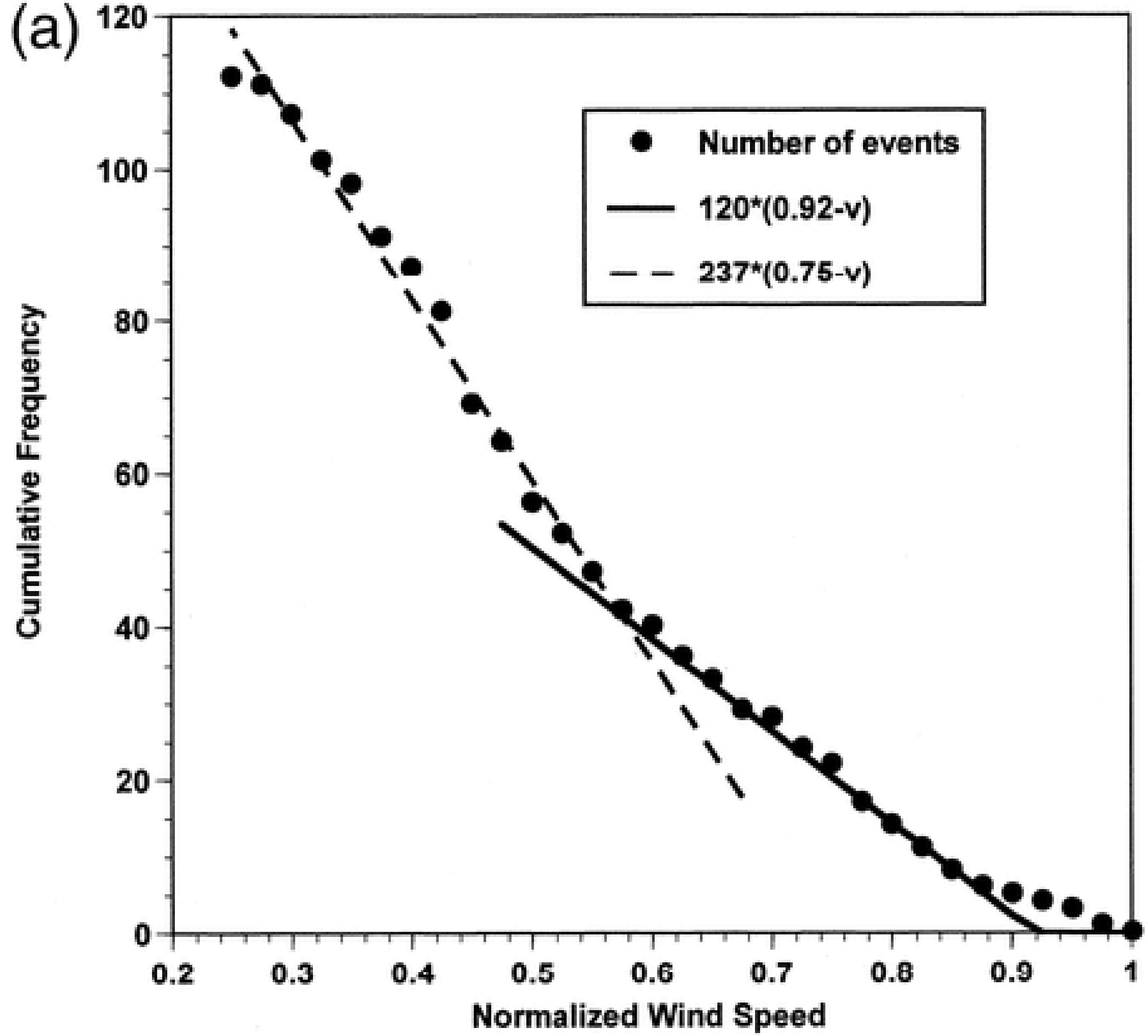
Mean surface wind speed

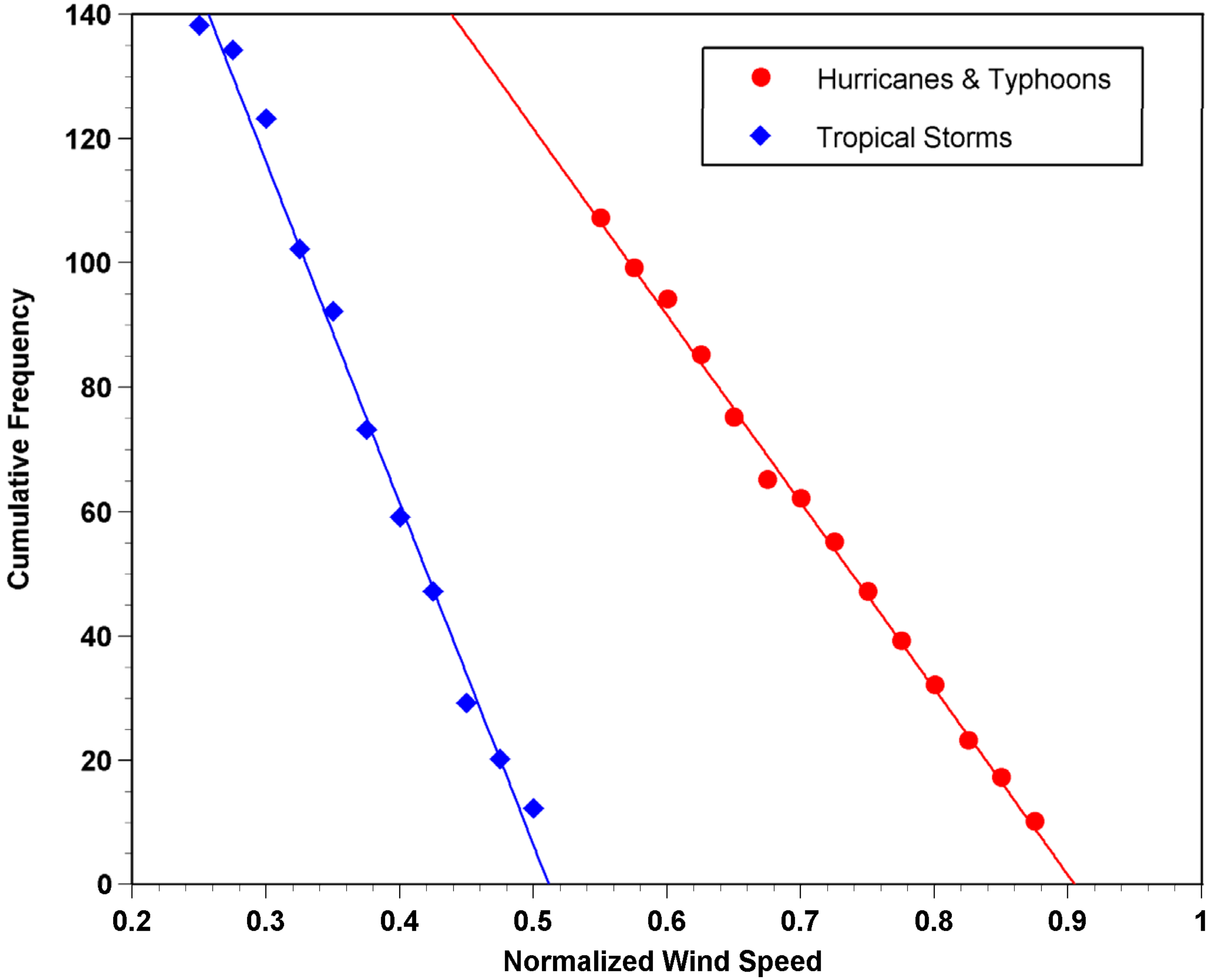
# Dependence on Sea Surface Temperature (SST):





# Relationship between potential intensity (PI) and intensity of real tropical cyclones


(a)
Number of events
120*(0.92-v)
237*(0.75-v)
Cumulative Frequency
Normalized Wind Speed
0
20
40
60
80
100
120
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

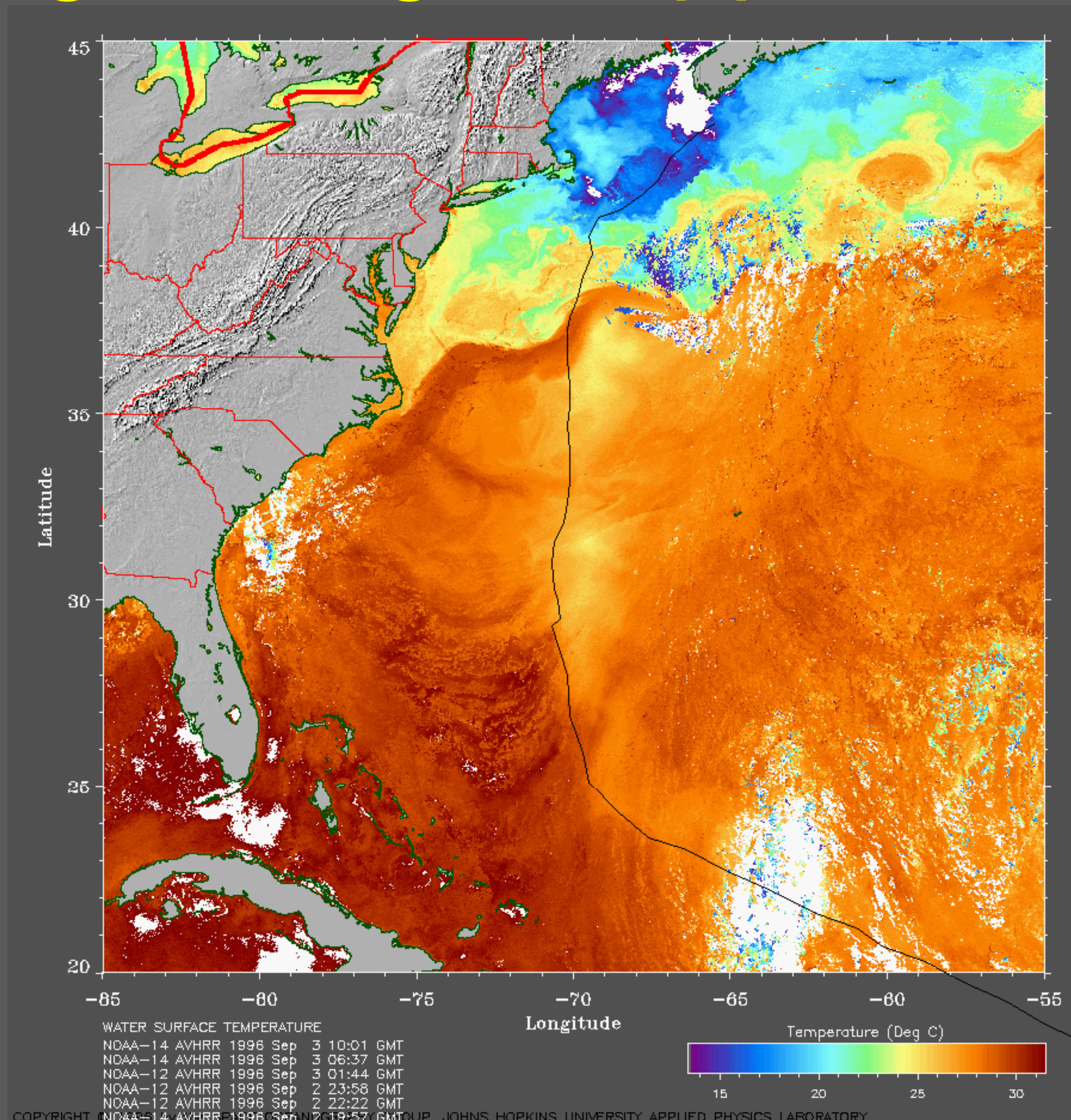


Hurricanes & Typhoons
Tropical Storms
Cumulative Frequency
Normalized Wind Speed
140
120
100
80
60
40
20
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

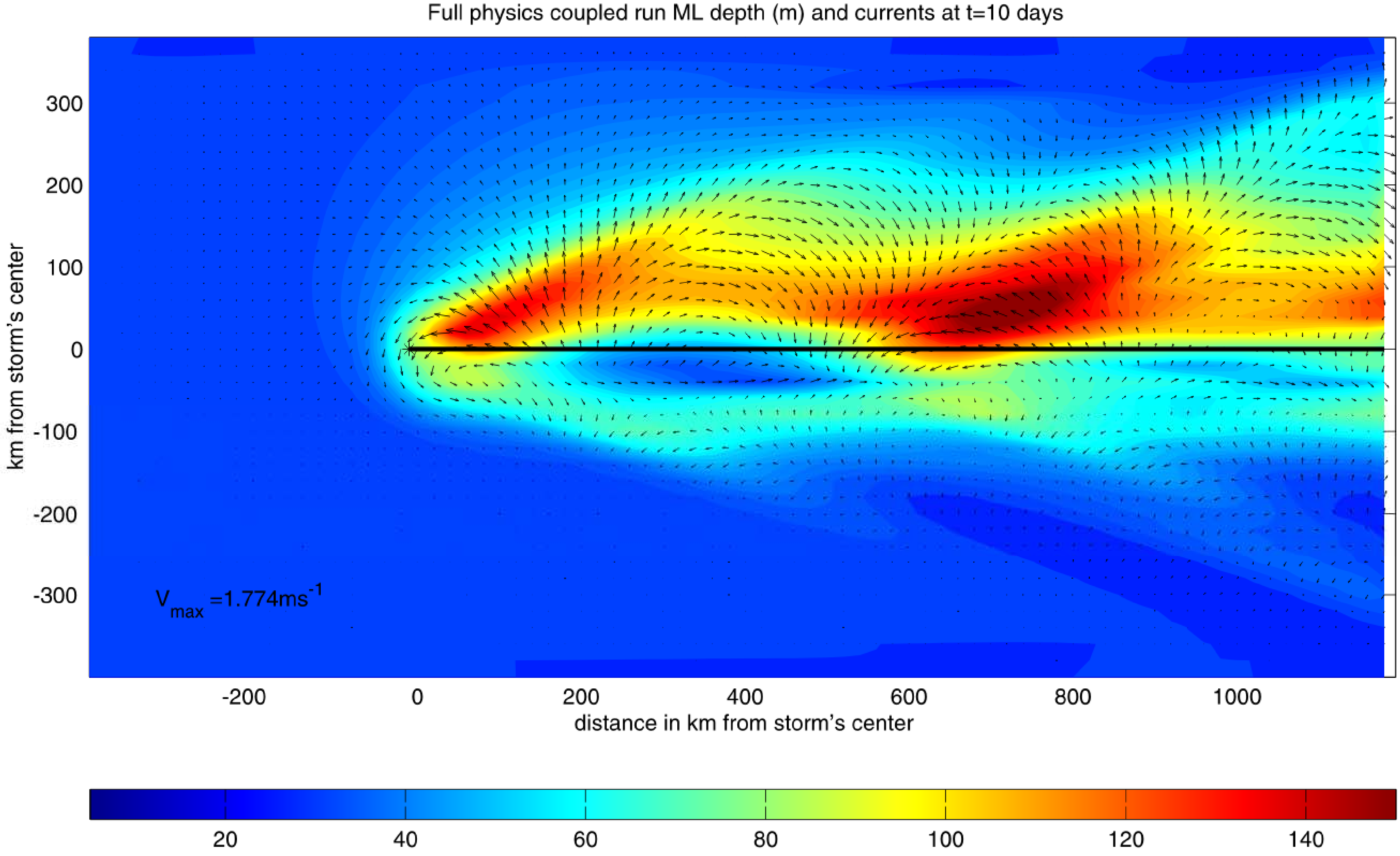
# Why do real storms seldom reach their thermodynamic potential?

One Reason:  Ocean Interaction

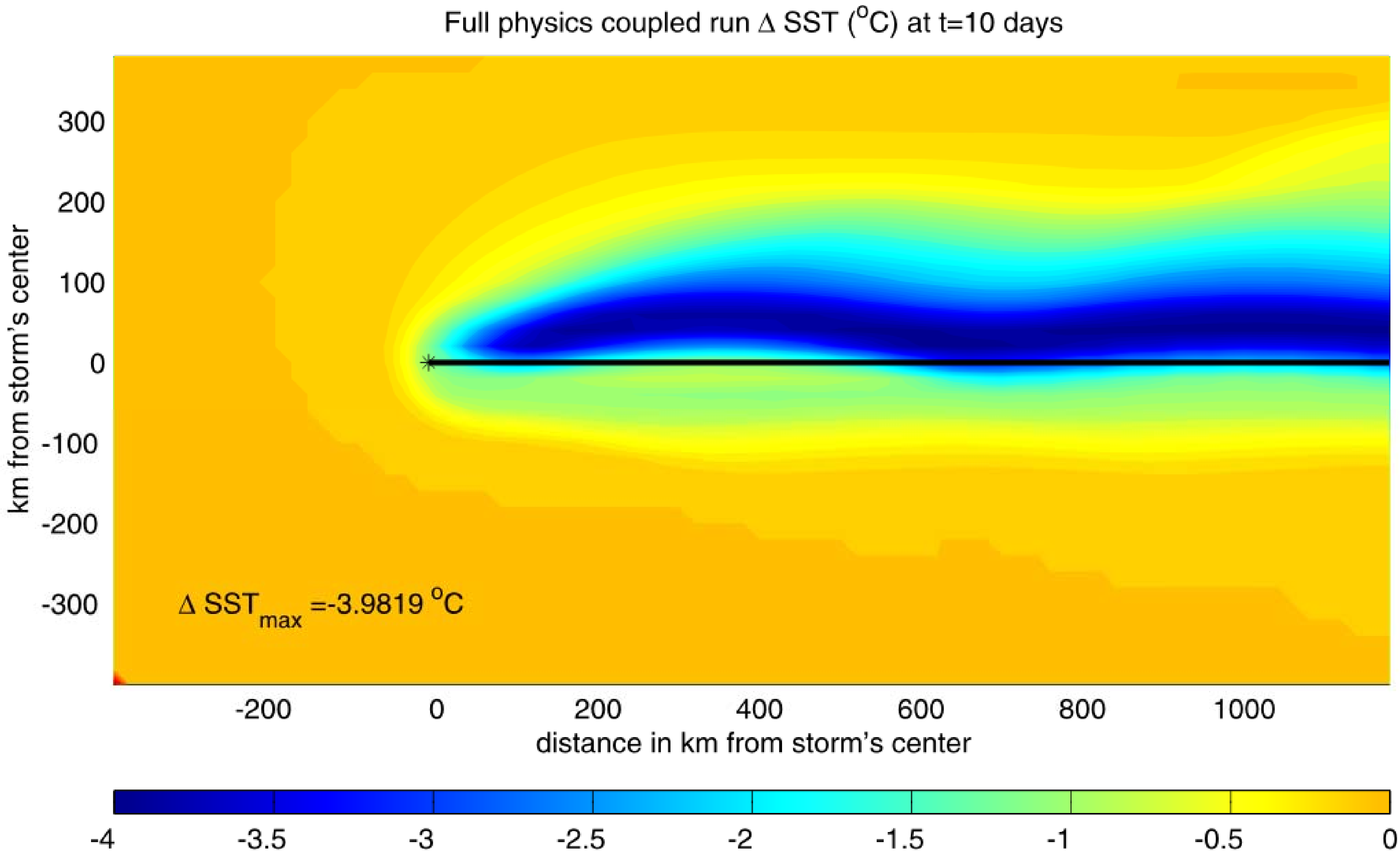
# Strong Mixing of Upper Ocean



# Mixed layer depth and currents

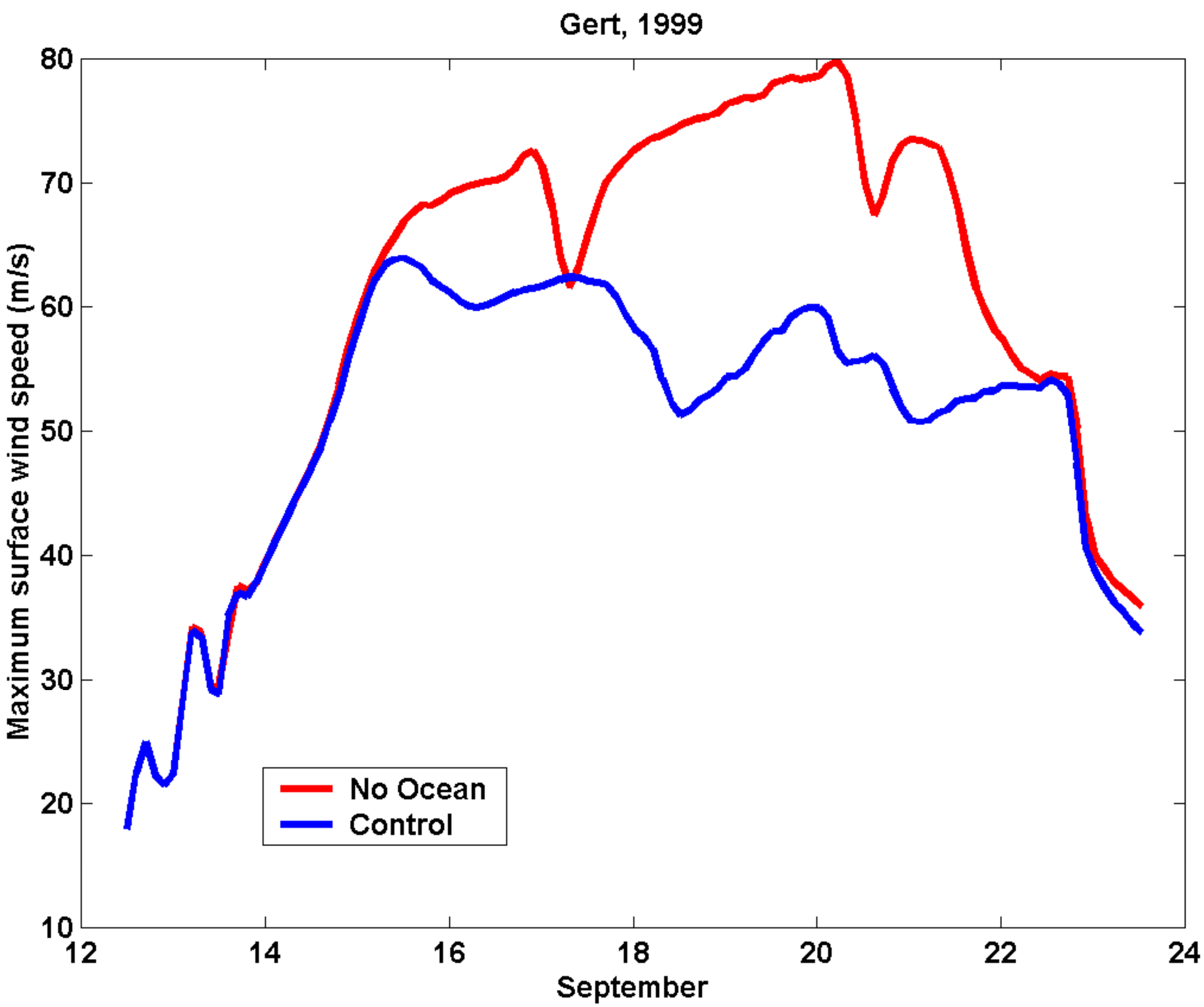


# SST Change

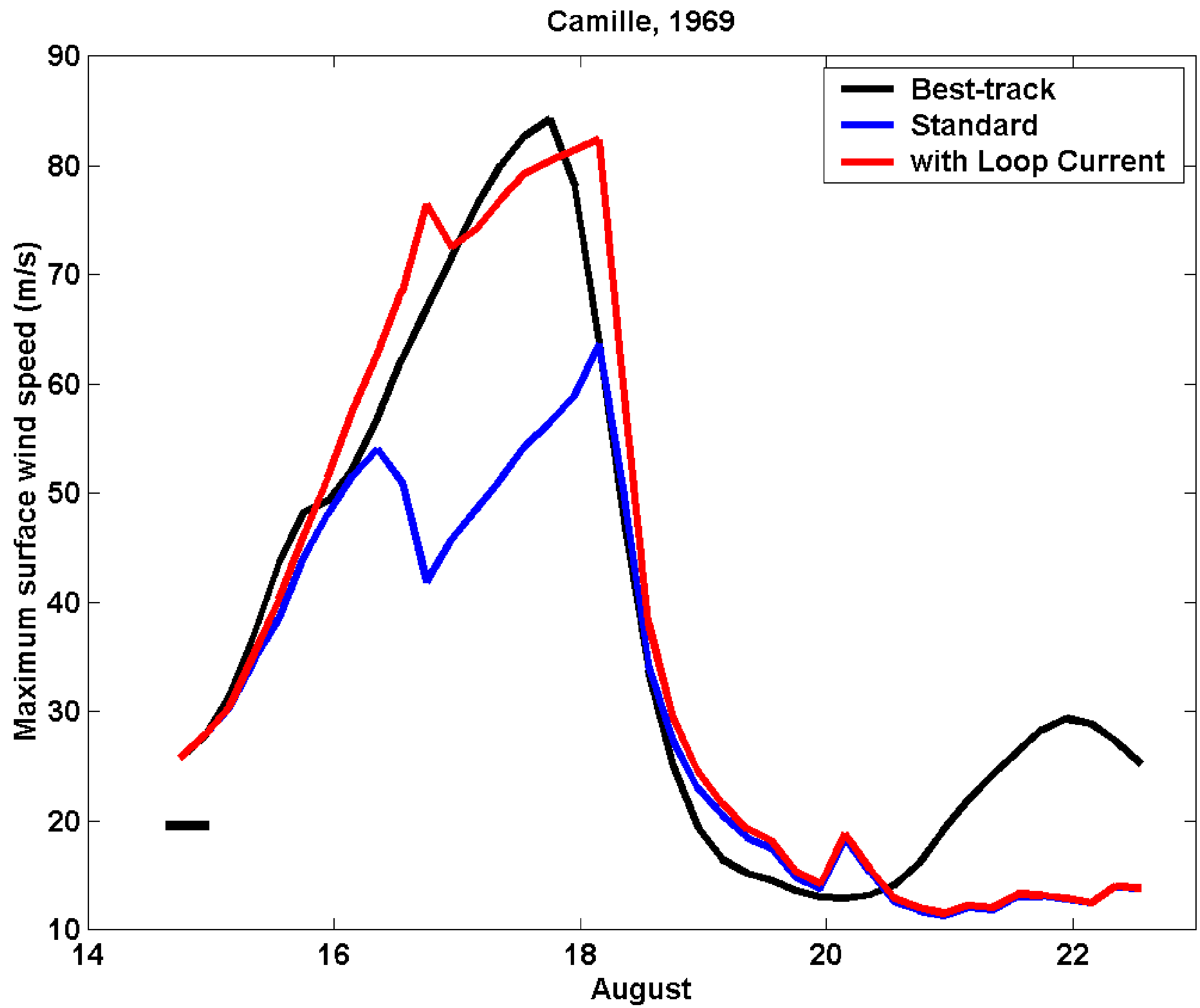


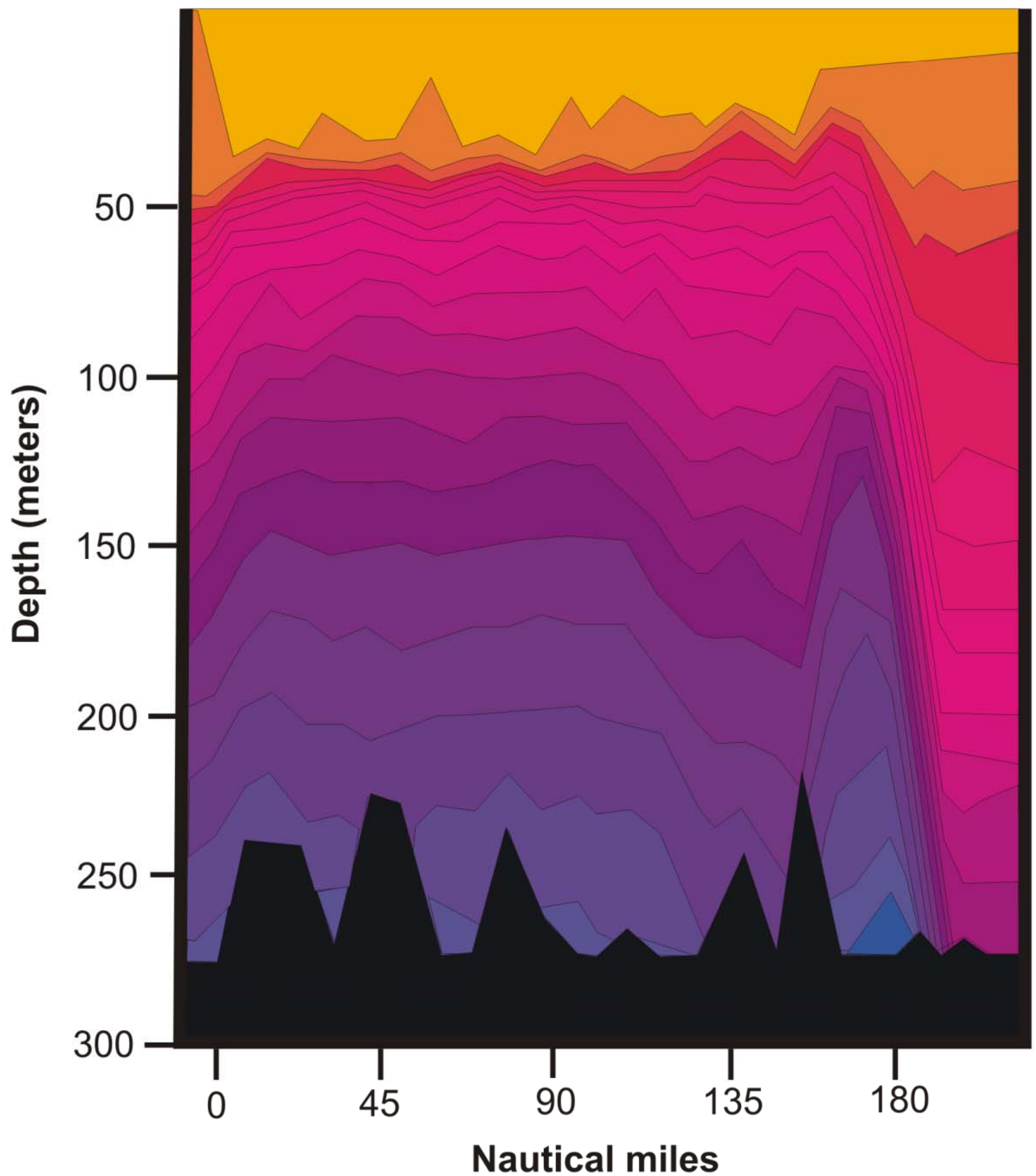
Full physics coupled run Δ SST (°C) at t=10 days
300
200
100
0
-100
-200
-300
km from storm's center
Δ SST$_{max}$ =-3.9819 °C
-200
0
200
400
600
800
1000
distance in km from storm's center
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0

# Comparing Fixed to Interactive SST:



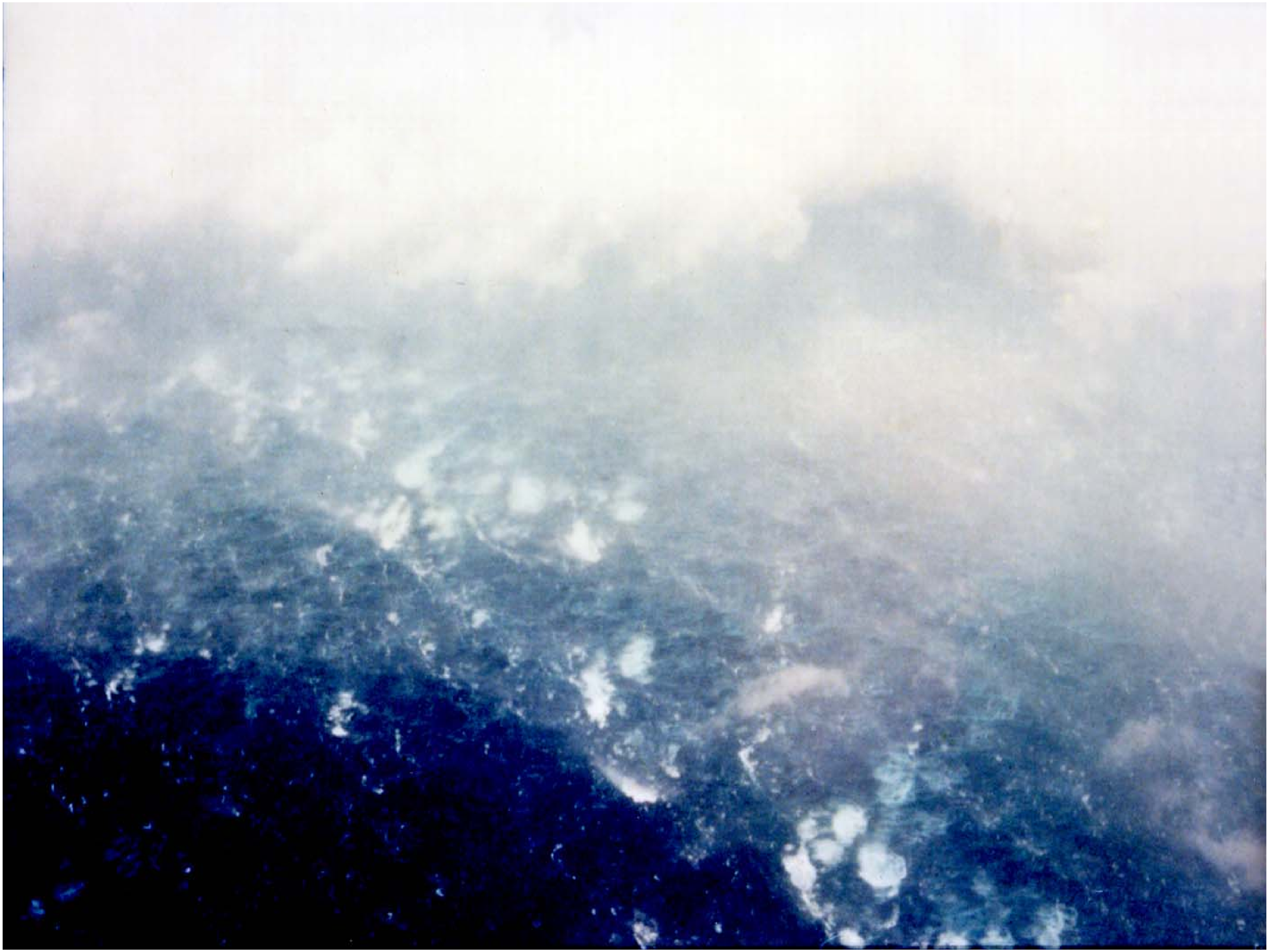
A good simulation of Camille can only be obtained by assuming that it traveled right up the axis of the Loop Current:

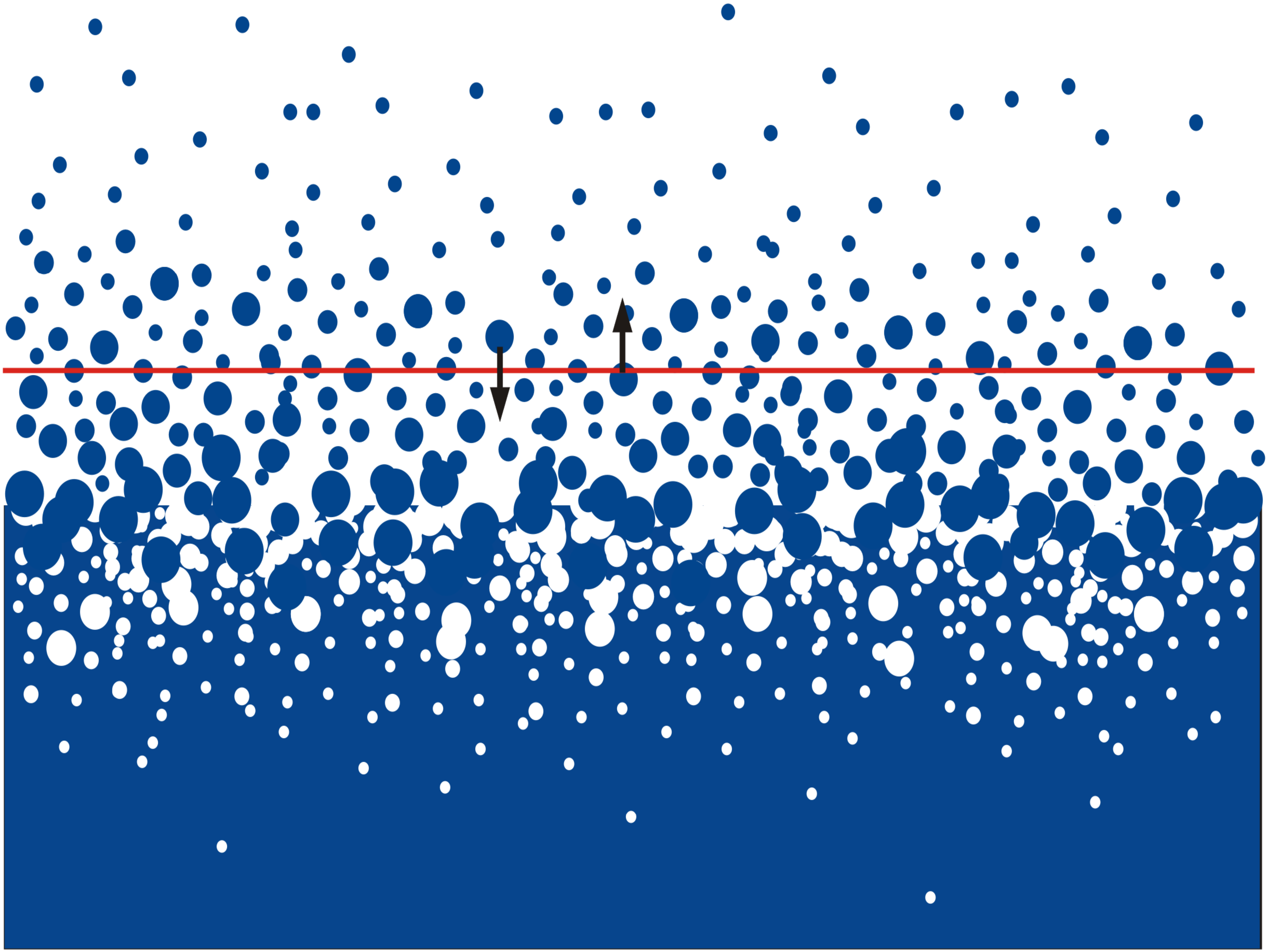




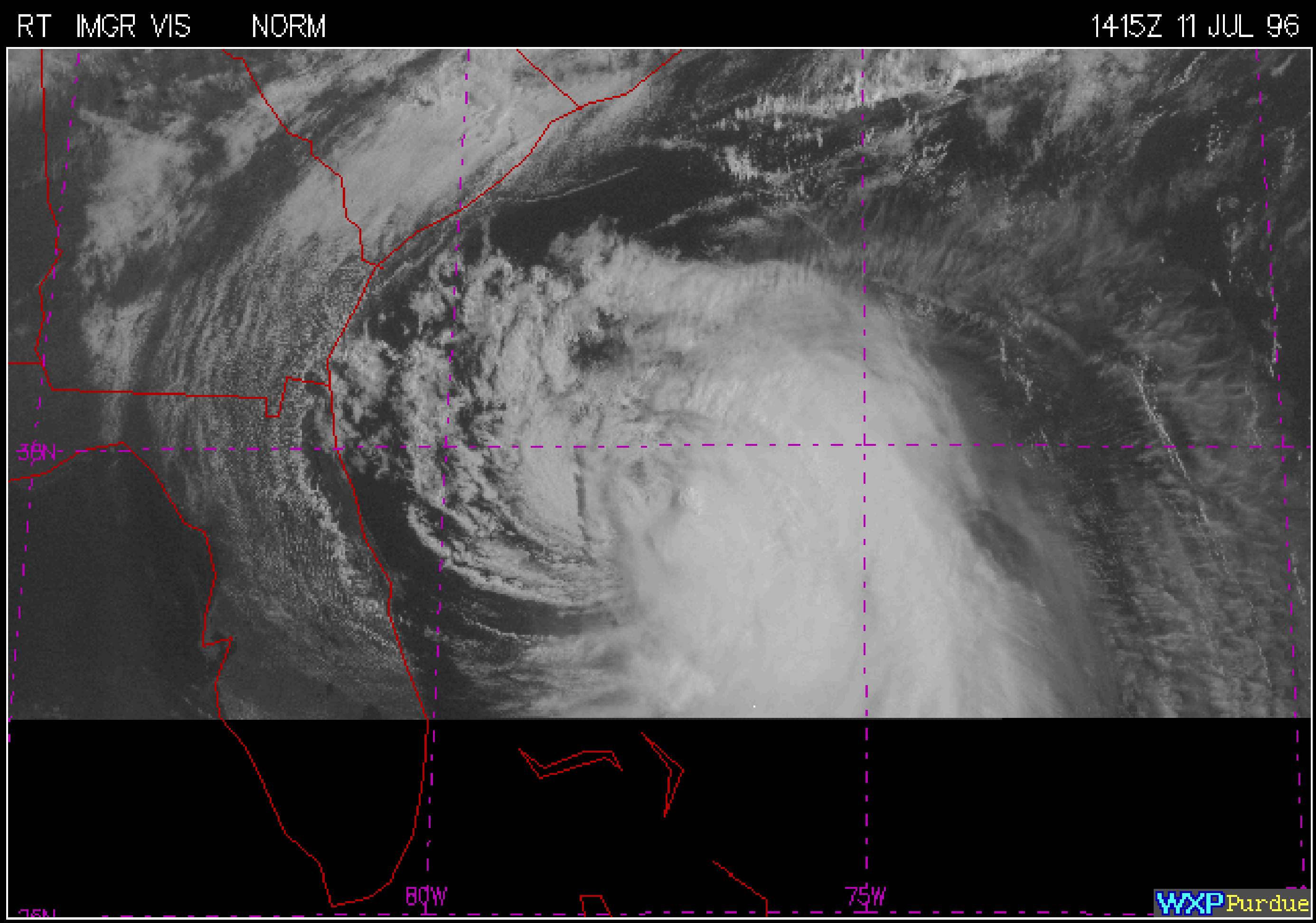
Depth (meters)
50
100
150
200
250
300
0
45
90
135
180
Nautical miles

# 2. Sea Spray





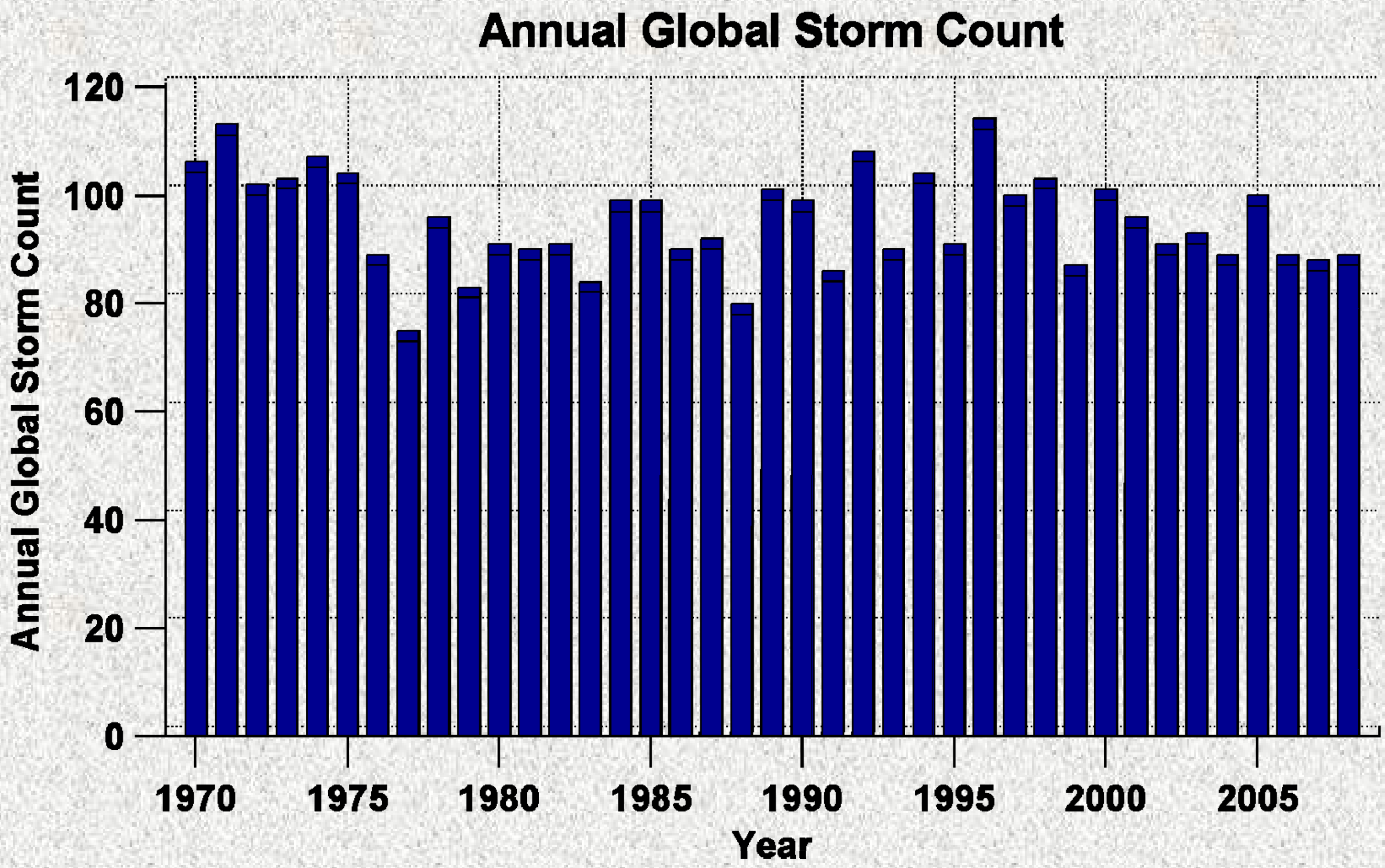
# 3. Wind Shear



# What controls global tropical cyclone frequency?

- In today's climate, tropical cyclones must be triggered by independent disturbances
- Tropical cyclone models also require finite amplitude perturbations to initiate hurricanes

# Global Tropical Cyclone Frequency, 1970-2008




Data Sources: NOAA/TPC and NAVY/JTWC

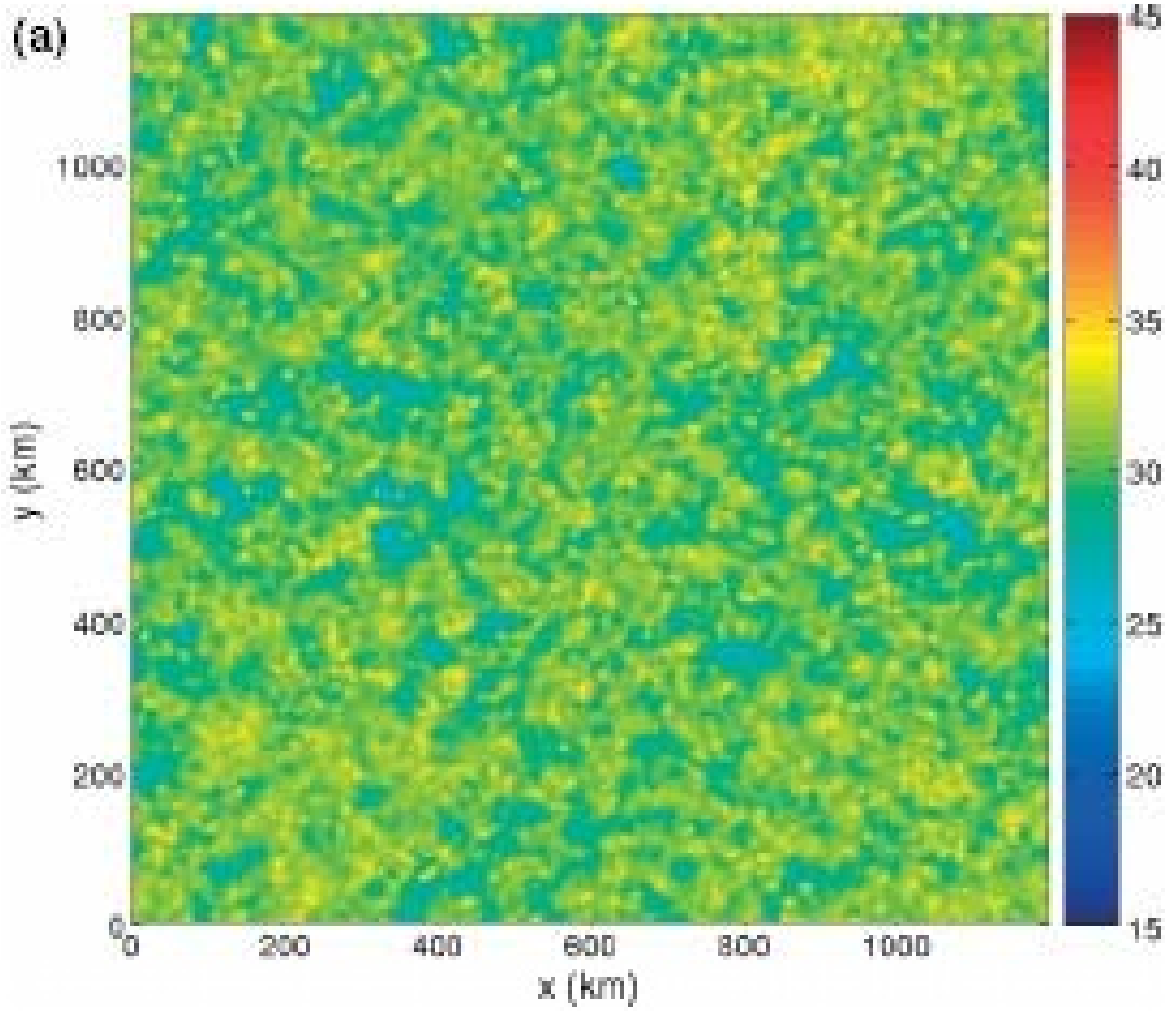
# When/Why Does Convection Form Clusters?

Monsoonal Thunderstorms, Bangladesh and India July 1985

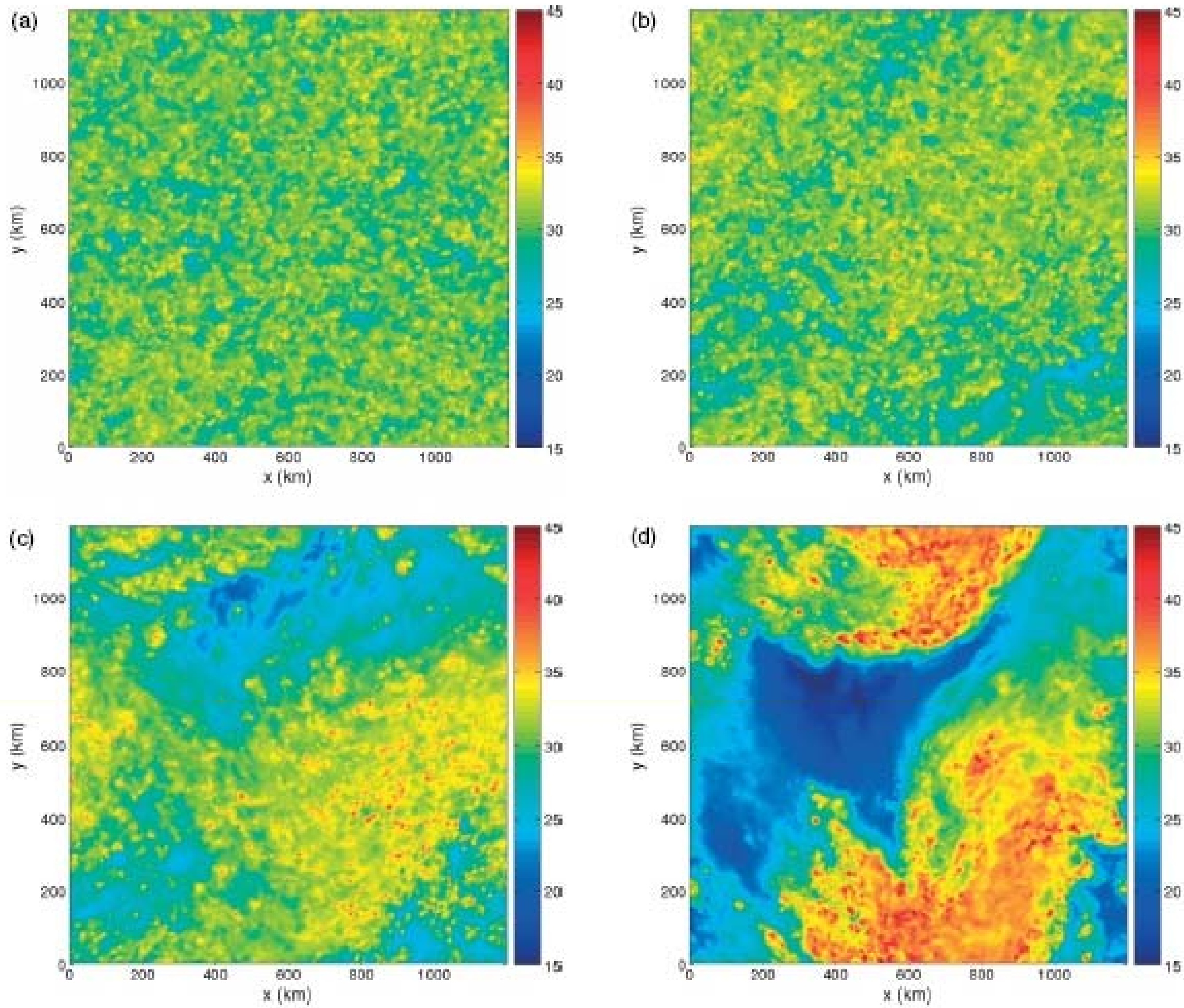
# Simplest Statistical Equilibrium State:

# Radiative-Convective Equilibrium

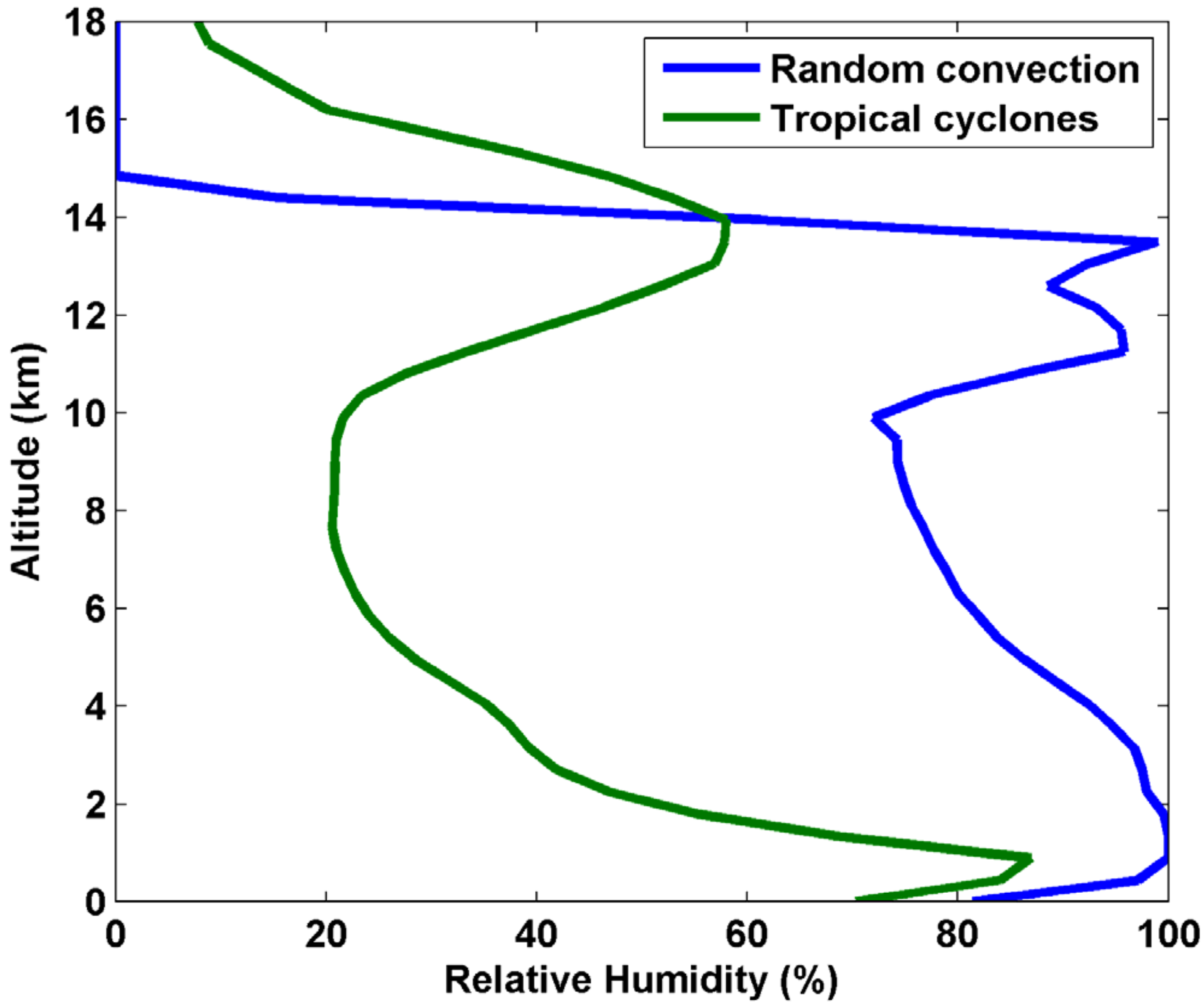
# Vertically integrated water vapor at 4 days (Nolan et al., QJRMS, 2007)



# Vertically integrated water vapor at 4 (a), 6 (b), 8 (c), and 10 (d) days (Nolan et al., QJRMS, 2007)



# Nolan et al., QJRMS, 2007

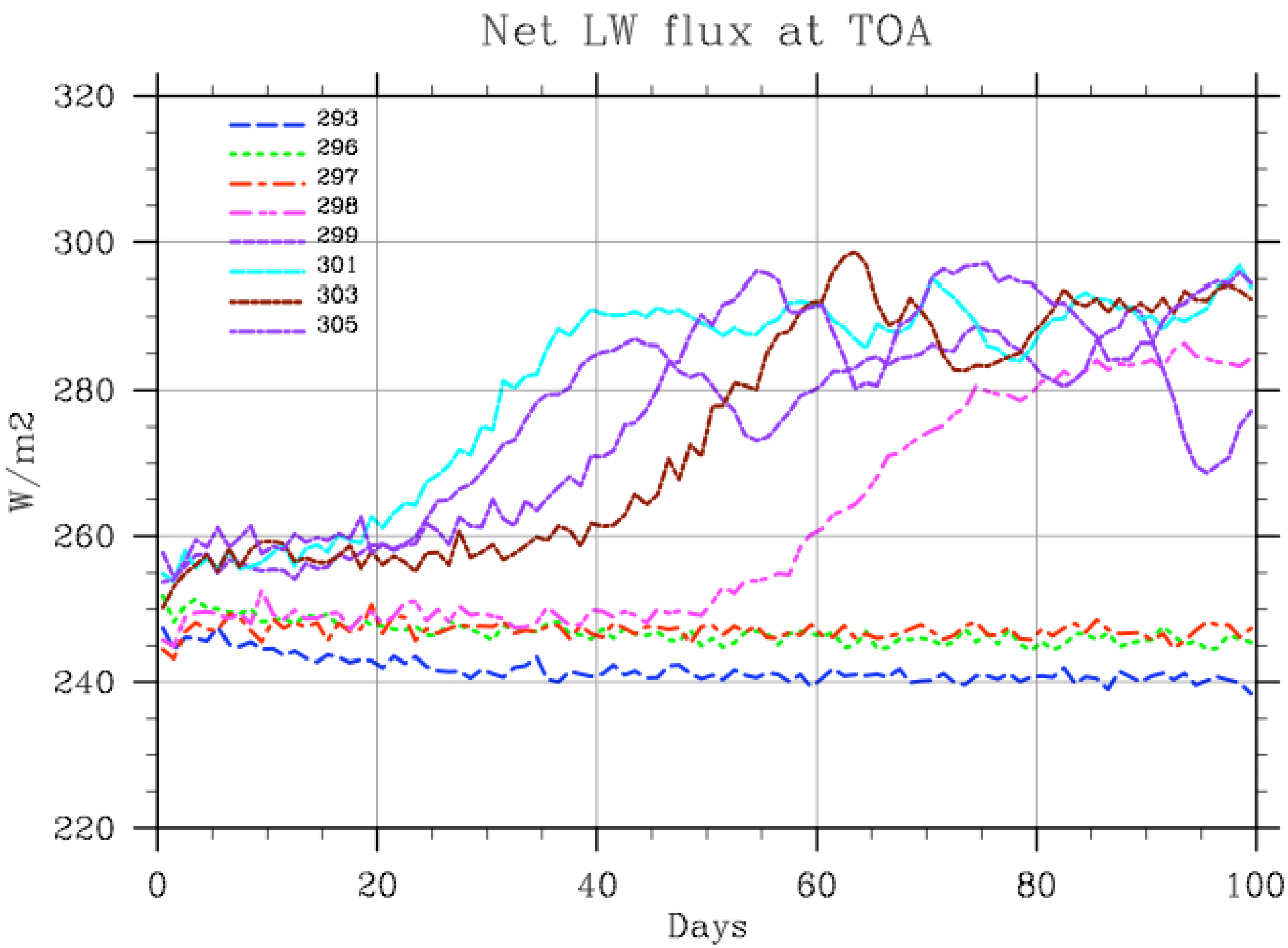


# Empirical Necessary Conditions for Self-Aggregation

(after Held et al., 1993; Bretherton et al., 2005; Nolan et al.; 2007)

- Small vertical shear of horizontal wind
- Interaction of radiation with clouds and/or water vapor
- Feedback of convective downdraft surface winds on surface fluxes
- Sufficiently high surface temperature

# Self-Aggregation is Temperature-Dependent (Nolan et al., 2007; Emanuel and Khairoutdinov, in preparation, 2009)



# Hypothesis

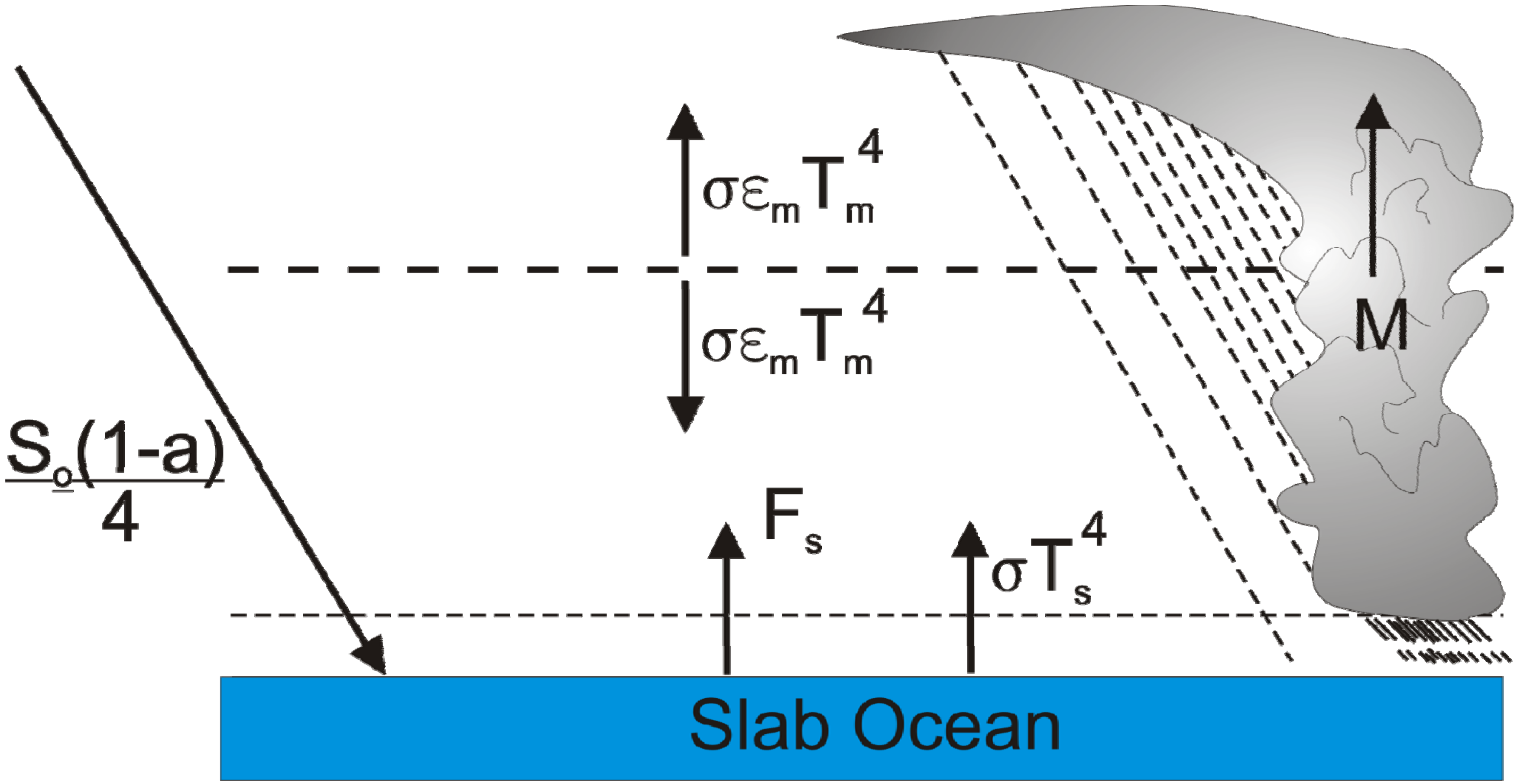
- At high temperature, convection self-aggregates
- →Horizontally averaged humidity drops dramatically
- →Reduced greenhouse effect cools system
- →Convection disaggregates
- →Humidity increases, system warms
- →System wants to be near phase transition to aggregated state

# Recipe for Self-Organized Criticality

(First proposed by David Neelin, but by different mechanism)

- System should reside near critical threshold for self-aggregation
- Convective cluster size should follow power law distribution

# Toy Model



$\frac{S_o(1-a)}{4}$
$\sigma \varepsilon_m T_m^4$
$\sigma \varepsilon_m T_m^4$
$F_s$
$\sigma T_s^4$
M
Slab Ocean

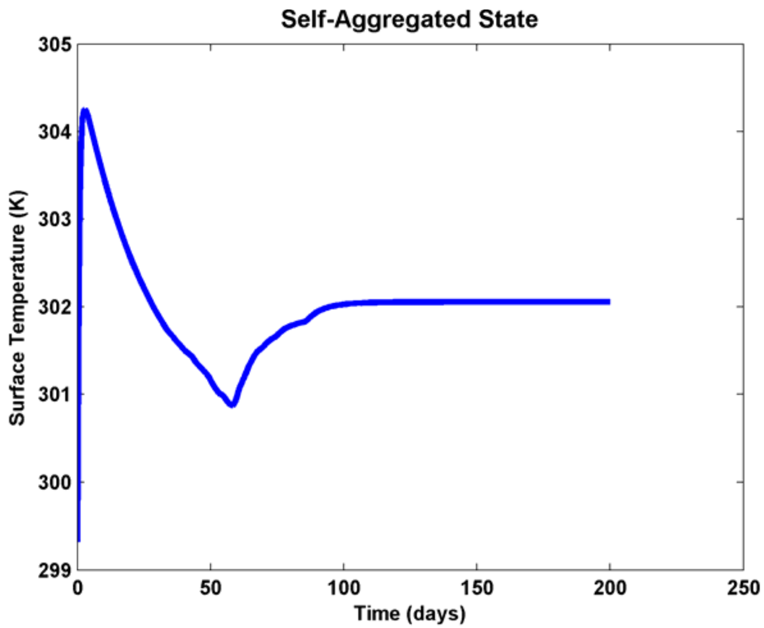
# Properties

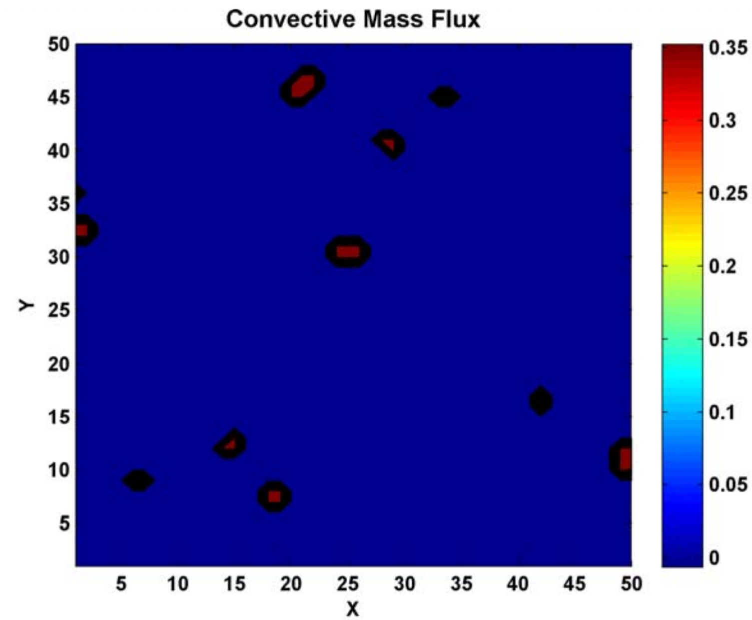
- PBL quasi-equilibrium enforced
- Bulk aerodynamic surface fluxes with convective gustiness
- Albedo and emissivity simple weighted average of clear and cloudy regions
- Water vapor-dependent clear sky emissivity
- Horizontally uniform temperature but variable moist static energy (i.e. water vapor) at mid-level
- Vertical motion calculated to enforce zero horizontal temperature gradient
- PBL moist static energy adjusted to yield zero domain-averaged vertical motion
- Slow horizontal diffusion of moisture at mid-level

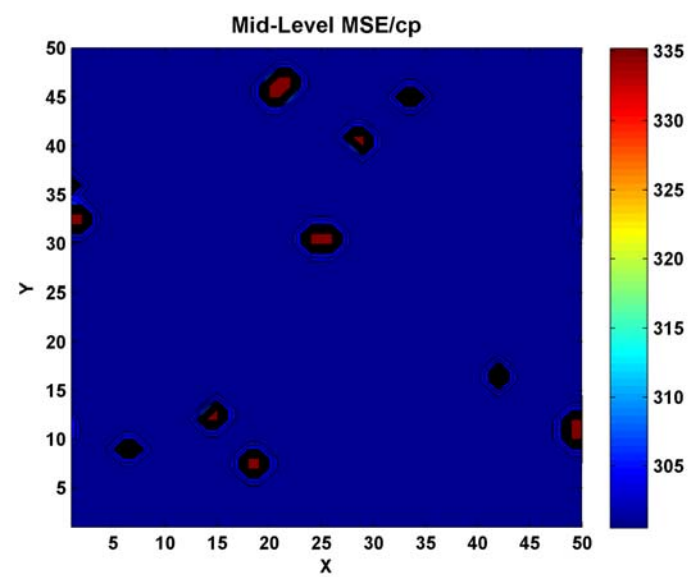
# Results
# Self-Aggregation Occurs for:

- Small or negative gross moist stability
- Sufficiently large feedback between convective gustiness and surface enthalpy fluxes
- Sufficiently high surface temperature

# Example:


Self-Aggregated State
Surface Temperature (K)
305
304
303
302
301
300
299
0
50
100
150
200
250
Time (days)

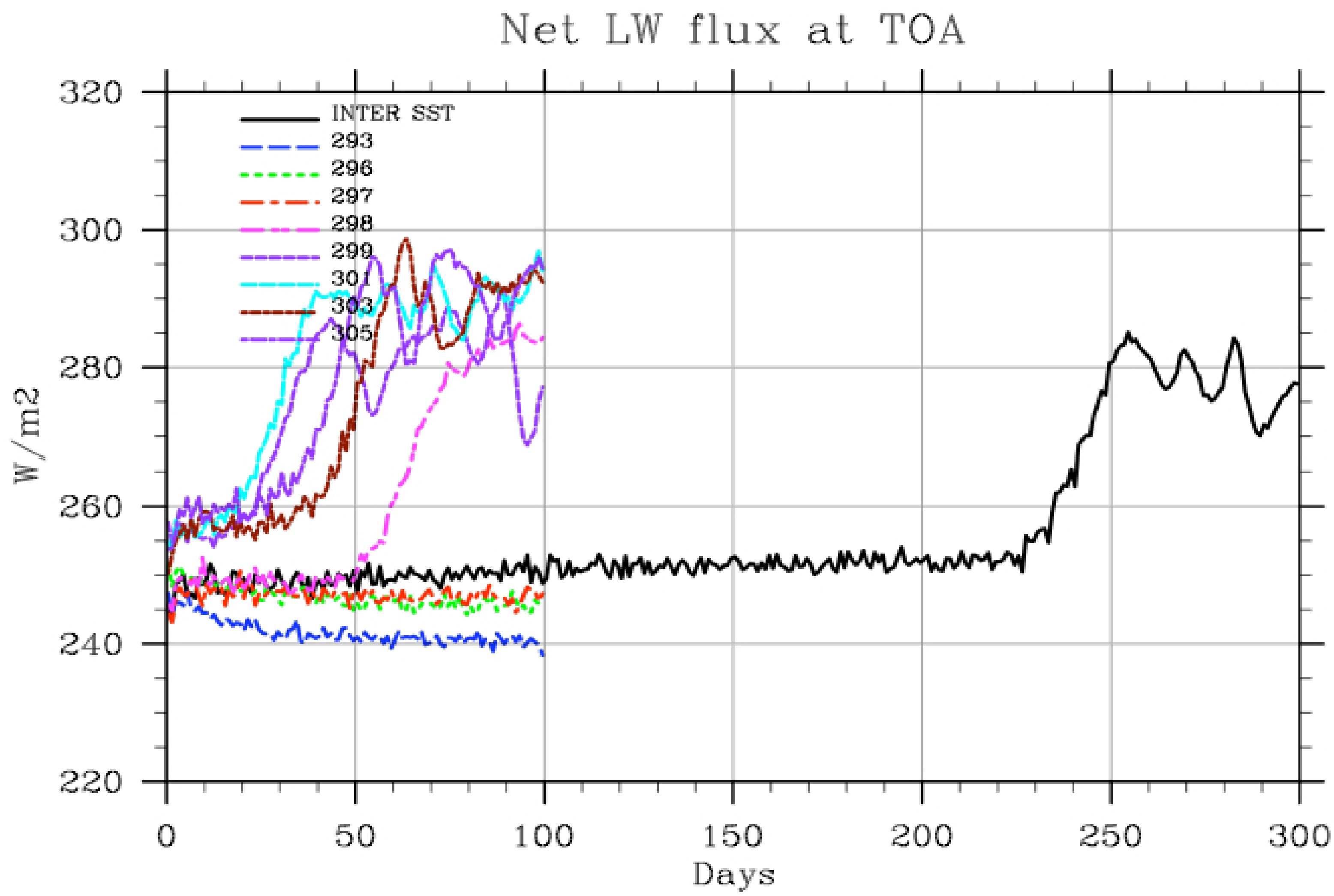

Convective Mass Flux
Y
50
45
40
35
30
25
20
15
10
5
5
10
15
20
25
30
35
40
45
50
X
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


Mid-Level MSE/cp
Y
50
45
40
35
30
25
20
15
10
5
5
10
15
20
25
30
35
40
45
50
X
335
330
325
320
315
310
305

# Summary of Toy Model Results

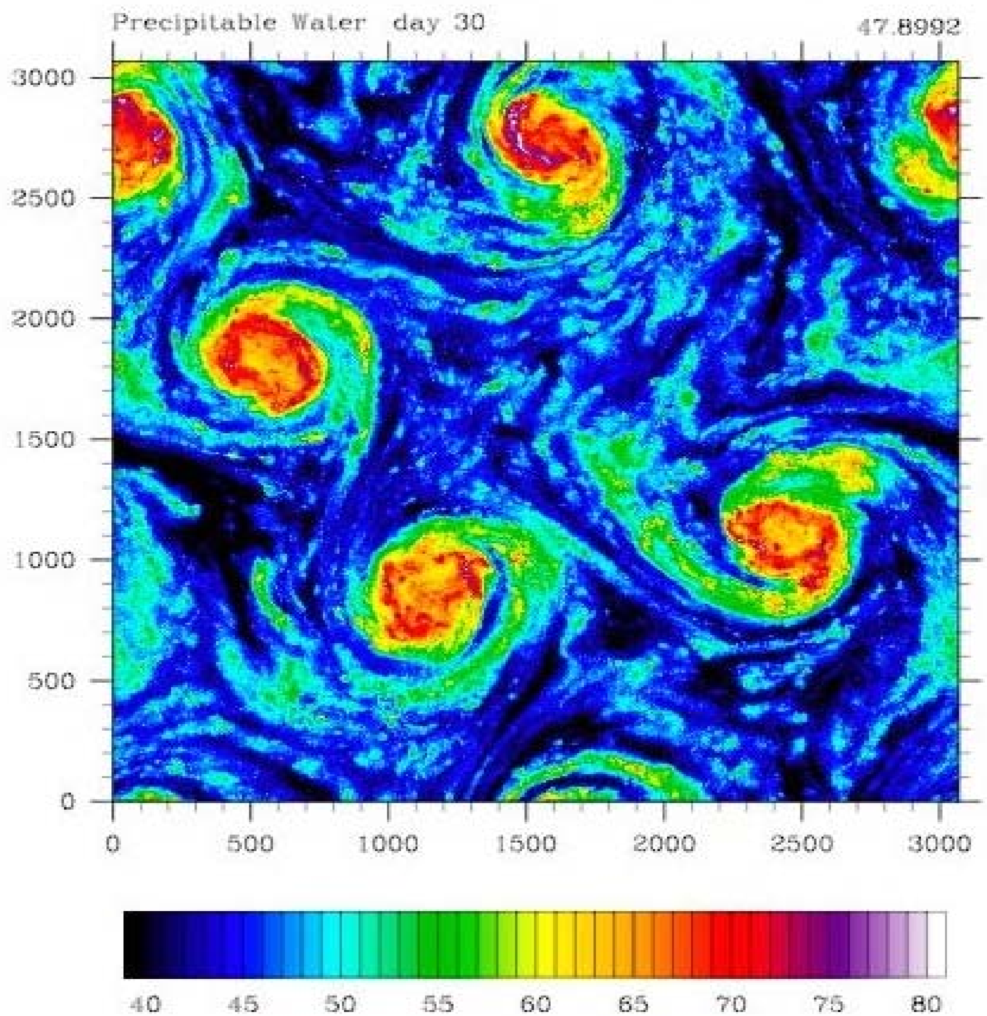
- Self-aggregation driven by convective gustiness at high temperature
- No self-aggregation at low temperature
- Aggregated state is much drier at mid levels
- System tends towards self-organized criticality (SOC)
- Climate sensitivity of SOC state much lower (0.04 $K/Wm^{-2}$) than sensitivity of uniform convection (0.2 $K/Wm^{-2}$)

# Preliminary Suggestion of Self-Organized Criticality in Full-Physics CRM



# Extension to f-plane

Distance between vortex centers scales as $V_{pot}/f$



# Summary

- Hurricanes are almost perfect Carnot heat engines, operating off the thermodynamic disequilibrium between the tropical ocean and atmosphere, made possible by the greenhouse effect

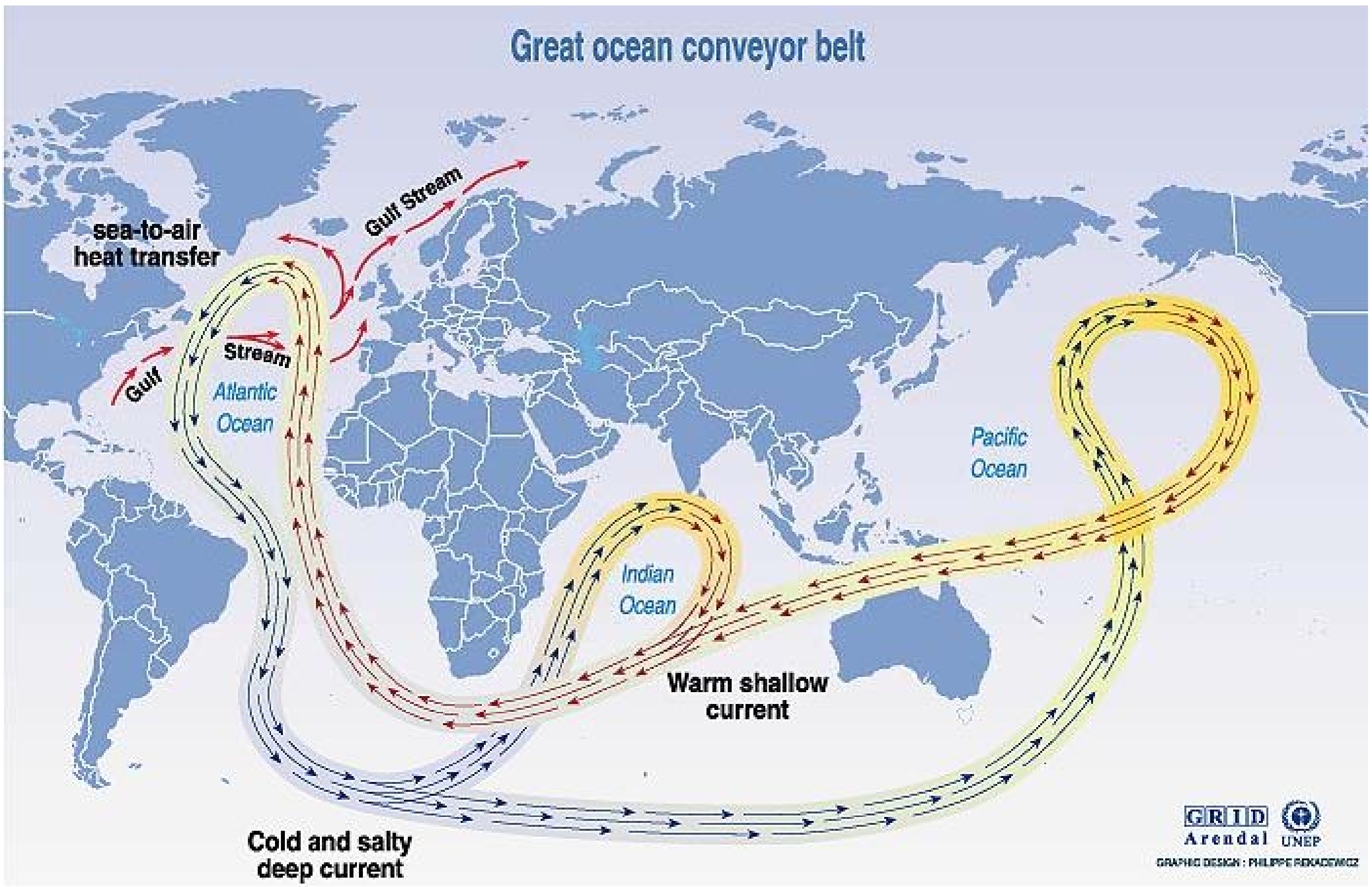
- Most hurricanes are prevented from reaching their potential intensity by storm-induced ocean cooling and environmental wind shear

- **Hurricanes result from a finite-amplitude instability of the tropical ocean-atmosphere system**

- **Clustering of convection into both non-rotating clusters and tropical cyclones may be an example of self-organized criticality in geophysics**

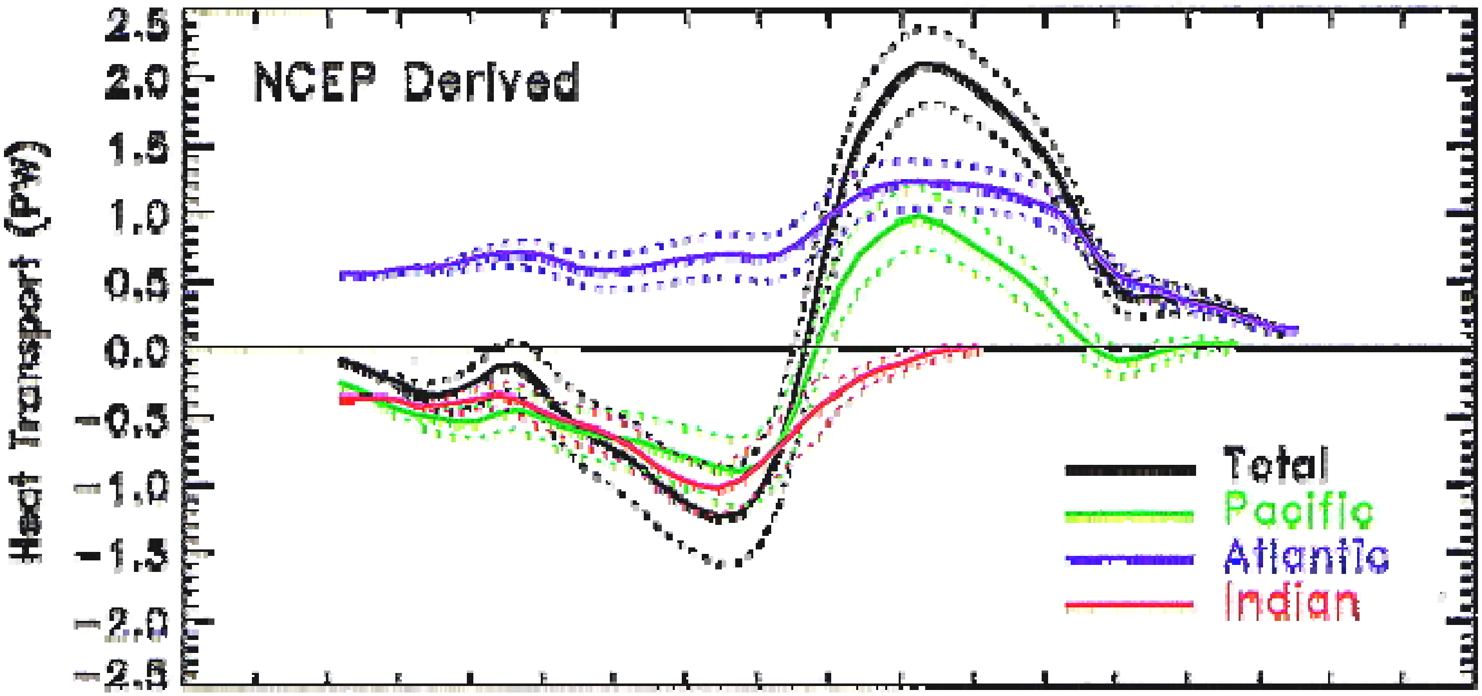

Ocean Feedback

# Ocean Thermohaline Circulation

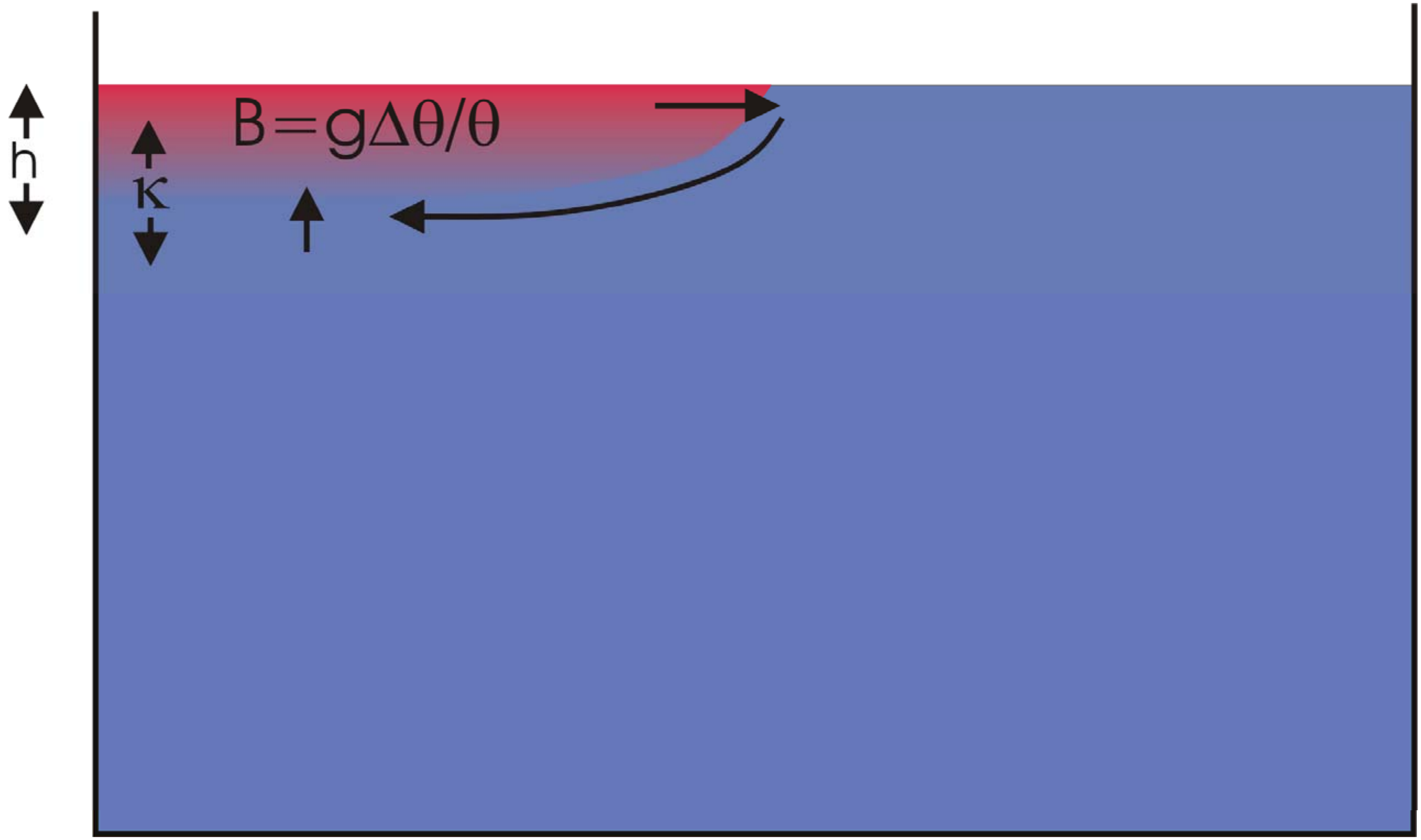



Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.

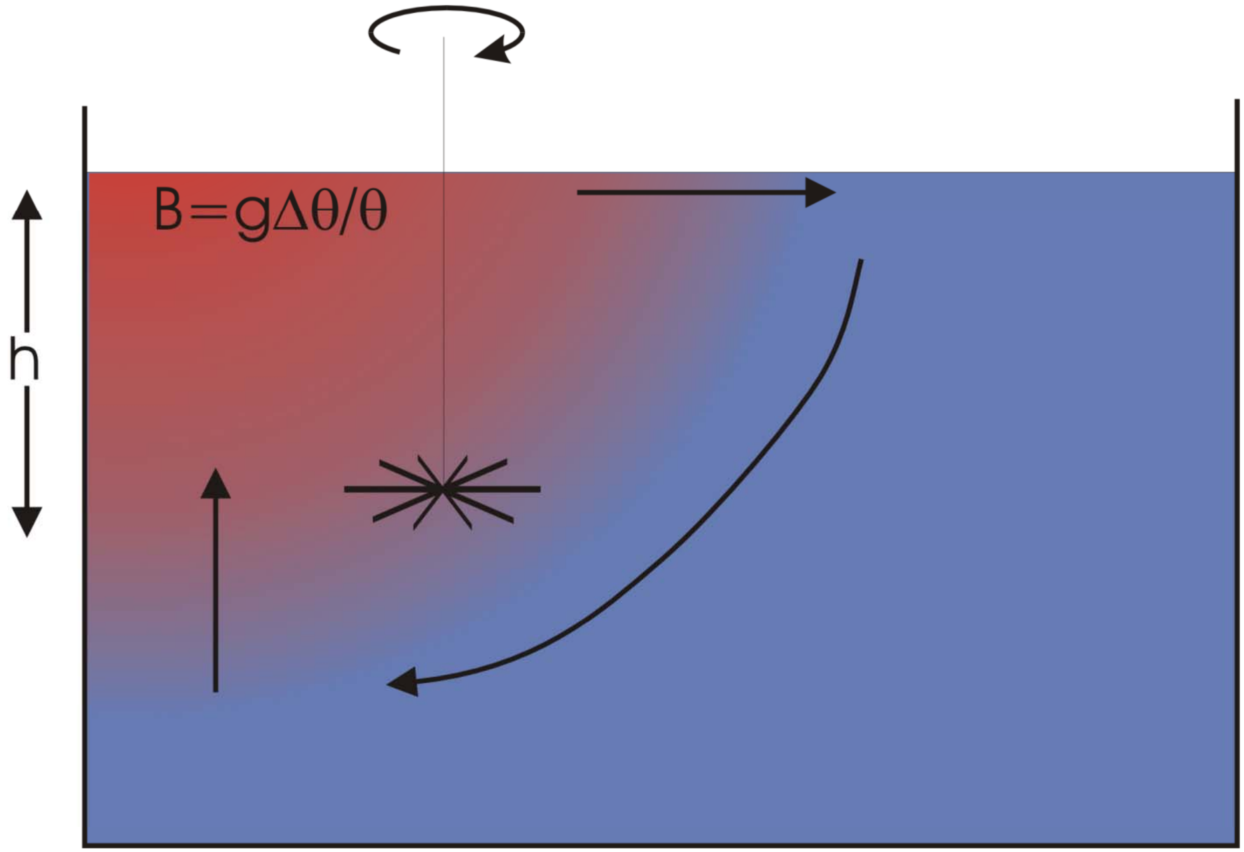
# TC Mixing May Induce Much or Most of the Observed Poleward Heat Flux by the Oceans




Trenberth and Caron, 2001



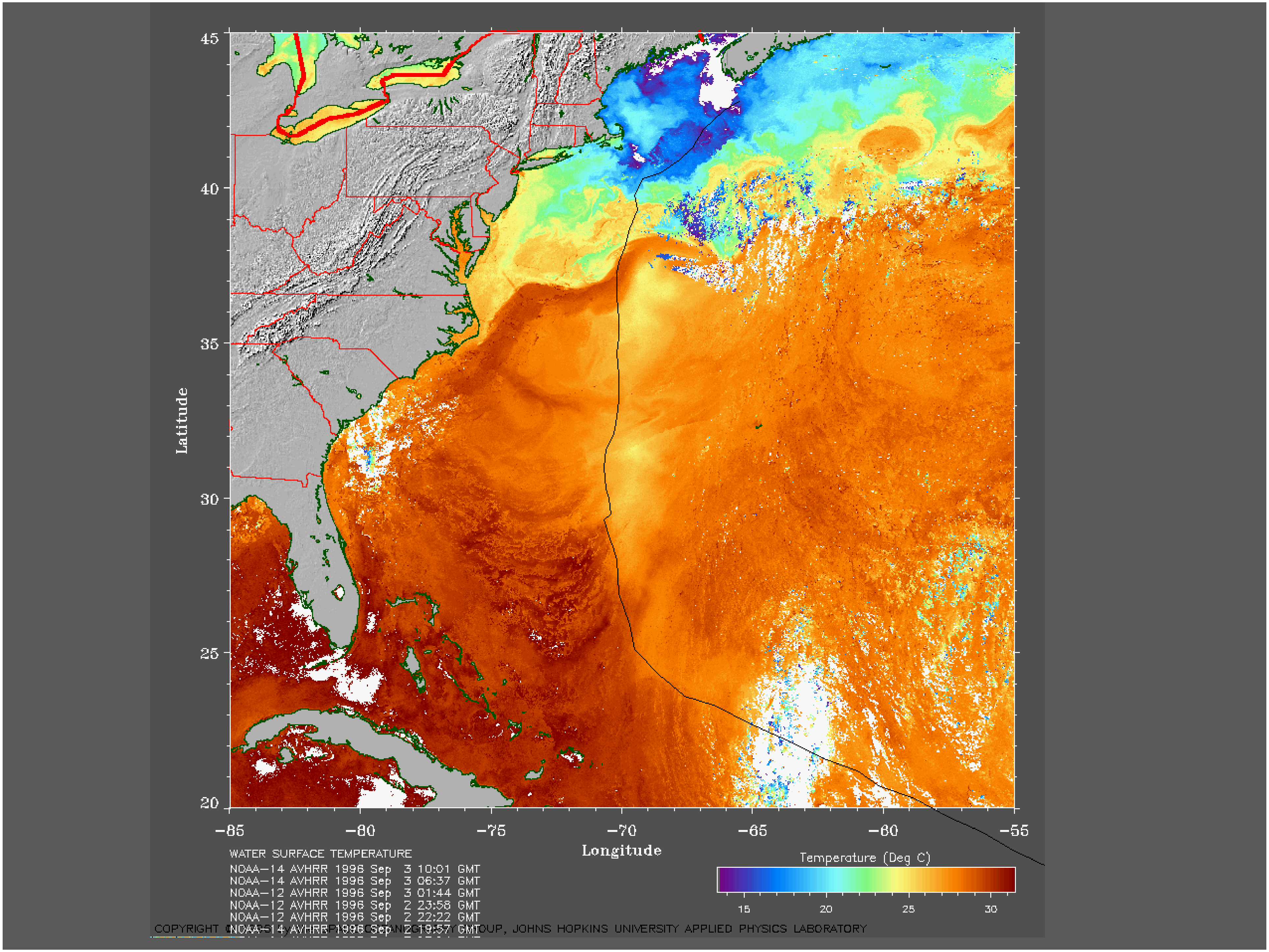

A hot plate is brought in contact with the left half of the surface of a swimming pool of cold water. Heat diffuses downward and the warm water begins to rise. The strength of the circulation is controlled in part by the rate of heat diffusion. In the real world, this rate is very, very small.




$$\text{Heat Flux} \sim P^{2/3} B^{2/3}$$

$$h \sim P^{1/3} B^{-2/3}$$

Adding a stirring rod to this picture greatly enhances the circulation by mixing the warm water to greater depth and bringing more cold water in contact with the plate. The strength of the lateral heat flux is proportional to the 2/3 power of the power put into the stirring, and the 2/3 power of the temperature of the plate.


45
40
35
30
25
20
Latitude
−85
−80
−75
−70
−65
−60
−55
Longitude
WATER SURFACE TEMPERATURE
NOAA−14 AVHRR 1996 Sep 3 10:01 GMT
NOAA−14 AVHRR 1996 Sep 3 06:37 GMT
NOAA−12 AVHRR 1996 Sep 3 01:44 GMT
NOAA−12 AVHRR 1996 Sep 2 23:58 GMT
NOAA−12 AVHRR 1996 Sep 2 22:22 GMT
NOAA−14 AVHRR 1996 Sep 2 19:57 GMT
Temperature (Deg C)
15
20
25
30
COPYRIGHT
OUP, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

Coupled Ocean-Atmosphere model run for 67 of the 83 tropical cyclones that occurred in calendar year 1996

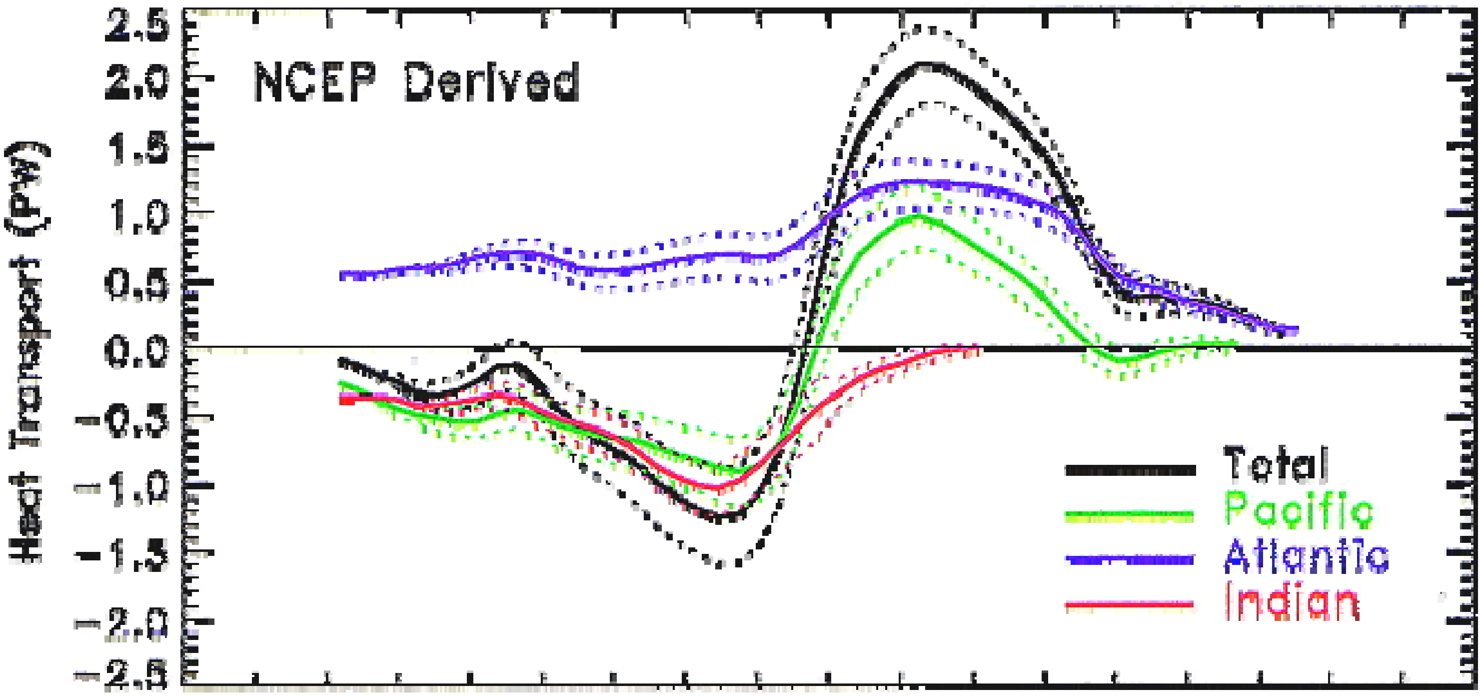
Accumulated TC-induced ocean heating divided by 366 days

Result:

Net column-integrated heating of ocean induced by global tropical cyclone activity:

$$(1.4 \pm 0.7) \times 10^{15} W$$

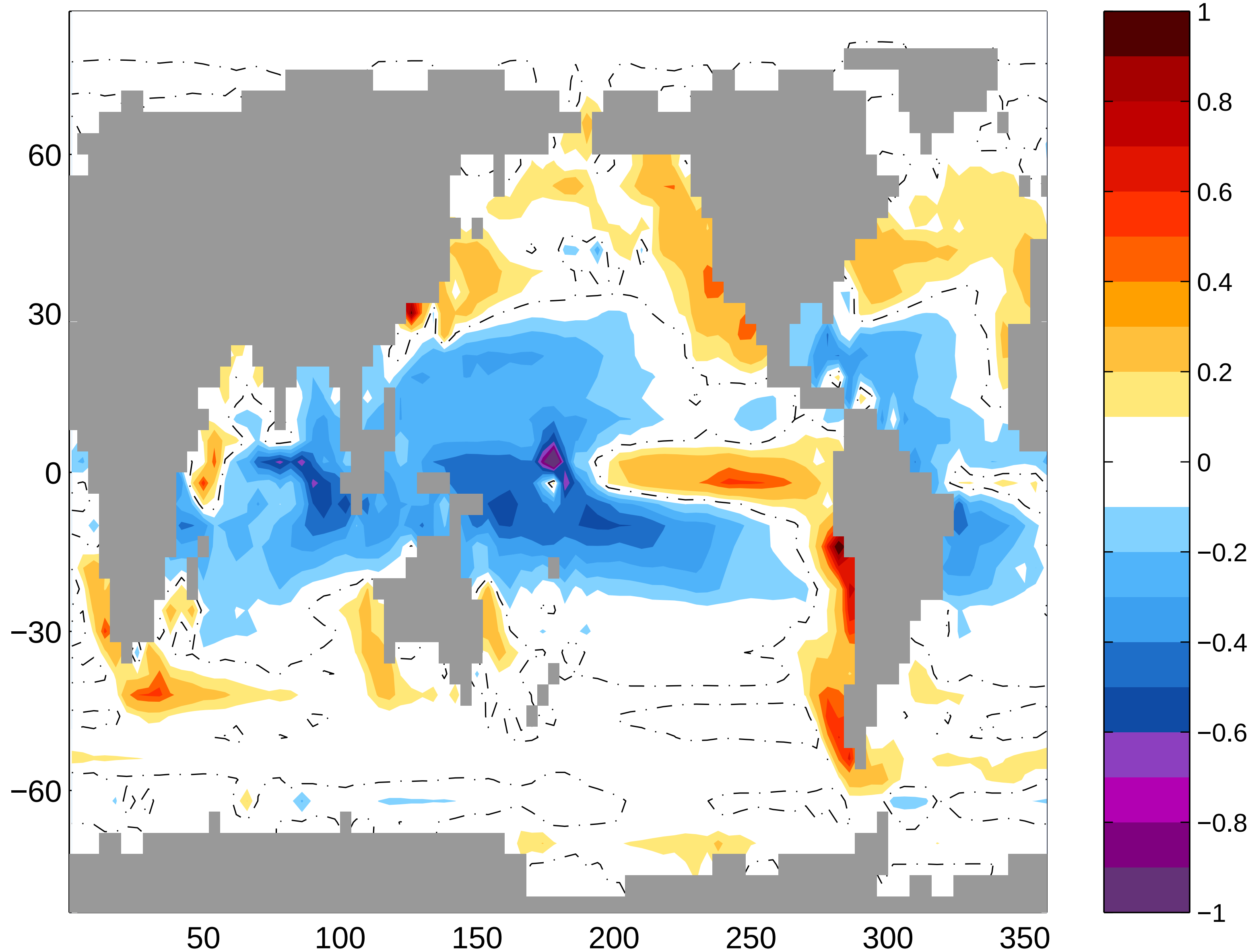
# TC Mixing May Induce Much or Most of the Observed Poleward Heat Flux by the Oceans




Trenberth and Caron, 2001

# Transient experiment by Rob Korty

$\Delta SST = SST_{hurricanes} - SST_{uniform\ mixing}$



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