Hurricane Science Tutorial

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Why Should You Care?

- **Forecasting**
  - Much progress in social science of response to warnings, requests to evacuate, etc.
- **Forecasters are ambassadors to meteorology**
  - Opportunity to inform public
  - Knowledge if hurricane science increases public interest and trust

Program

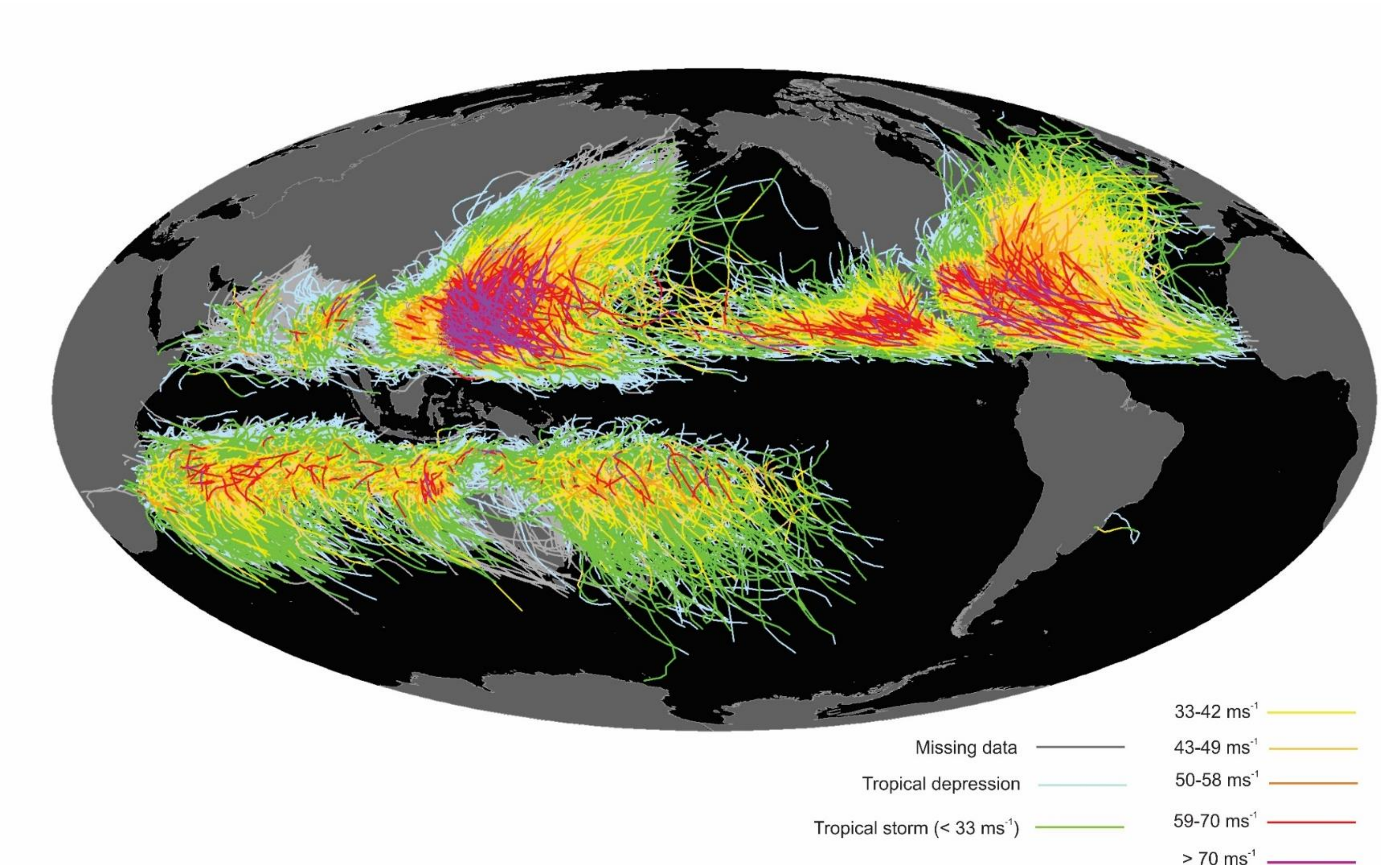
- Brief overview of hurricanes
- Current understanding
  - Basic state of the tropical atmosphere
  - Instability of the basic state – genesis
  - Energy cycle of mature hurricanes – concept of potential intensity
  - Negative influences on hurricanes
  - Statistics of hurricane intensification
  - Hurricane motion
  - Hurricanes and climate change
- Summary

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

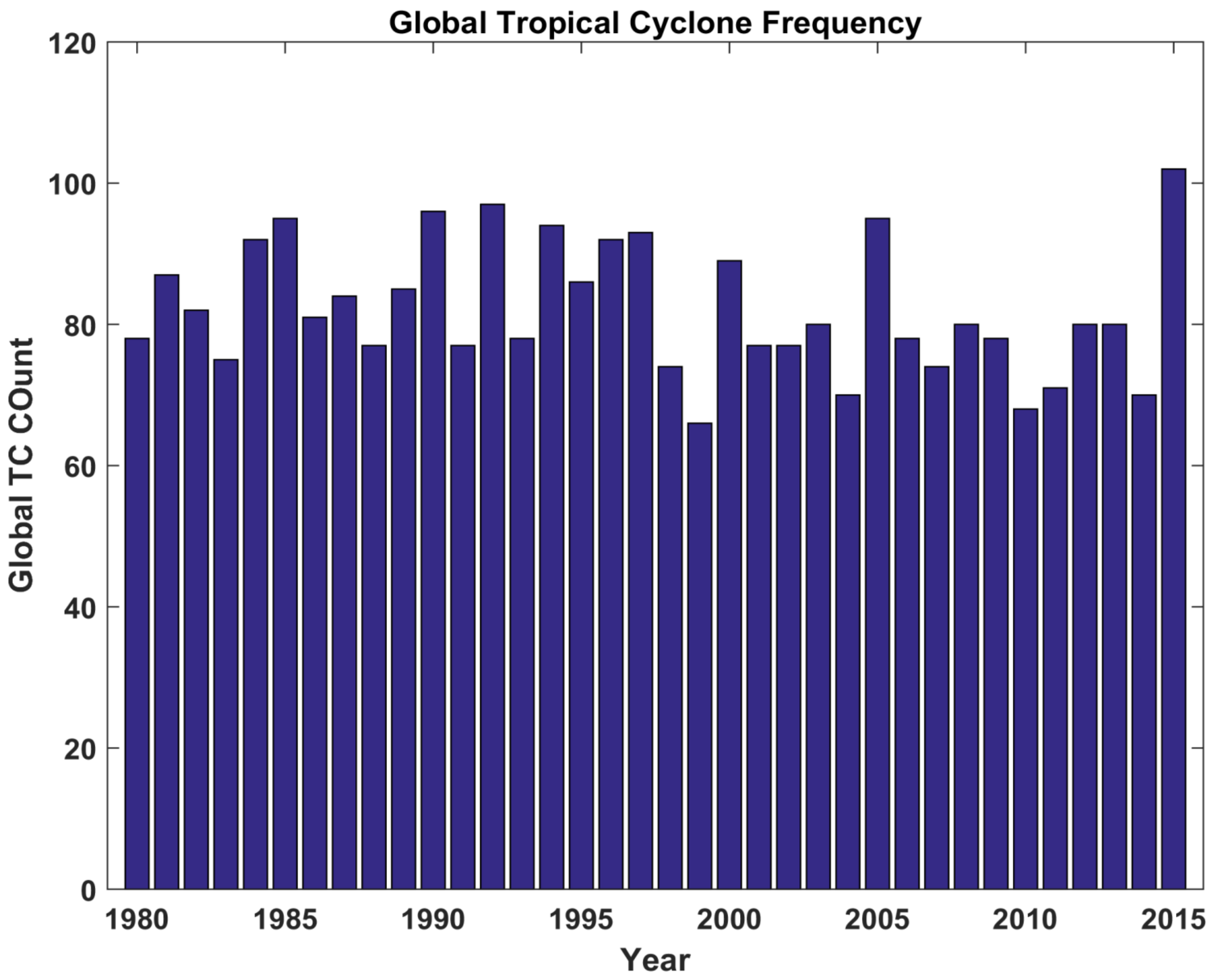
A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface

Global Climatology



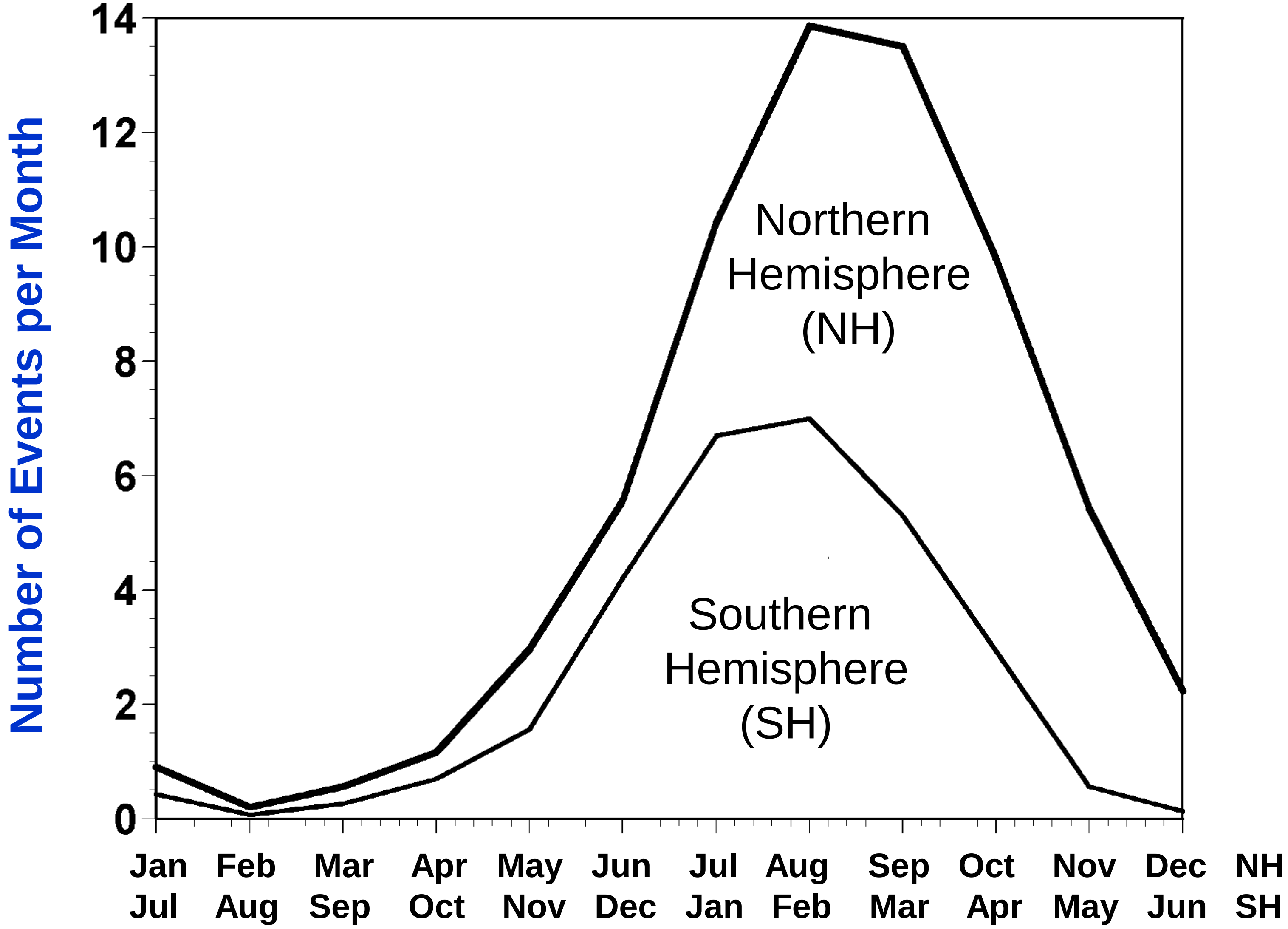
Tracks of all tropical cyclones in the historical record from 1851 to 2010. The tracks are colored according to the maximum wind at 10 m altitude, on the scale at lower right.

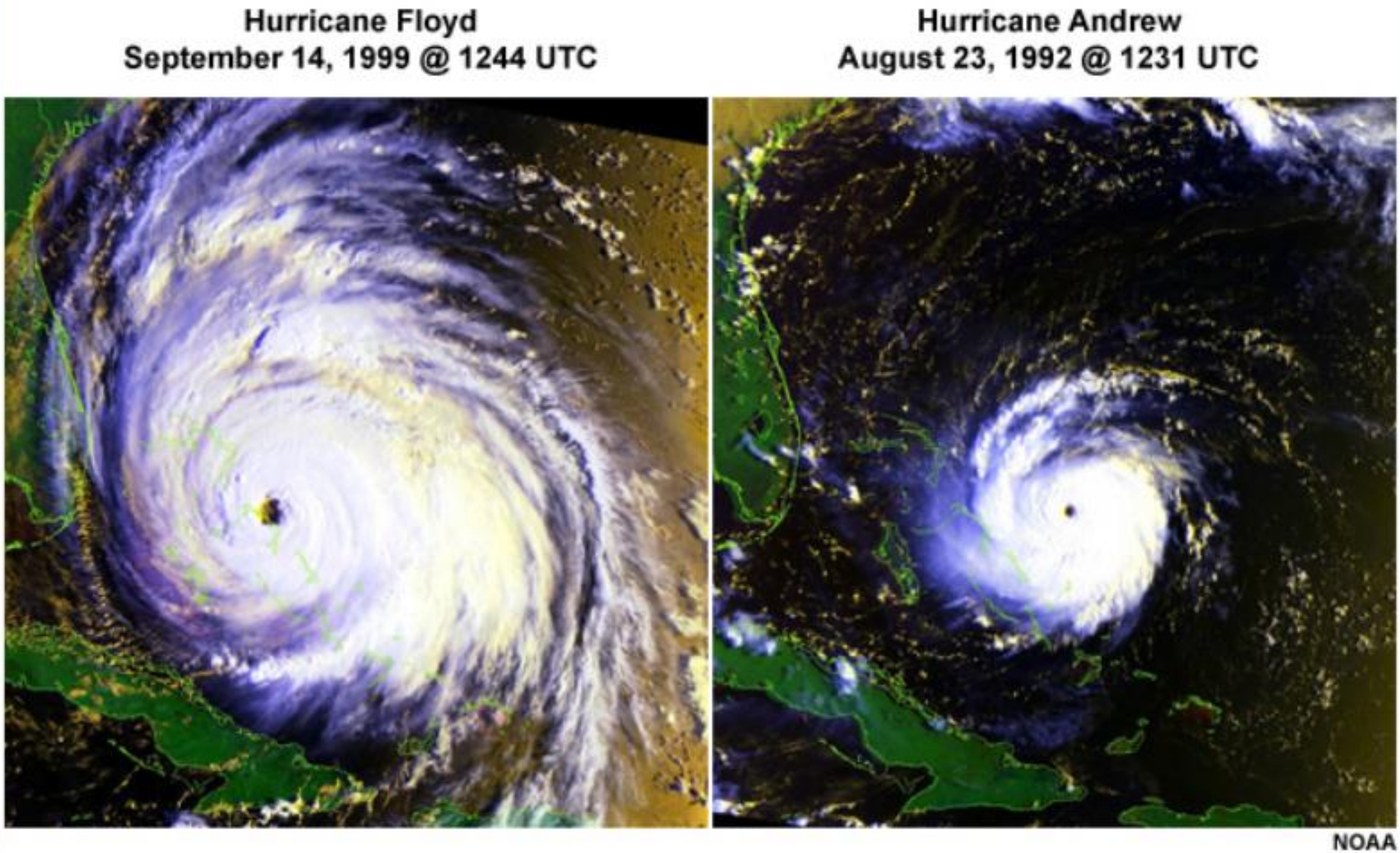
Global Tropical Cyclone Frequency, 1980-2015



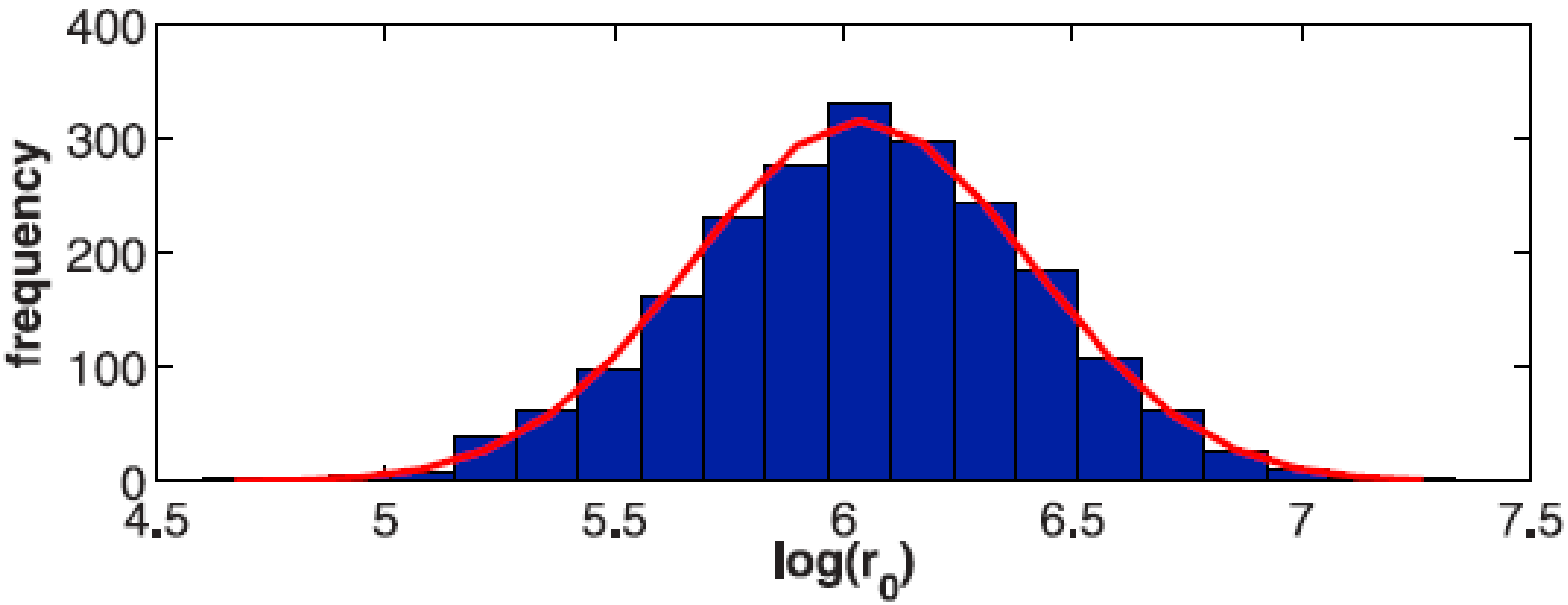
Data Sources: NOAA/TPC and NAVY/JTWC

Annual Cycle of Tropical Cyclones





The spiral rainbands of Hurricane Floyd (left, 1999) versus the more compact Hurricane Andrew (right, 1992)



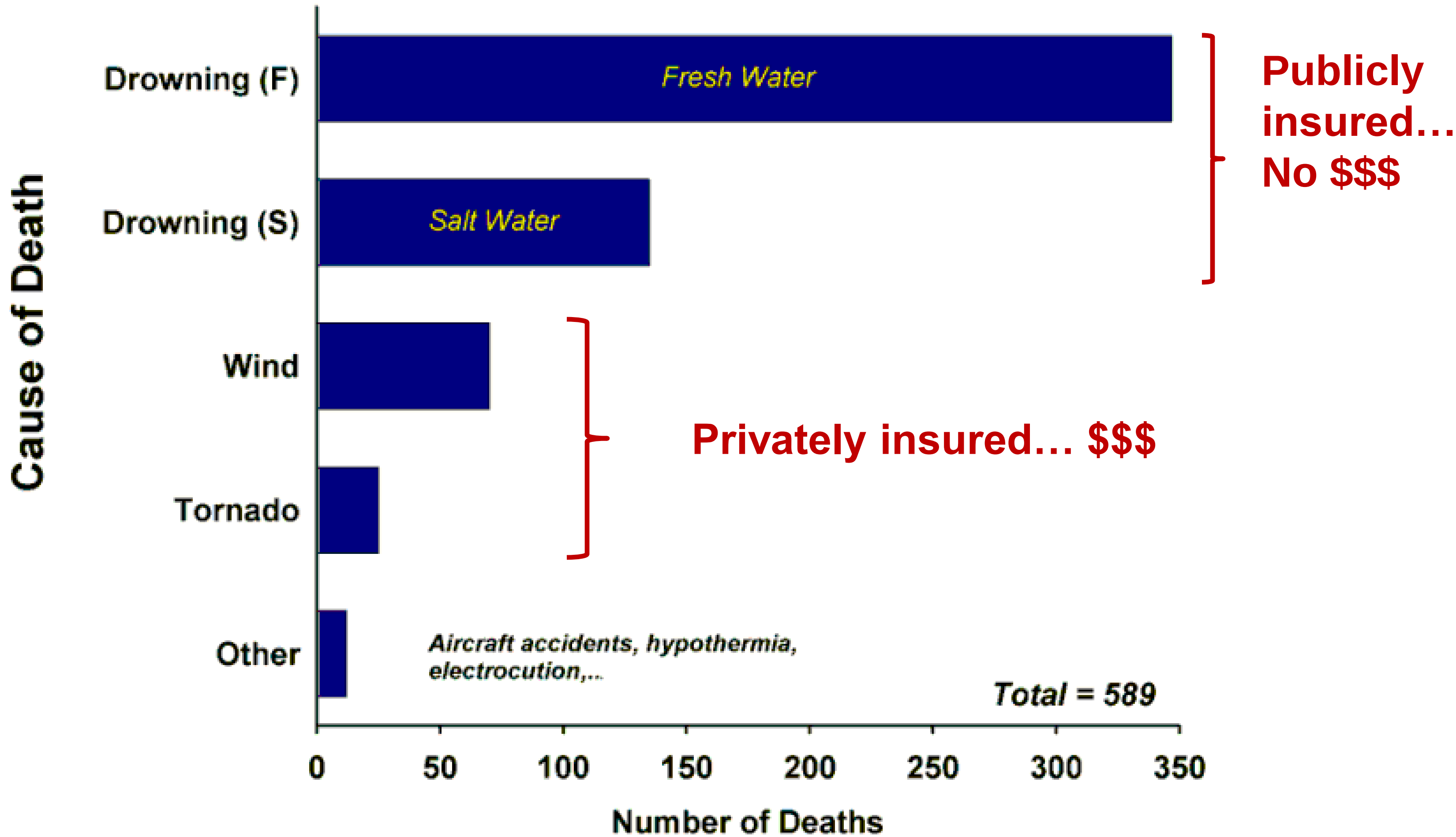
Outer radius very nearly follows a log-normal distribution with a median value of about 420 km (Courtesy Dan Chavas)

The Global Hurricane Hazard

- About 10,000 deaths per year since 1971
- $700 Billion 2015 U.S. Dollars in Damages Annually since 1971

EM-DAT, 2016: The OFDA/CRED International Disaster Database
http://www.emdat.be/.

U. S. Hurricane Mortality (1970-1999)

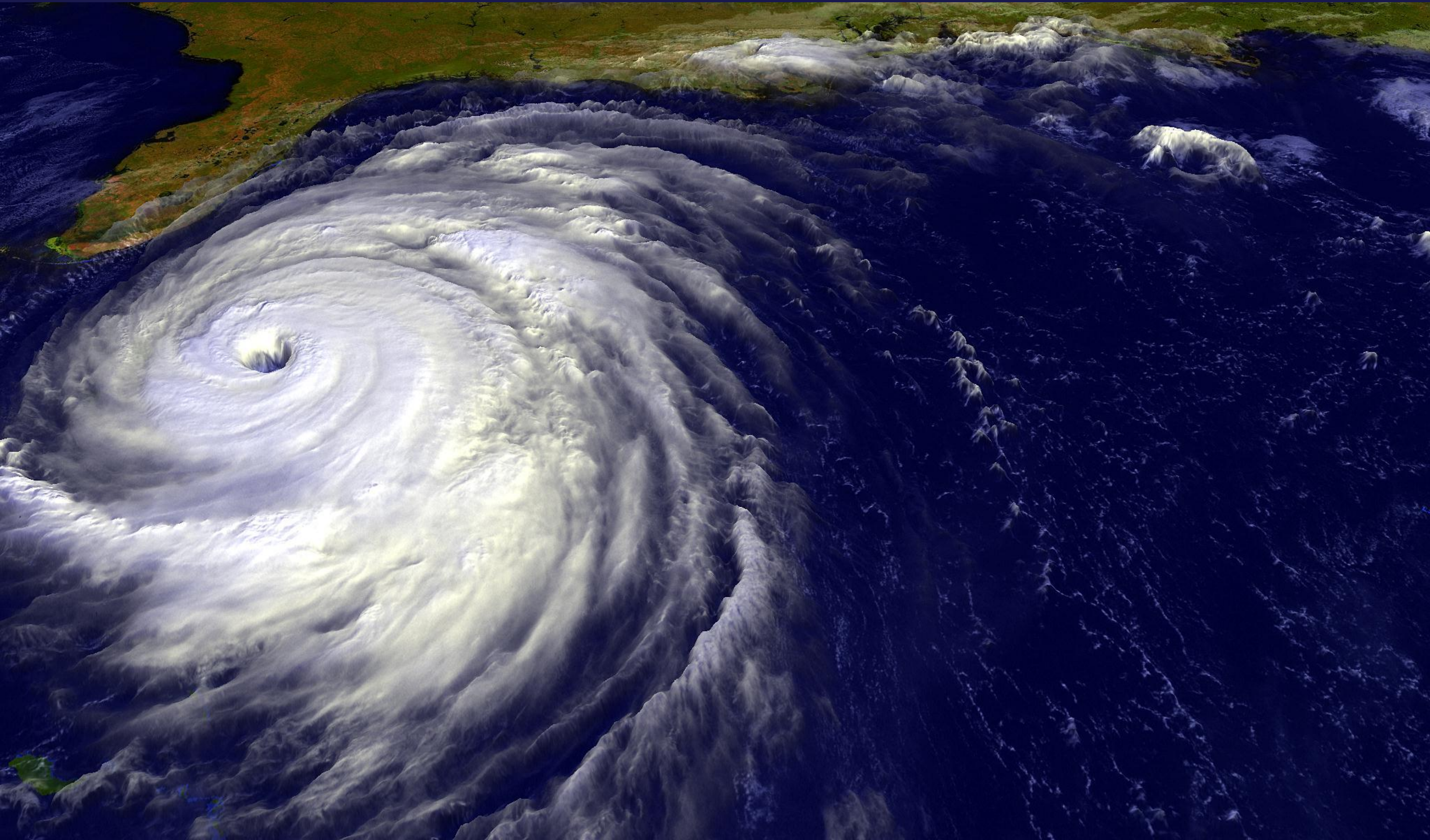


Source: Rappaport, E. N., 1999:
The threat to life in inland areas of the United States from Atlantic tropical cyclones.
Prepreints 23rd Conferenceon Hurricanes and Tropical Meteorology,
American Meteorological Society (10-15 Jan 1999, Dallas Tx), 339-342.

QUIZ

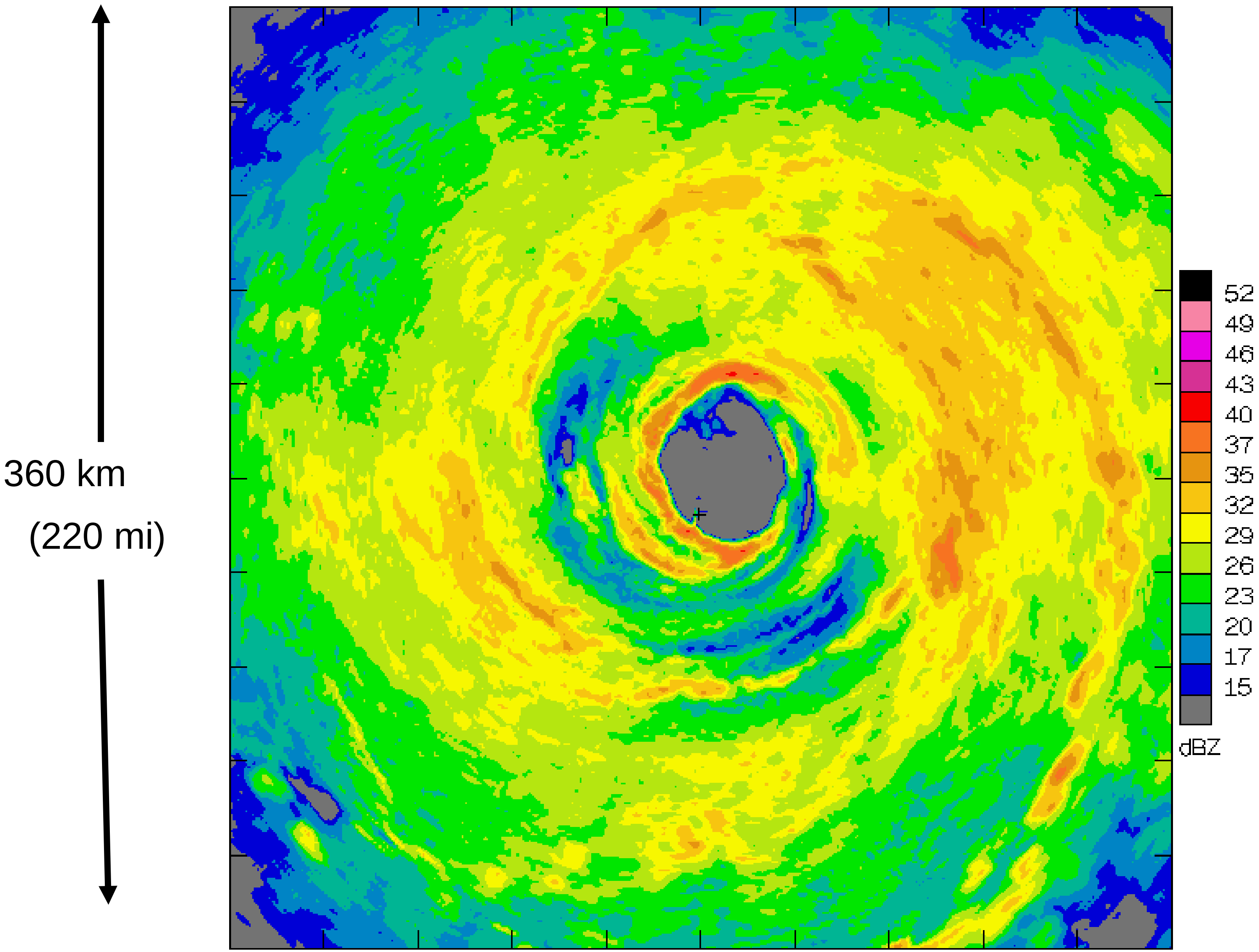
- In an average year, the globe experiences
  1. 50-60 TCs
  2. 75-85 TCs
  3. 100-110 TCs
- The most lethal aspect of a hurricane is
  1. Wind
  2. Rain and storm surge

The View from Space

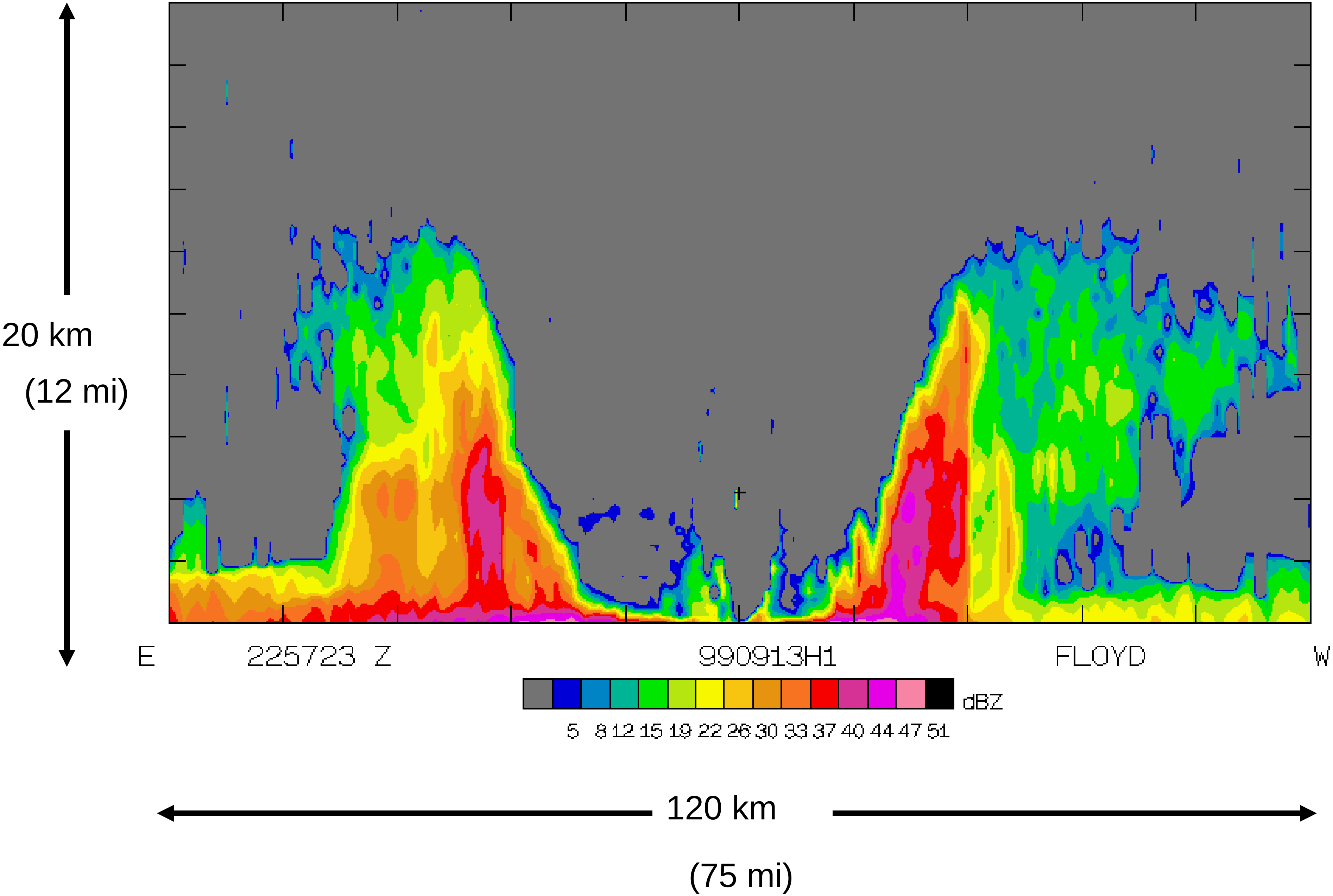


View of the eye of Hurricane Katrina on August 28th, 2005, as seen from a NOAA WP-3D hurricane reconnaissance aircraft.

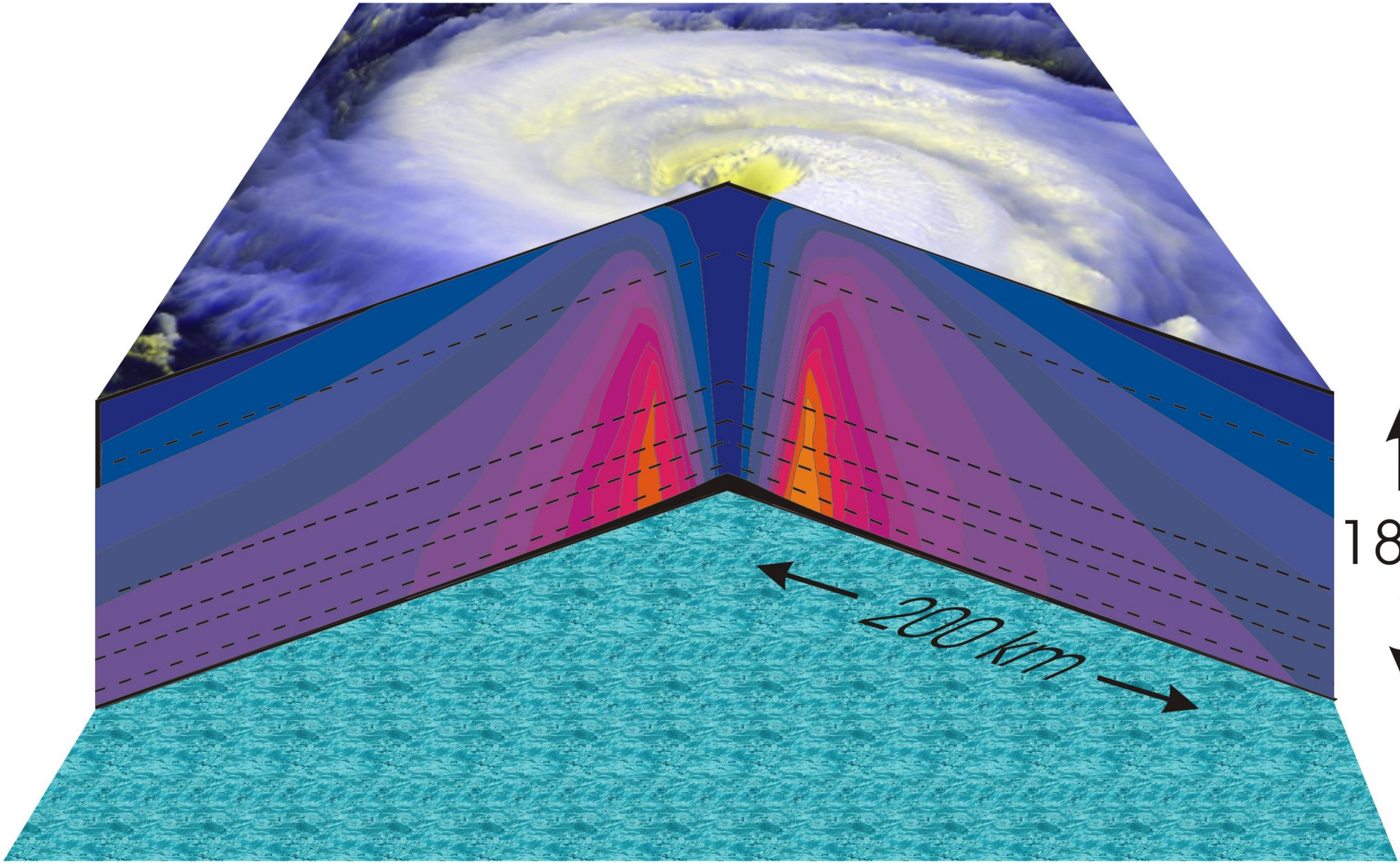
Airborne Radar: Horizontal Map



Airborne Radar: Vertical Slice



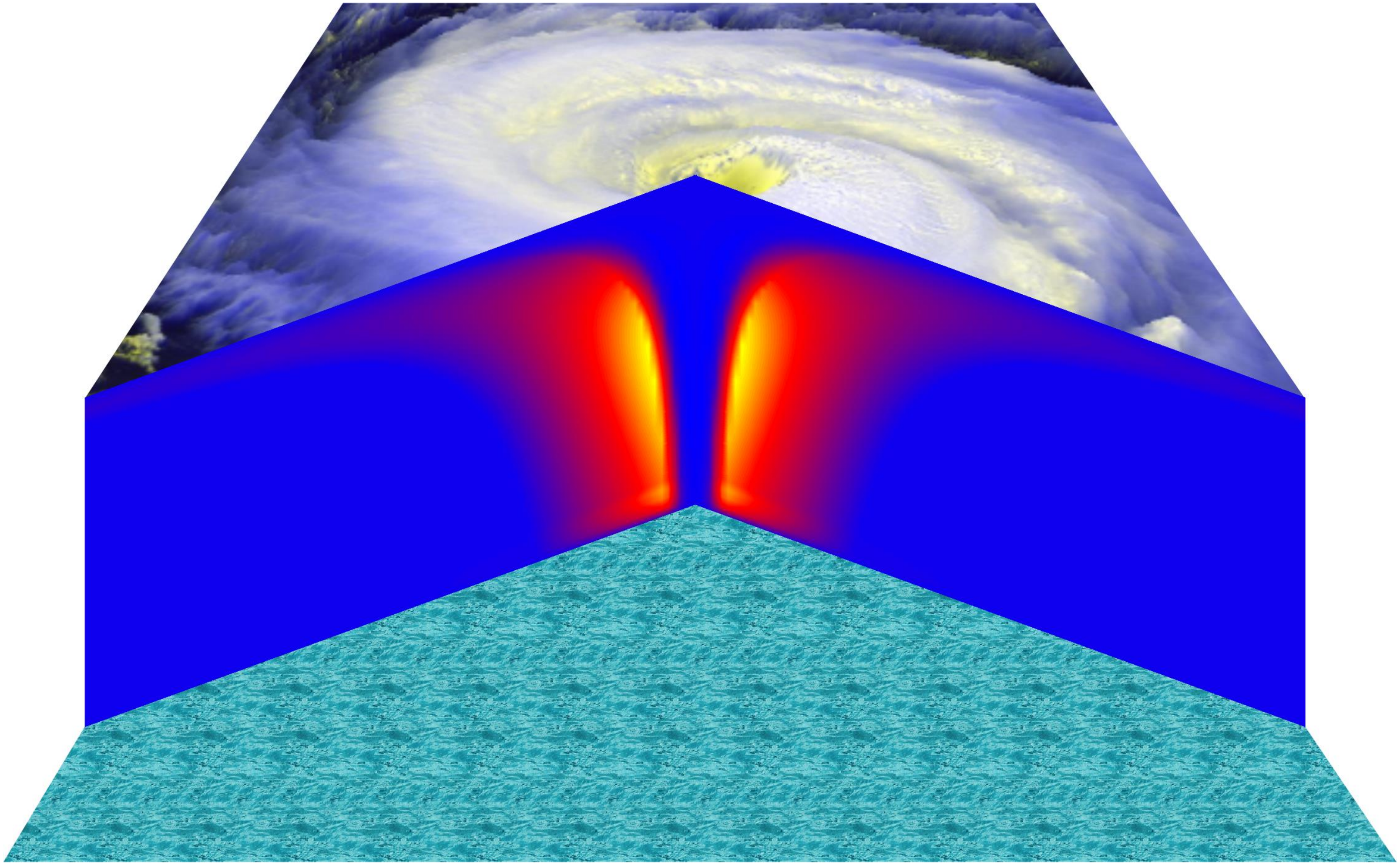
Hurricane Structure: Wind Speed



Azimuthal component of wind

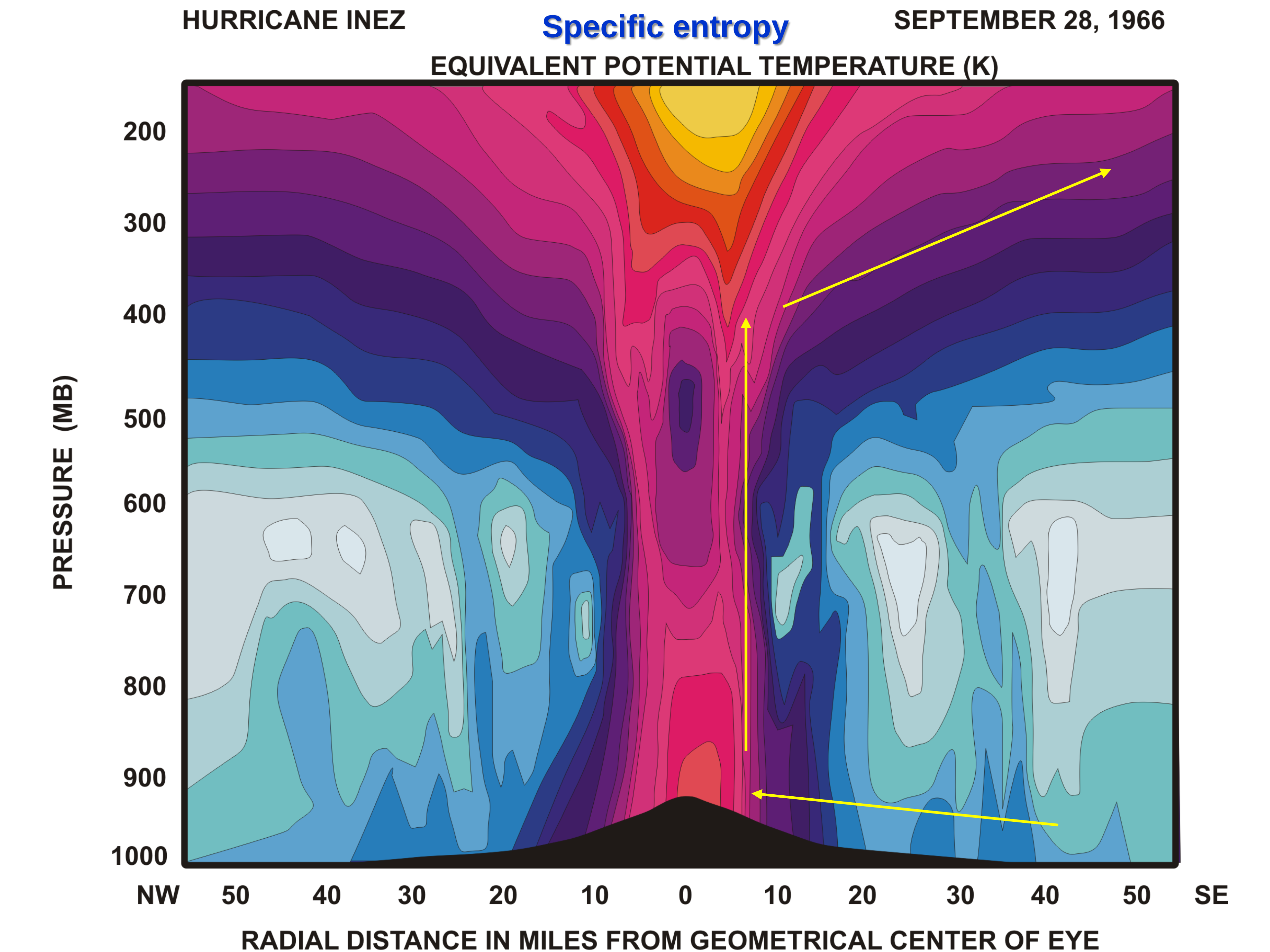
< 11 5 ms^{-1} - > 60 ms^{-1}

Vertical Air Motion



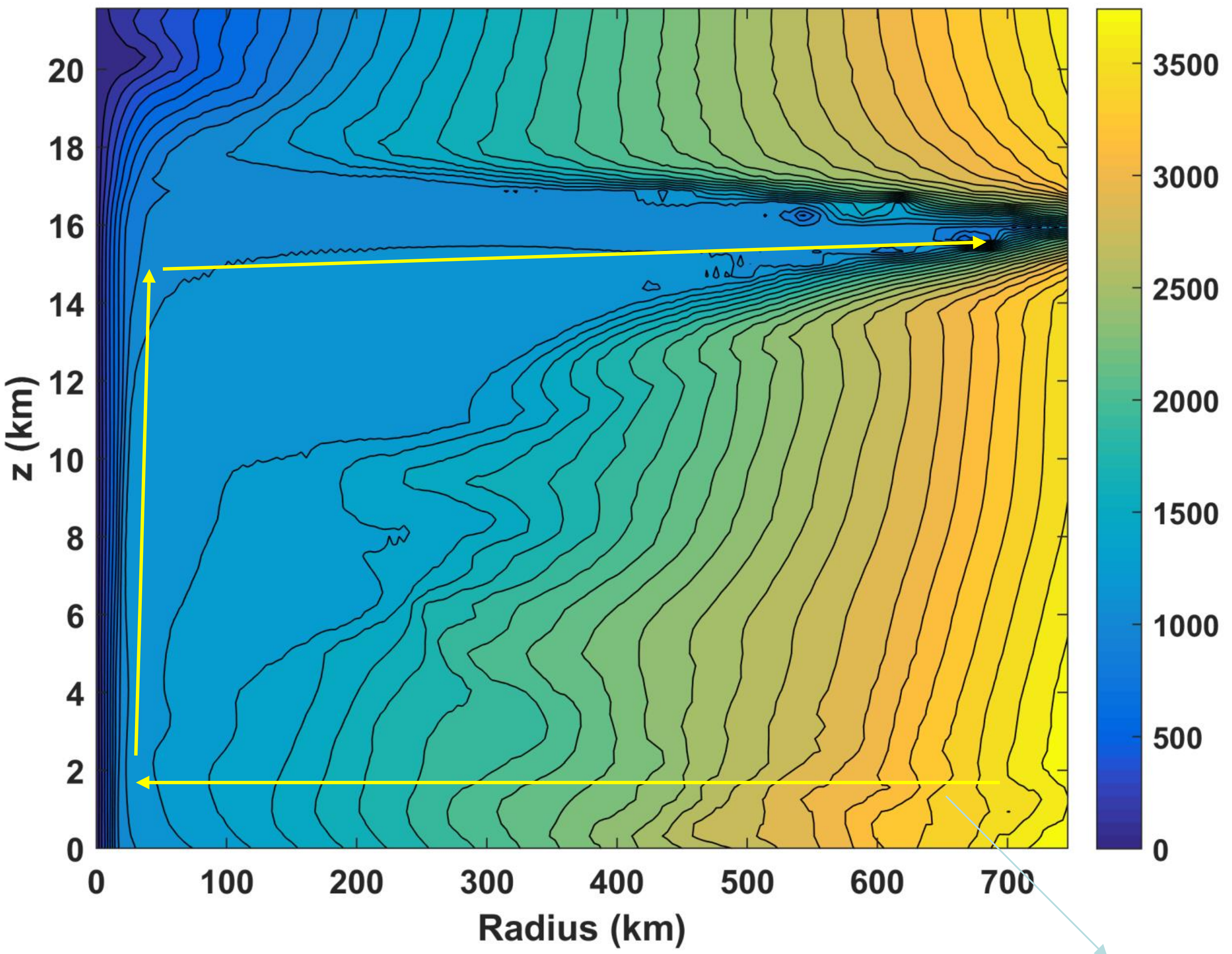
Updraft Speed

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

Absolute angular momentum per unit mass

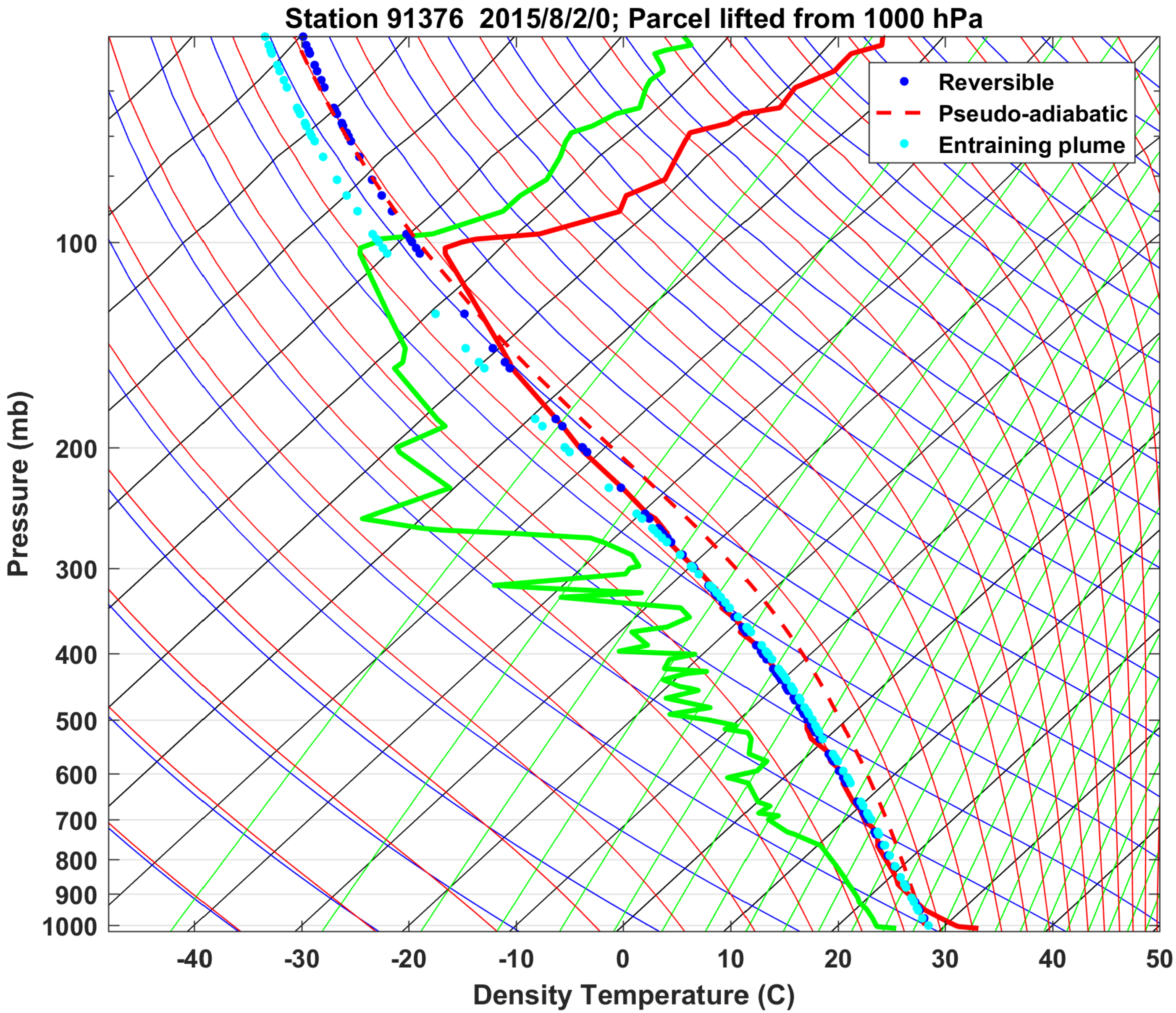
$$M = rV + \Omega r^2$$



Starting Point: Radiative-Moist Convective Equilibrium

- Equilibrium state in which convective and radiative energy fluxes balance at each altitude
- Vertical profile nearly neutral to moist convection
- Strongly-two way interaction: Radiation drives profile toward instability, convection lofts water that strongly affects radiative transfer
- Jump in humidity near ocean surface

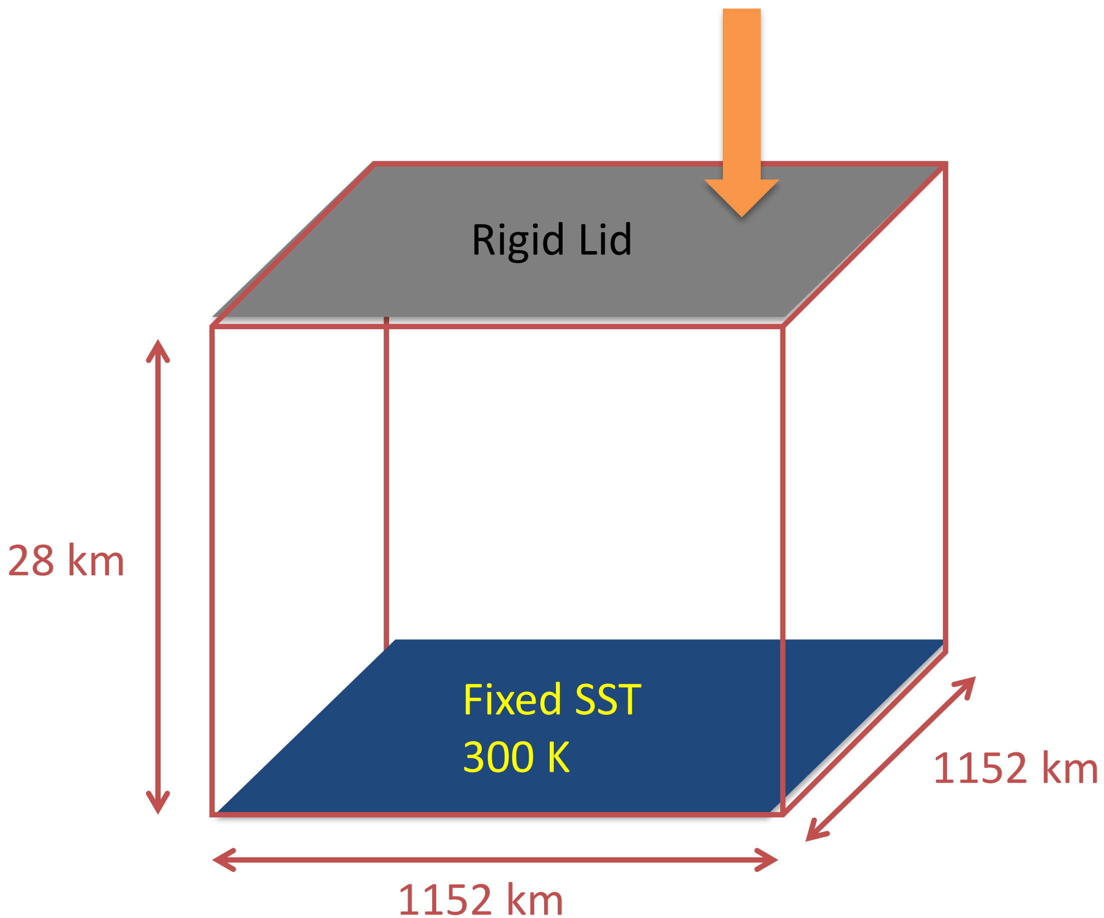
Majuro, 00 GMT August 2, 2015



The radiation physicist’s heart knoweth its own bitterness, but a stranger meddleth not with its joy

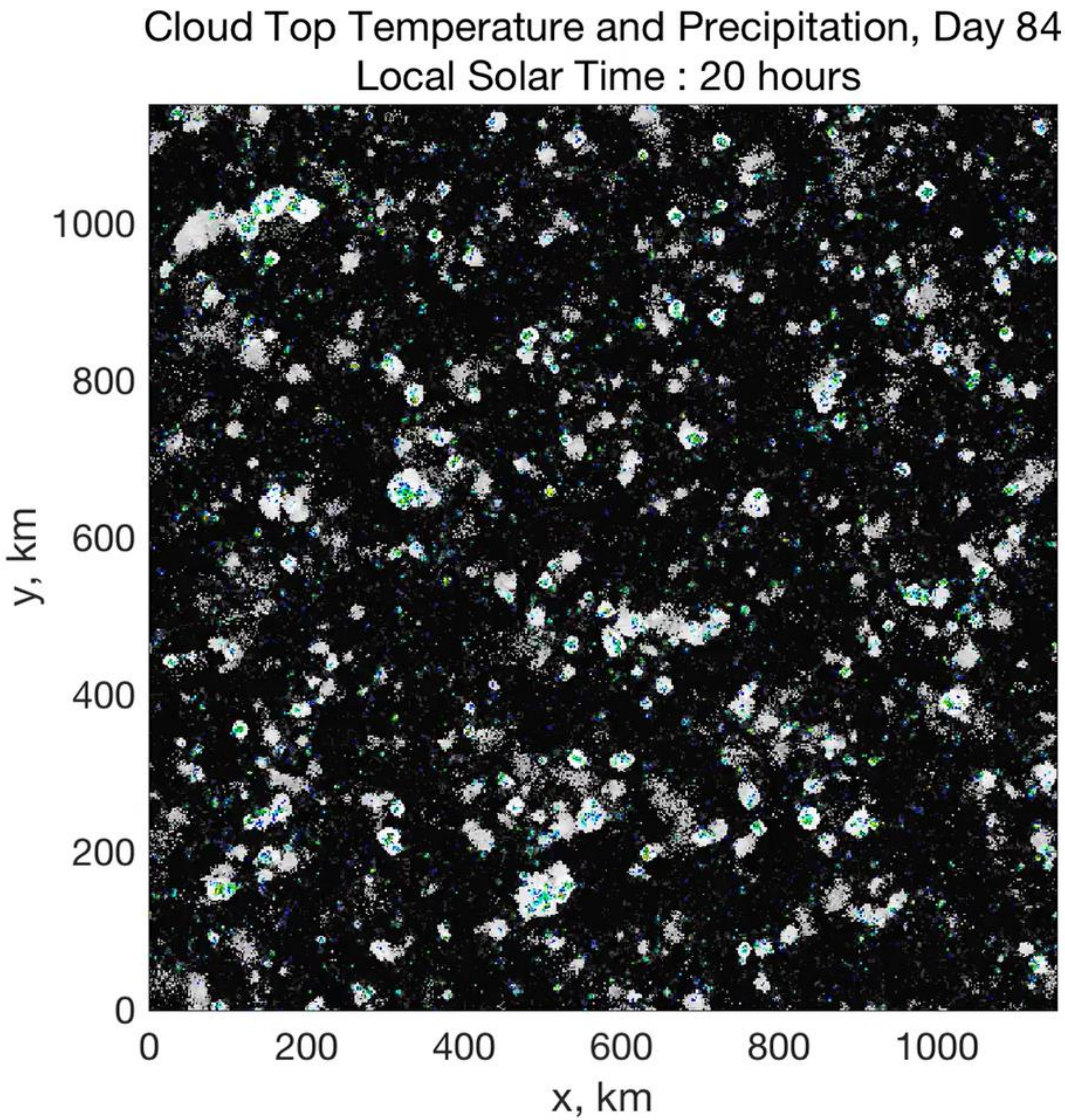
Cloud-permitting models of radiative-convective equilibrium run in moderately large domains

Example: System for Atmospheric Modeling (SAM) of Khairoutdinov and Randall (2003)

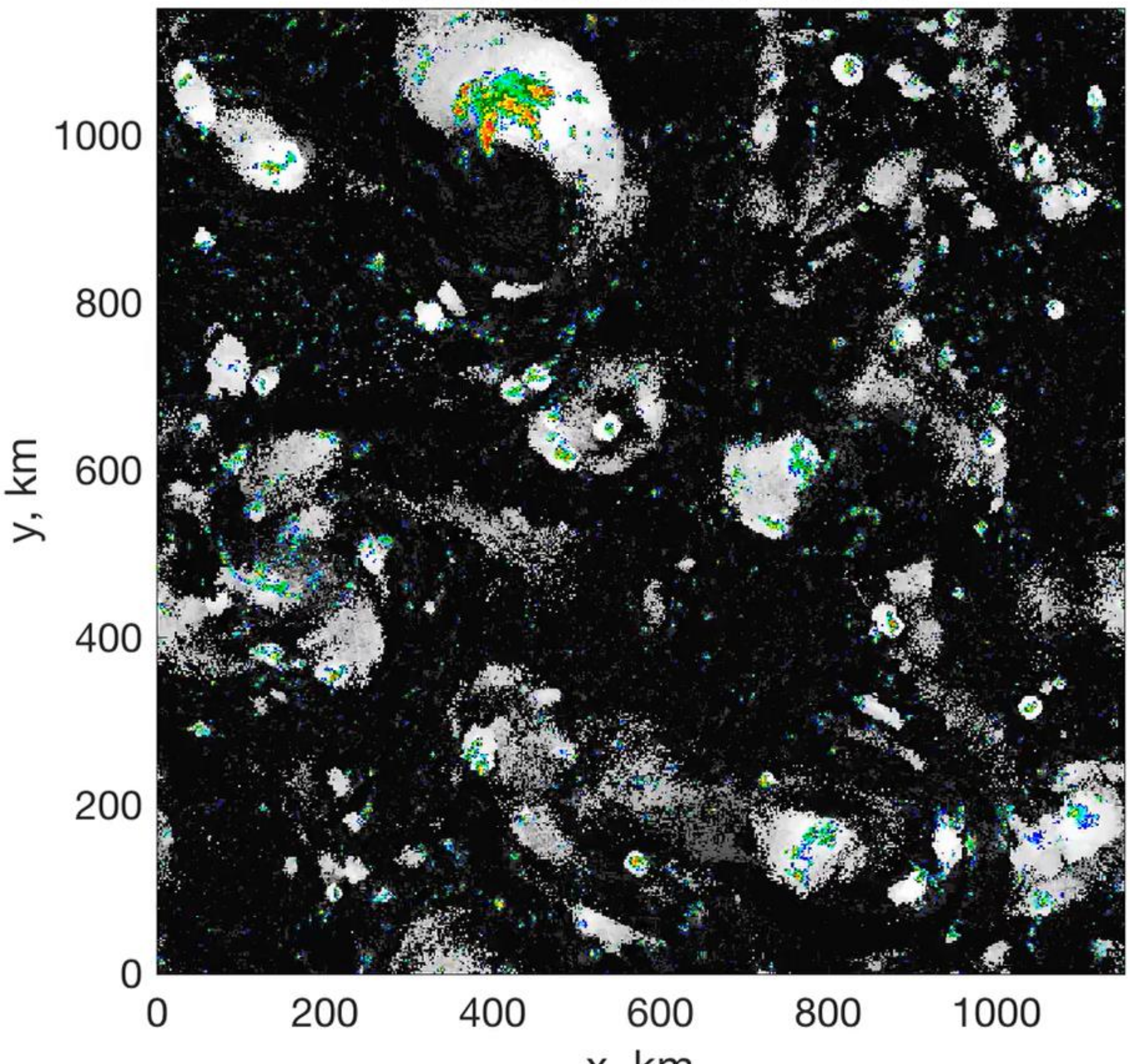


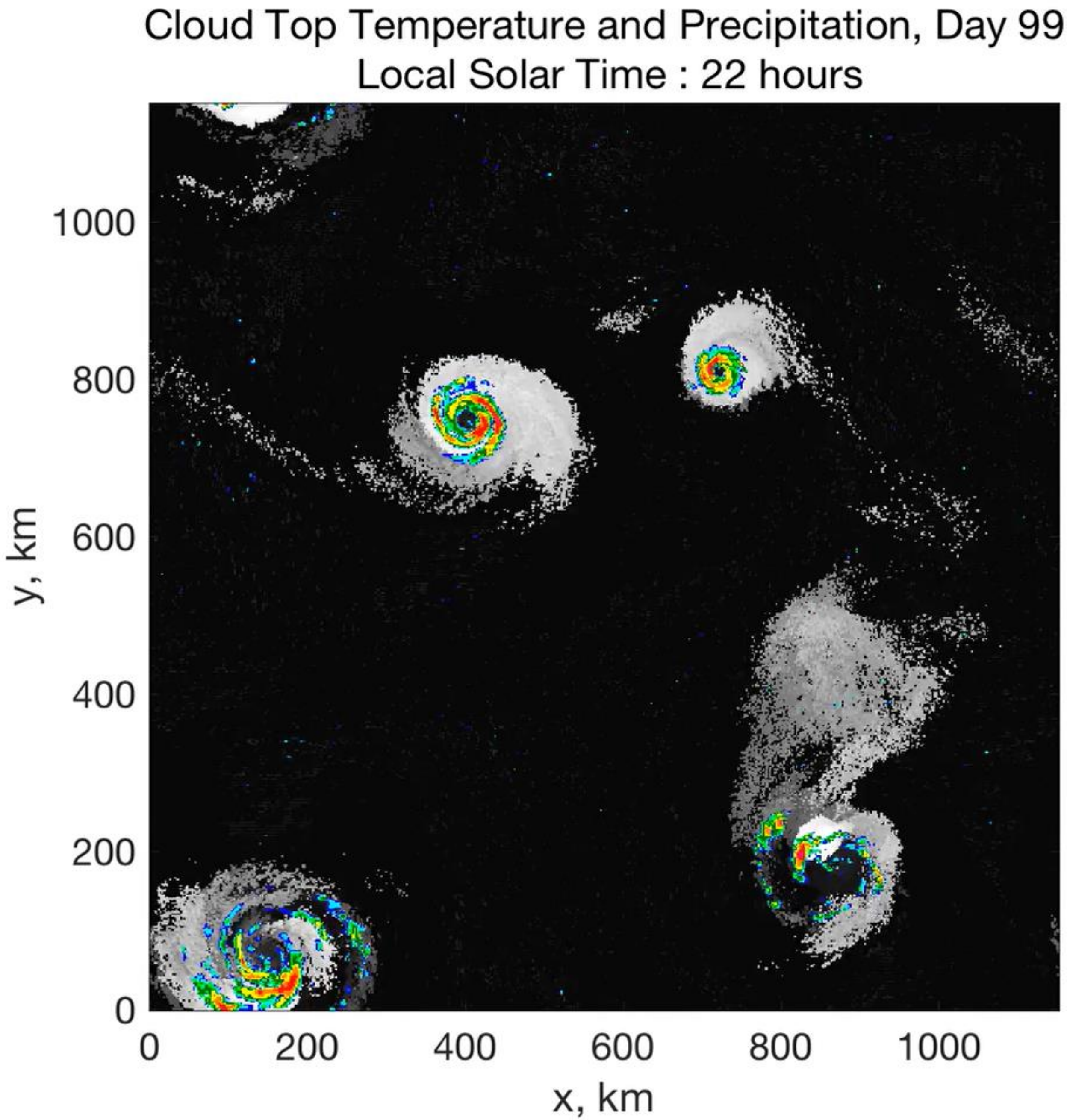
- Horizontal Resolution: 2km
- Vertical Resolution: 64 levels
- Periodic lateral boundaries
- Initial sounding from domain average of smaller domain run in RCE
- No solar fluxes; specified radiative cooling rate.

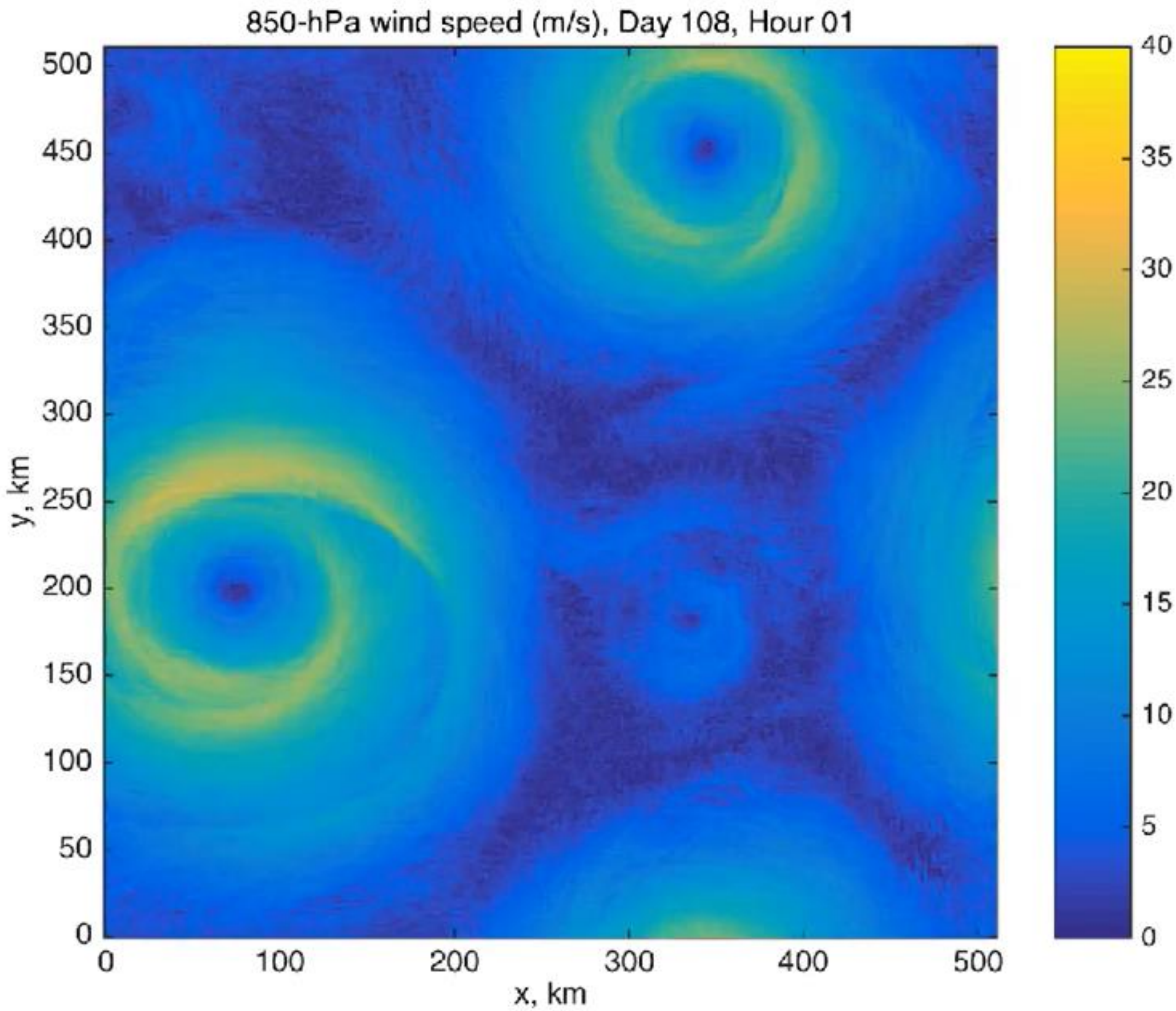
Courtesy Tim Cronin, MIT

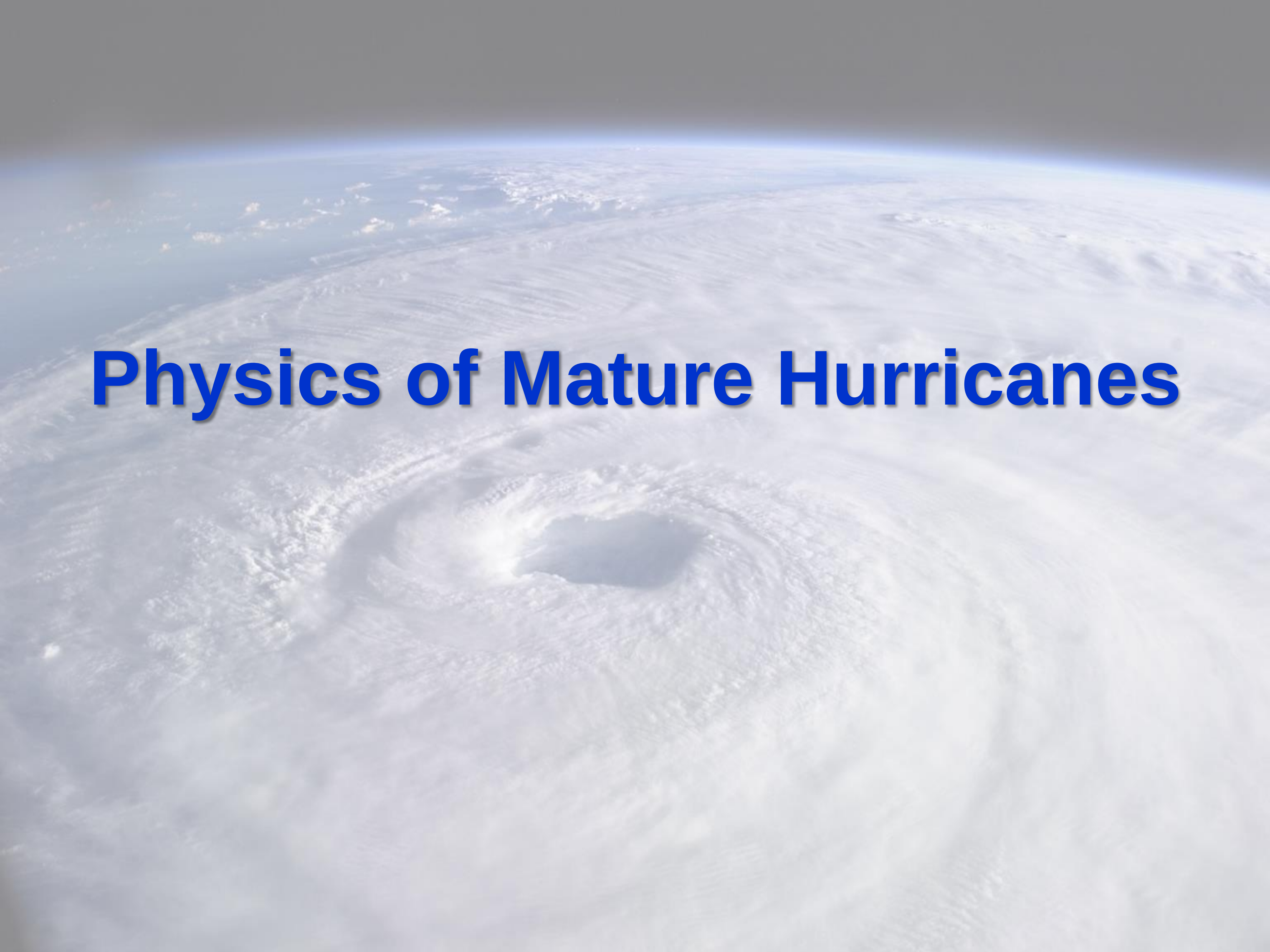

Cloud Top Temperature and Precipitation, Day 84
Local Solar Time : 20 hours
y, km
x, km
0
200
400
600
800
1000

Cloud Top Temperature and Precipitation, Day 89
Local Solar Time : 20 hours



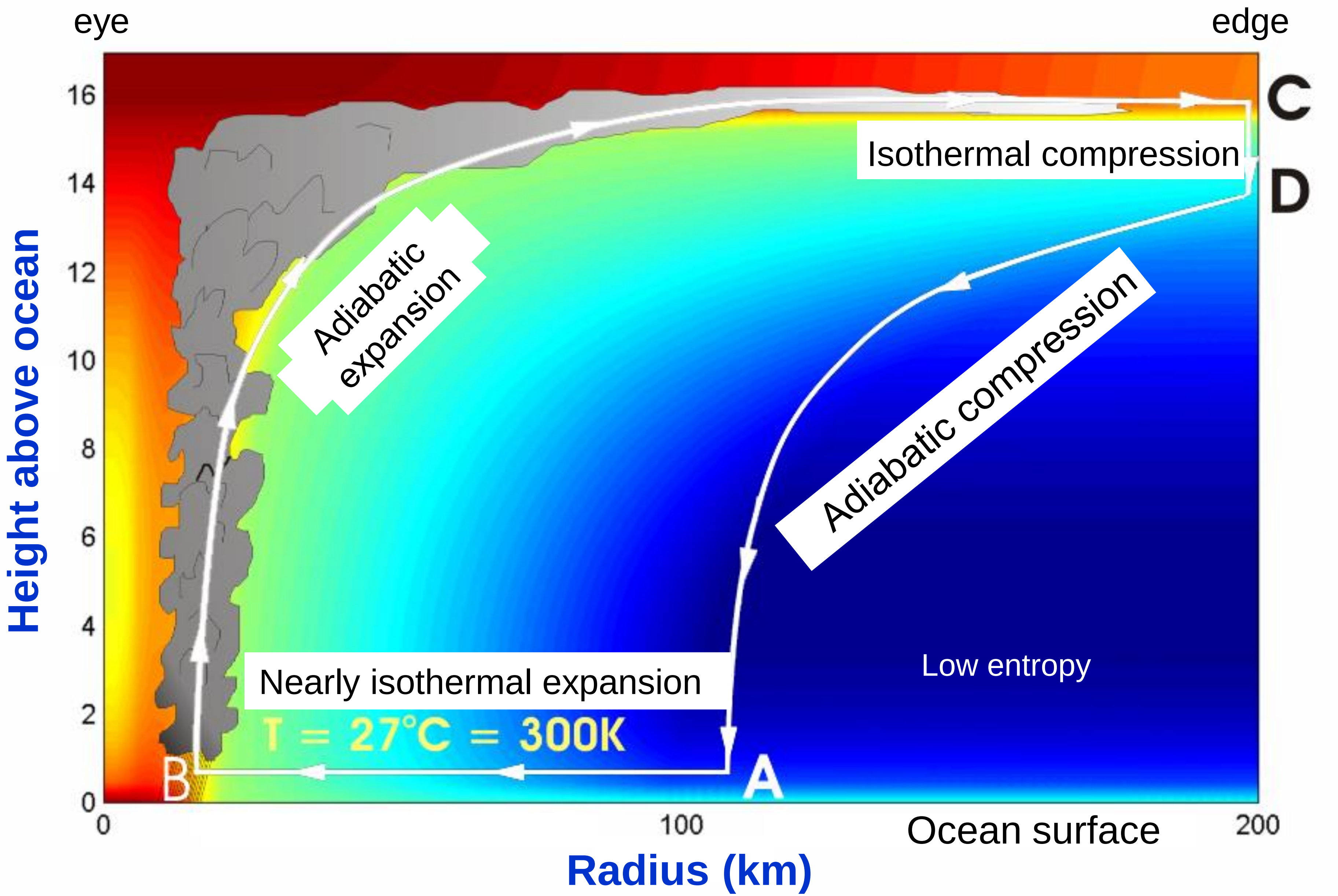

Cloud Top Temperature and Precipitation, Day 99
Local Solar Time : 22 hours
y, km
1000
800
600
400
200
0
0
200
400
600
800
1000
x, km


850-hPa wind speed (m/s), Day 108, Hour 01
y, km
x, km
0
50
100
150
200
250
300
350
400
450
500
0
5
10
15
20
25
30
35
40



Physics of Mature Hurricanes

Cross-section through a Hurricane & 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 hurricanes: Air cools radiatively. But since the 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:

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

Theoretical Upper Bound on Hurricane Maximum Wind Speed:

Surface temperature

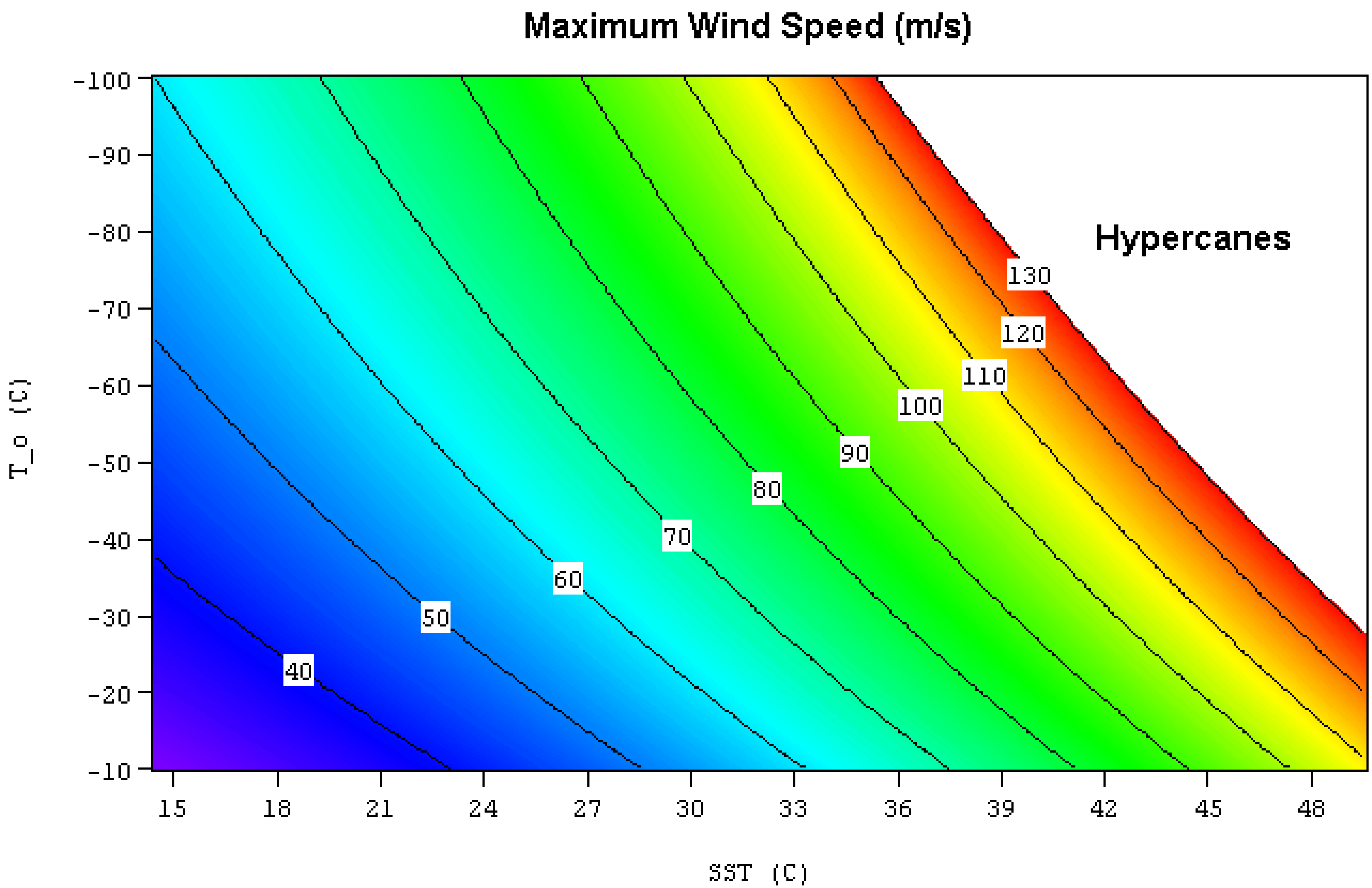
$$|V_{max}|^2 \cong \boxed{\frac{C_k}{C_D}} \, \frac{T_s - T_o}{T_o} \underbrace{\left(k_0^* - k\right)}$$

Ratio of exchange coefficients of enthalpy and momentum

Outflow temperature

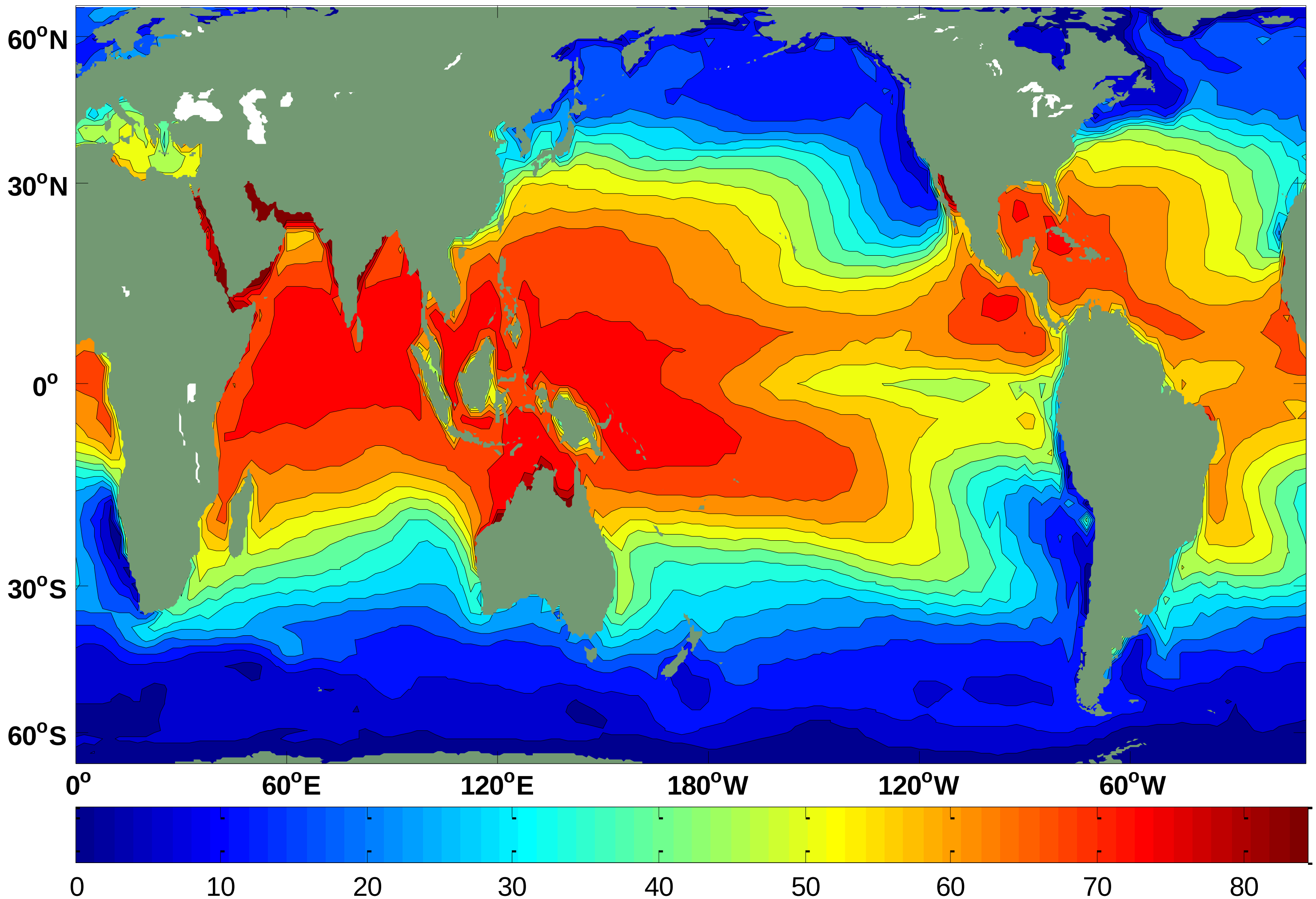
Air-sea enthalpy disequilibrium

$$k = c_p T + L_v q$$

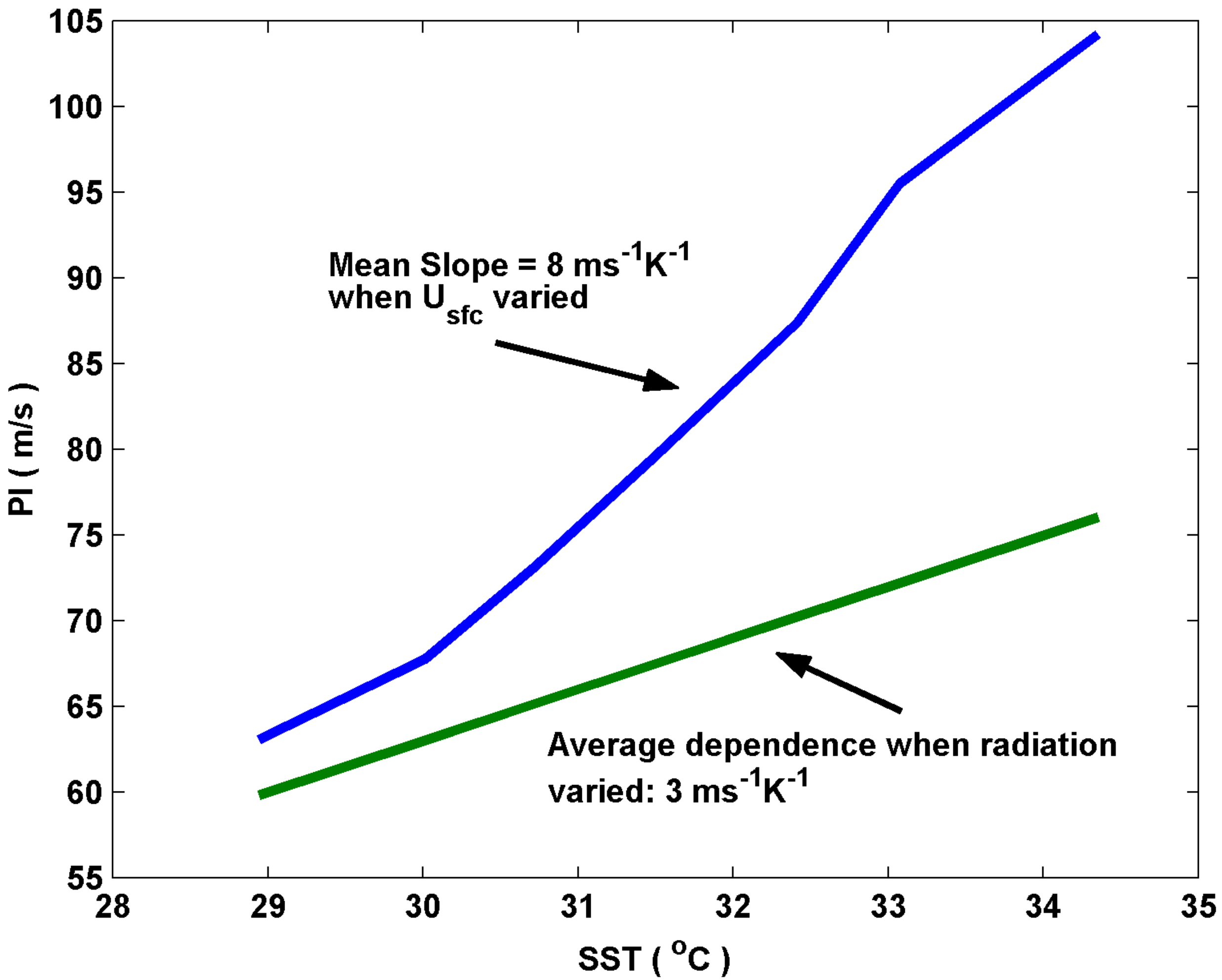


$\mathscr{H} =$ 0.75 $C_k/C_D =$ 1.2

Annual Maximum Potential Intensity (m/s)



Dependence on Sea Surface Temperature (SST):

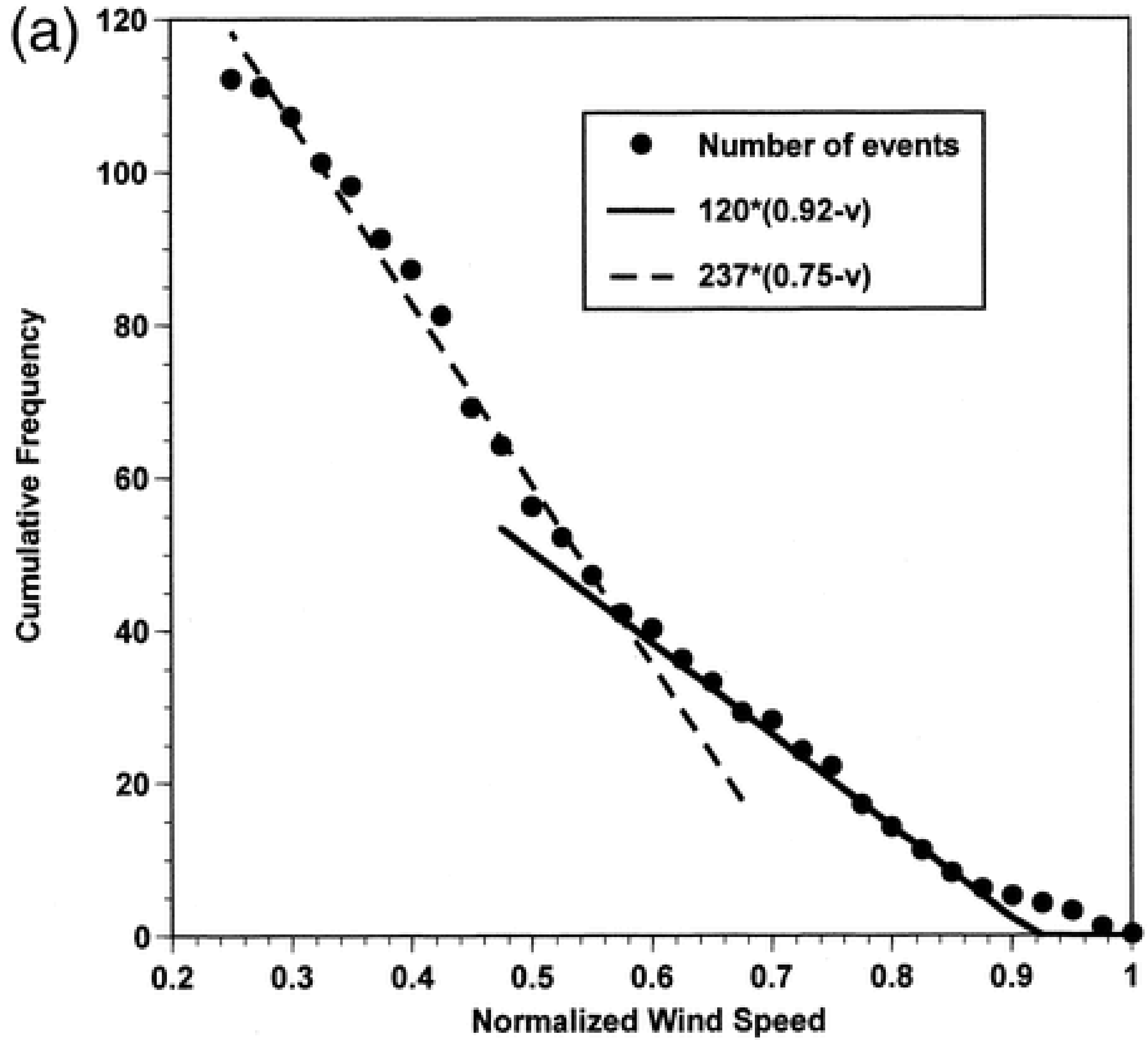


Potential Intensity is not the same thing as SST!

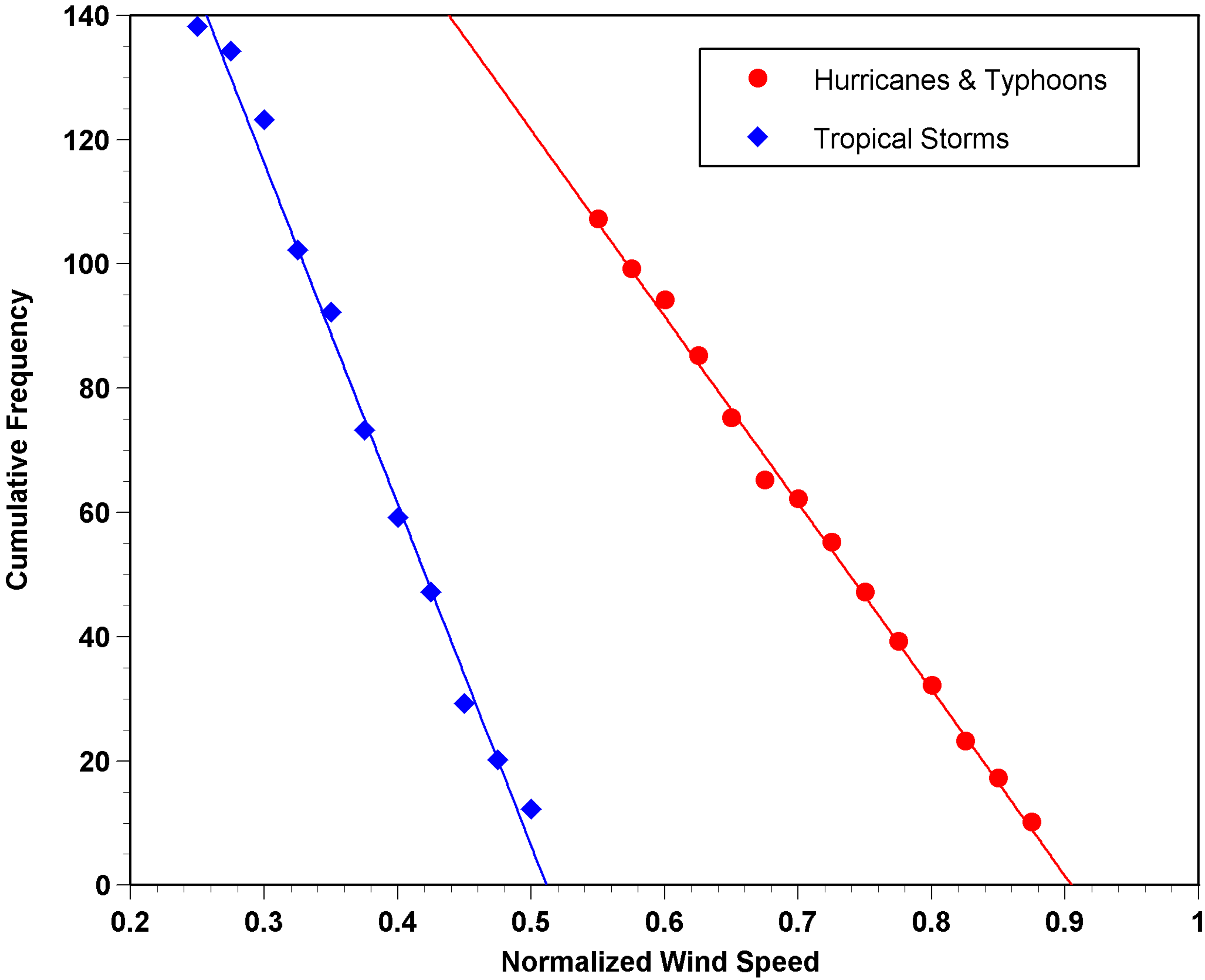
QUIZ

- Tropical cyclones are powered by
  1. Latent heat
  2. Surface heat fluxes
  3. Horizontal temperature gradients
- The upper limit on hurricane wind speeds is determined by
  1. Sea surface temperature
  2. How warm the ocean is relative to the atmosphere above

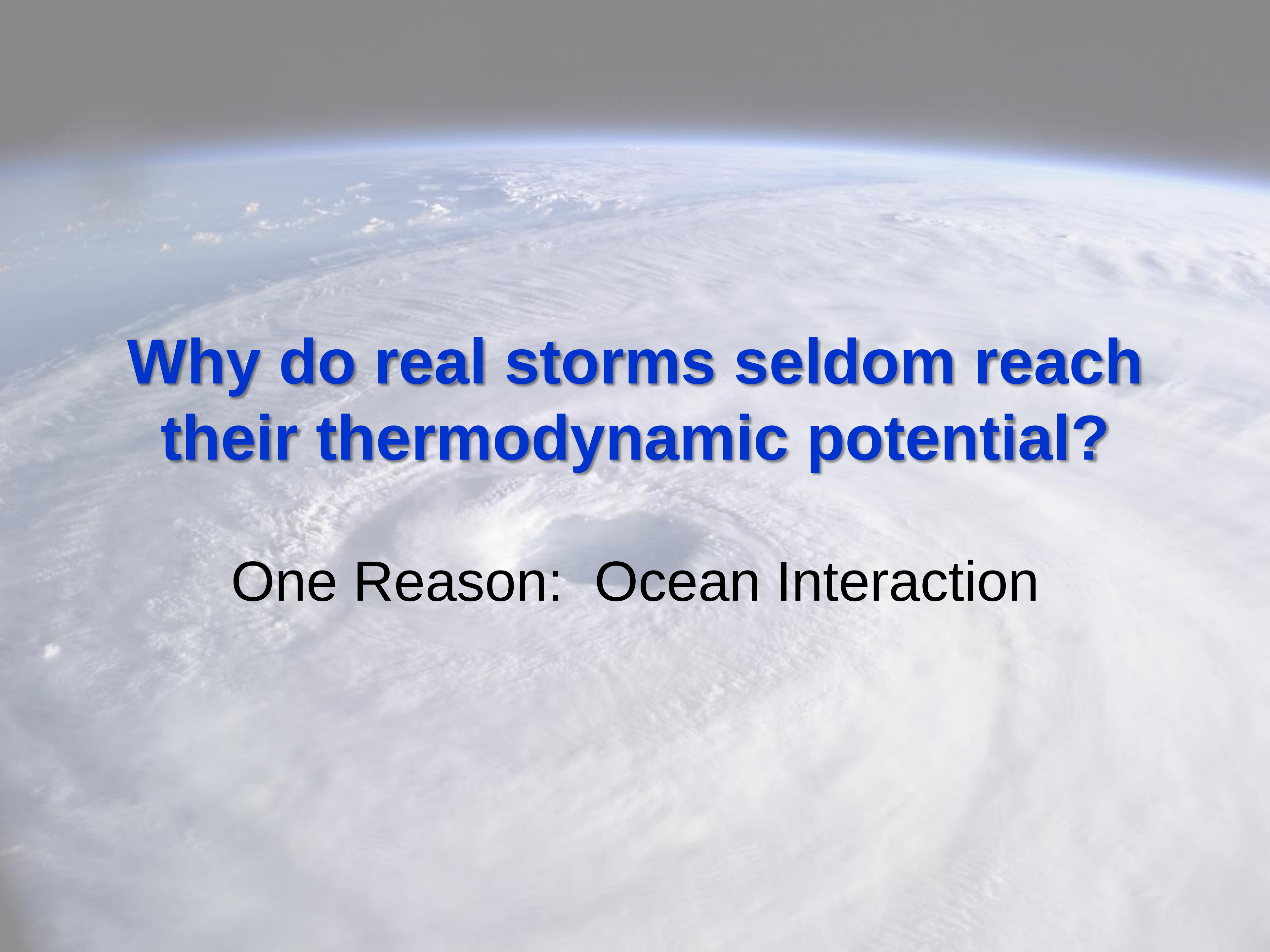
Relationship between potential intensity (PI) and intensity of real tropical cyclones



(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



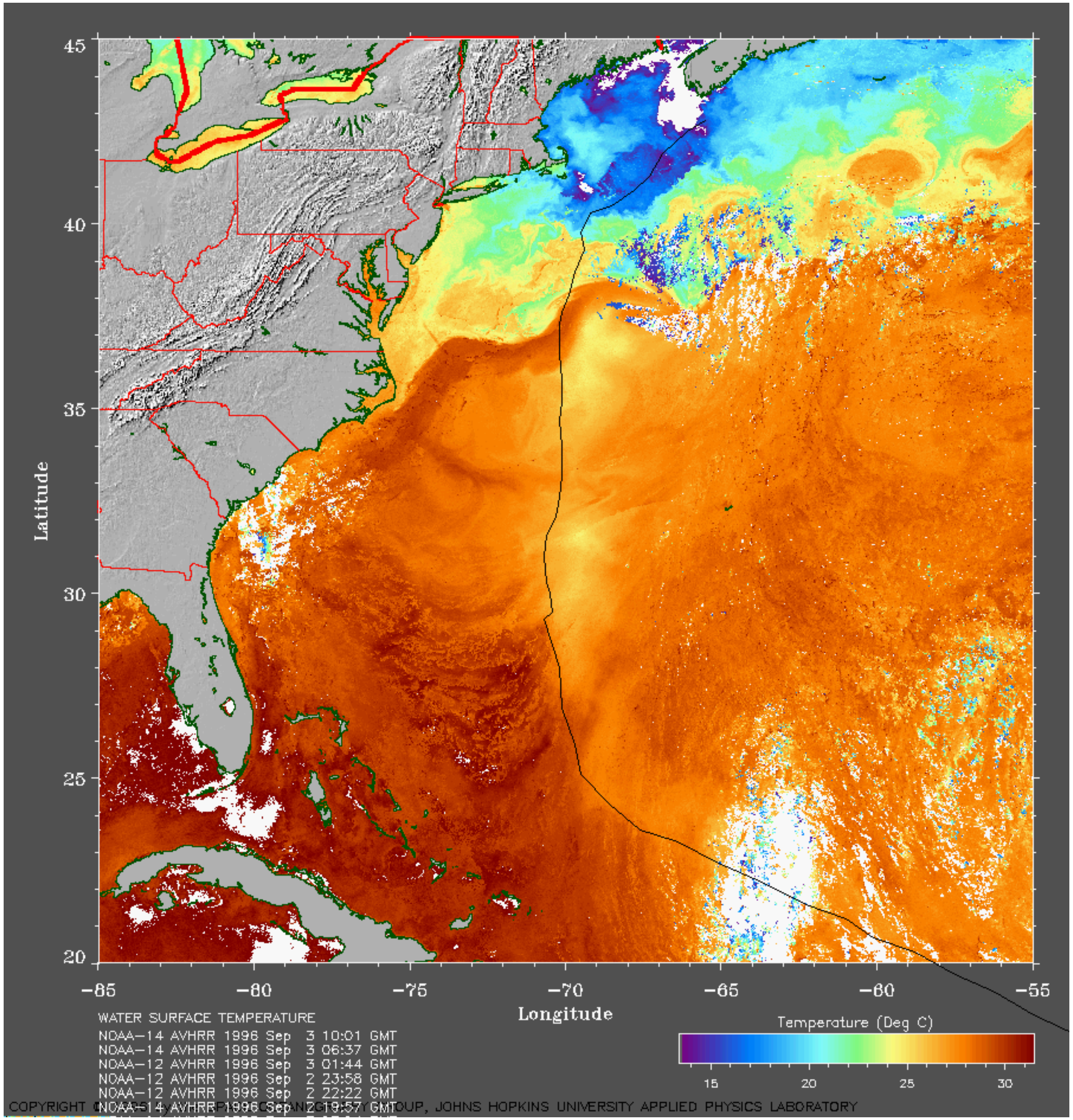
Hurricanes & Typhoons
Tropical Storms
Cumulative Frequency
Normalized Wind Speed
0
20
40
60
80
100
120
140
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



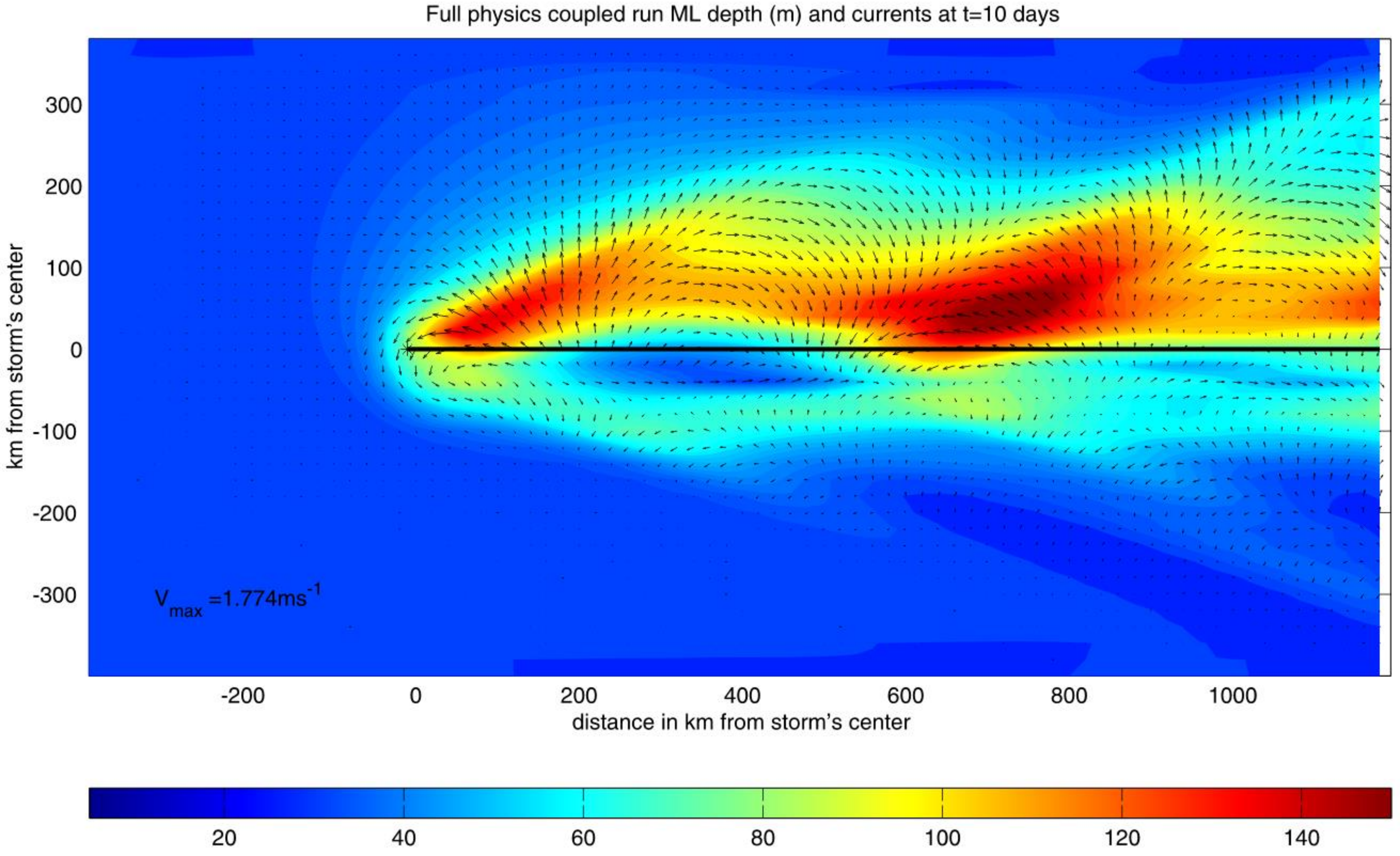
Why do real storms seldom reach their thermodynamic potential?

One Reason: Ocean Interaction

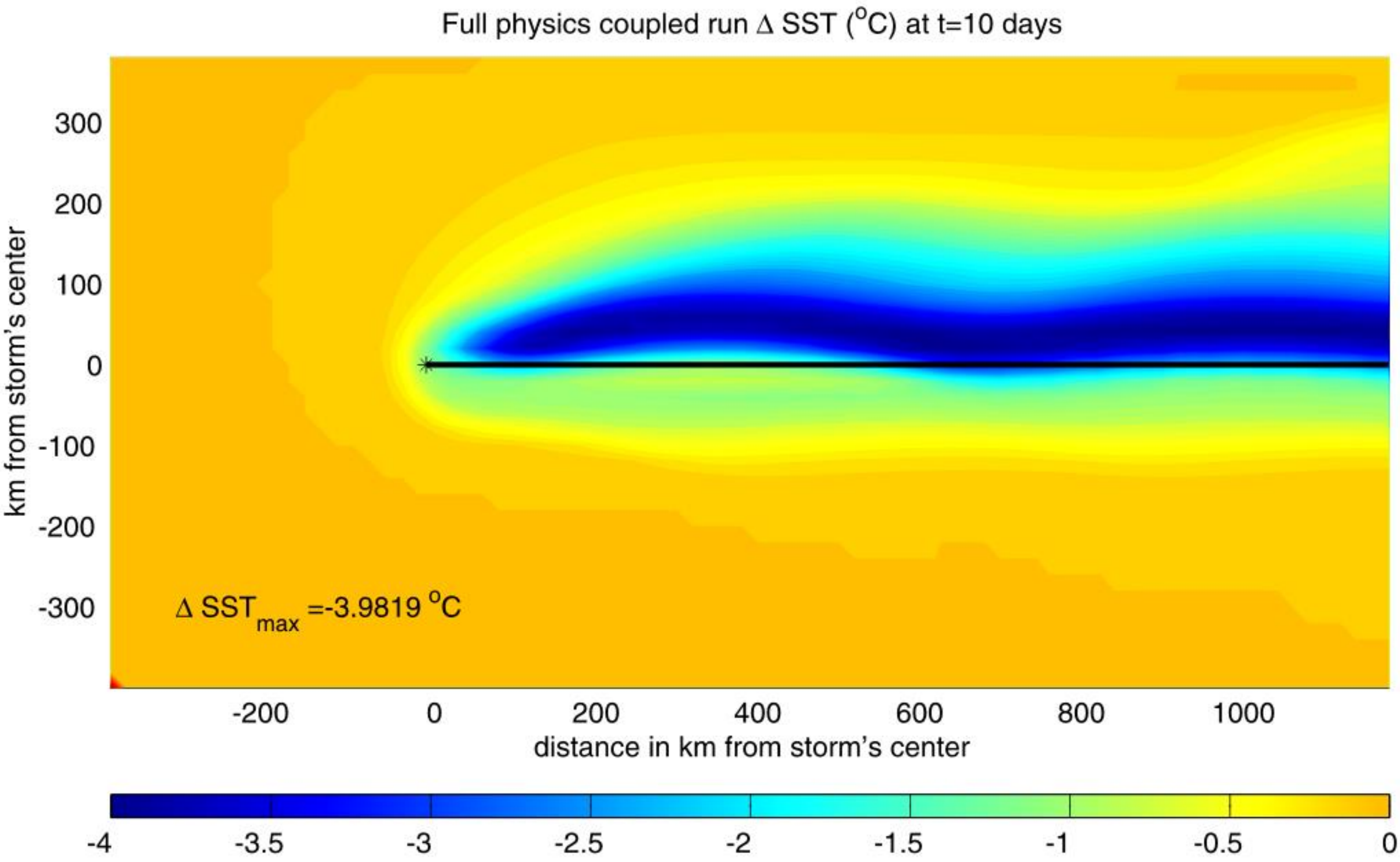
Strong Mixing of Upper Ocean



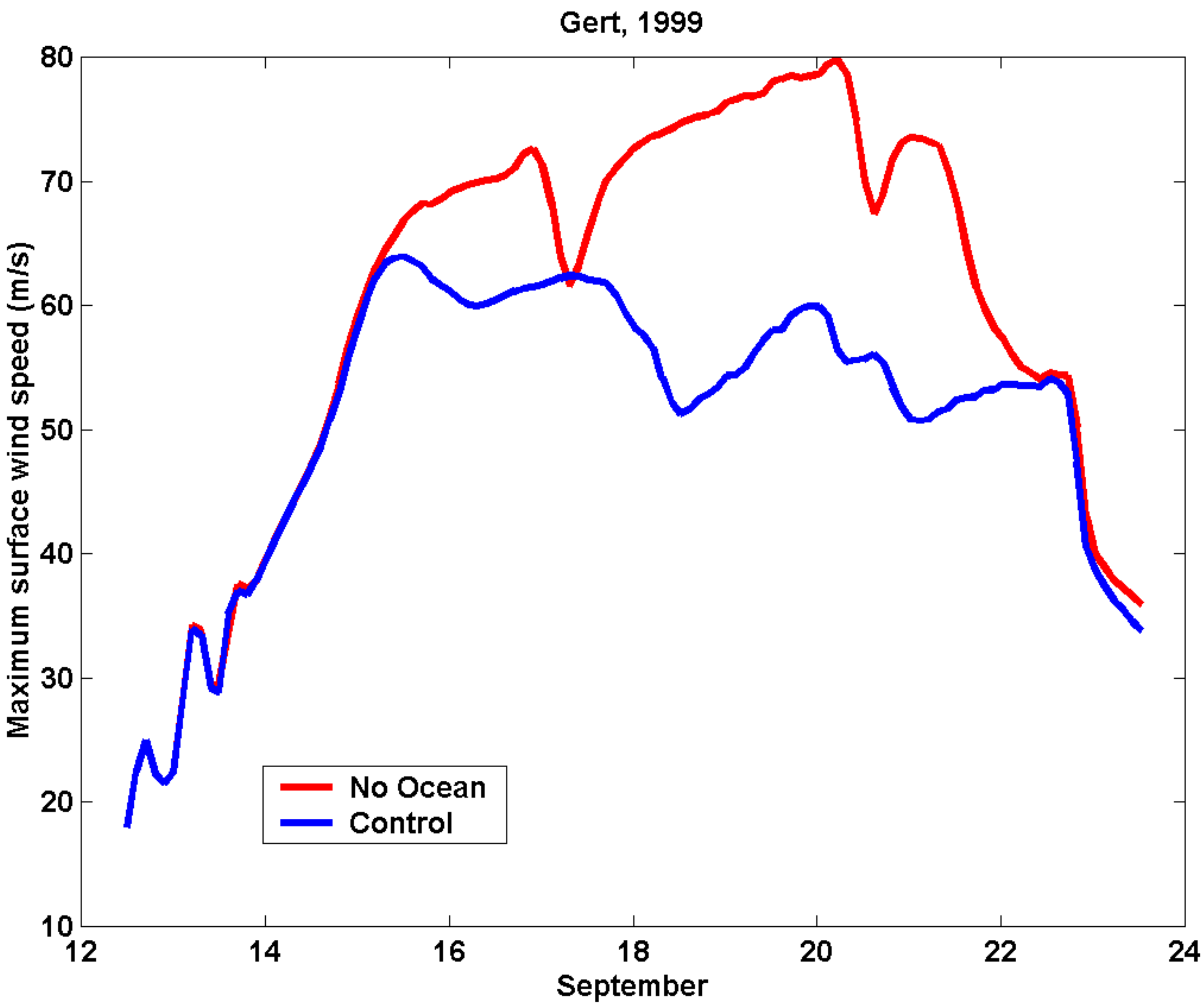
Mixed layer depth and currents



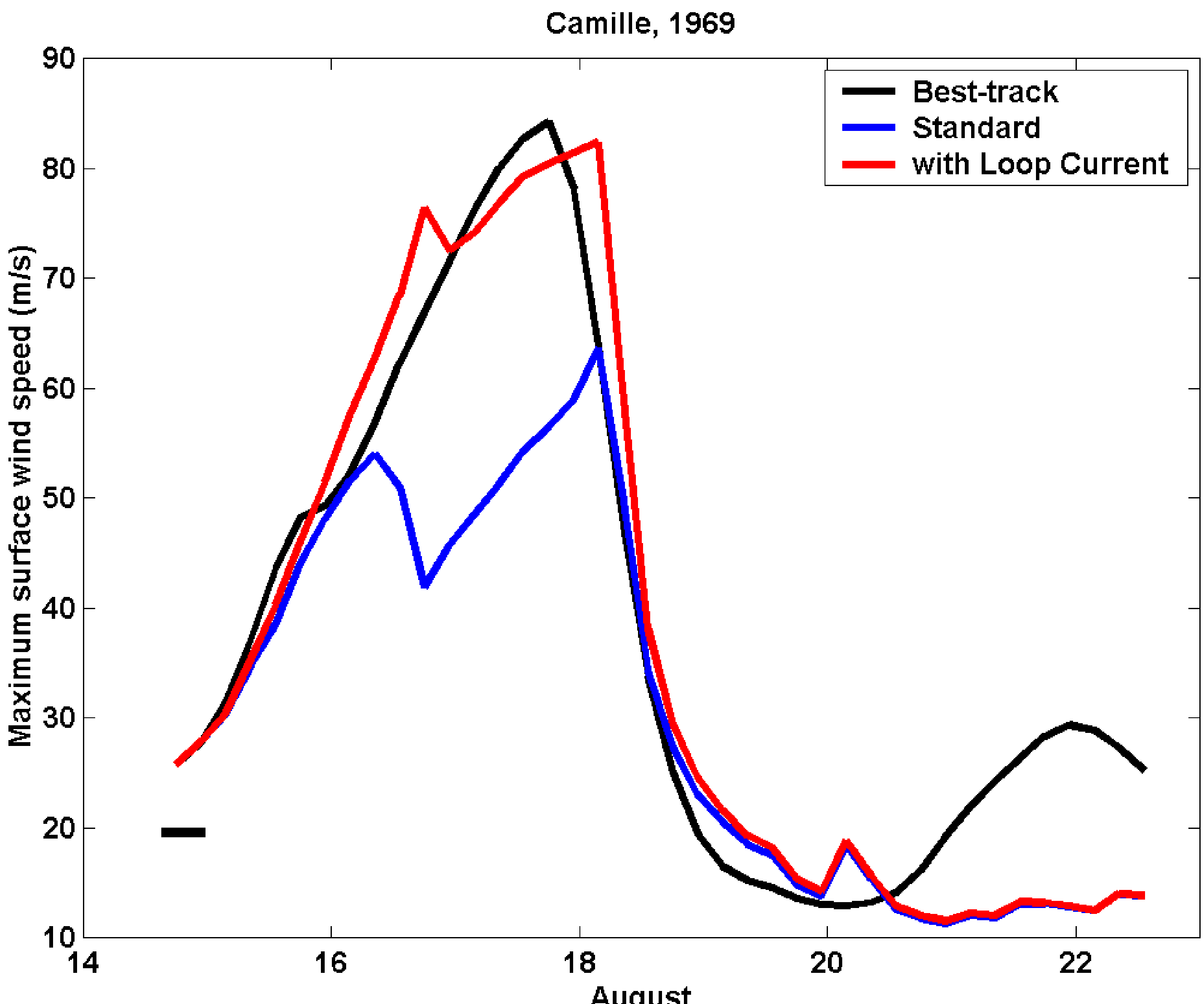
SST Change


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:



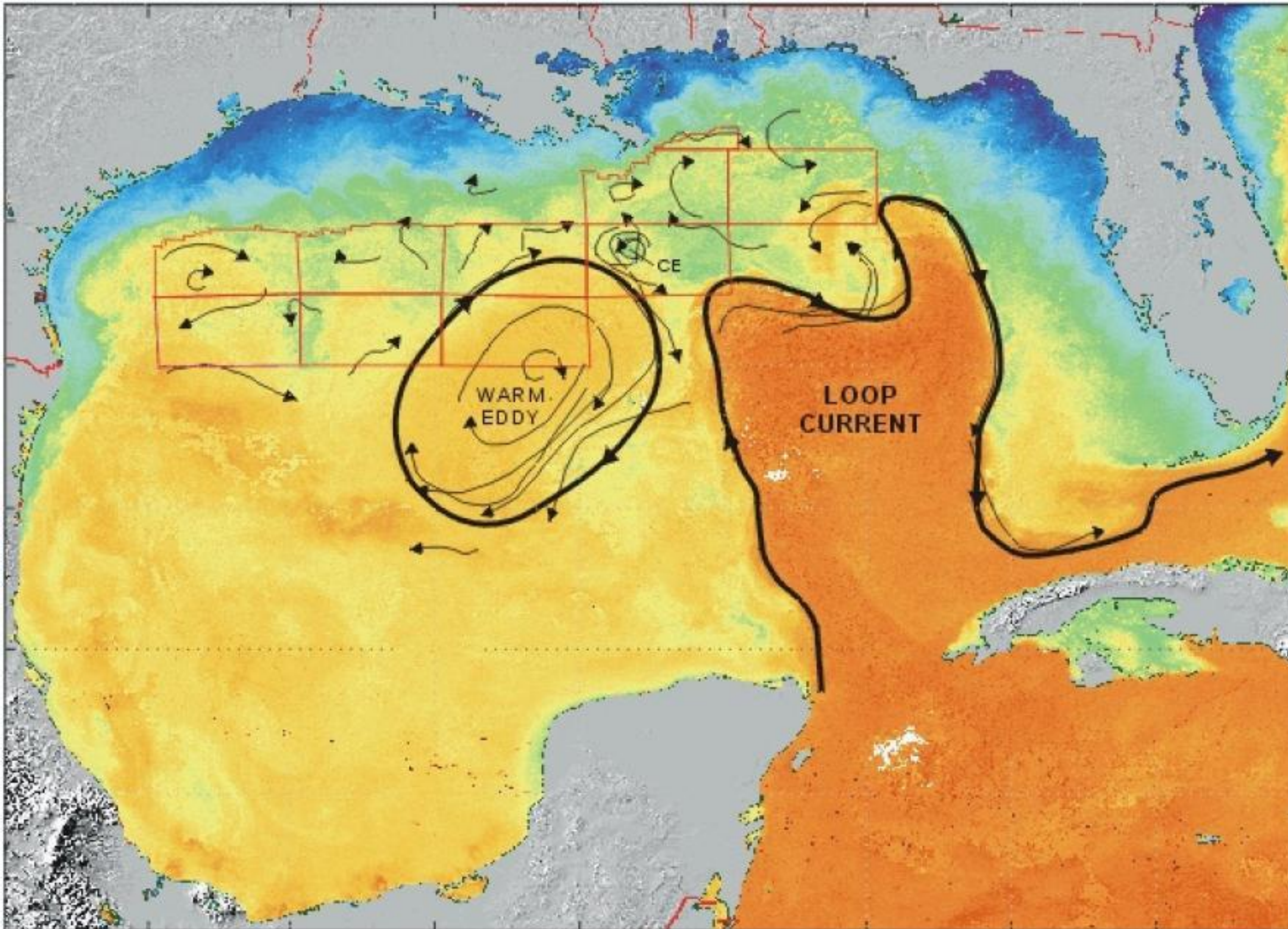
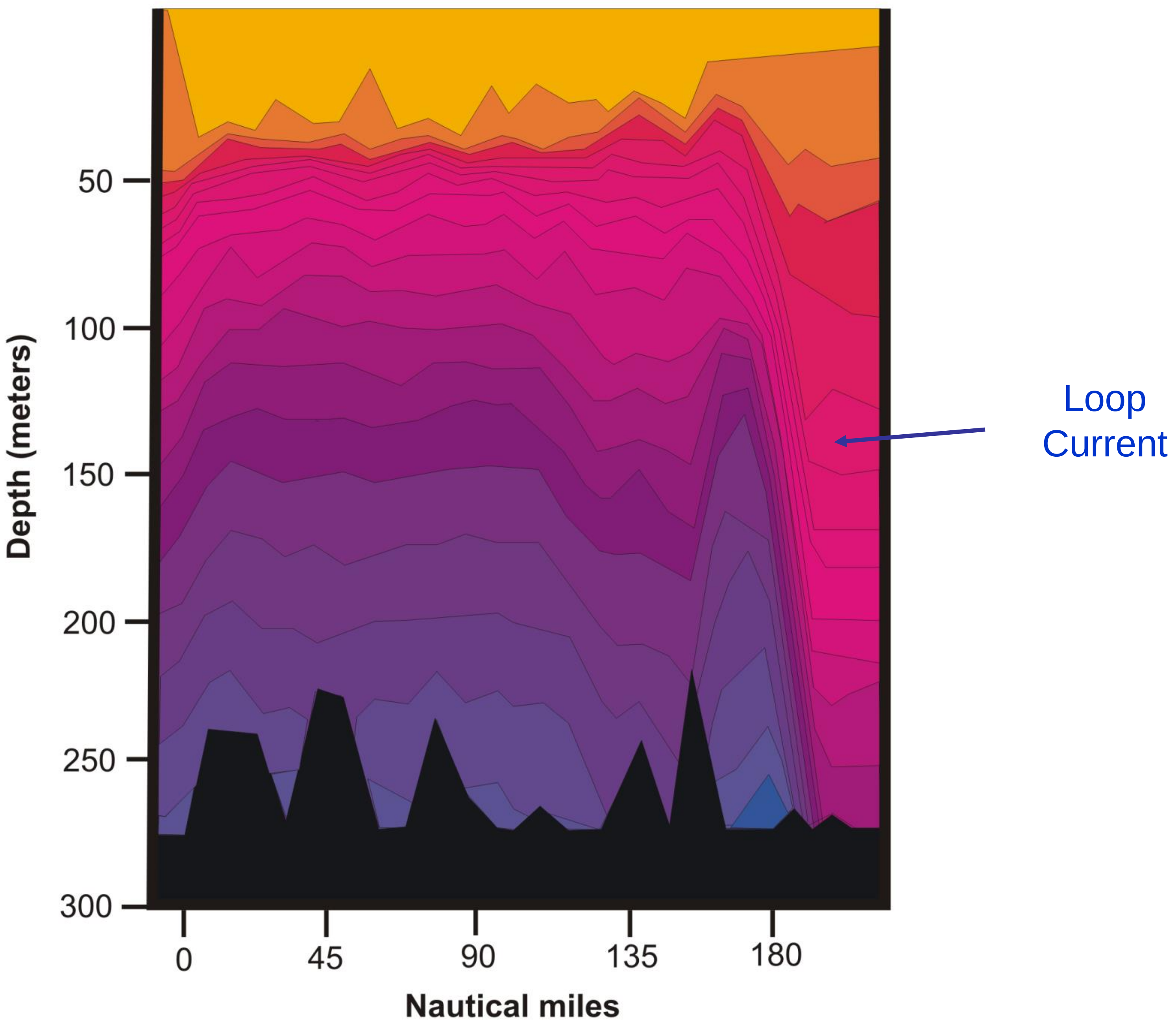
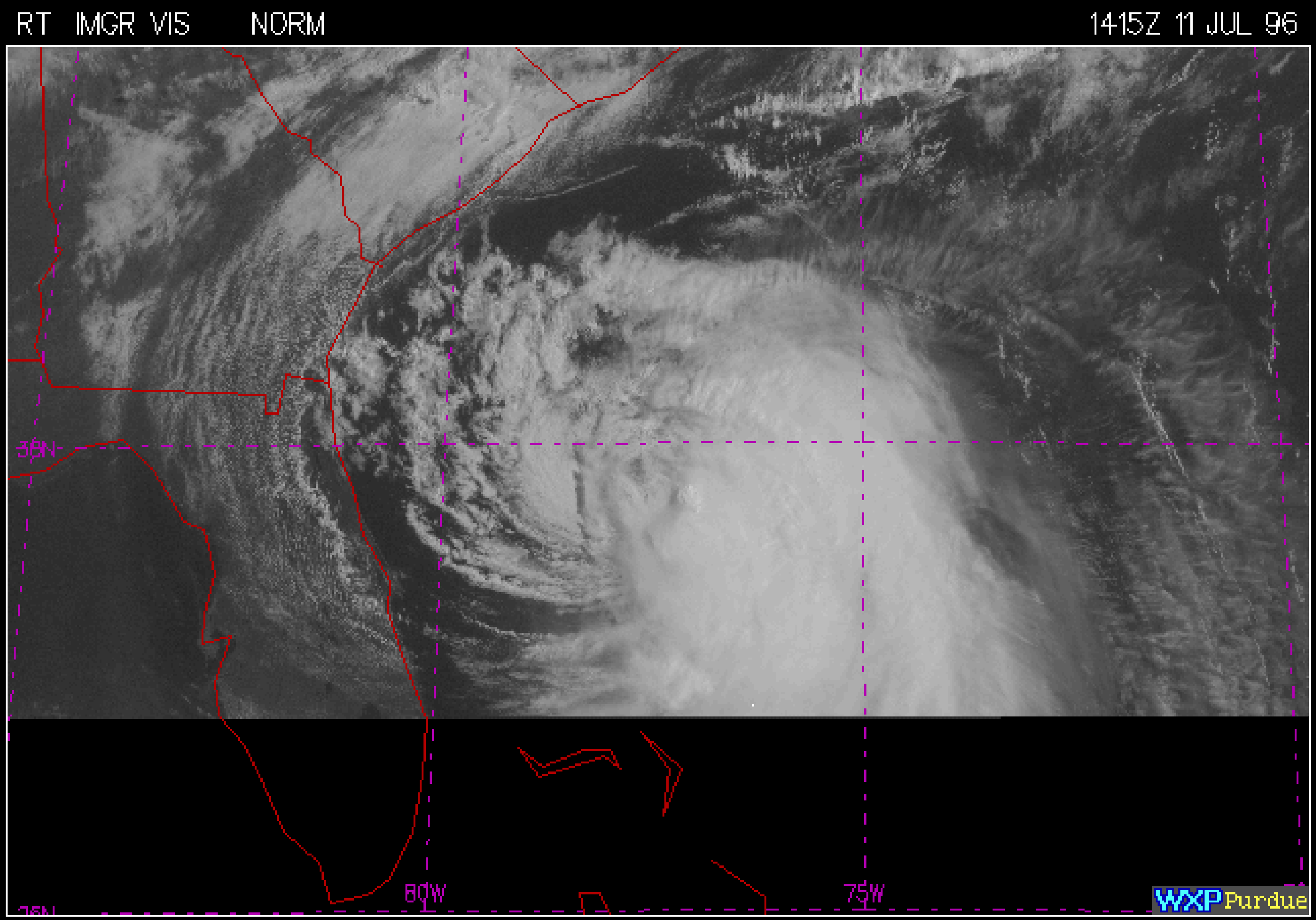
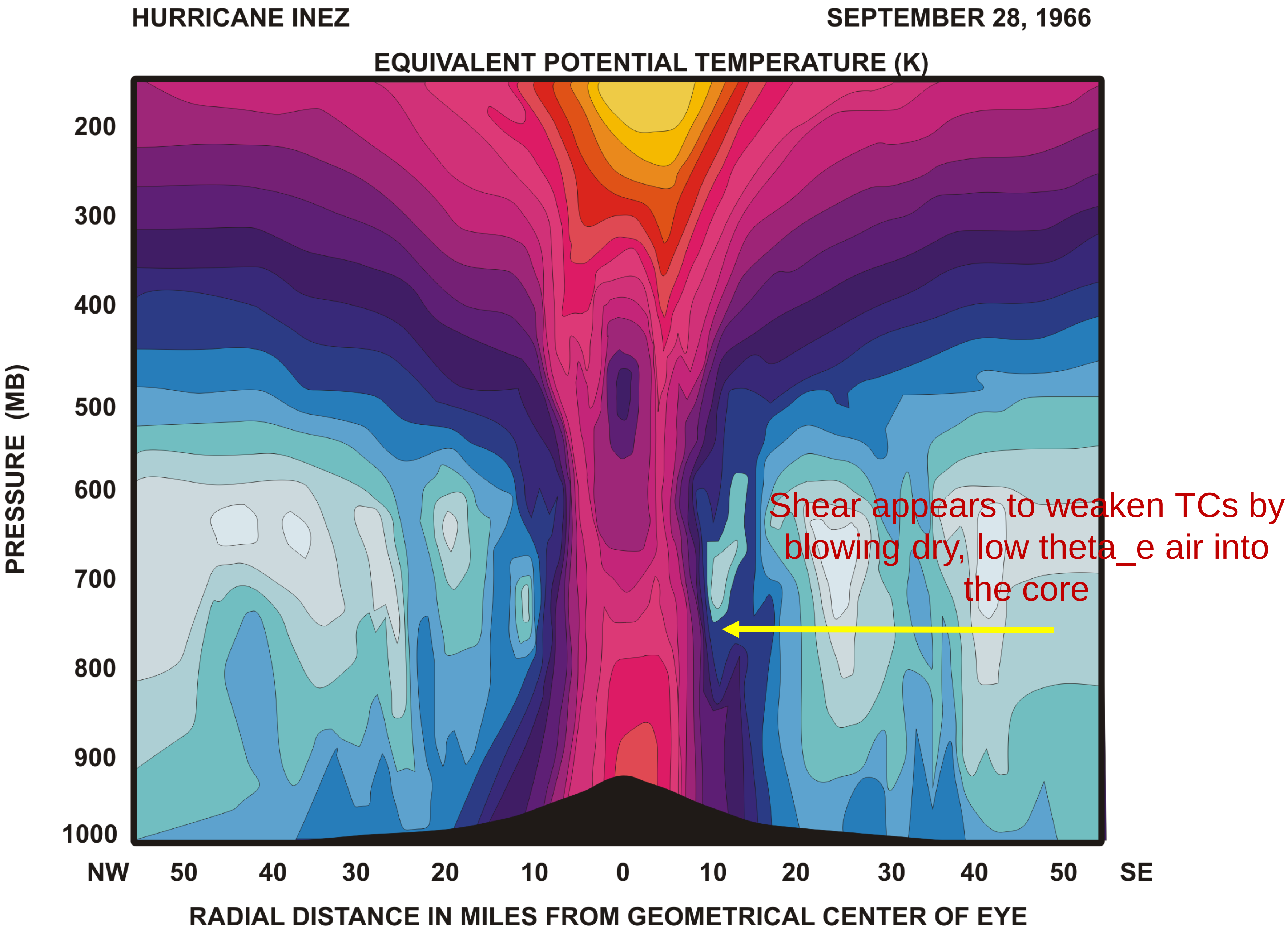


Figure 15. Loop and eddy currents in the Gulf of Mexico (image courtesy of Horizon Marine, Inc.).

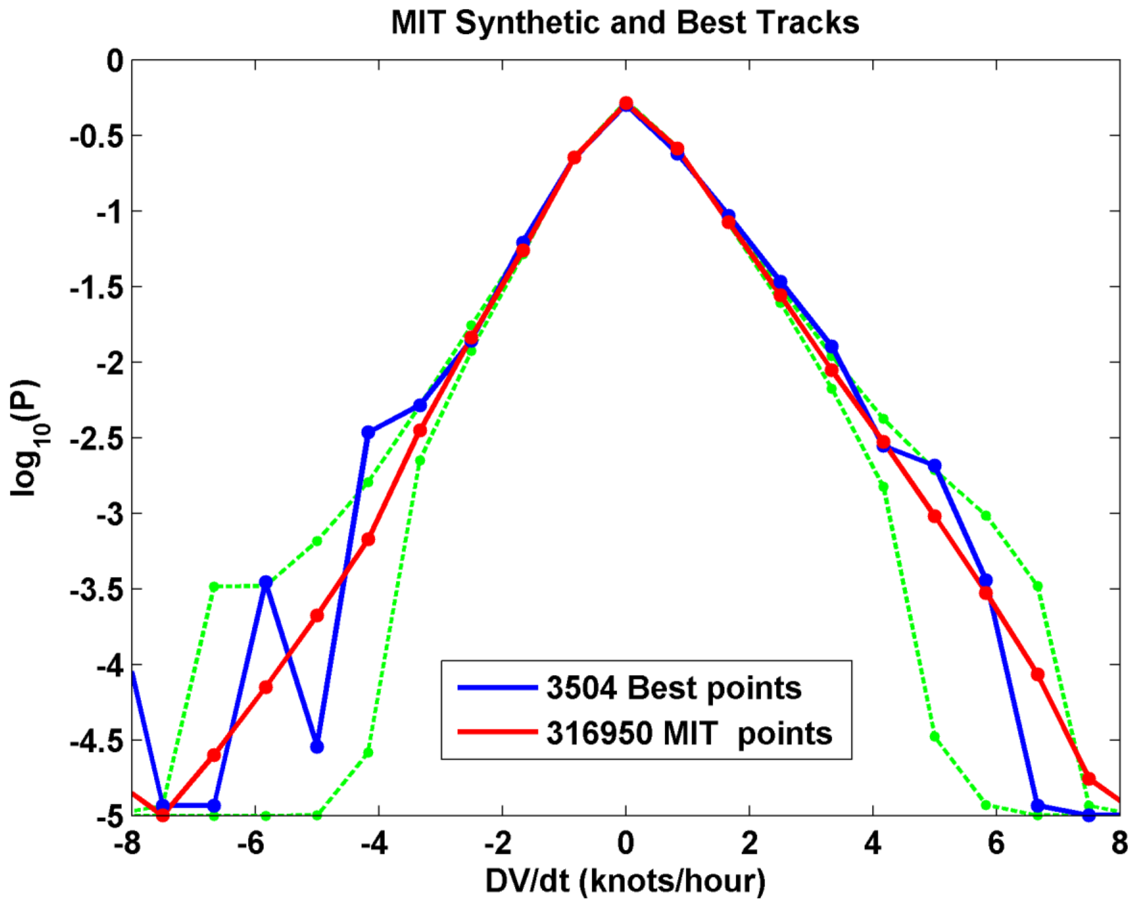

Depth (meters)
50
100
150
200
250
300
0
45
90
135
180
Nautical miles
Loop
Current

Wind Shear




HURRICANE INEZ
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
Shear appears to weaken TCs by blowing dry, low theta_e air into the core

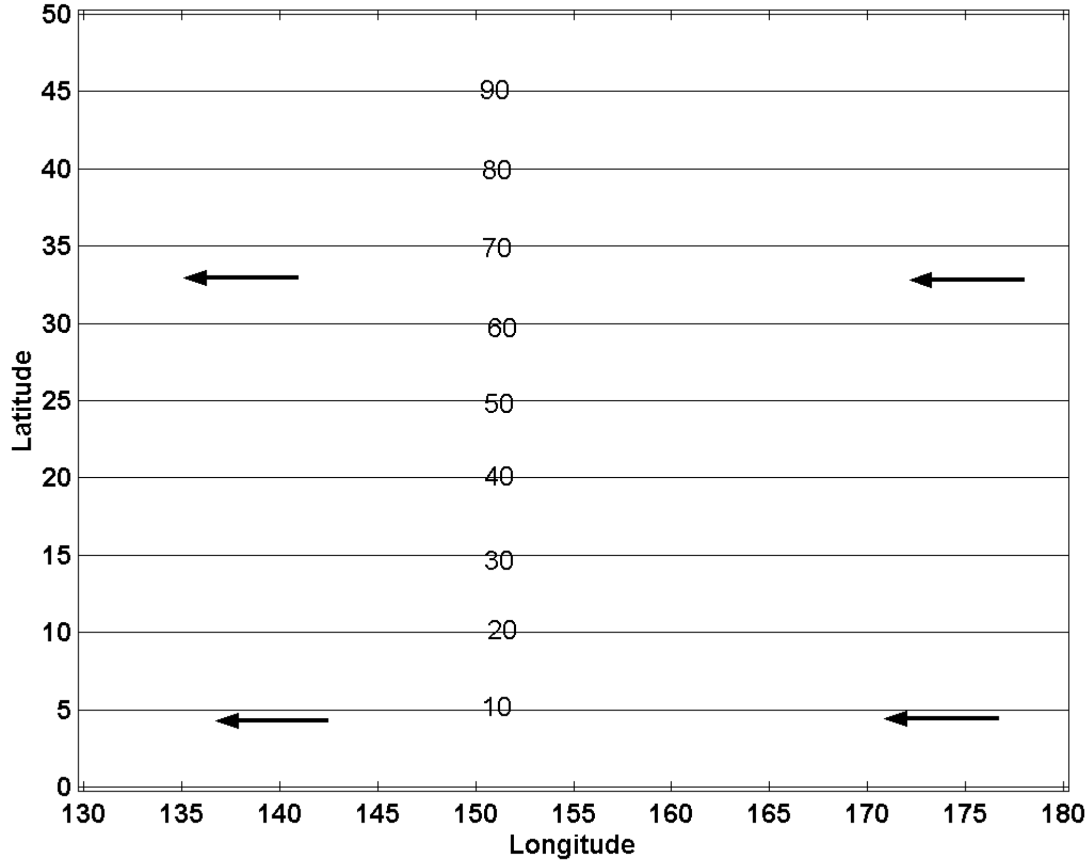
Statistics of Hurricane Intensification

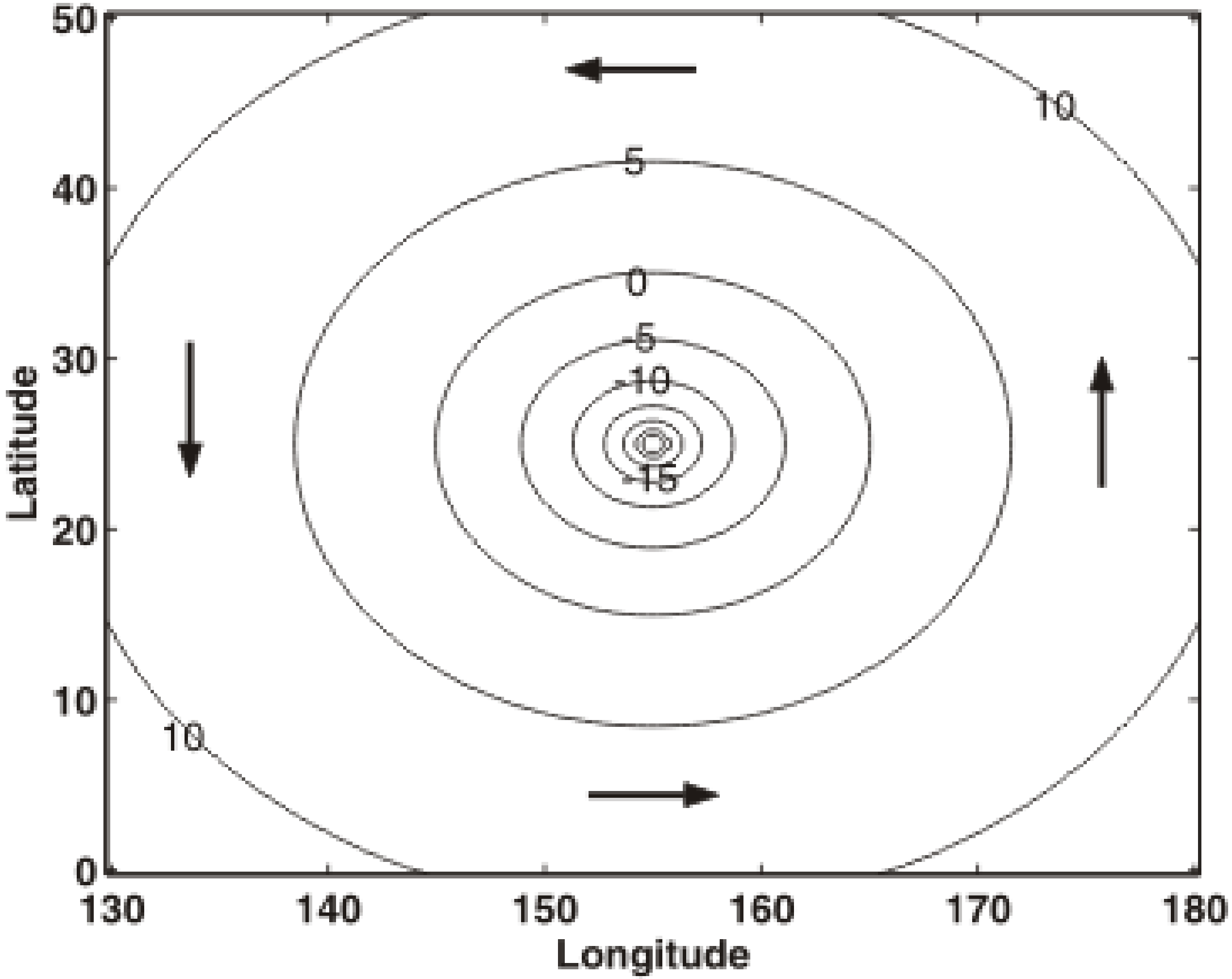


Common logarithms of the probability densities of open-ocean tropical cyclone intensity change rates in the North Atlantic region from 3504 observations (blue) and from 316 950 synthetic samples (red) of hurricane-intensity storms. Green lines or dots indicate the 5th and 95th percentiles of 1000 subsamples of the synthetic tracks data at the rate of the observed data for each intensity change bin. All distributions are bounded below by 1025. The synthetic data are subsampled every 6 h and rounded to 5 kt to match the best track data

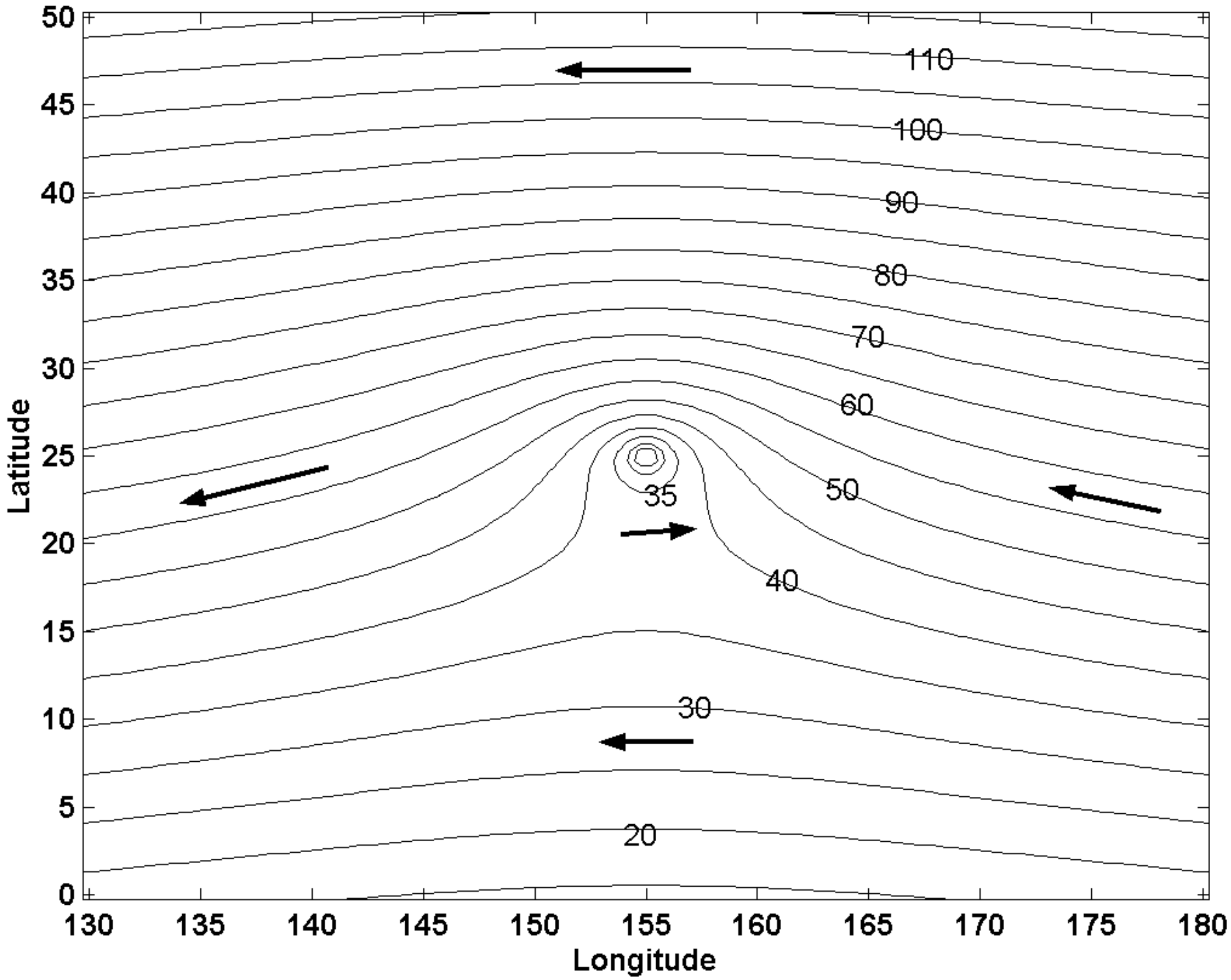
Tropical Cyclone Motion

Tropical cyclones move approximately with a suitably defined vertical vector average of the flow in which they are embedded

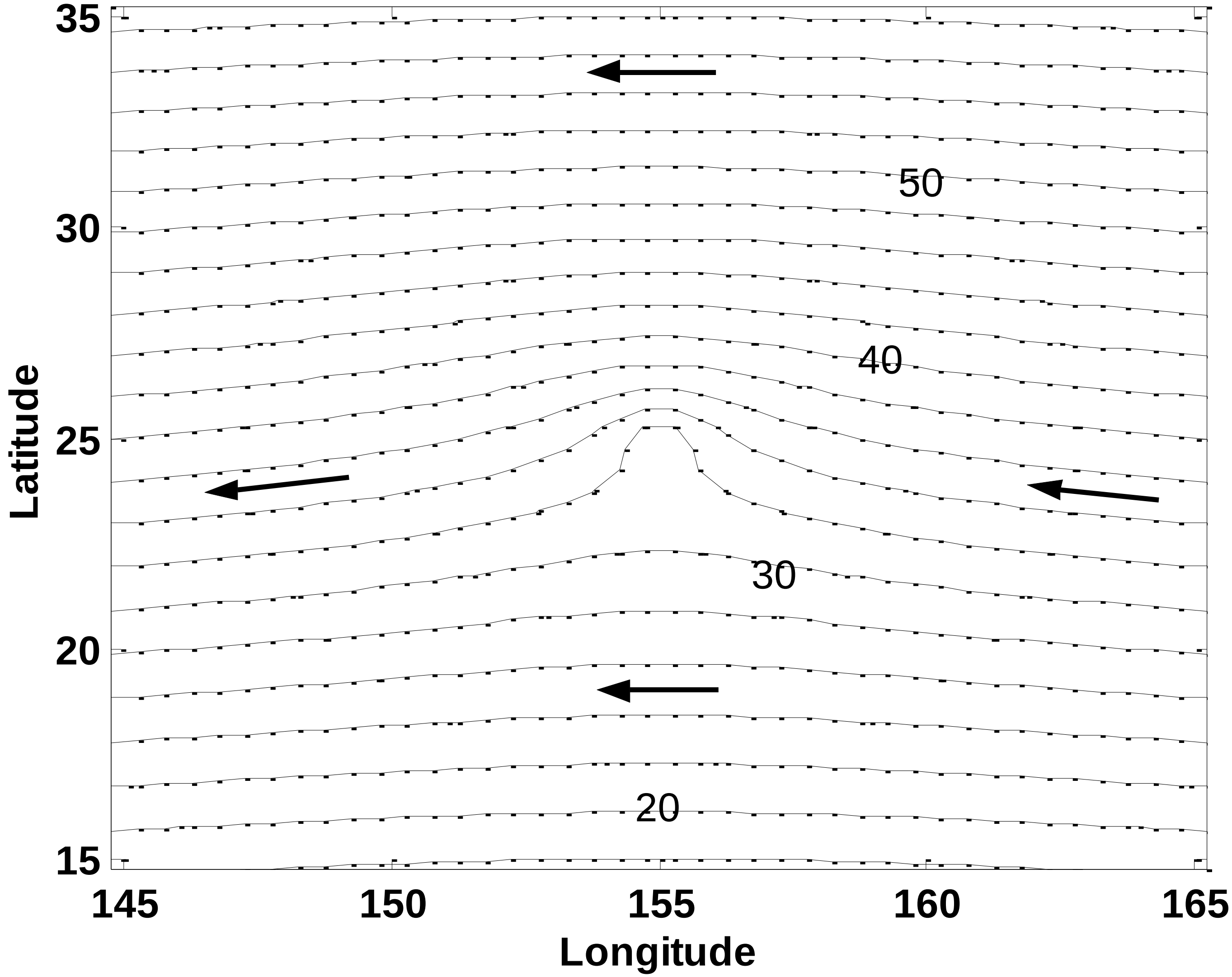




50
40
30
20
10
0
Latitude
130
140
150
160
170
180
Longitude
10
5
0
-5
-10
-15
10

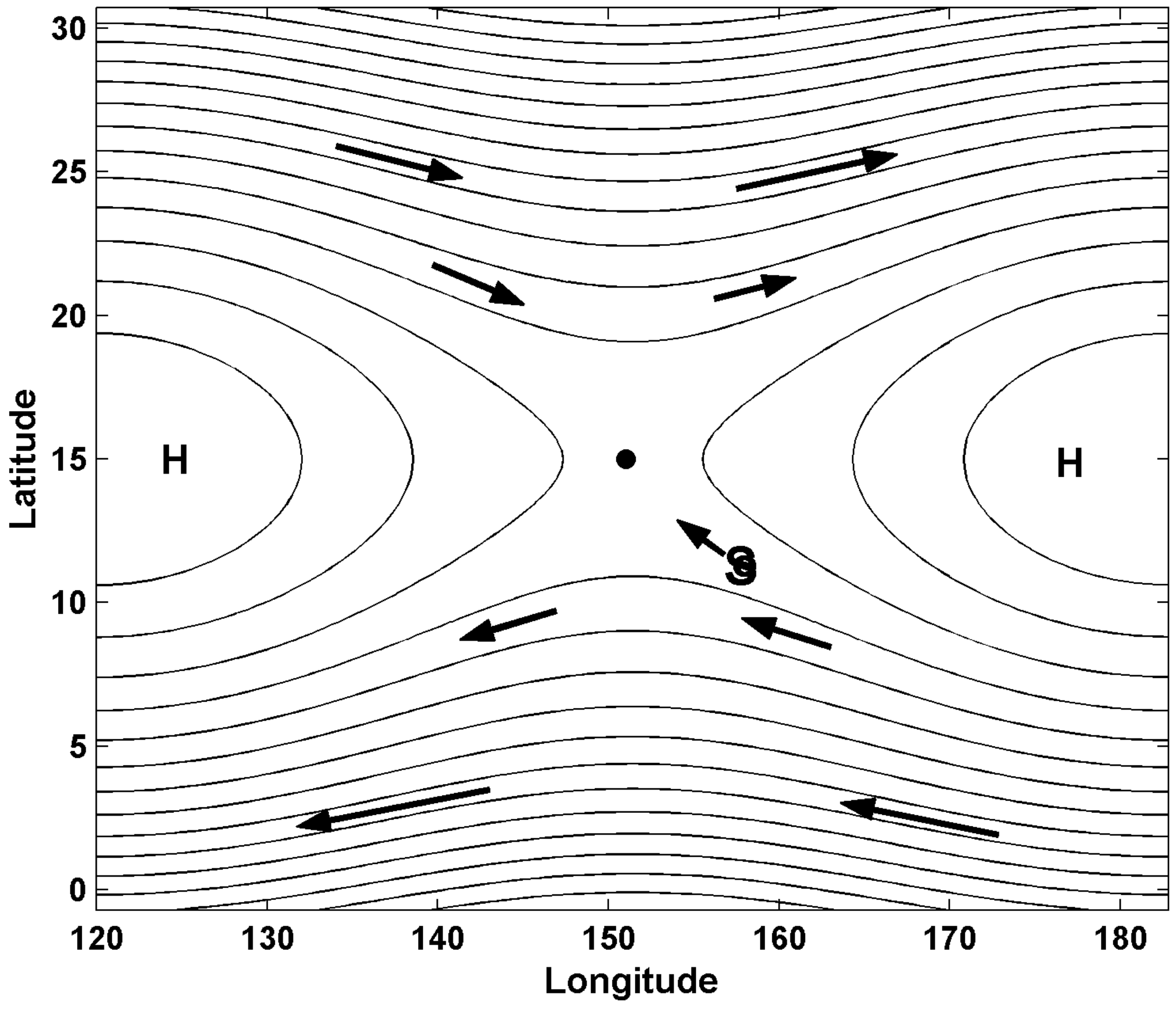


110
100
90
80
70
60
50
40
35
30
20
Latitude
Longitude
0
5
10
15
20
25
30
35
40
45
50
130
135
140
145
150
155
160
165
170
175
180

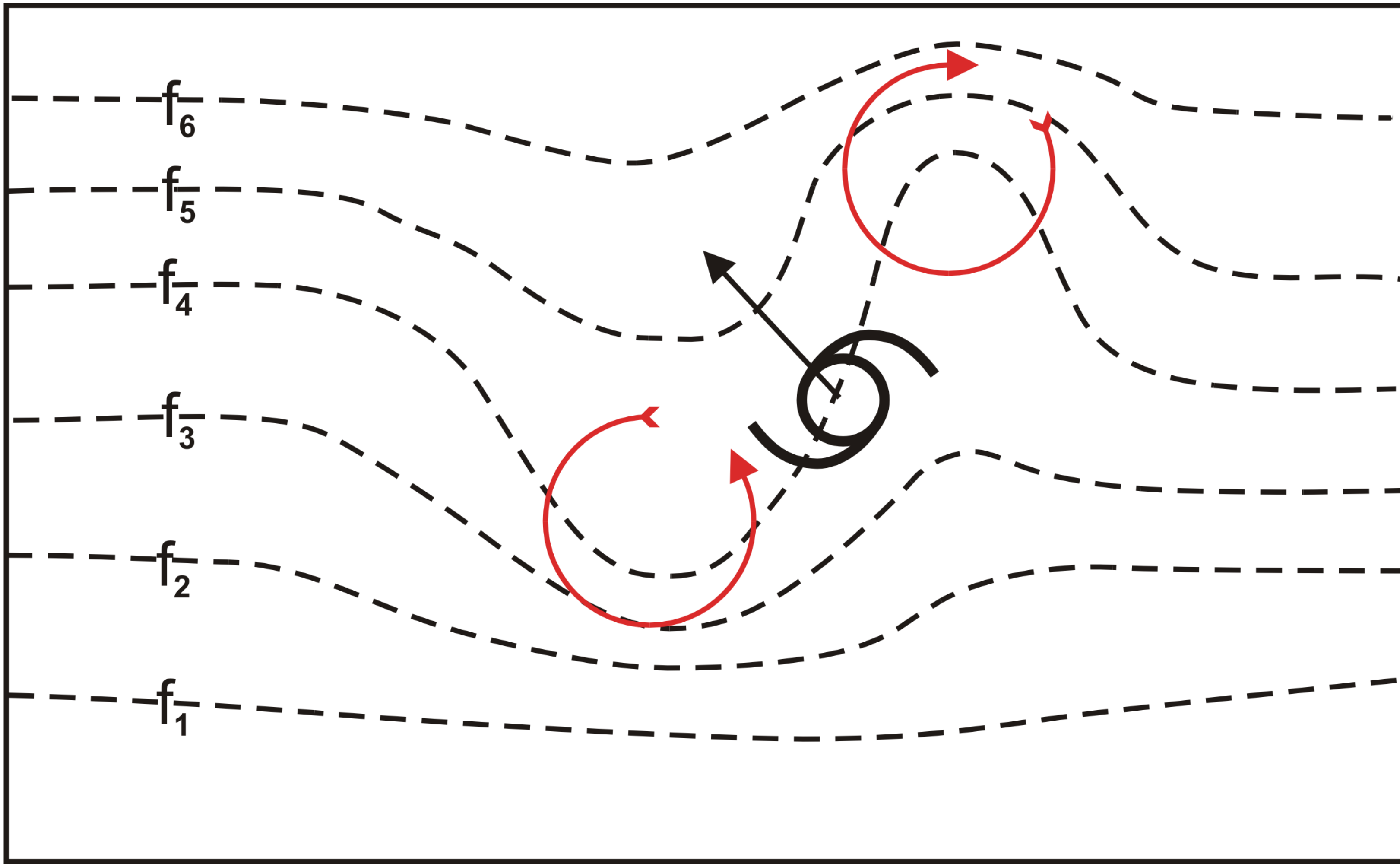


35
30
25
20
15
Latitude
145
150
155
160
165
Longitude
50
40
30
20

Lagrangian chaos:



Vortices in interacting with Earth's vorticity:

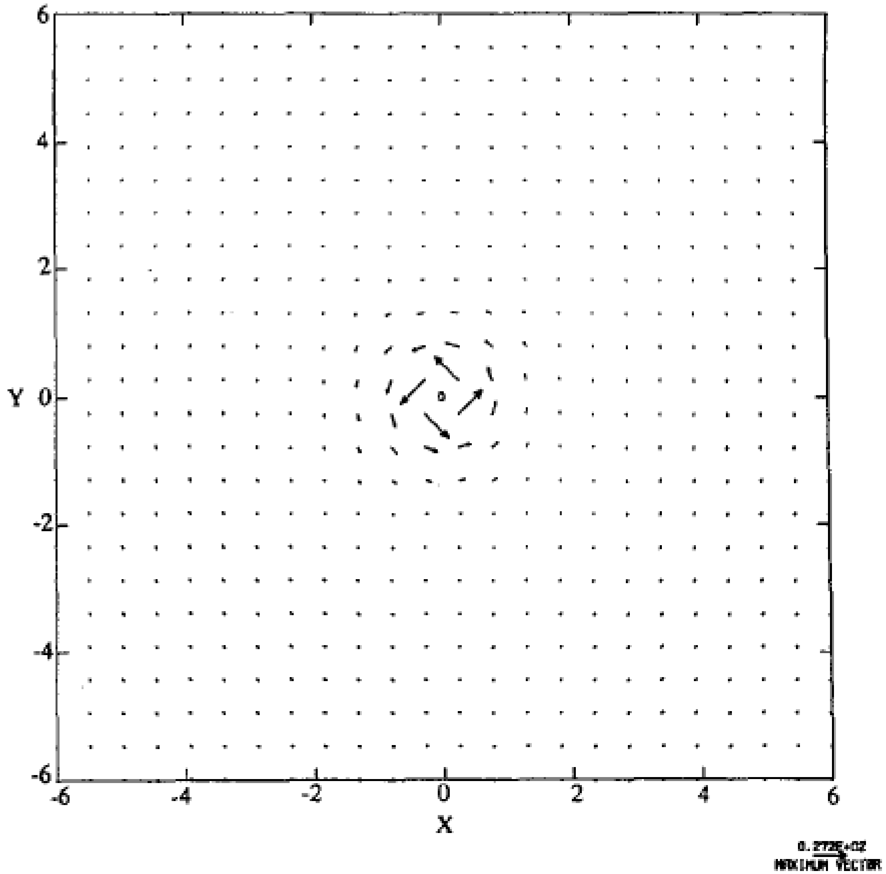


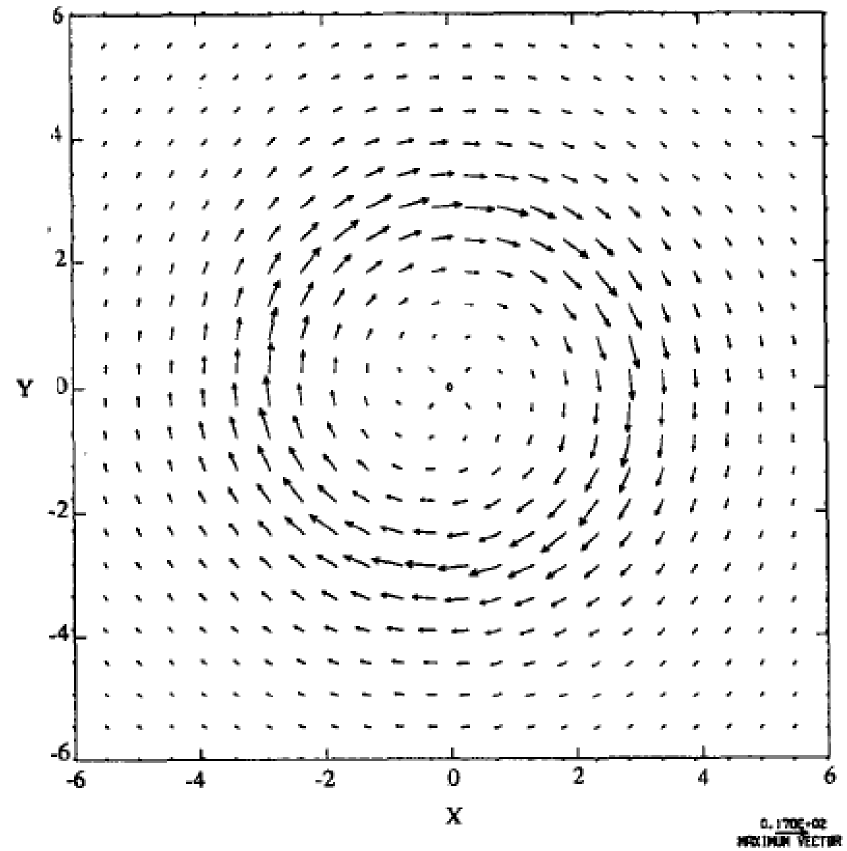
Baroclinic vortices in shear: A simple model

- Two layers, with upper layer moving with respect to lower layer
- Lower layer contains point vortex, whose circulation projects outward and upward
- Upper layer has point source of zero vorticity air co-located with lower point vortex; zero PV air separated from surroundings by a single, expanding contour

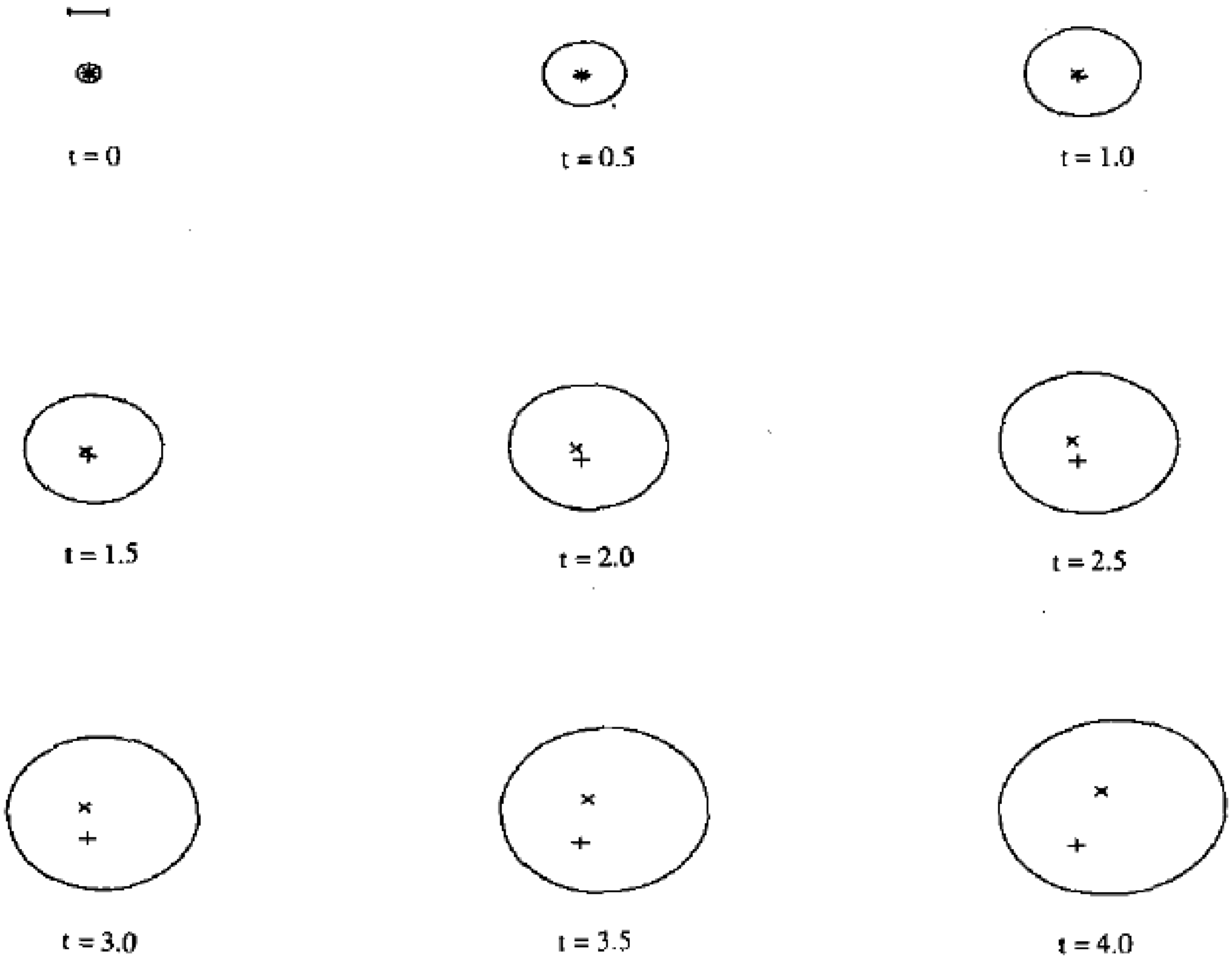
(From Wu and Emanuel, 1993)

Lower (left) and upper (right) flows for zero shear:





Evolution of upper layer vortex patch when weak shear is present



Evolution of upper layer vortex patch when moderate shear is present

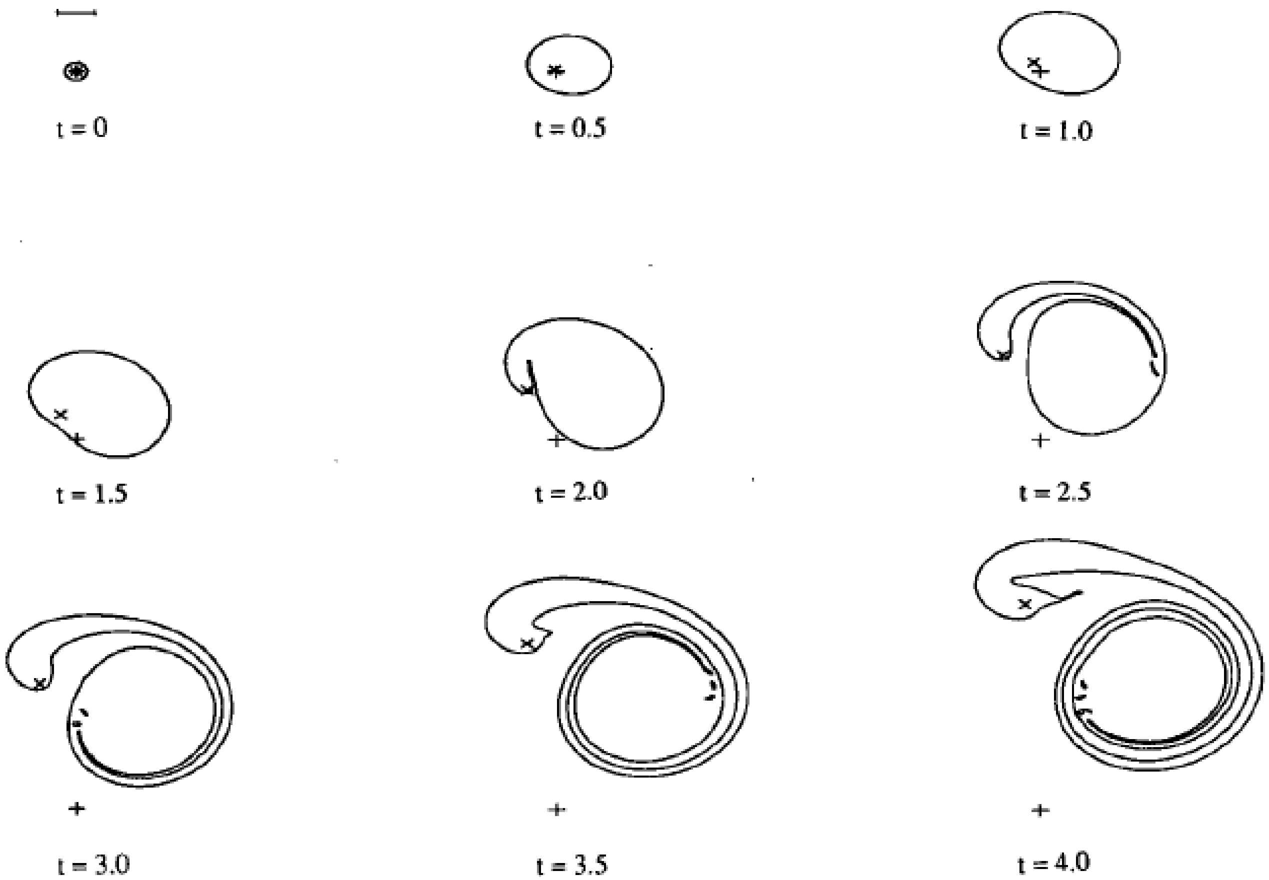
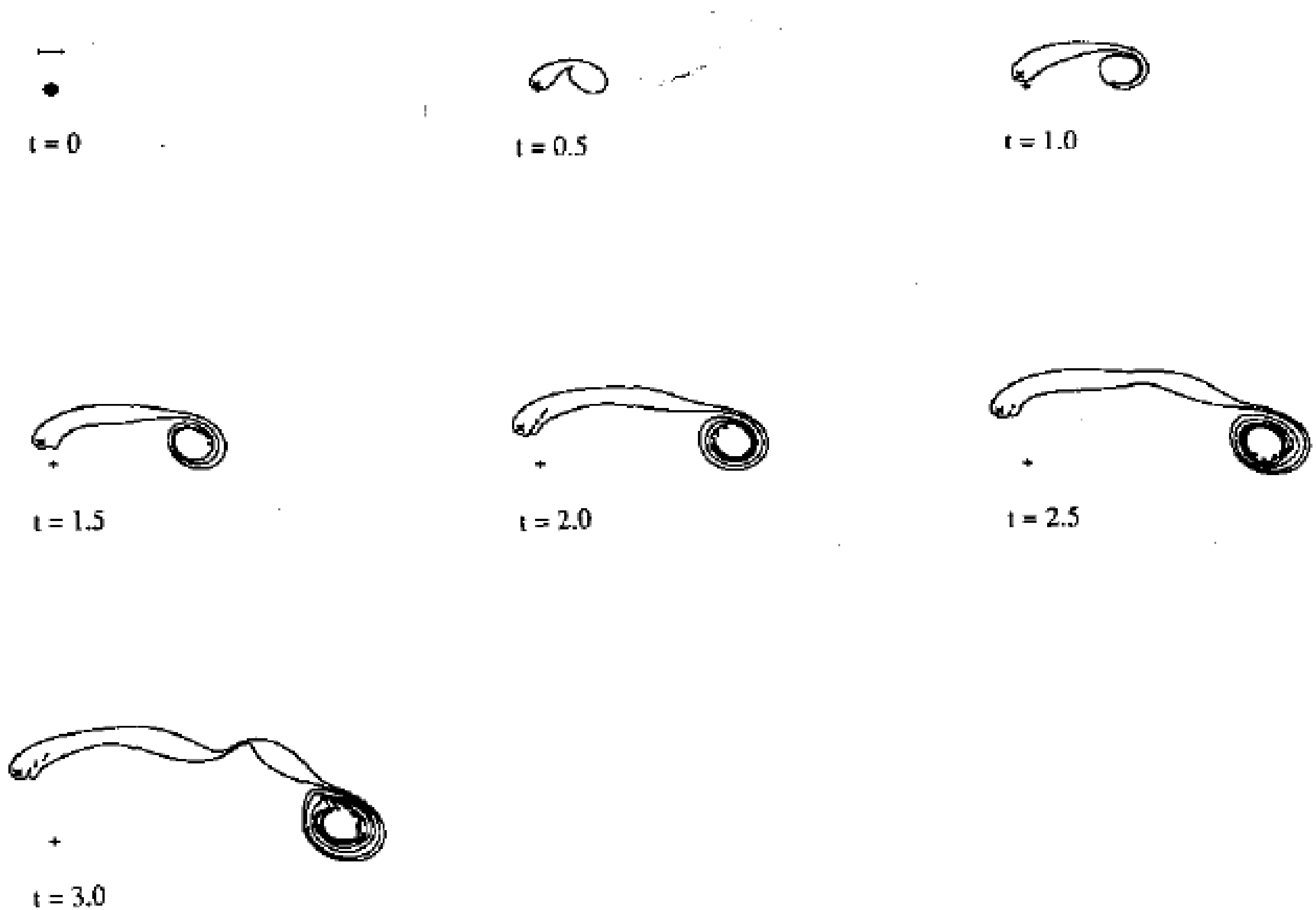


FIG. 5. The evolution of the upper-layer vortex patch for $\epsilon = 0.25$, $\gamma = 0.79$, and $\chi = 1.25$. The lower-layer point vortex is shown as "×." The initial position of the point vortex is indicated as "+." The time interval between each plot is 0.5. The unit length scale (500 km) is shown in the upper left corner.

Evolution of upper layer vortex patch when strong shear is present



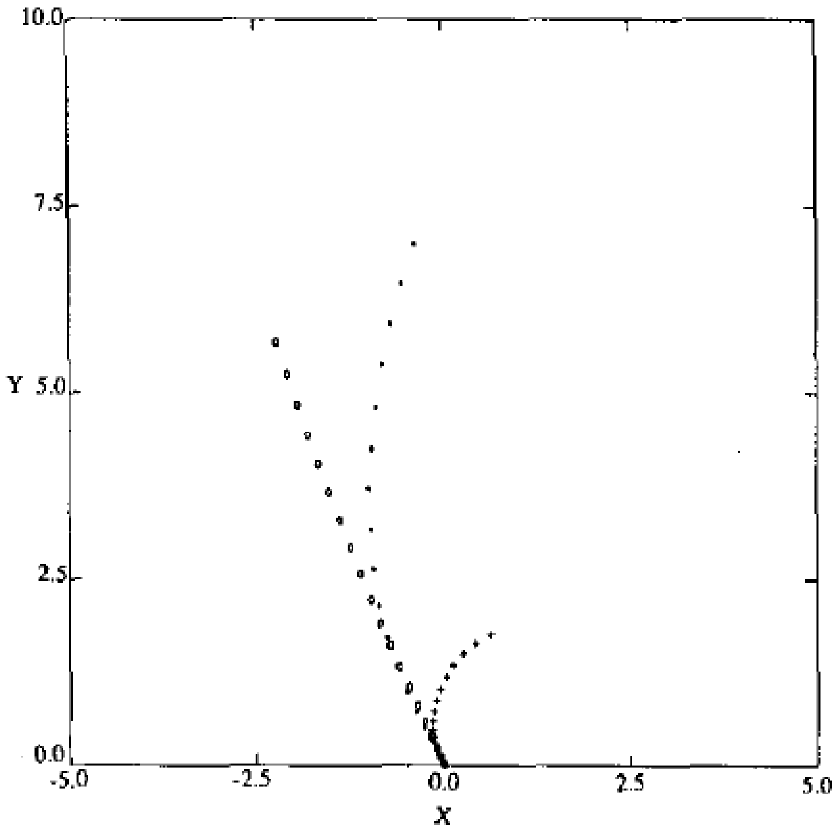


FIG. 11. Trajectories (units of 500 km) of the lower-layer vortex for $\epsilon = 0.25$, $\gamma = 0.79$, and $\chi = 0.25$ (shown as "+"); $\chi = 1.25$ (shown as "$*$"); and $\chi = 5$ (shown as "O").

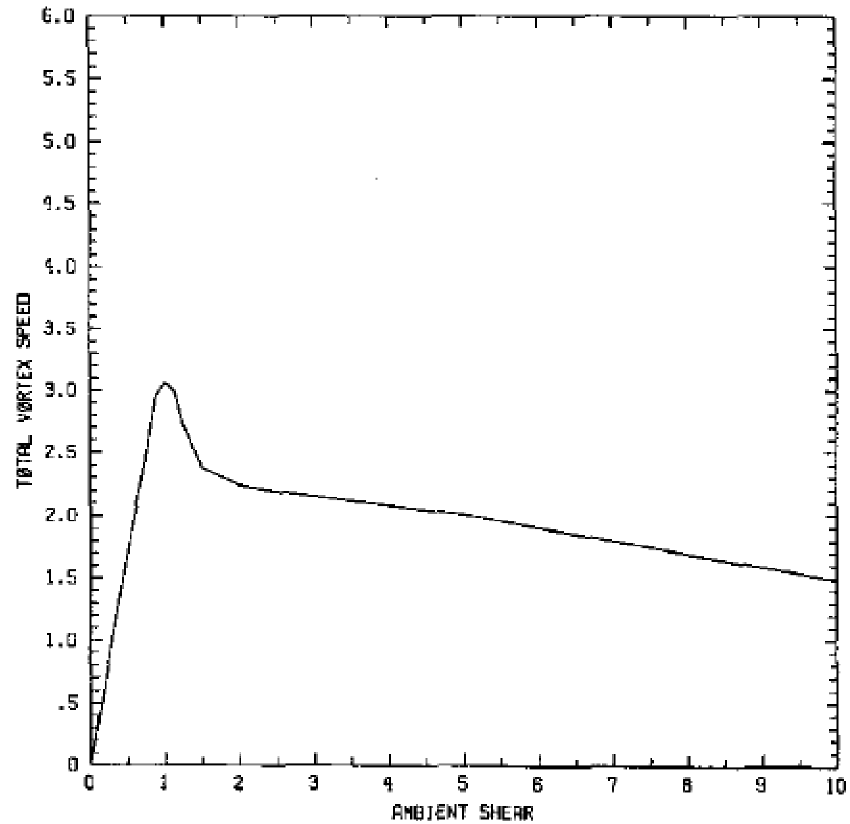
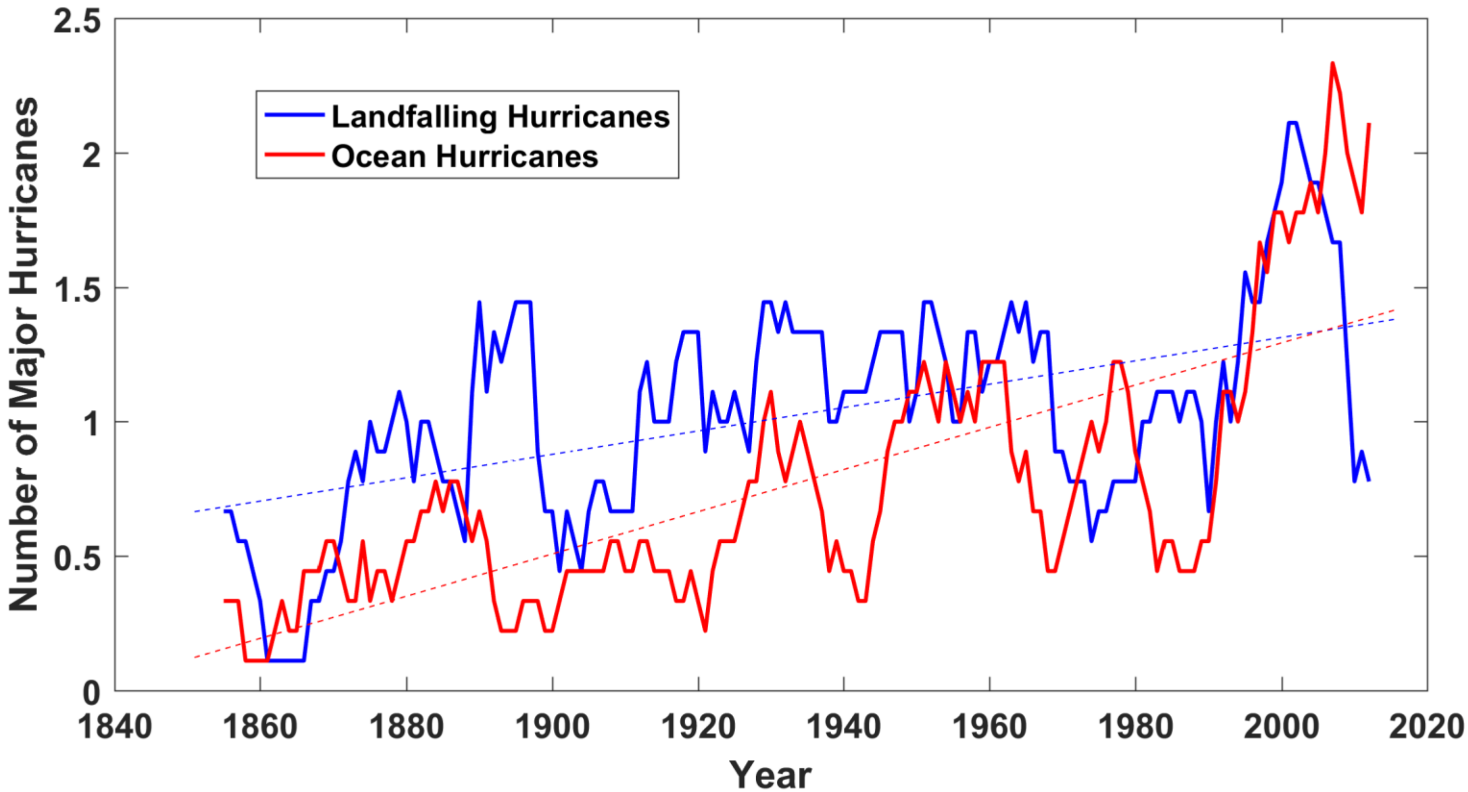


FIG. 12. The relation between the maximum induced vortex speed and the magnitude of the vertical shears (χ) for $\epsilon = 0.25$ and $\gamma = 0.79$.

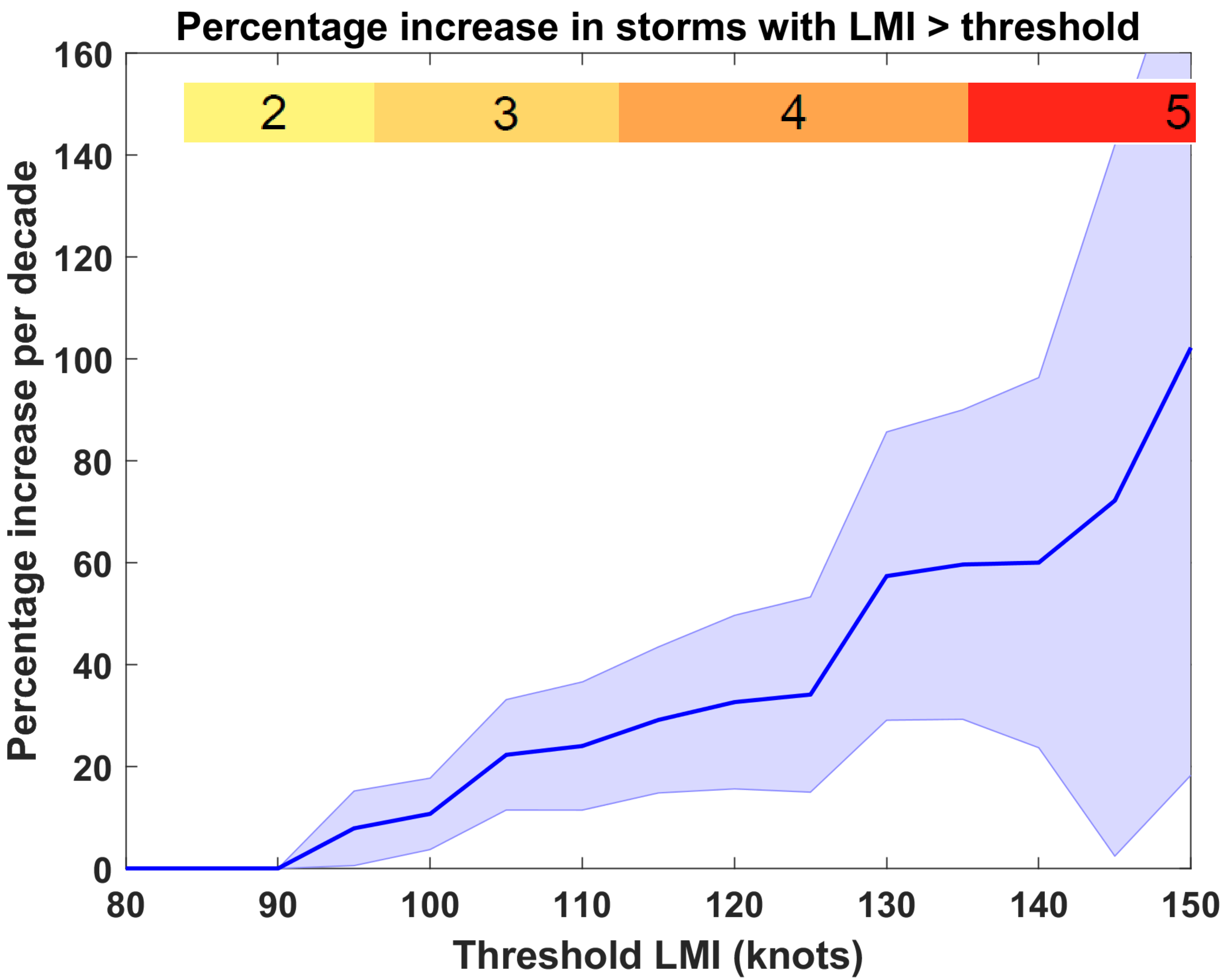
Hurricanes and Climate

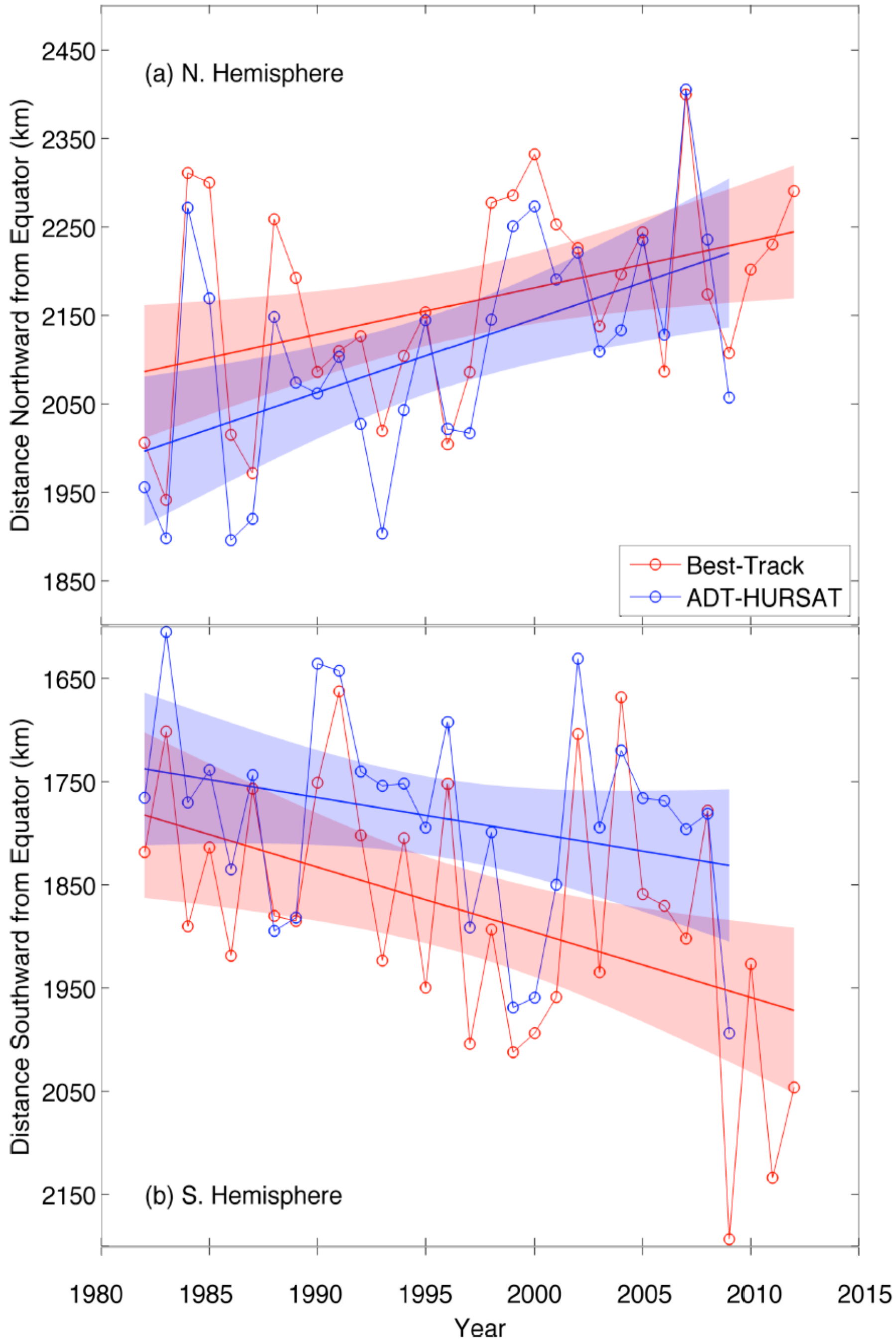
Prior to 1970, Many Storms Were Missed



Major hurricanes in the North Atlantic, 1851-2016, smoothed using a 10-year running average. Shown in blue are storms that either passed through the chain of Lesser Antilles or made landfall in the continental U.S.; all other major hurricanes are shown in red. The dashed lines show the best fit trend lines for each data set.

Trends in Global TC Frequency Over Threshold Intensities, from Historical TC Data, 1980-2016. Trends Shown Only When $p < 0.05$.



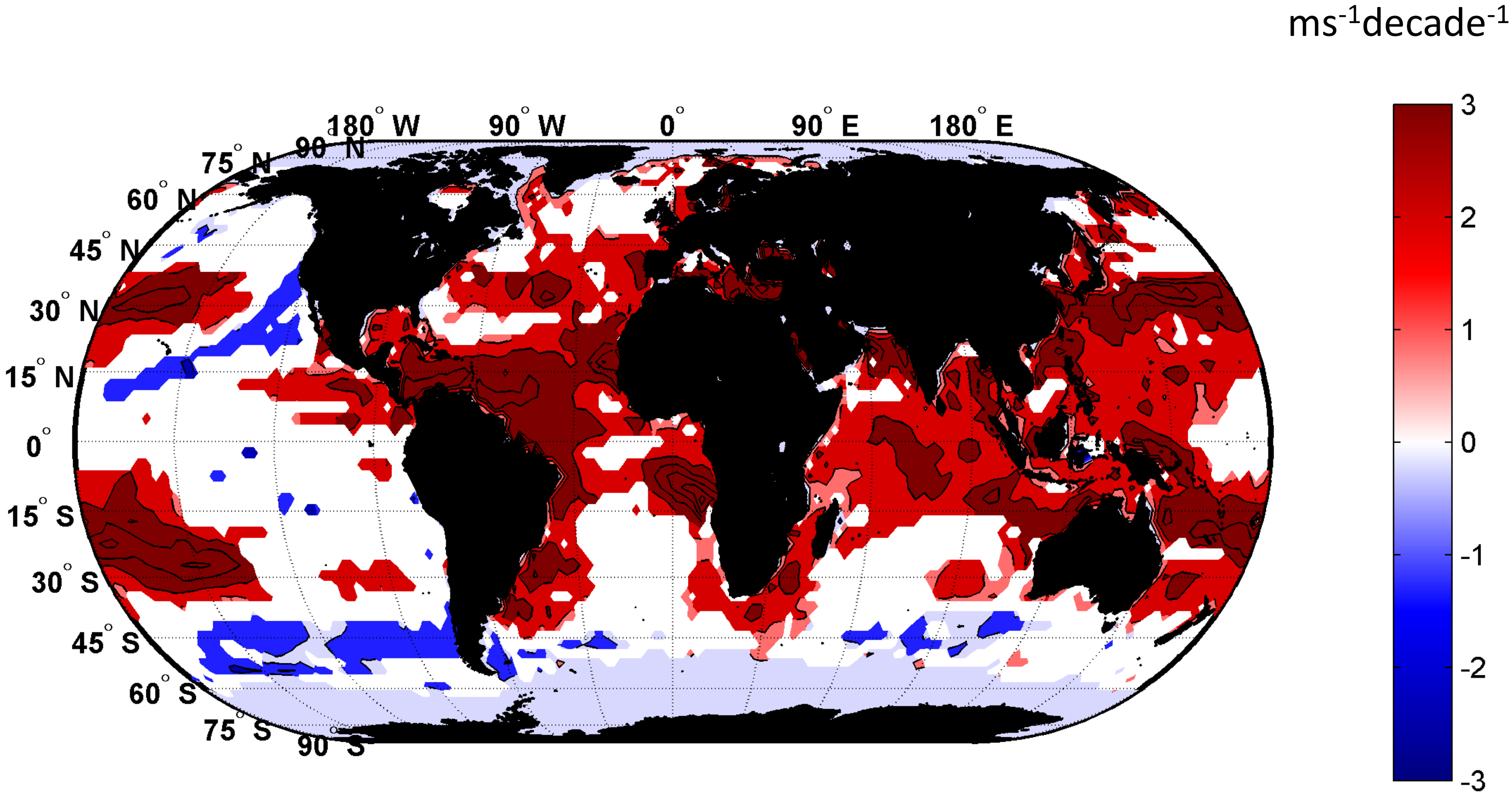


Hurricanes are reaching peak intensity at higher latitudes

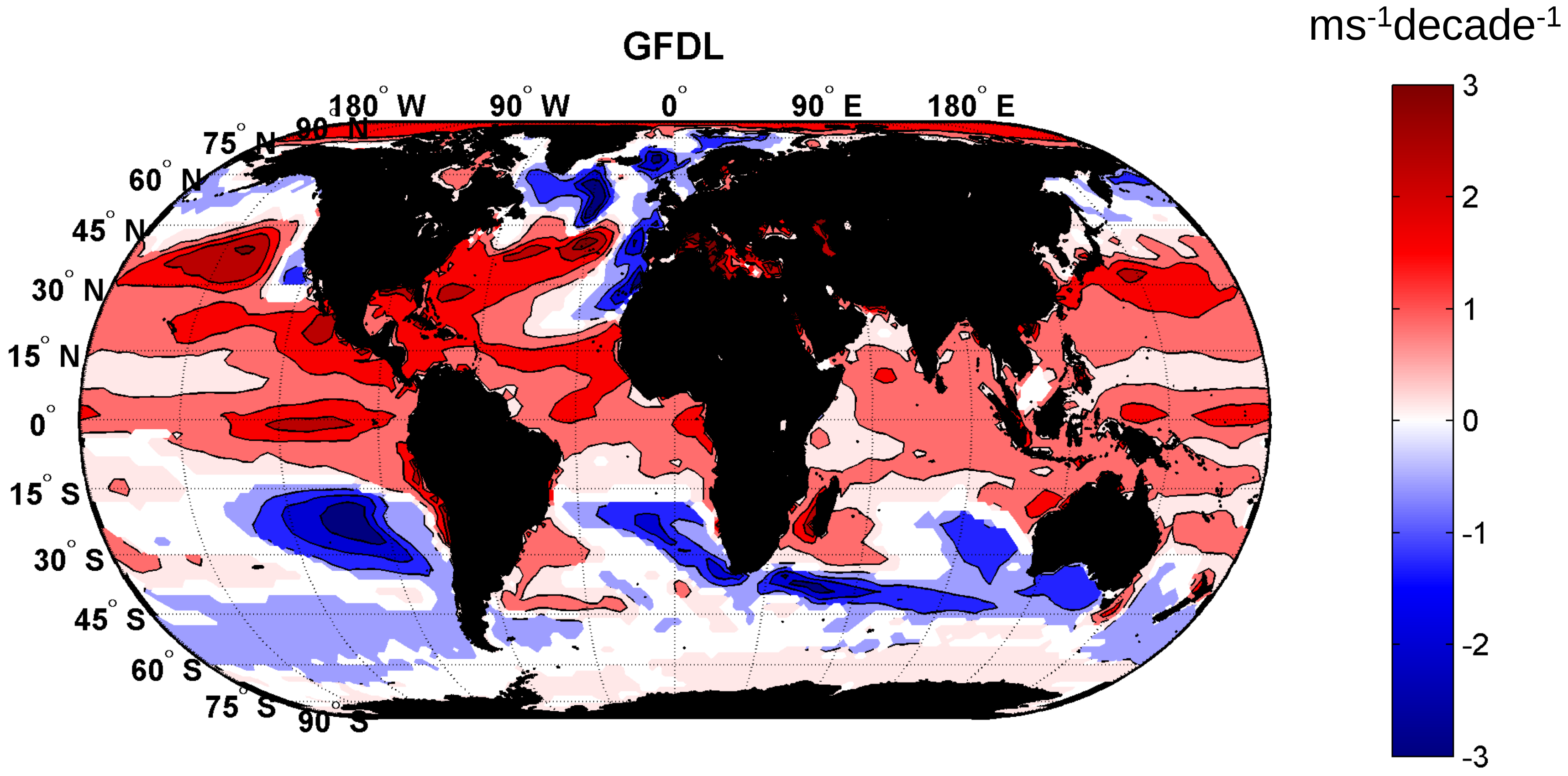
Time series of the latitudes at which tropical cyclones reach maximum intensity.

From *Kossin et al. (2014)*

Trends in Thermodynamic Potential for Hurricanes, 1980-2010
(NCAR/NCEP Reanalysis)



Projected Trend Over 21st Century: GFDL model under RCP 8.5



Inferences from Basic Theory:

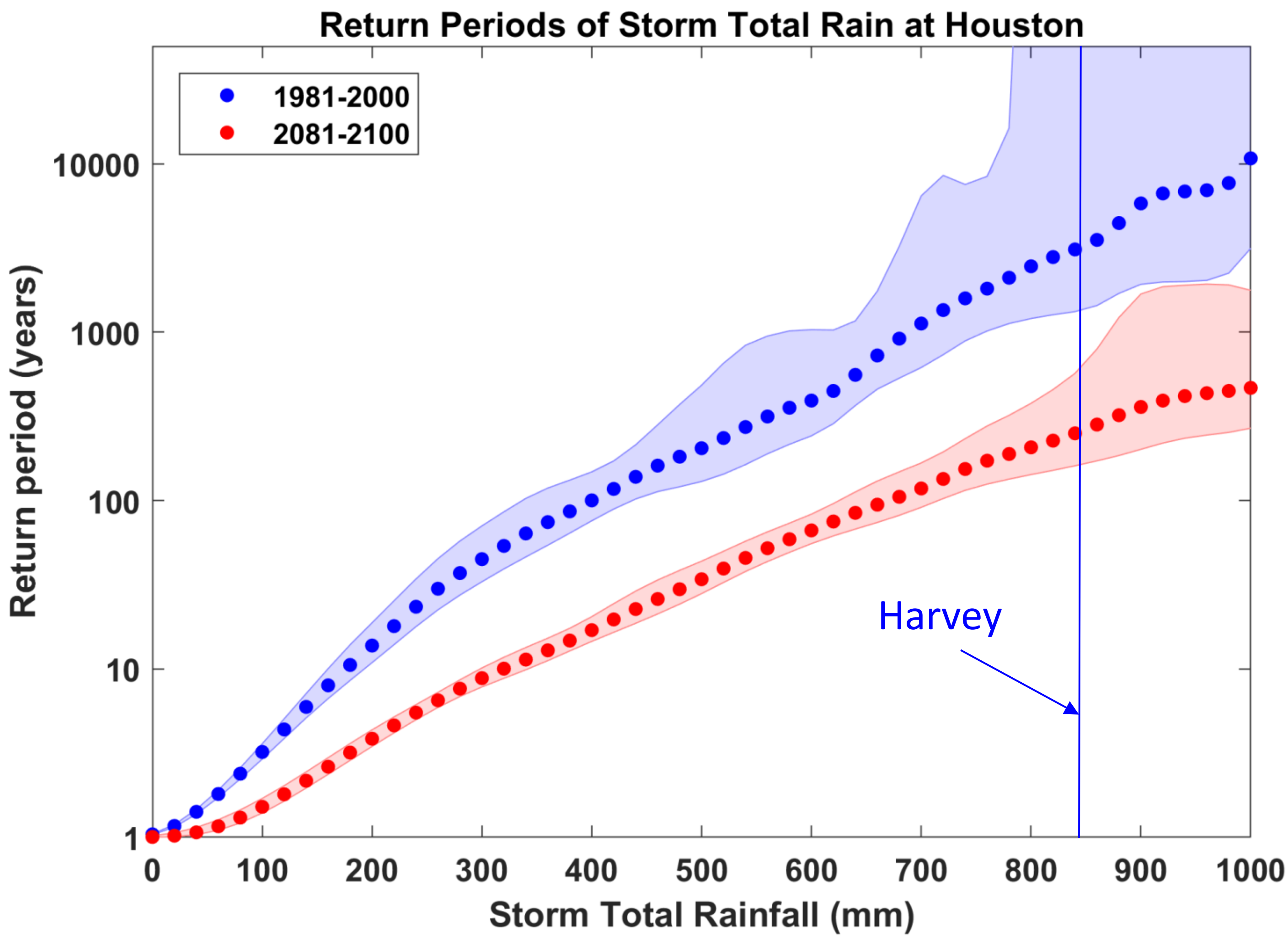
- Potential intensity increases with global warming
- Incidence of high-intensity hurricanes should increase
- Increases in potential intensity should be faster in sub-tropics
- Hurricanes will produce substantially more rain: Clausius-Clapeyron yields ~7% increase in water vapor per 1^{o}C warming

2017 Hurricane Records

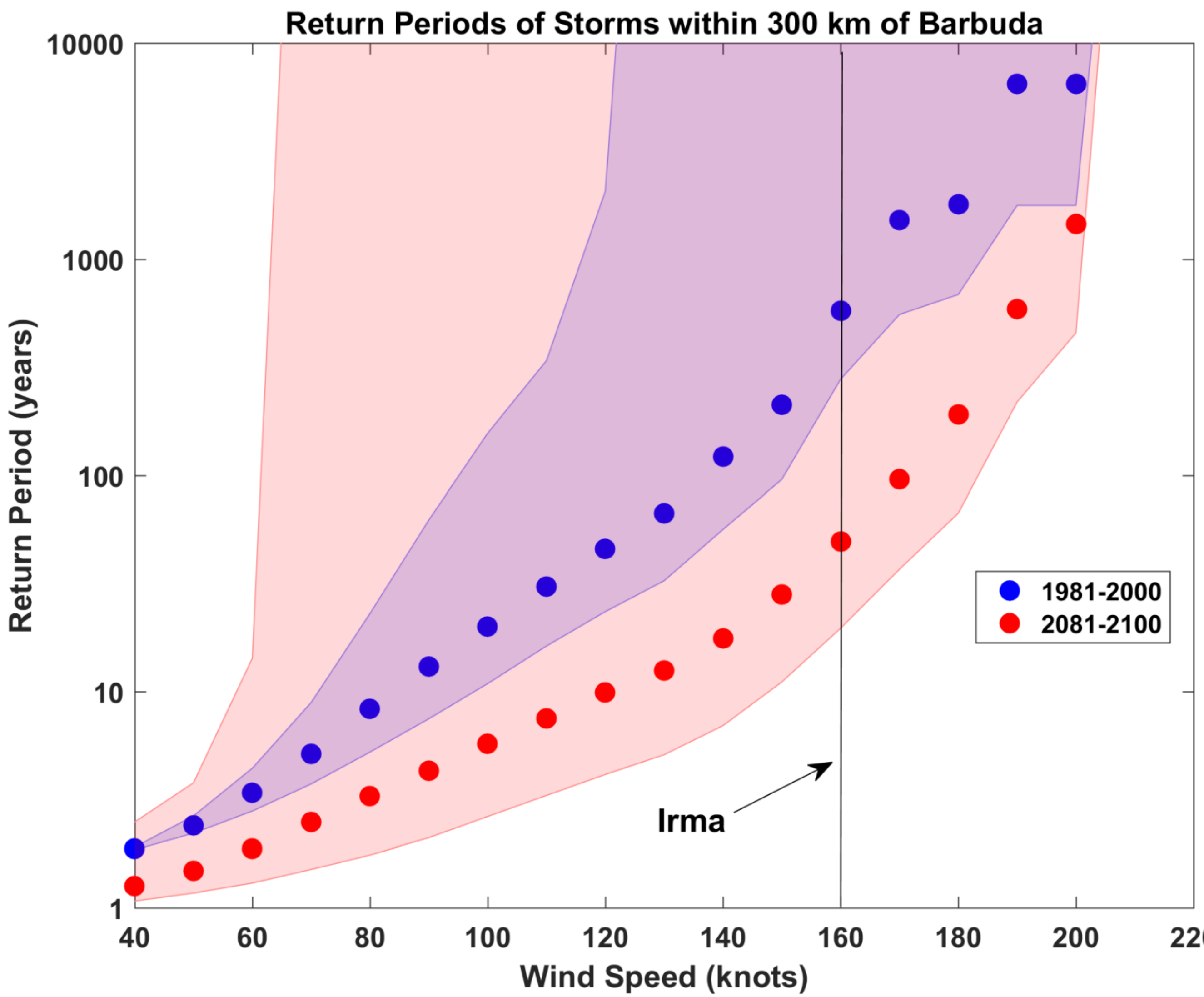
- Harvey’s storm total rainfall was largest ever recorded from a hurricane in the U.S.
- Hurricane Irma sustained Category 5 winds for longer than ever recorded in any tropical cyclone on the planet
- Hurricane Irma was the first recorded Atlantic hurricane to reach Cat 4 status outside the Caribbean and the second strongest hurricane ever recorded in the Atlantic
- The 2017 hurricanes caused more than $300 billion in damages, the largest of any hurricane season on record

Dominica in the wake of Hurricane Maria

Probability of Storm Accumulated Rainfall at Houston, from 6 Climate models, 1981-2000 and 2081-2100, Based on 2000 Events Each. Shading shows spread among the models.



Probabilities of Storms of Irma's Intensity within 300 km of Barbuda, from 6 Climate models, 1981-2000 and 2081-2100, Based on 2000 Events Each. Shading shows spread among the models.



Summary

- Hurricanes appear to result from the instability of the radiative-convective equilibrium of the tropical atmosphere

- 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 move with some vertical average of the environmental flow plus effects due to the earth’s rotation and curvature, and to wind shear

- **Hurricanes are expected to become more intense and rain more as the climate warms**