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 of hurricane science increases public interest and trust

Program

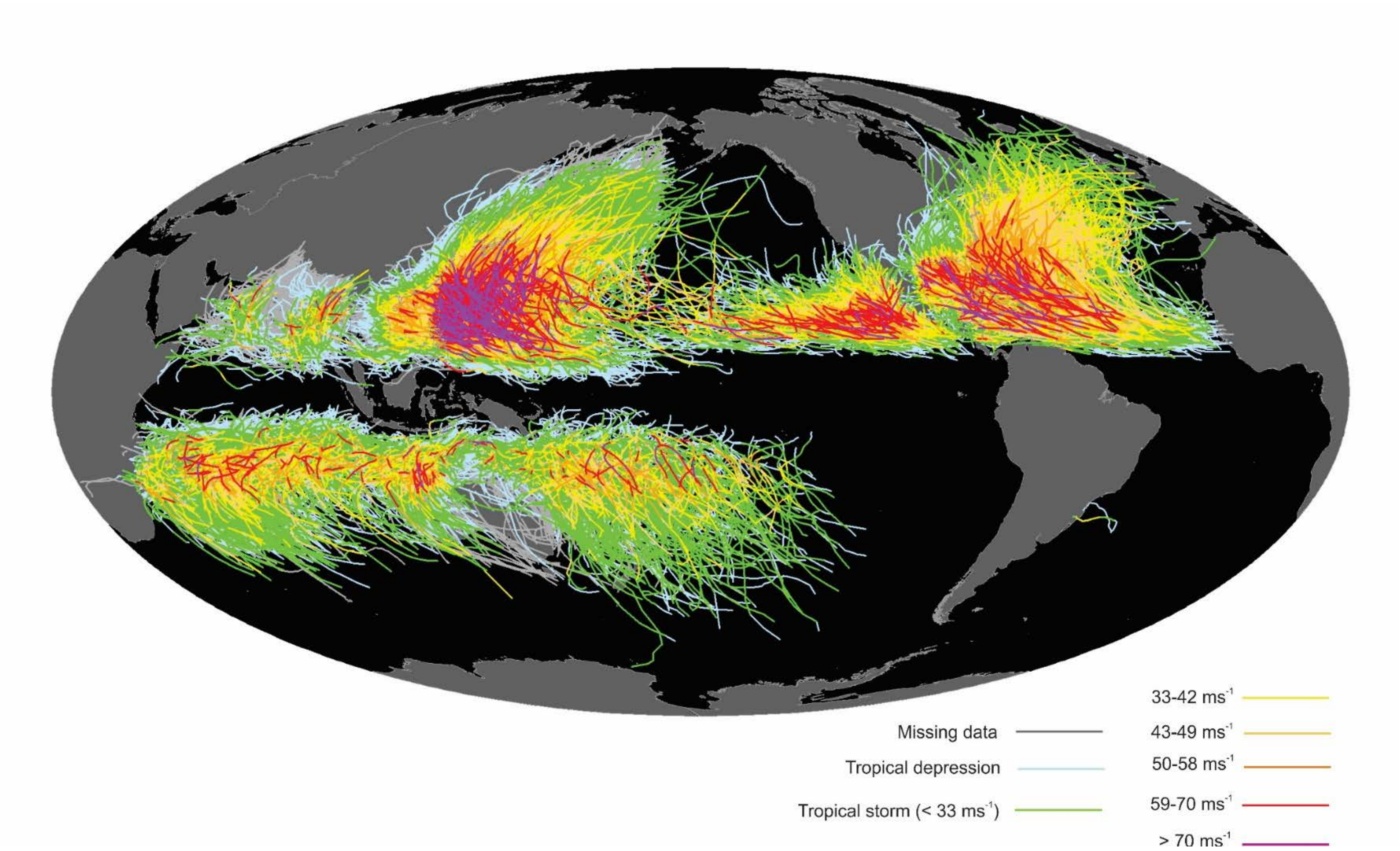
- Brief overview of hurricanes
- Current understanding
  - Basic state of the tropical atmosphere
  - Instability of the basic state – genesis
  - Energy cycle of mature hurricanes – concept of potential intensity
  - Negative influences on hurricanes
  - Statistics of hurricane intensification
  - Hurricane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

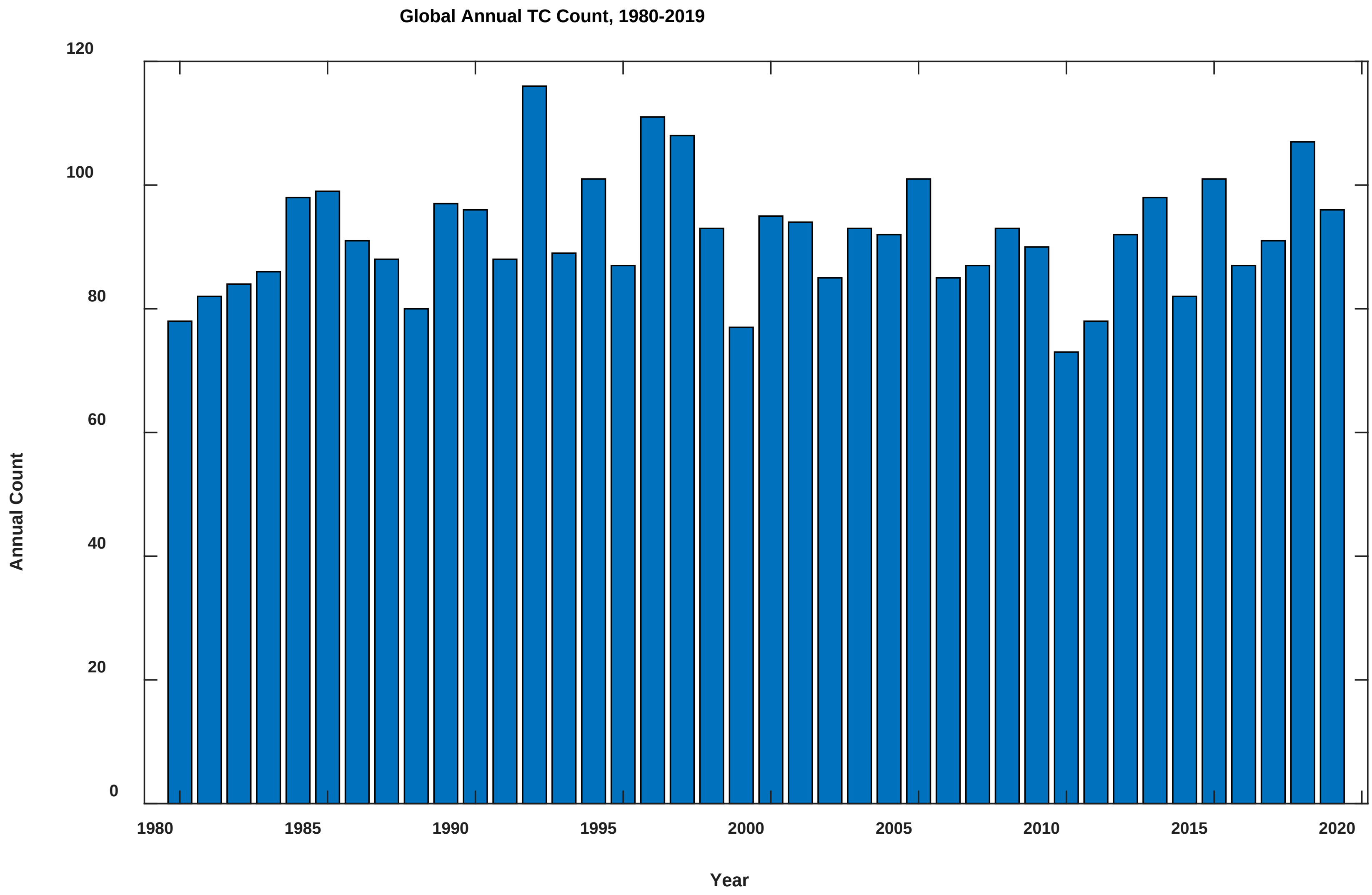
A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface

Global Climatology



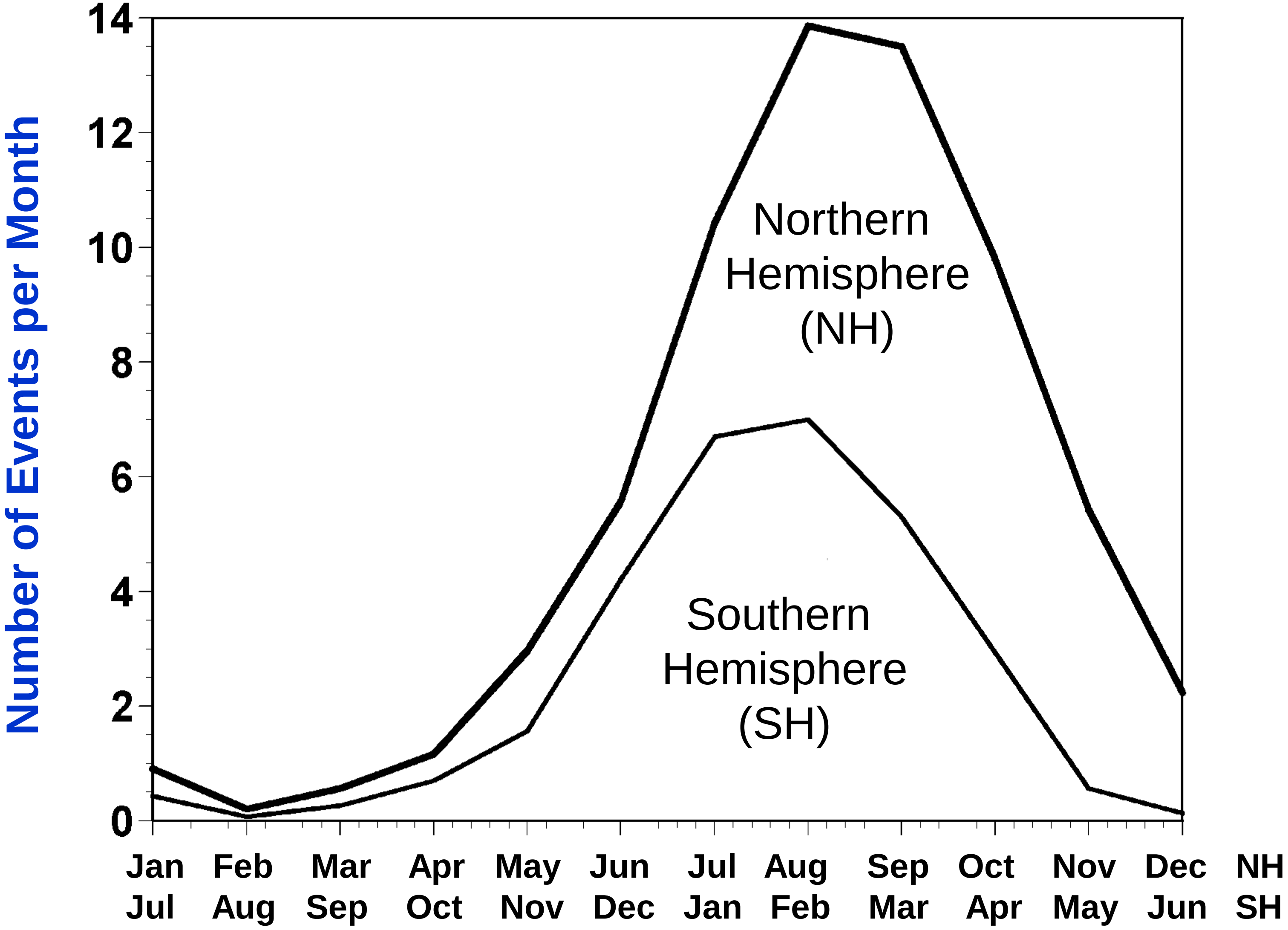
Tracks of all tropical cyclones in the historical record from 1851 to 2010. The tracks are colored according to the maximum wind at 10 m altitude, on the scale at lower right.

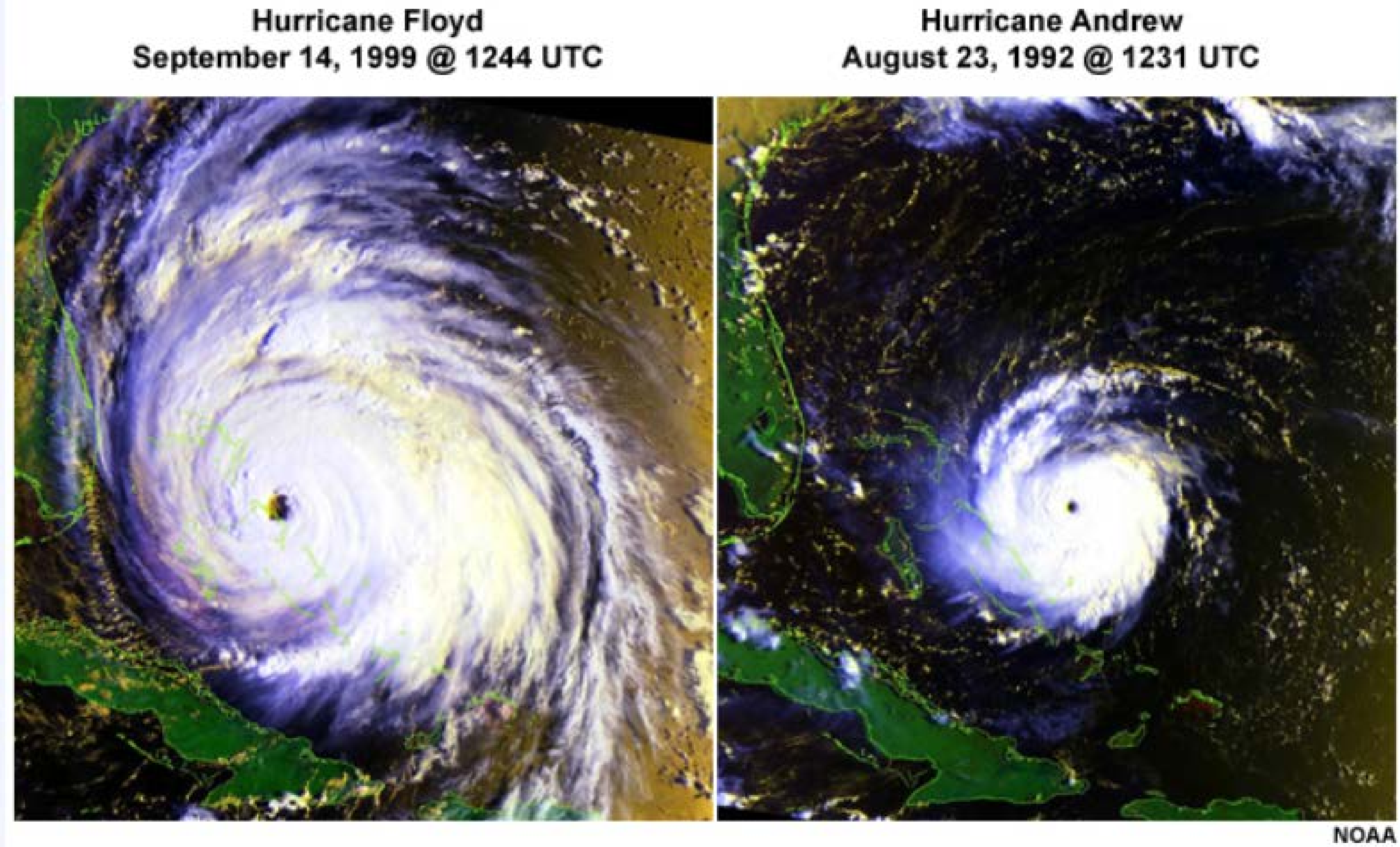
Global Tropical Cyclone Frequency, 1980-2019



Data Sources: NOAA/TPC and NAVY/JTWC

Annual Cycle of Tropical Cyclones





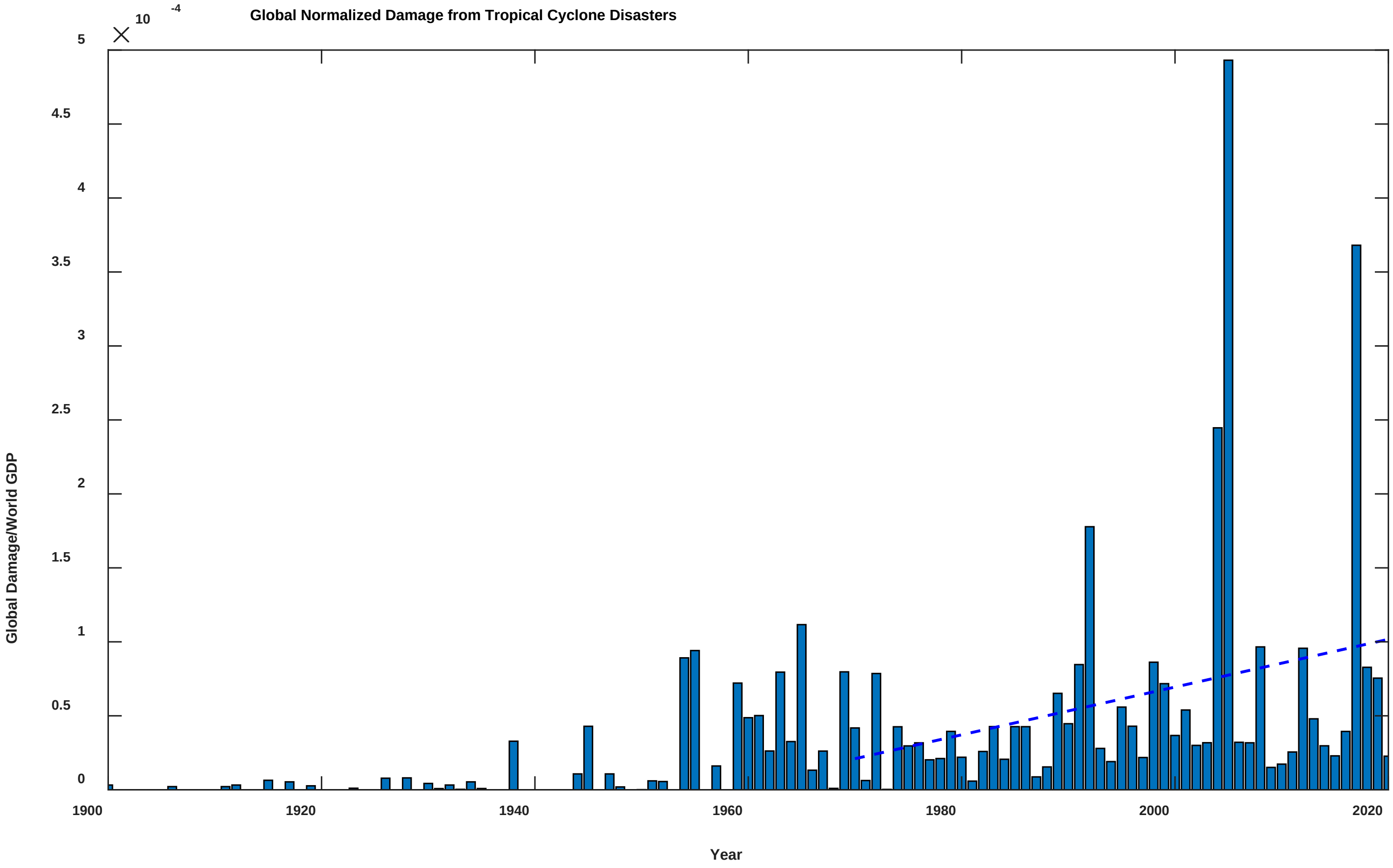
The spiral rainbands of Hurricane Floyd (left, 1999) versus the more compact Hurricane Andrew (right, 1992)

The Global Hurricane Hazard

- About 15,000 deaths per year since 1971
- $ 1.1 trillion 2015 U.S. dollars in damages ($21 billion/yr) since 1971
- Global population exposed to hurricane hazards has tripled since 1970

EM-DAT, 2020: The OFDA/CRED International Disaster Database http://www.emdat.be/.

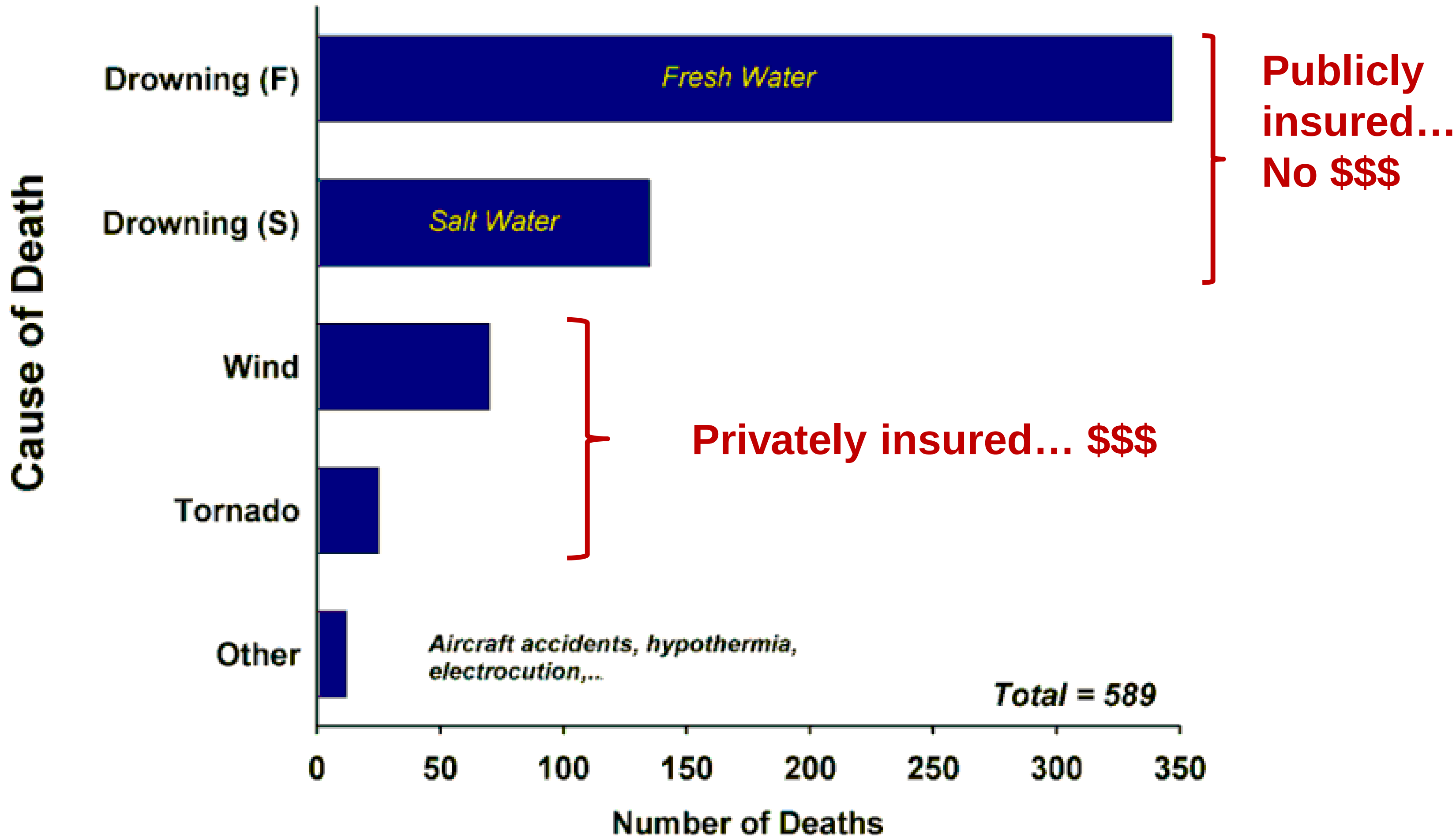
Global Tropical Cyclone Damage Normalized by Gross World Product



- 380% increase since 1970
- Population of TC-prone regions increased by ~200%
- Suggests that climate change has contributed to increasing damage

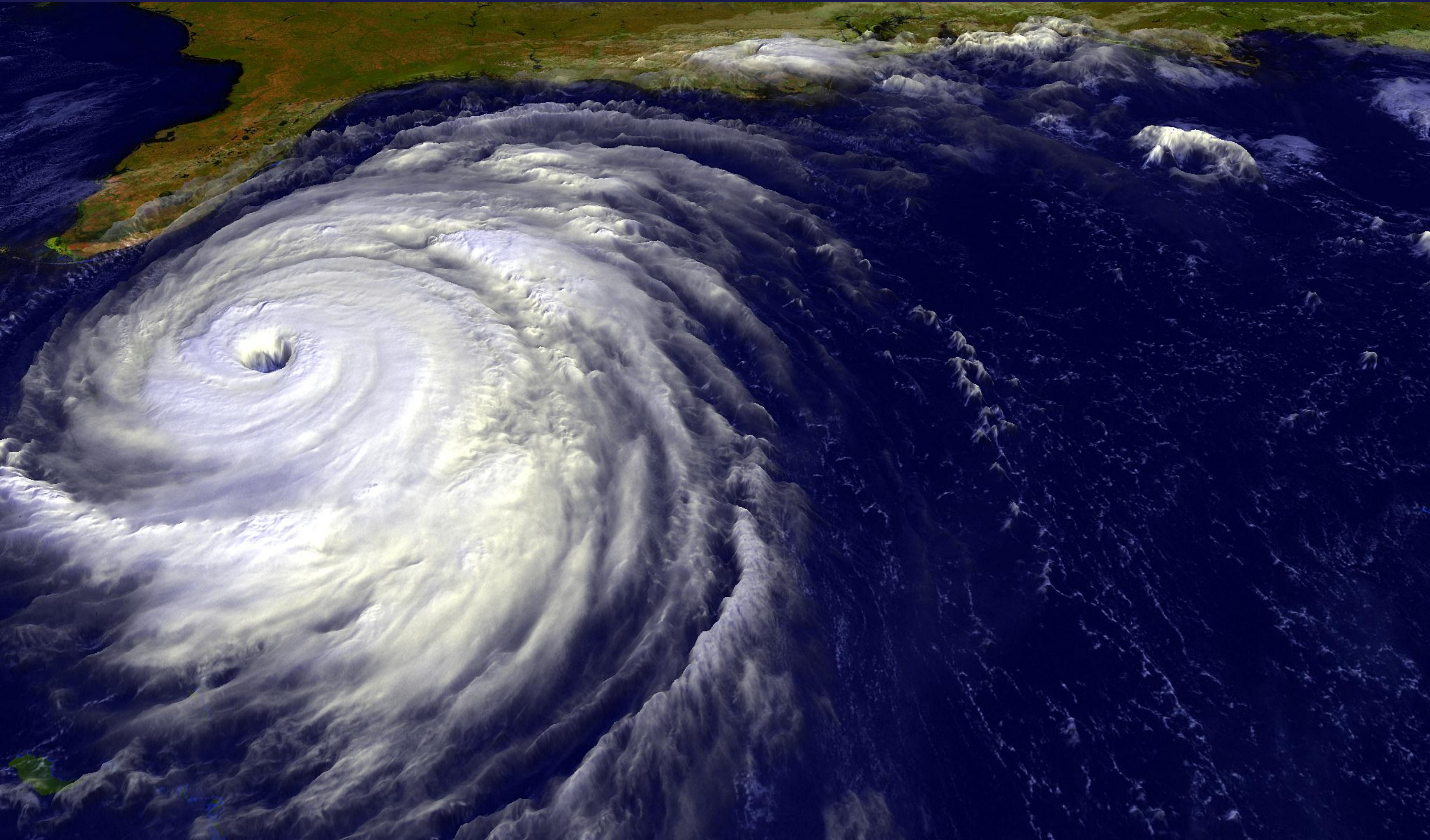
EM-DAT, 2020: The OFDA/CRED International Disaster Database http://www.emdat.be/.

U. S. Hurricane Mortality (1970-1999)



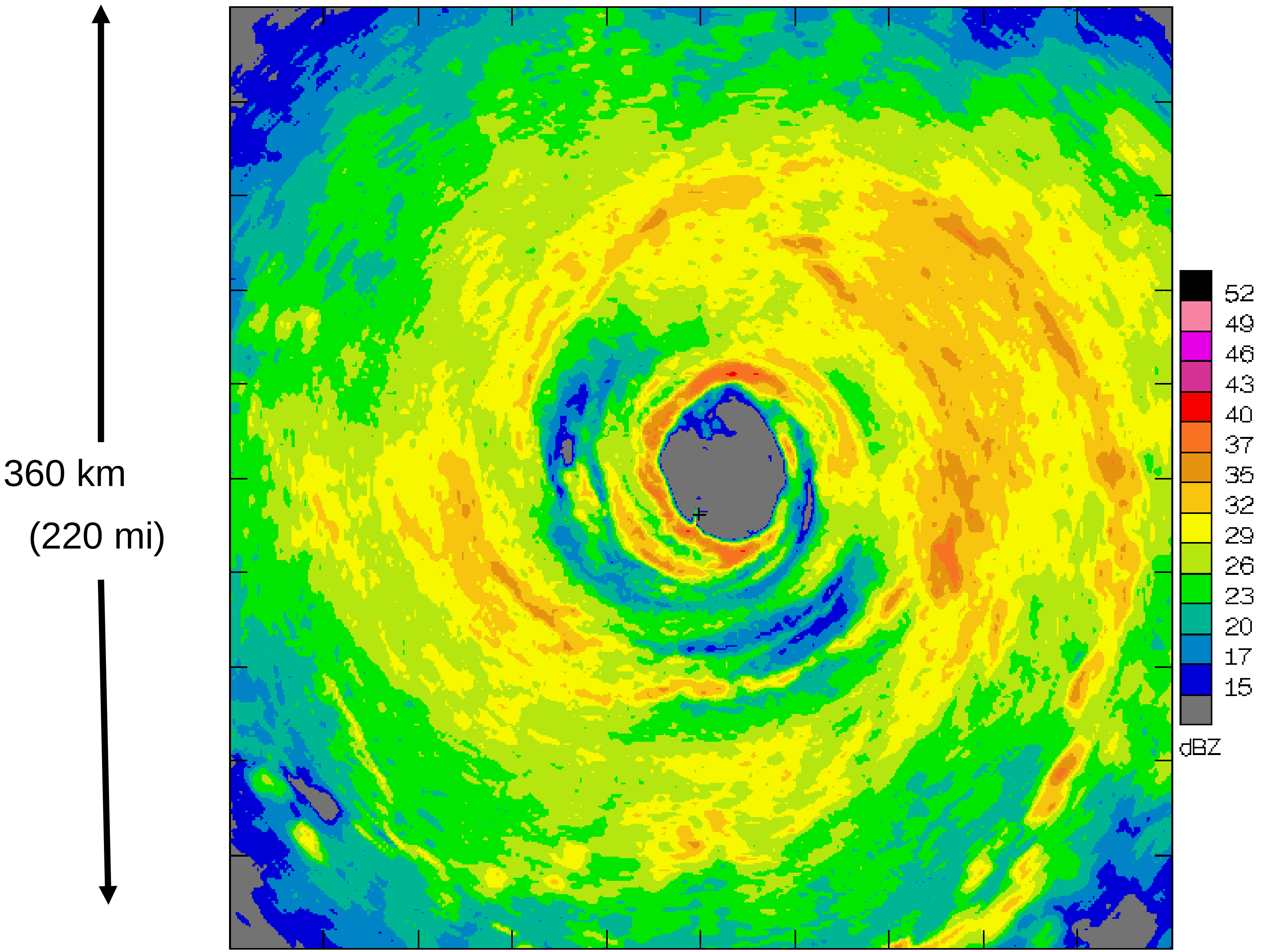
Source: Rappaport, E. N., 1999:
The threat to life in inland areas of the United States from Atlantic tropical cyclones.
Prepreints 23rd Conferenceon Hurricanes and Tropical Meteorology ,
American Meteorological Society (10-15 Jan 1999, Dallas Tx), 339-342.

The View from Space

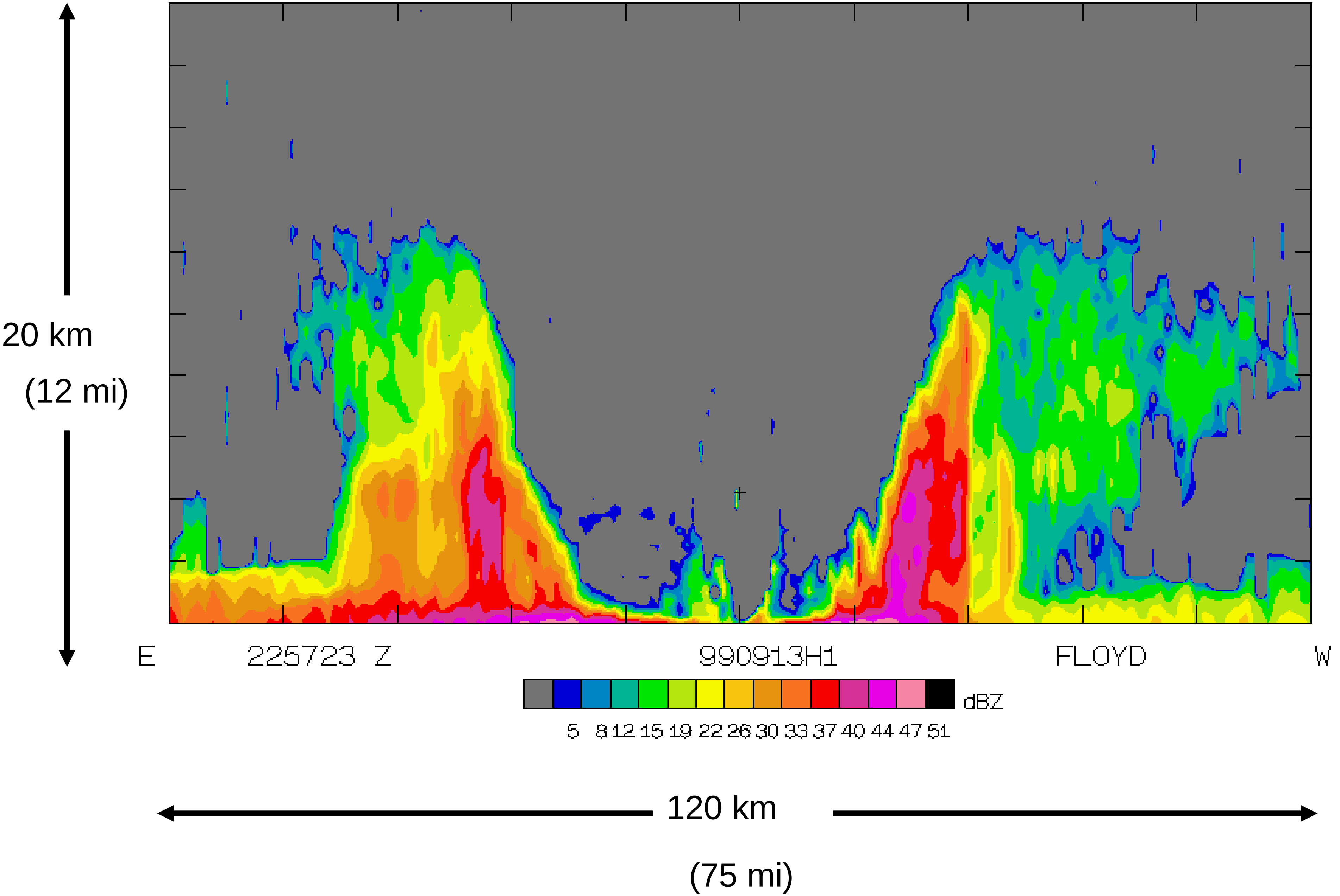


View of the eye of Hurricane Katrina on August 28th, 2005, as seen from a NOAA WP-3D hurricane reconnaissance aircraft.

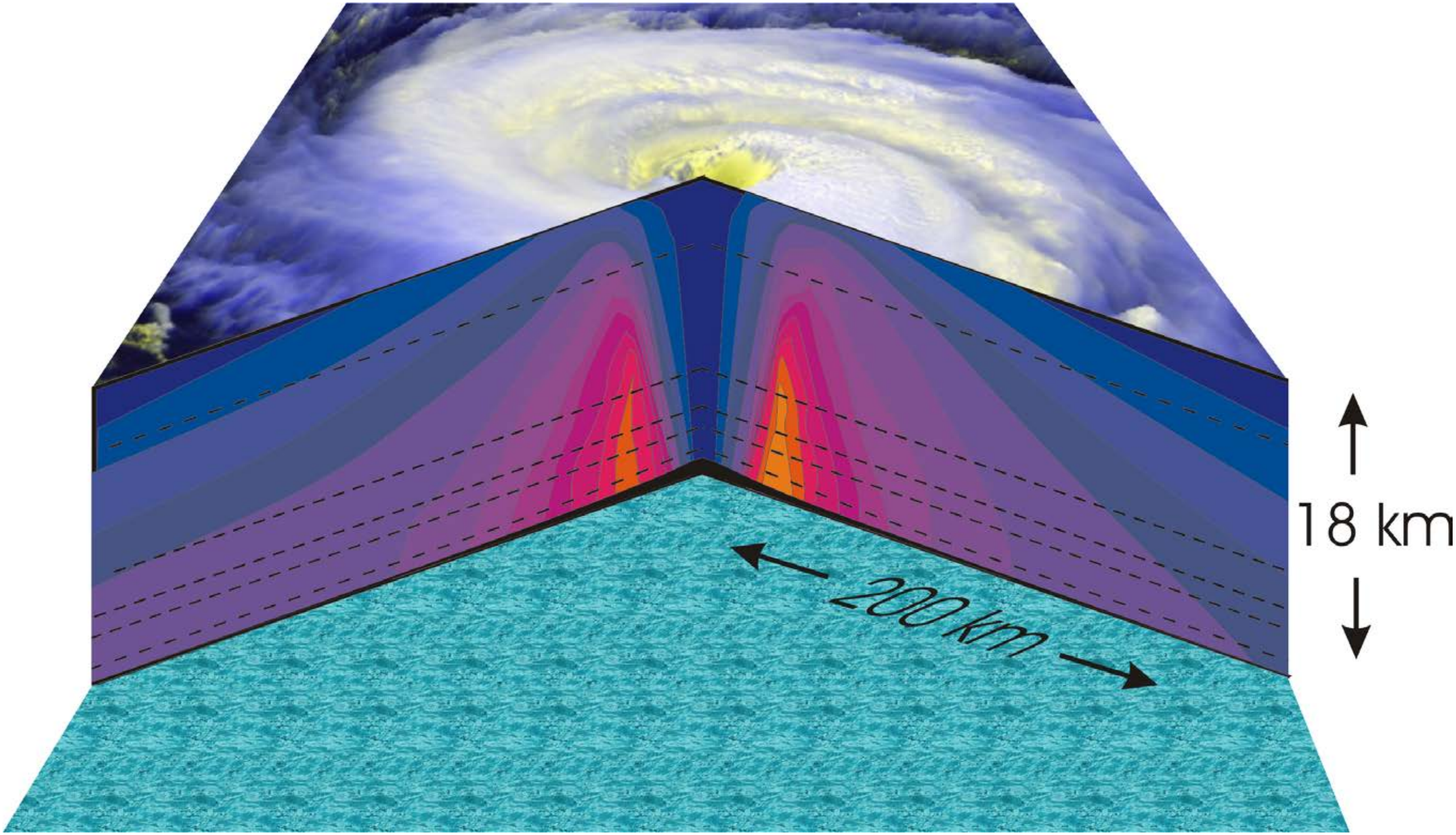
Airborne Radar: Horizontal Map



Airborne Radar: Vertical Slice



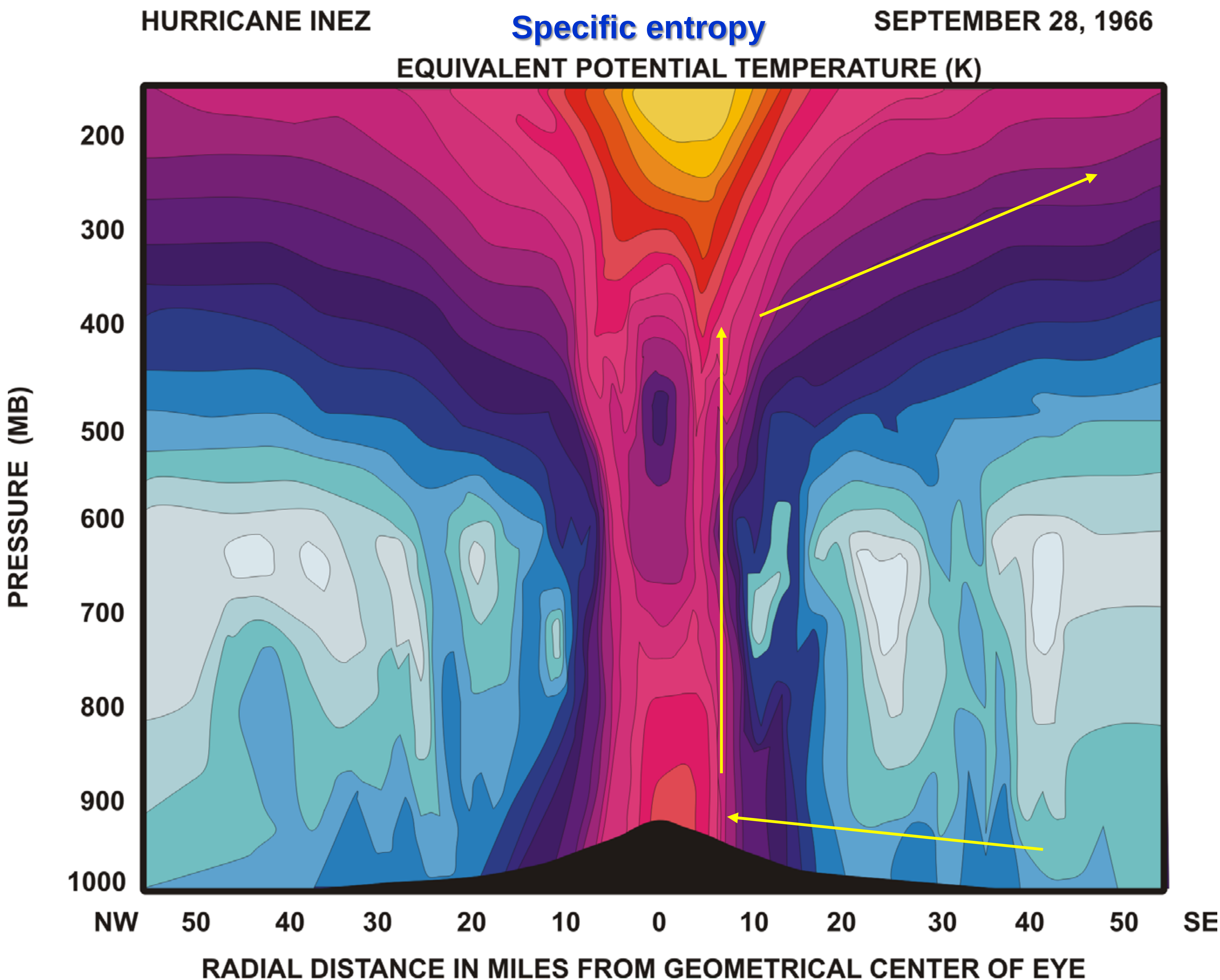
Hurricane Structure: Wind Speed



Azimuthal component of wind

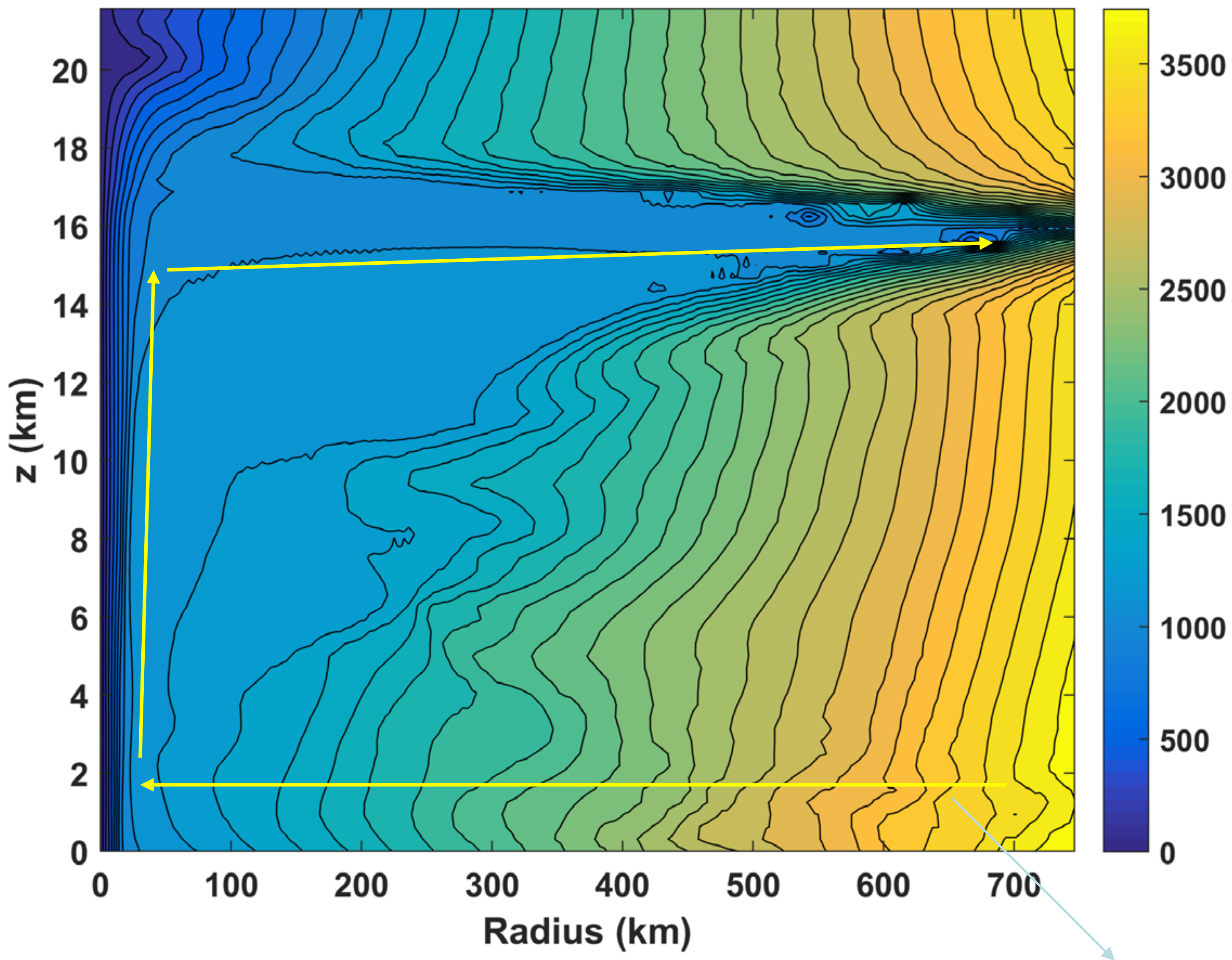
< 11 5 ms^{-1} - > 60 ms^{-1}

Specific entropy

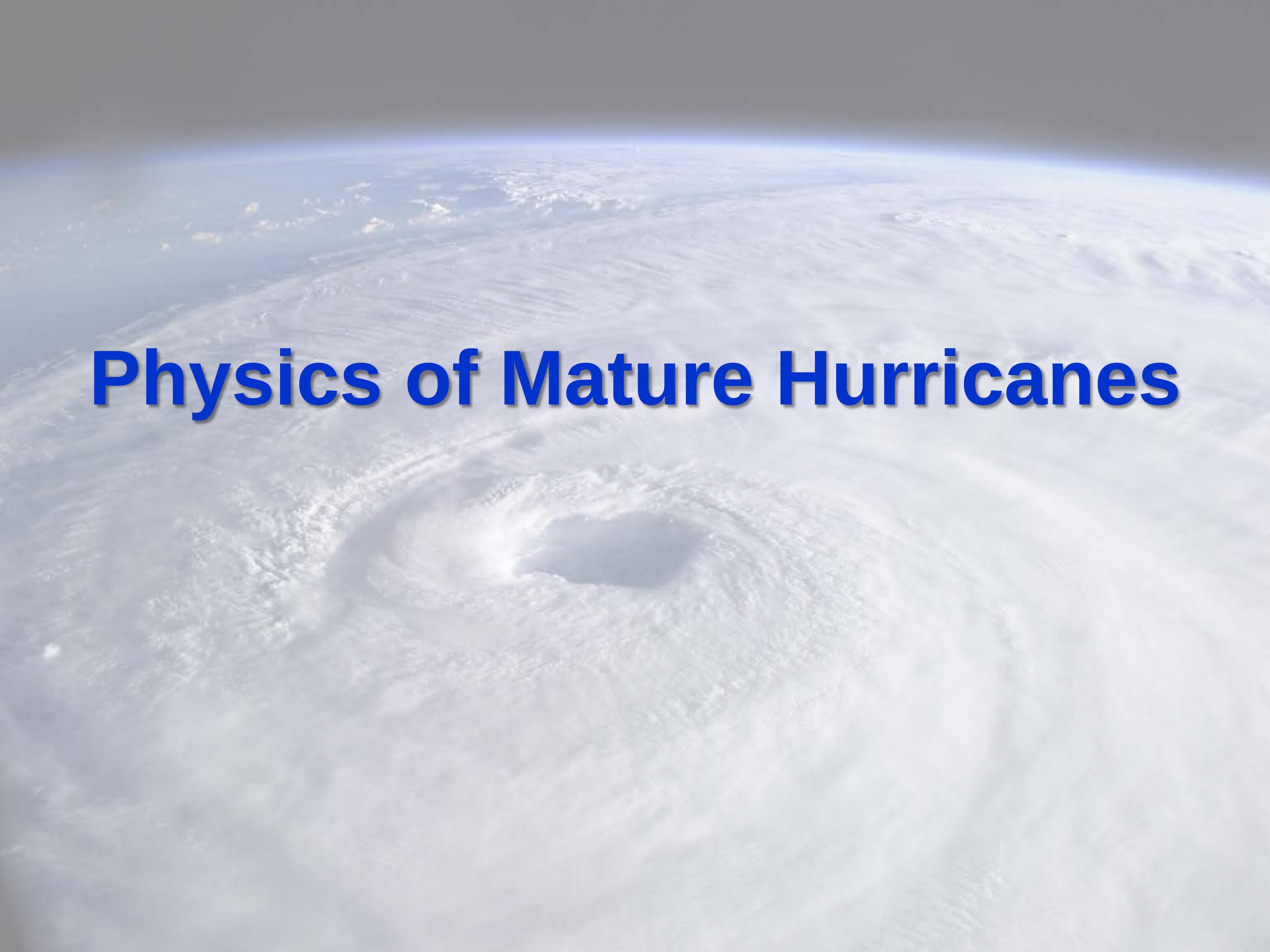


Absolute angular momentum per unit mass

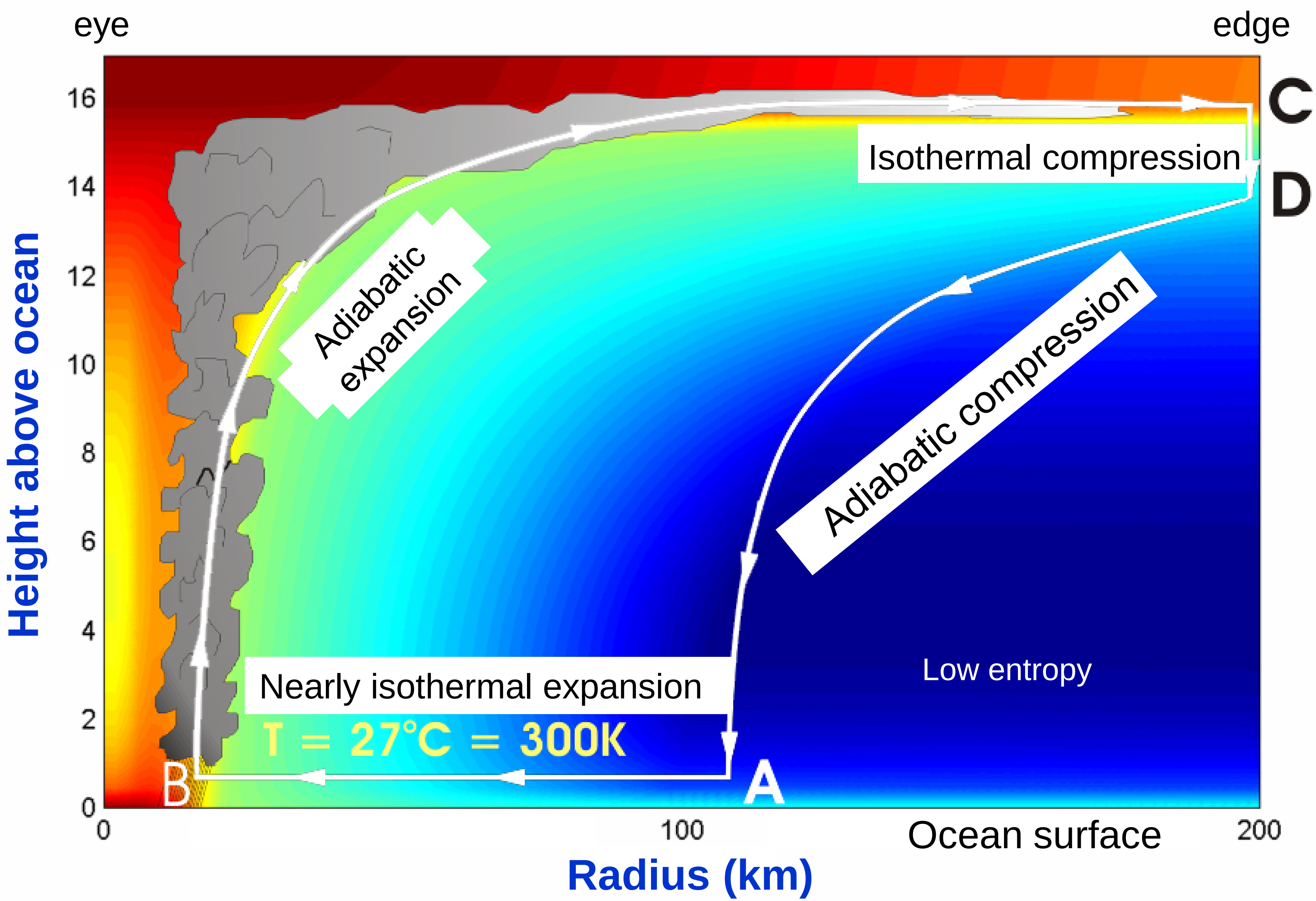
$$M = rV + \Omega r^2$$



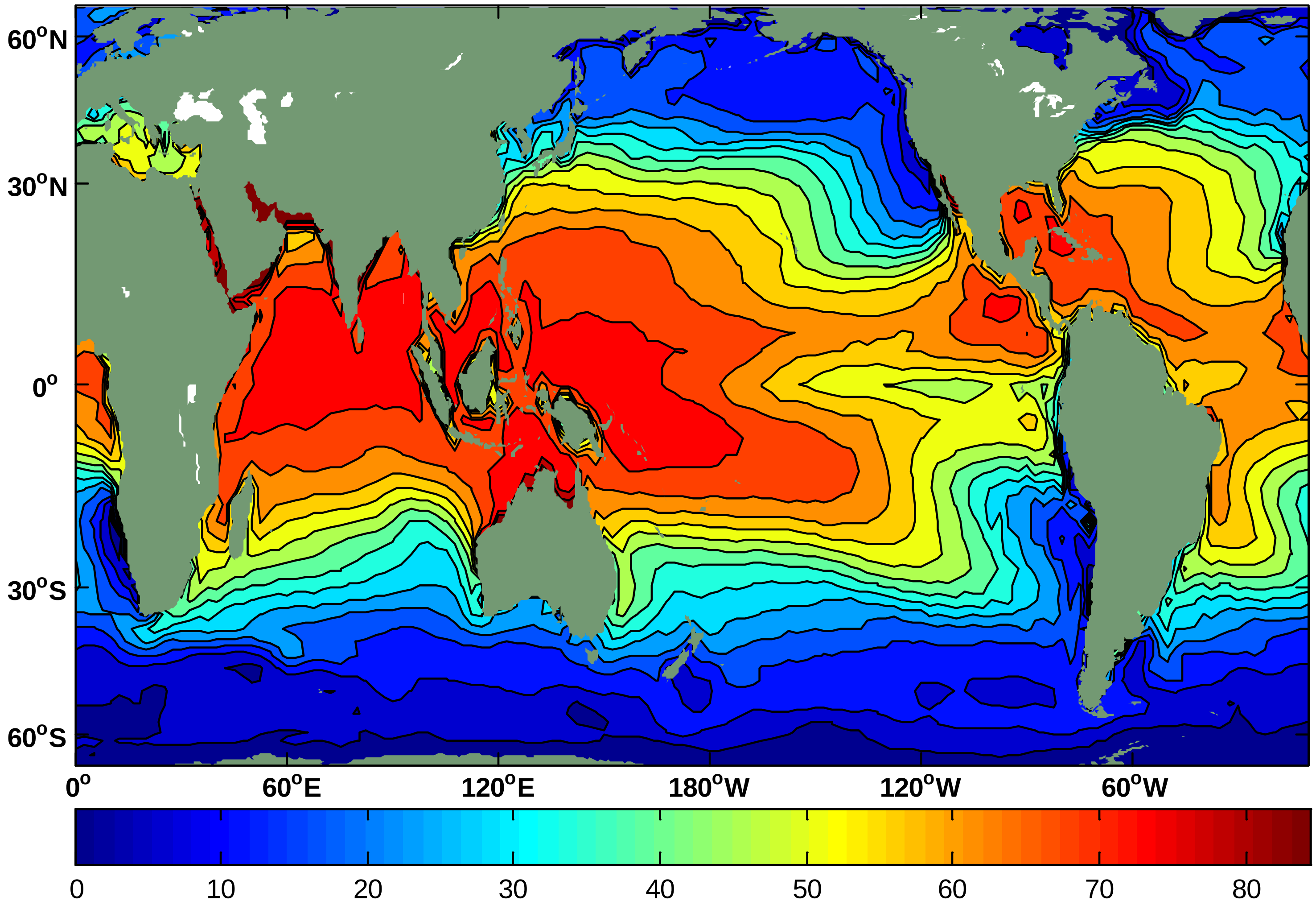
Physics of Mature Hurricanes

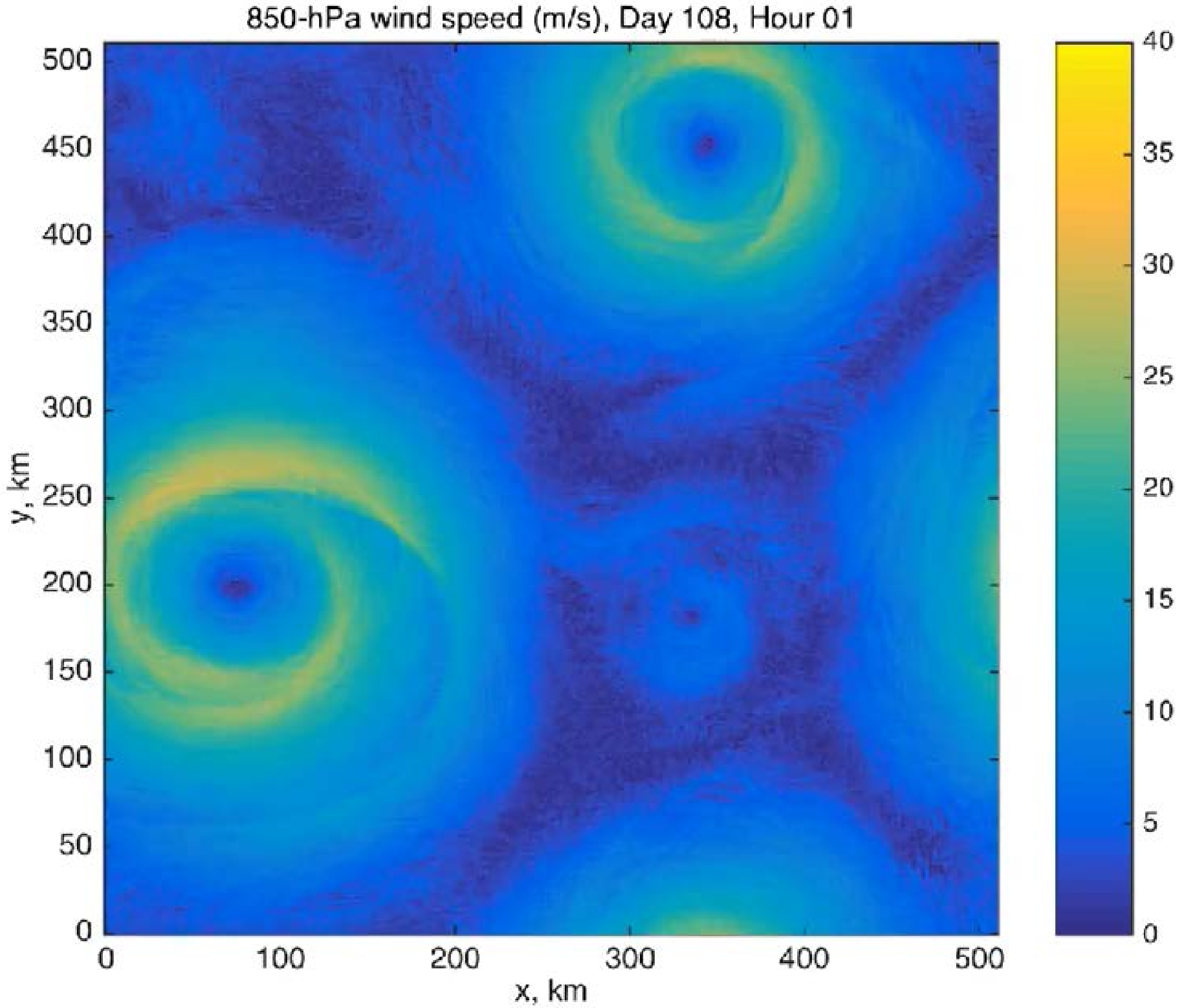


Cross-section through a Hurricane & Energy Production

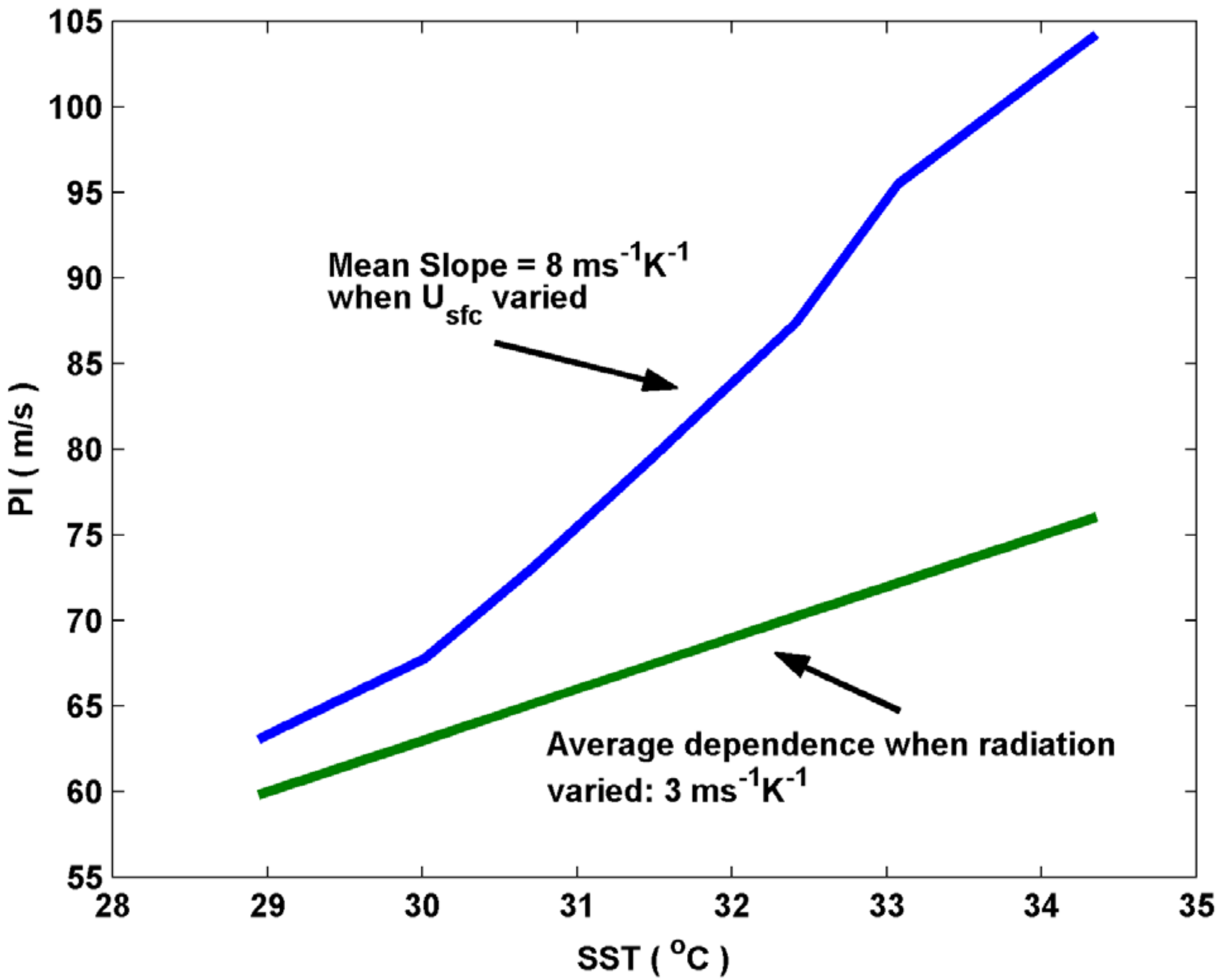


Annual Maximum Potential Intensity (m/s)




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

Dependence on Sea Surface Temperature (SST):

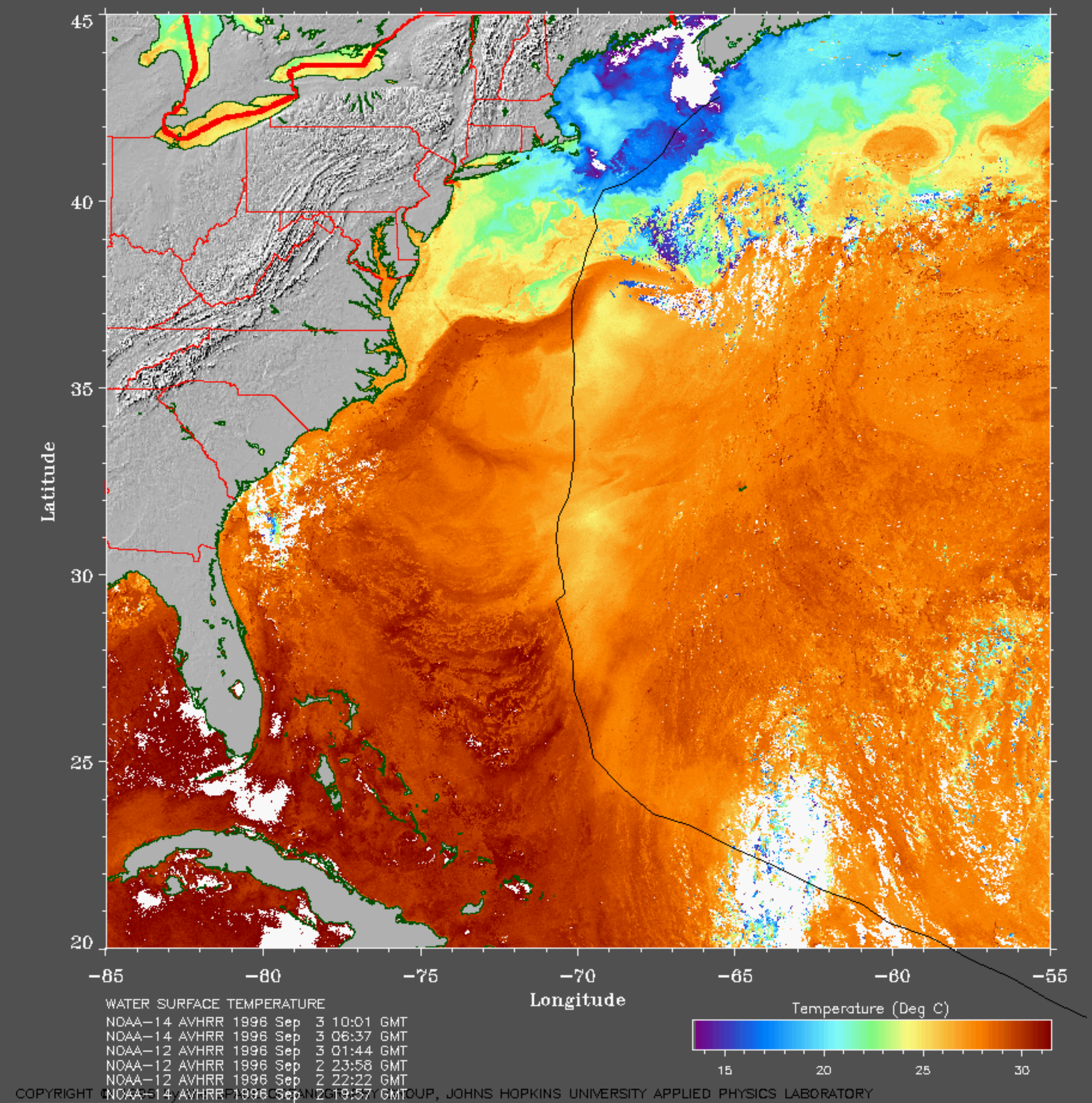


Potential Intensity is not the same thing as SST!

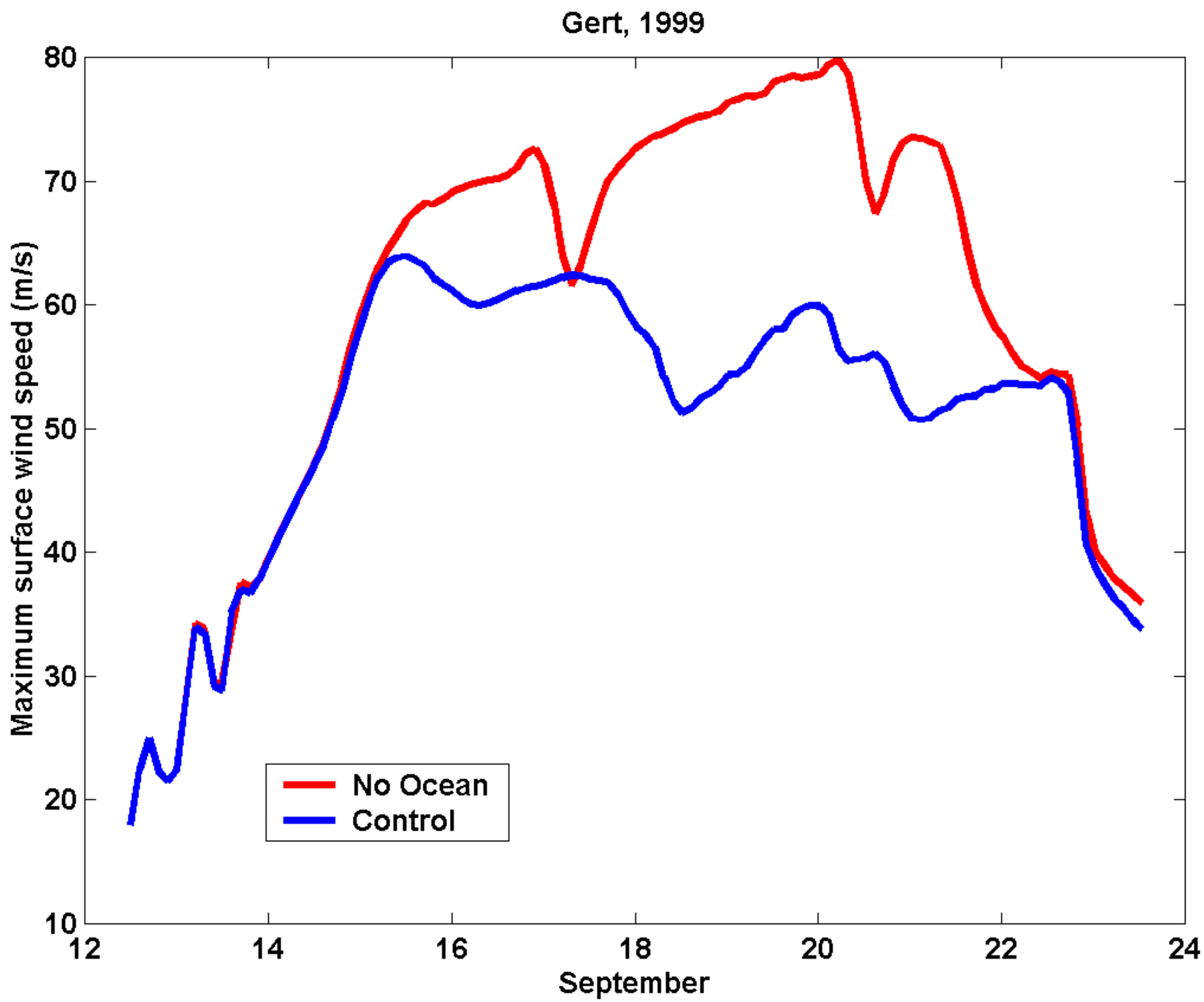
Why do real storms seldom reach their thermodynamic potential?

One Reason: Ocean Interaction

Strong Mixing of Upper Ocean



Comparing Fixed to Interactive SST:



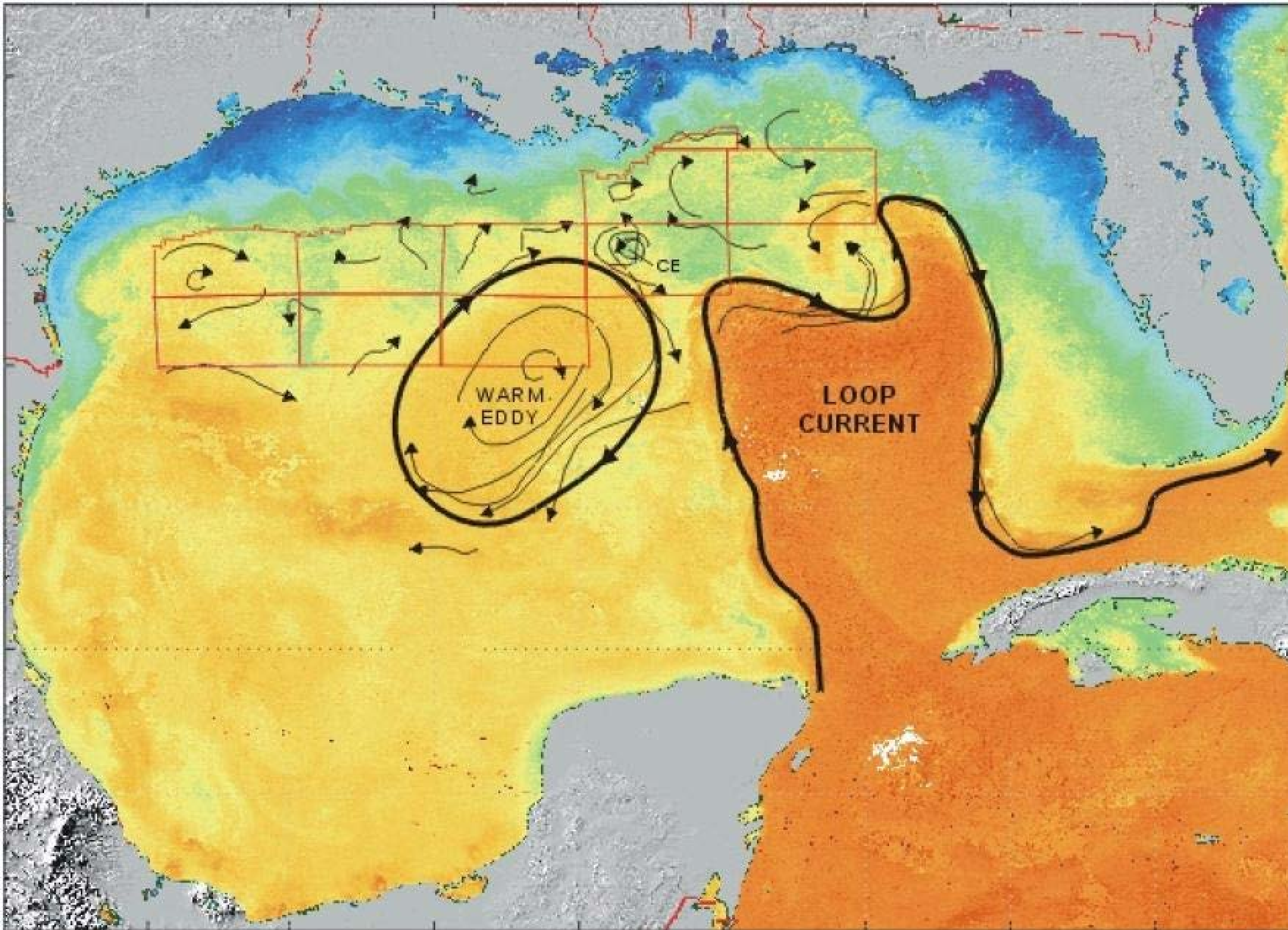
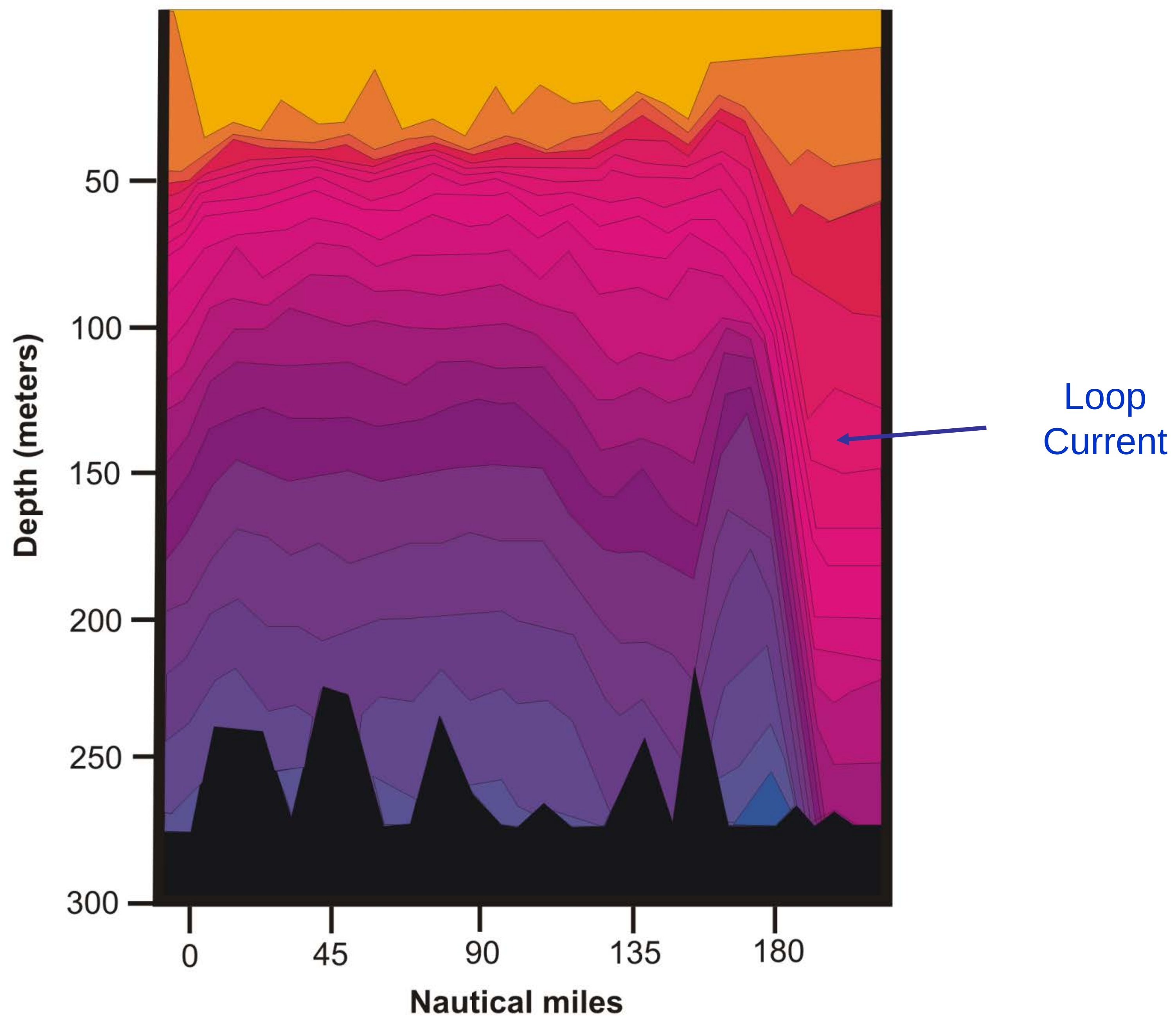
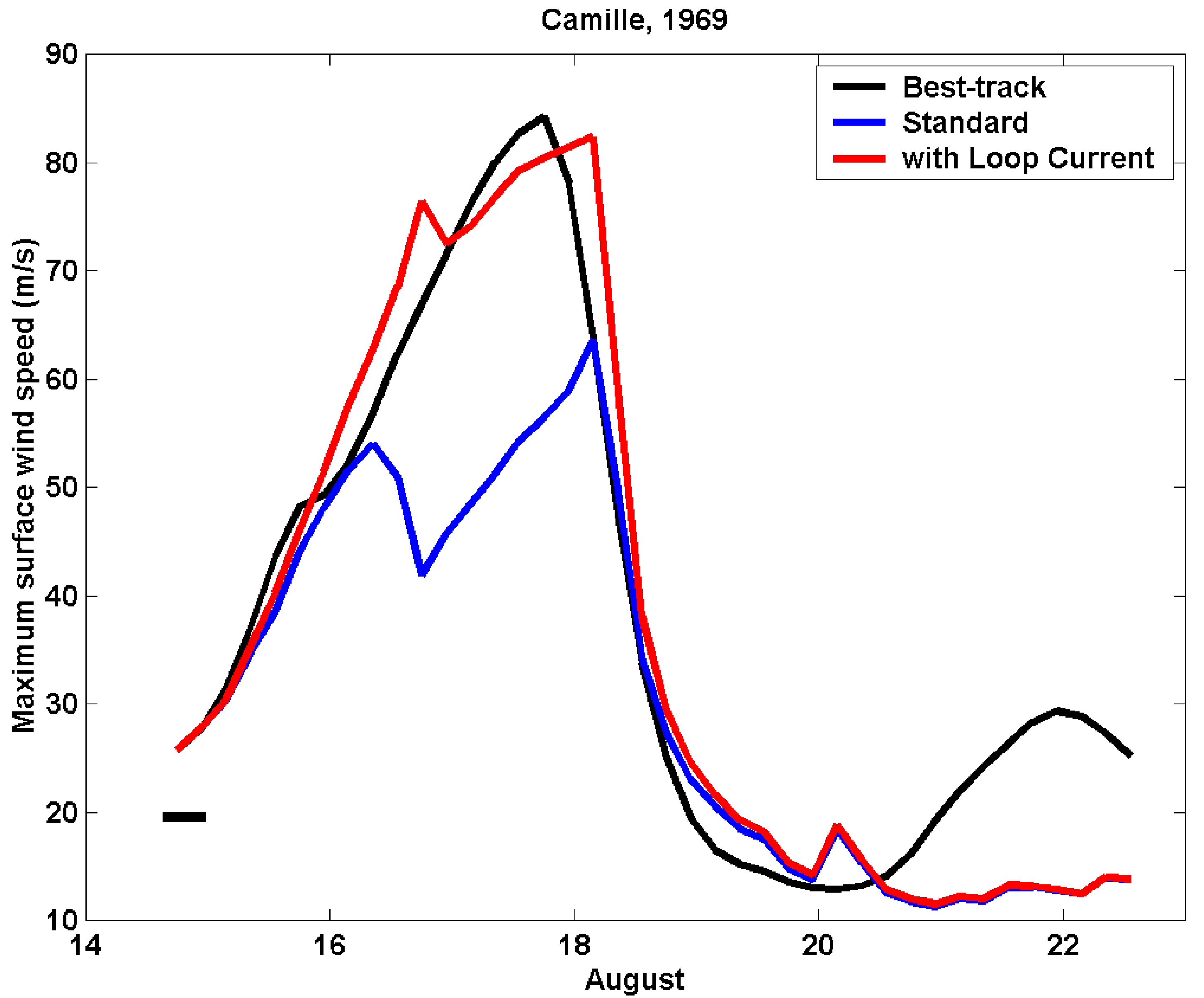


Figure 15. Loop and eddy currents in the Gulf of Mexico (image courtesy of Horizon Marine, Inc.).

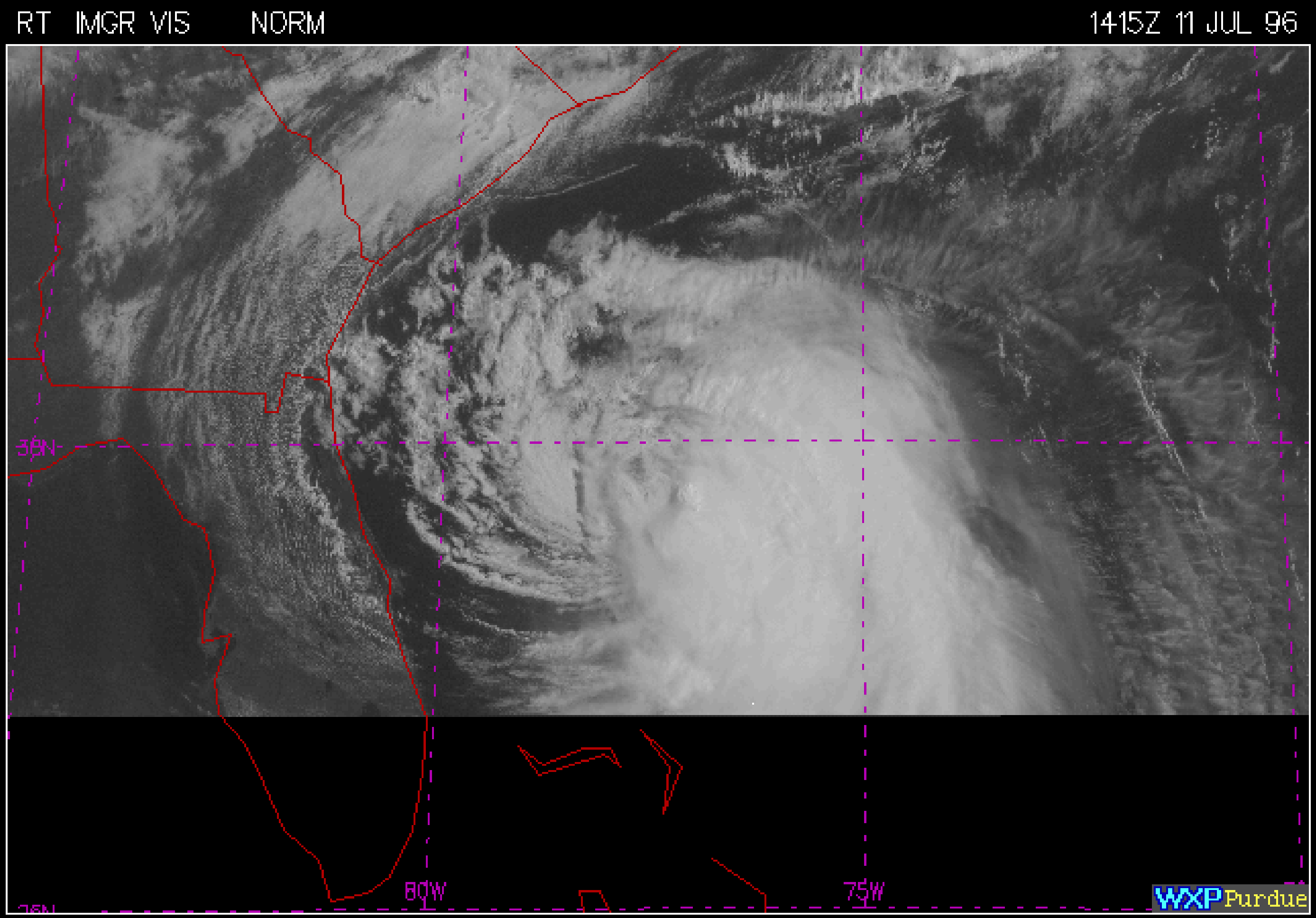


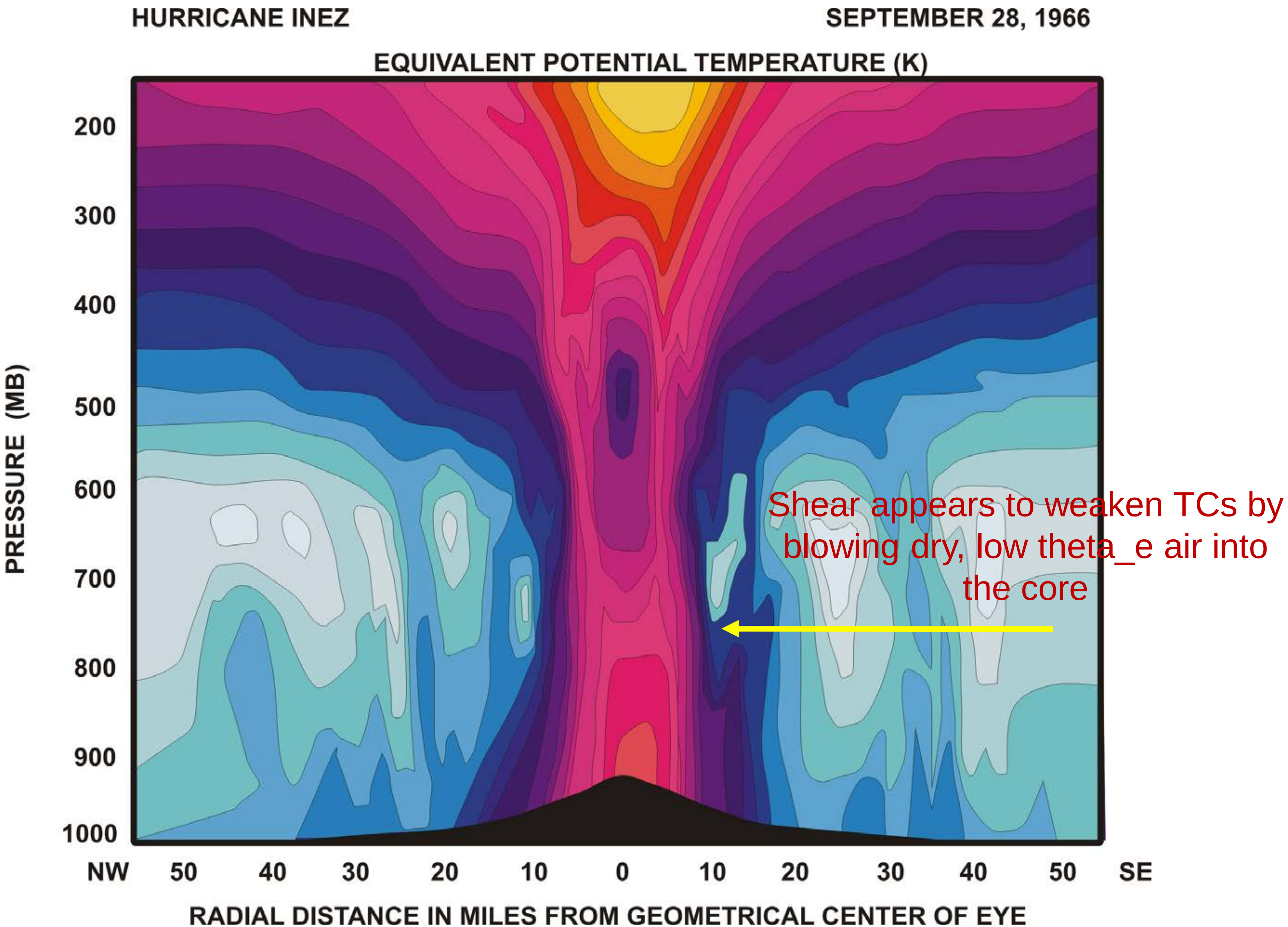
Loop
Current
Depth (meters)
50
100
150
200
250
300
0
45
90
135
180
Nautical miles

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

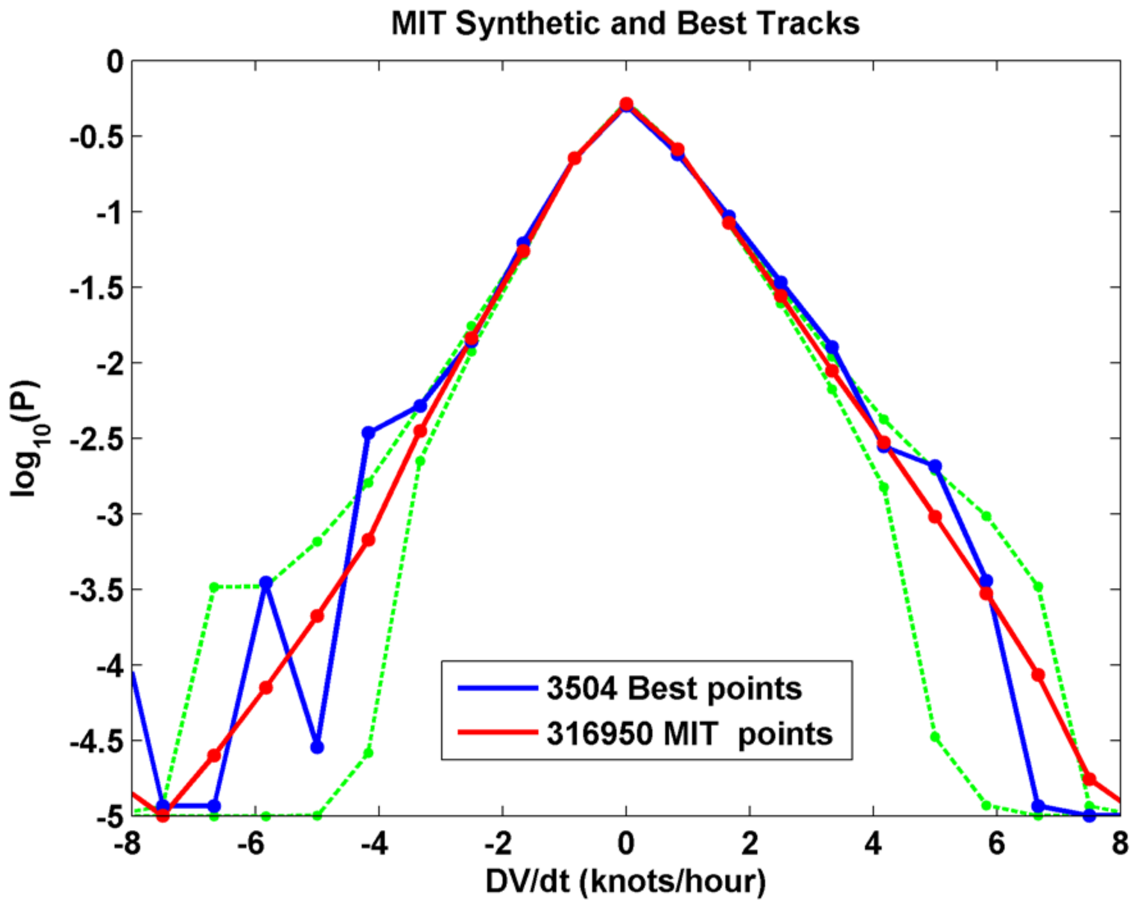


Wind Shear




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

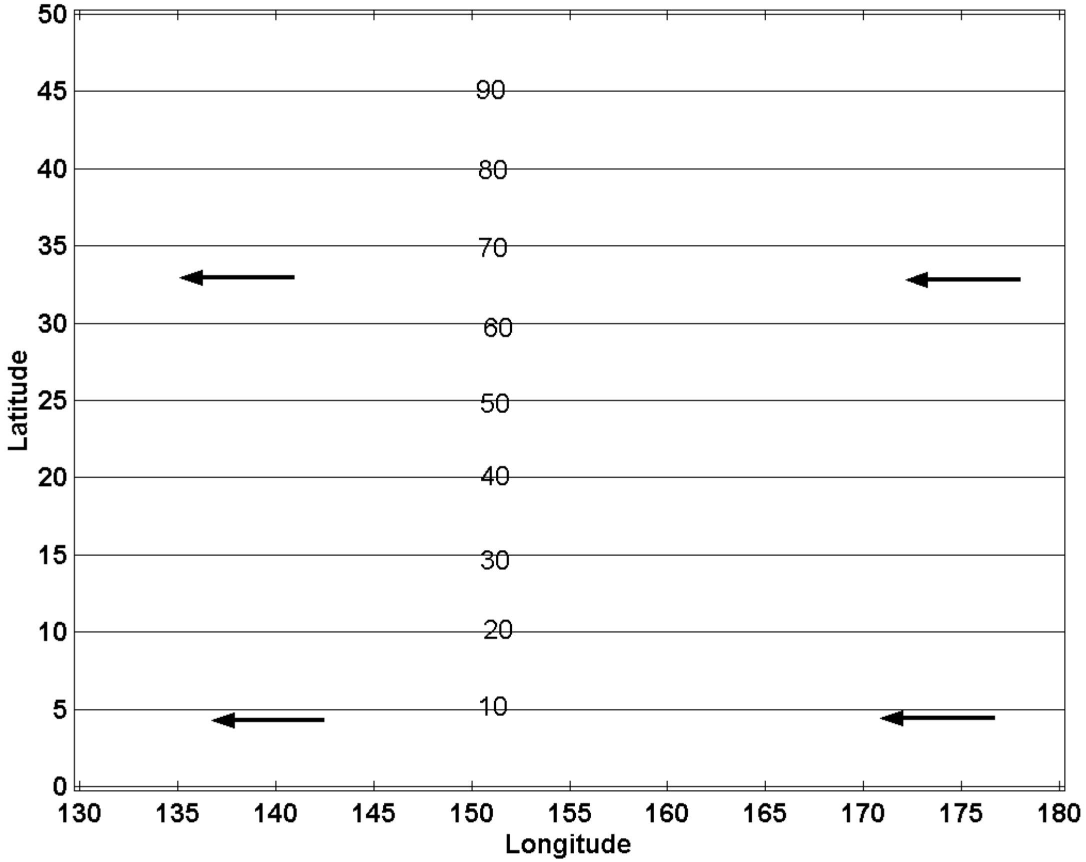
Statistics of Hurricane Intensification

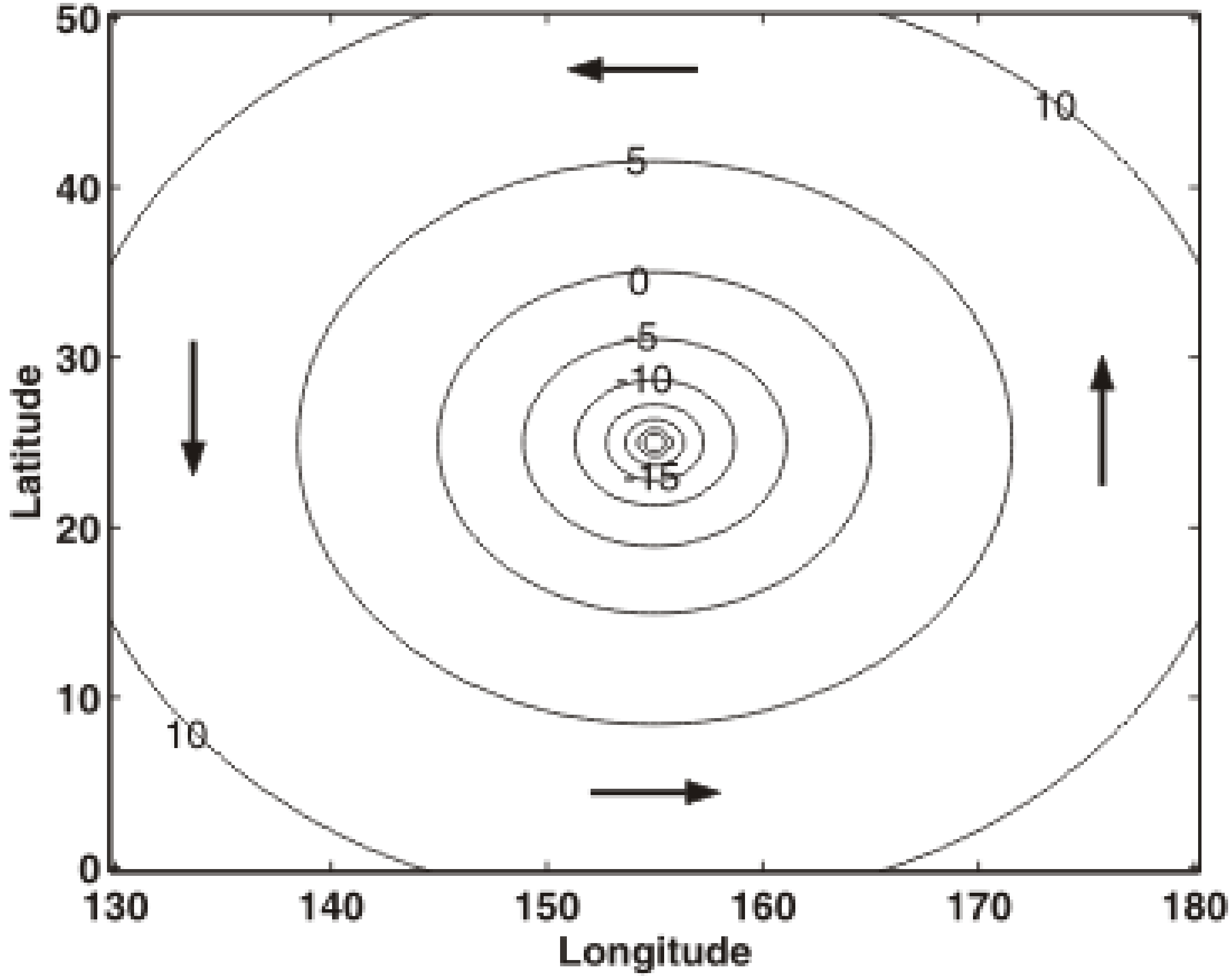


Common logarithms of the probability densities of open-ocean tropical cyclone intensity change rates in the North Atlantic region from 3504 observations (blue) and from 316 950 synthetic samples (red) of hurricane-intensity storms. Green lines or dots indicate the 5th and 95th percentiles of 1000 subsamples 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

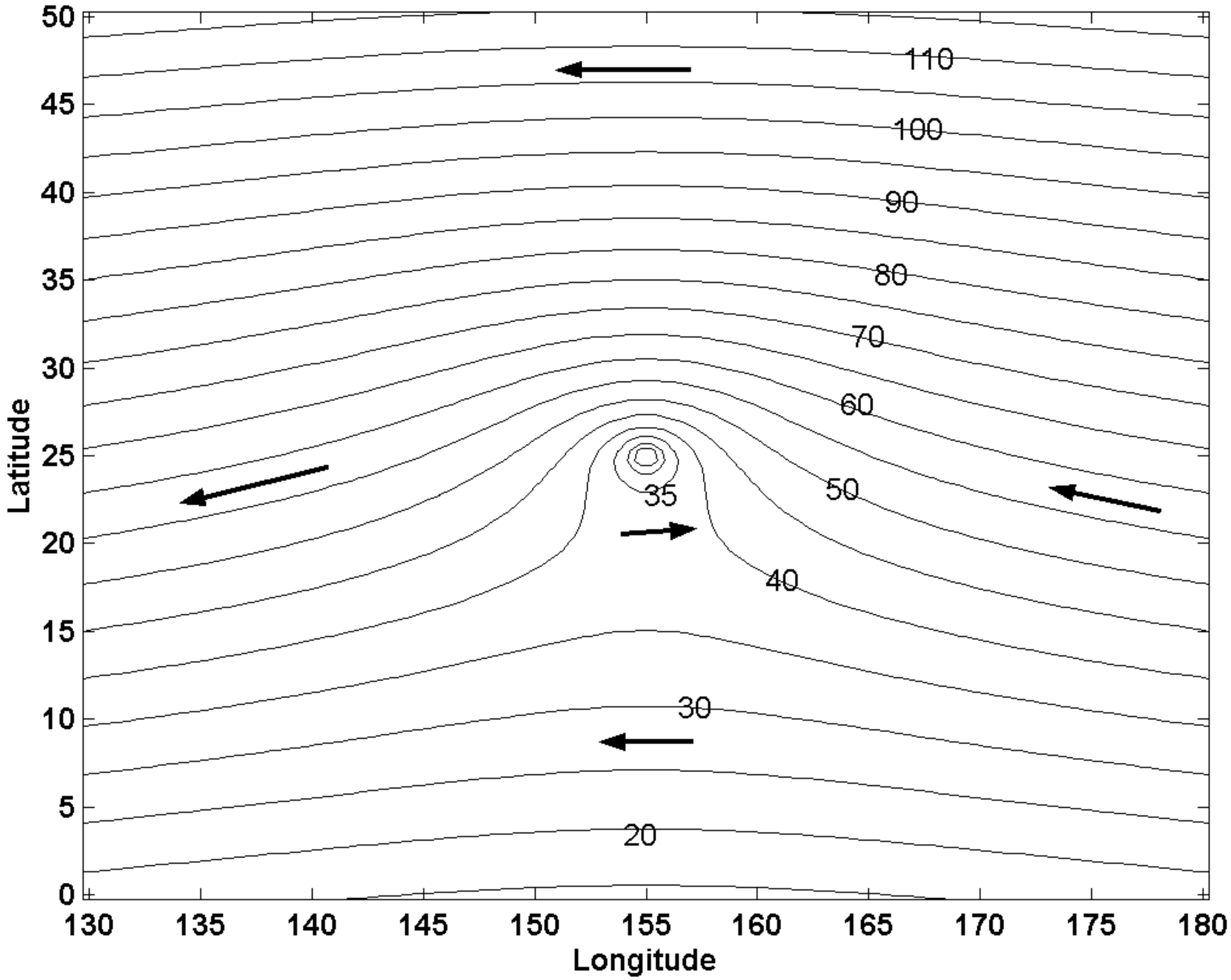
Tropical Cyclone Motion

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

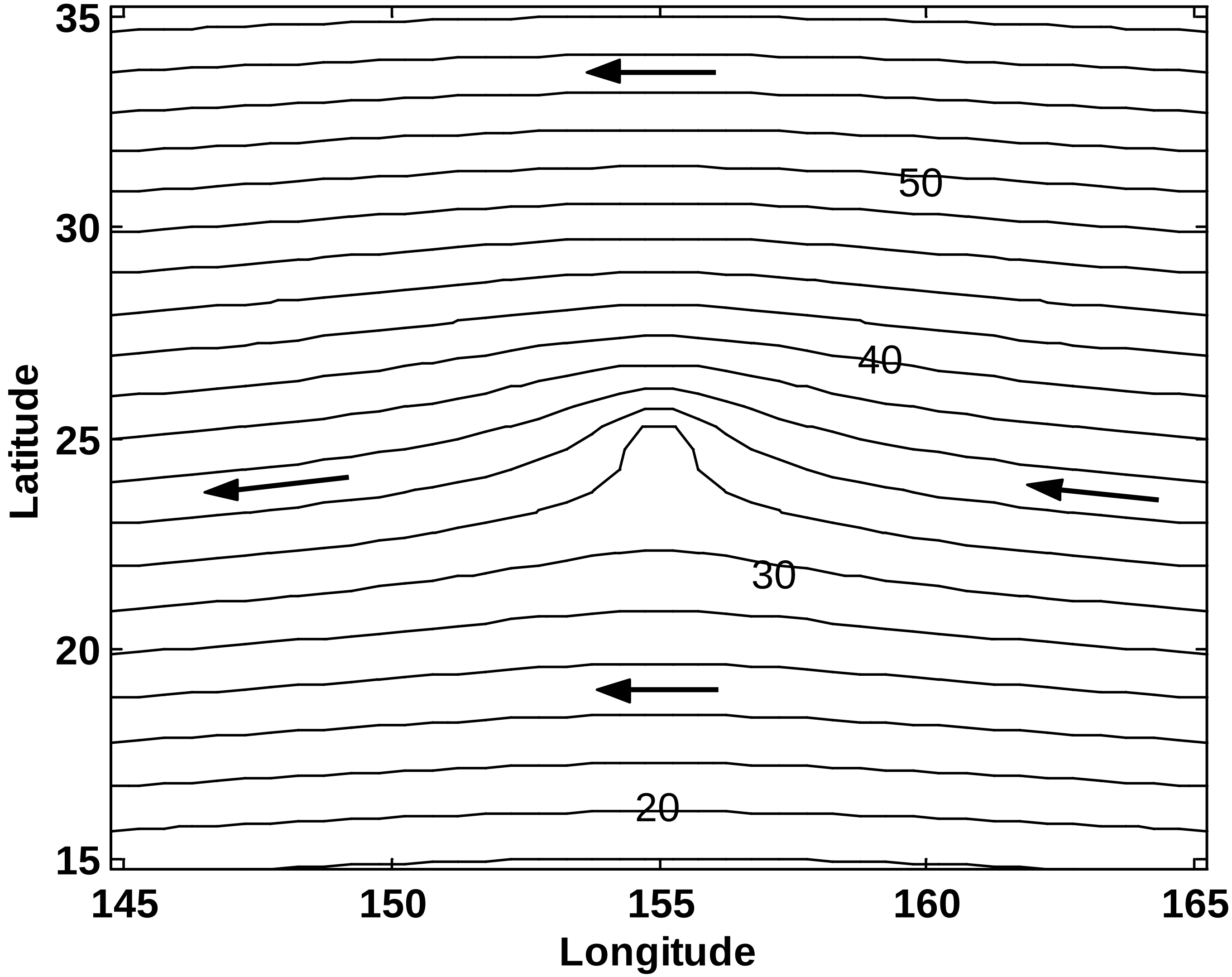




50
40
30
20
10
0
Latitude
130
140
150
160
170
180
Longitude
10
5
0
-5
-10
-15
10

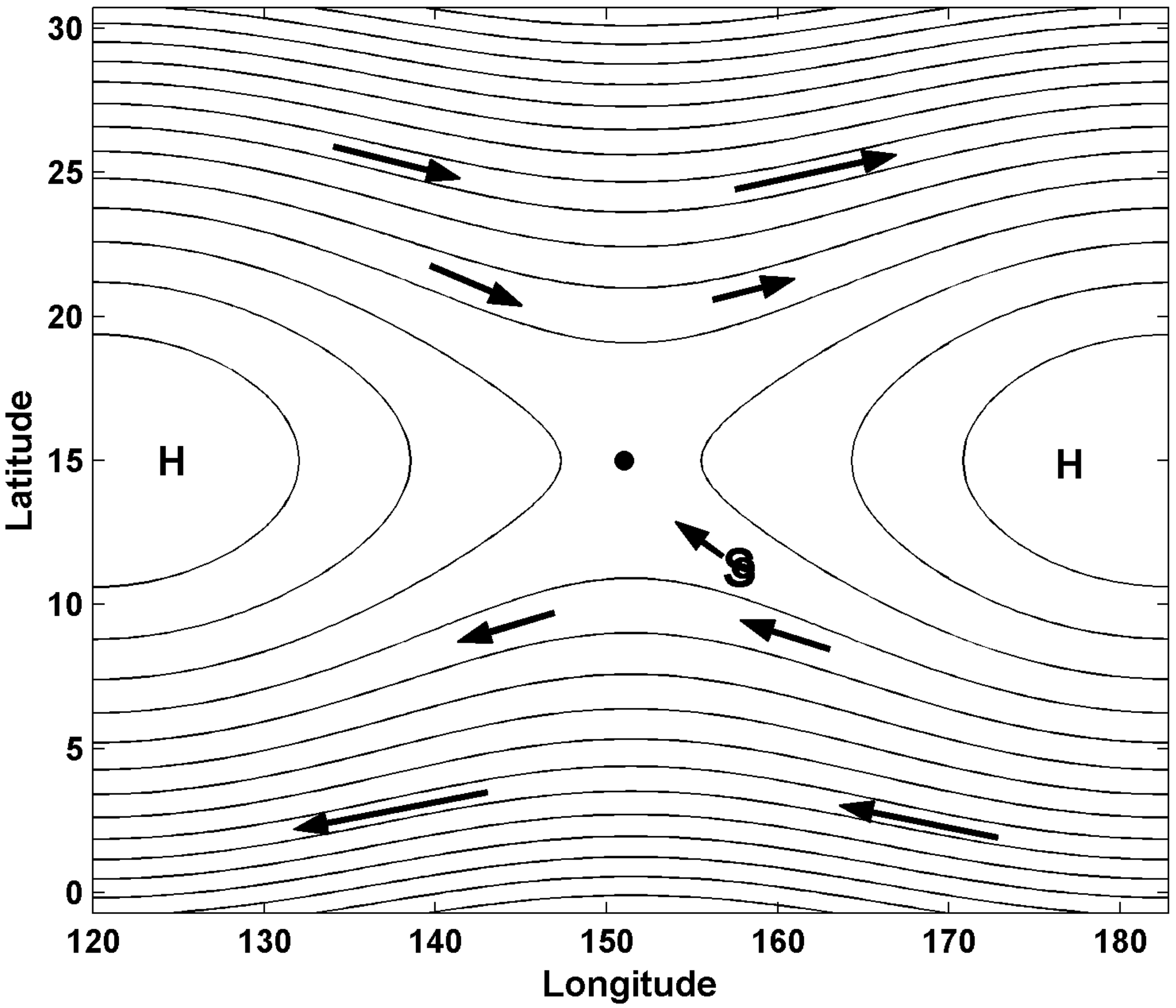


110
100
90
80
70
60
50
35
40
30
20
Latitude
50
45
40
35
30
25
20
15
10
5
0
130
135
140
145
150
155
160
165
170
175
180
Longitude

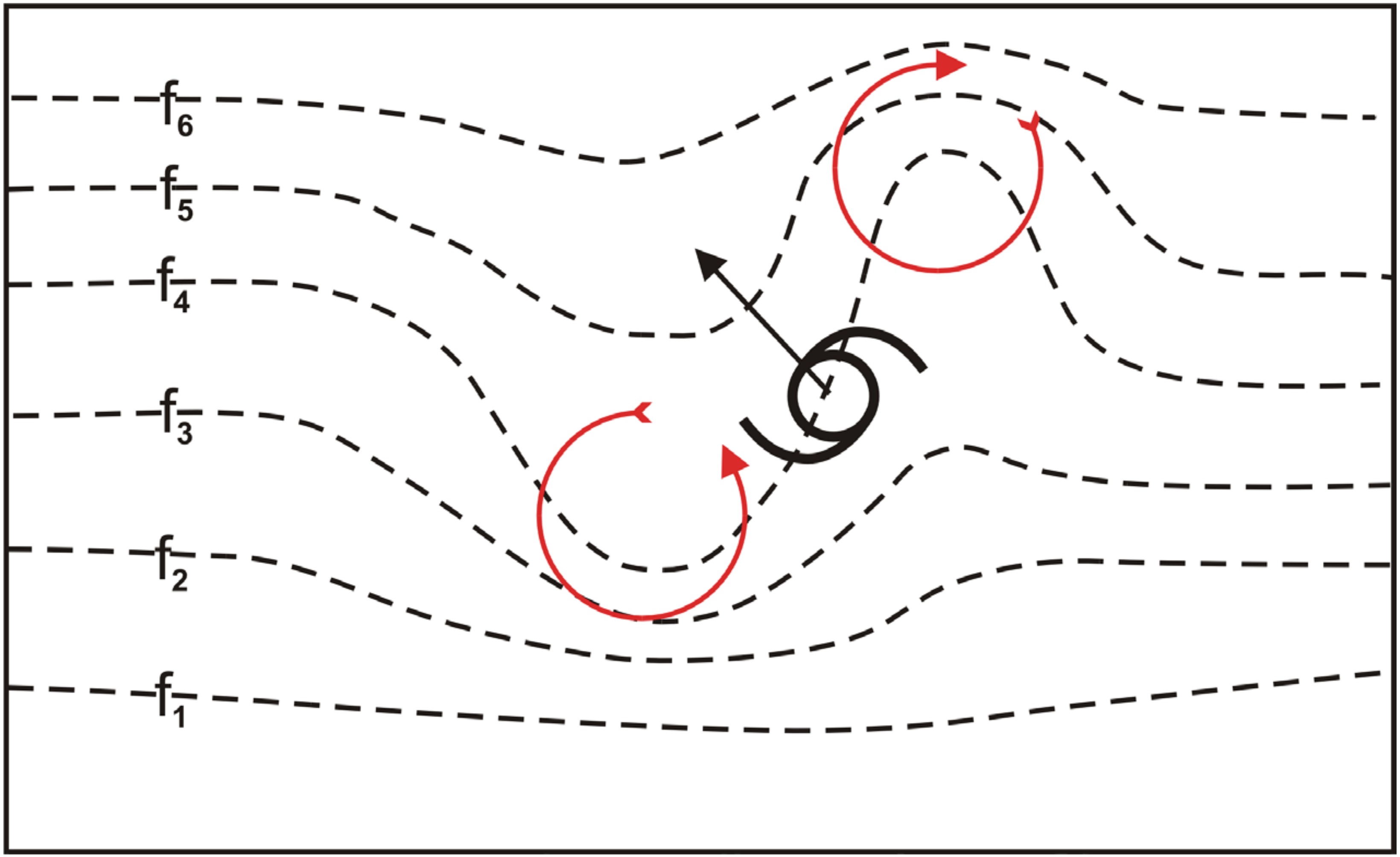


35
30
25
20
15
145
150
155
160
165
Latitude
Longitude
50
40
30
20

Lagrangian chaos:

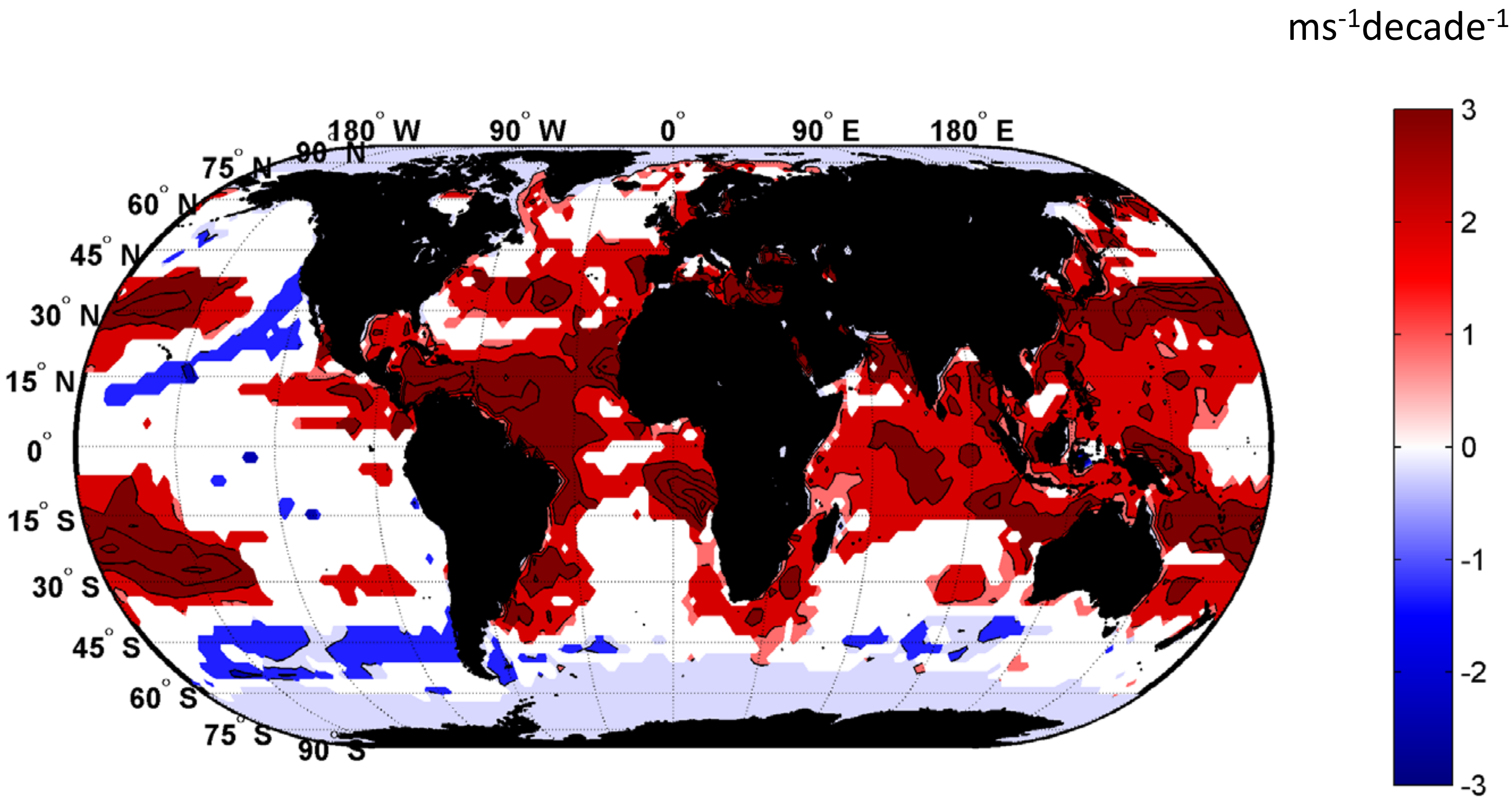


Vortices in interacting with Earth’s vorticity:



Hurricanes and Climate

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



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

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 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**