Introduction to Tropical Cyclones

Program

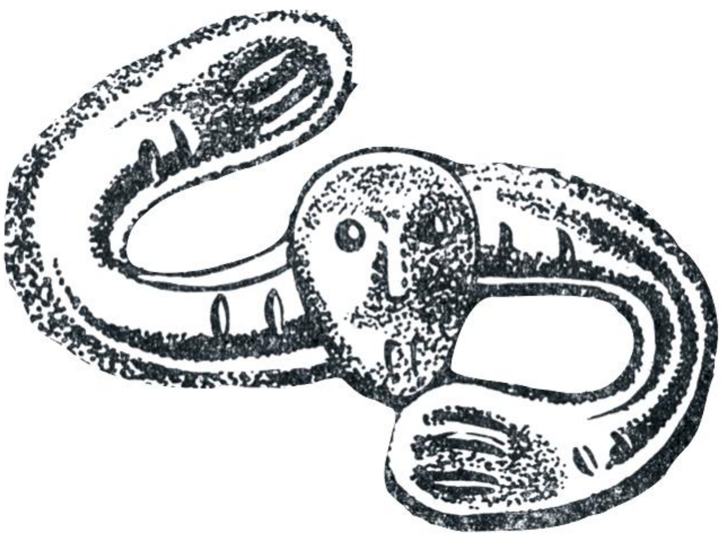
- **Overview of hurricanes**
- **Physics of mature, steady hurricanes**
- **Hurricanes and climate change**

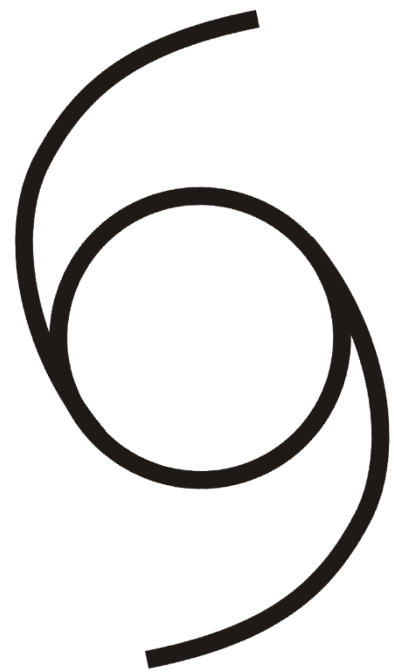
Overview: What is a Hurricane?

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

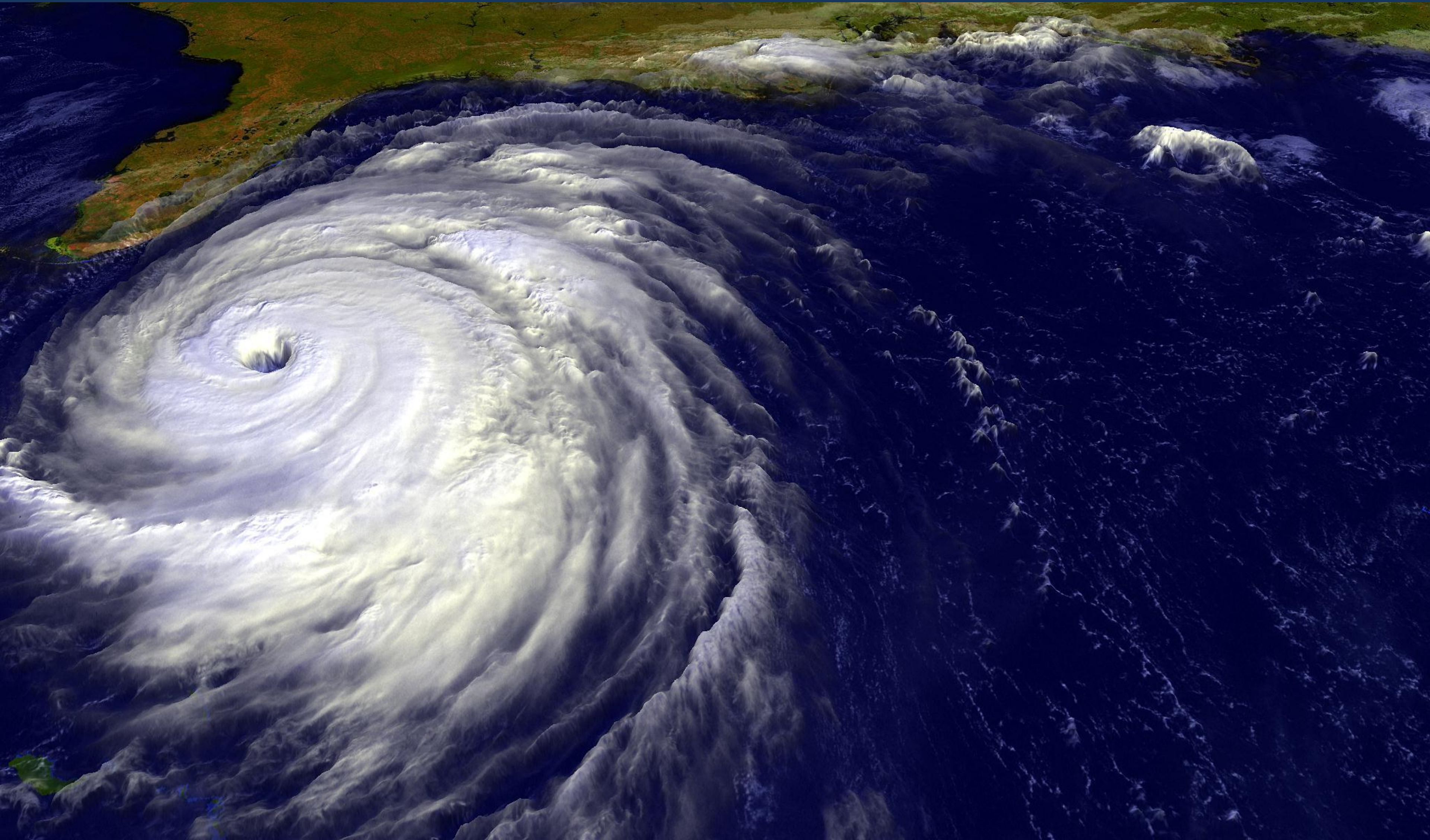
A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface

The word *Hurricane* is derived from the Mayan word *Huracan* and the Taino and Carib word *Hunraken*, a terrible God of Evil, and brought to the West by Spanish explorers

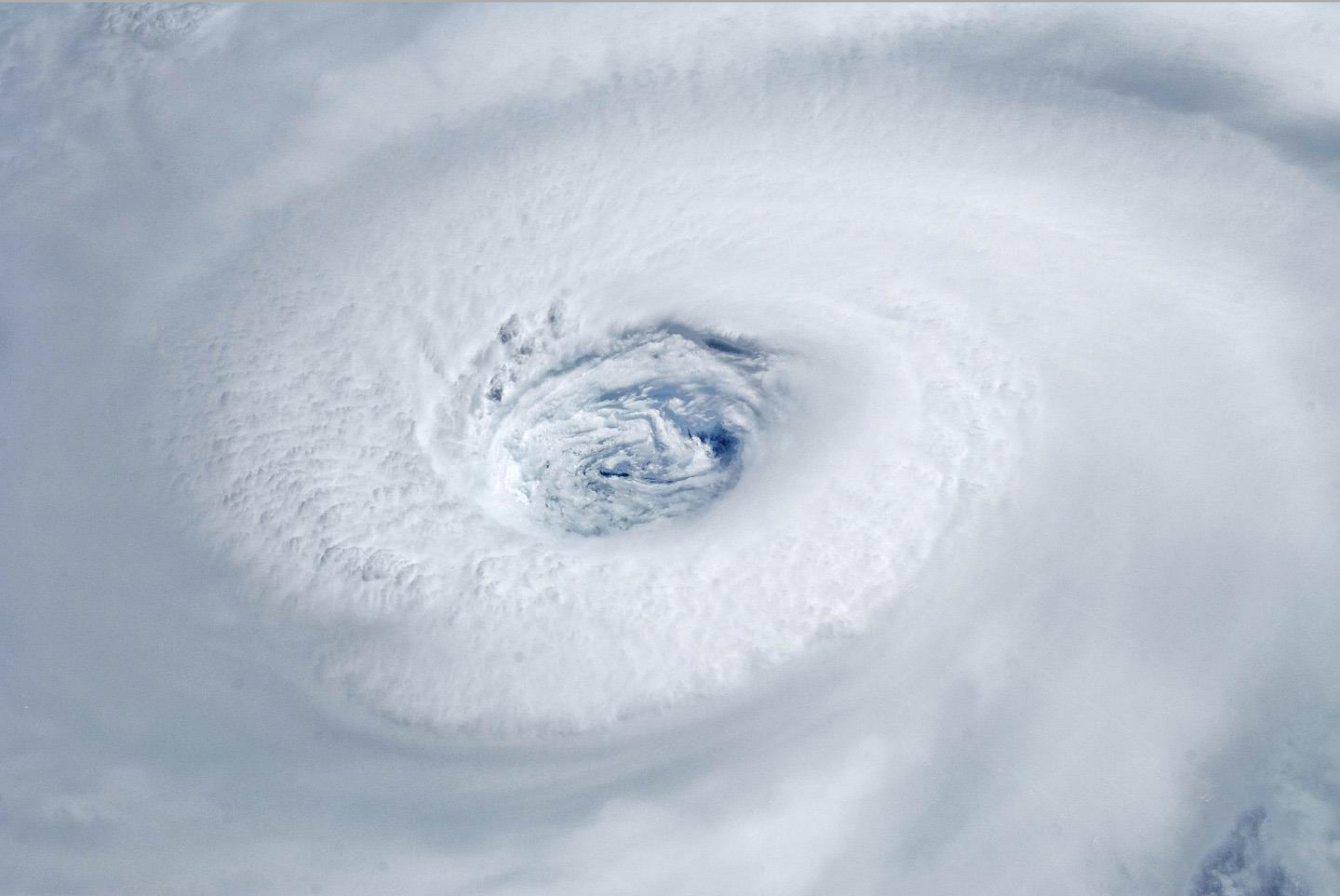




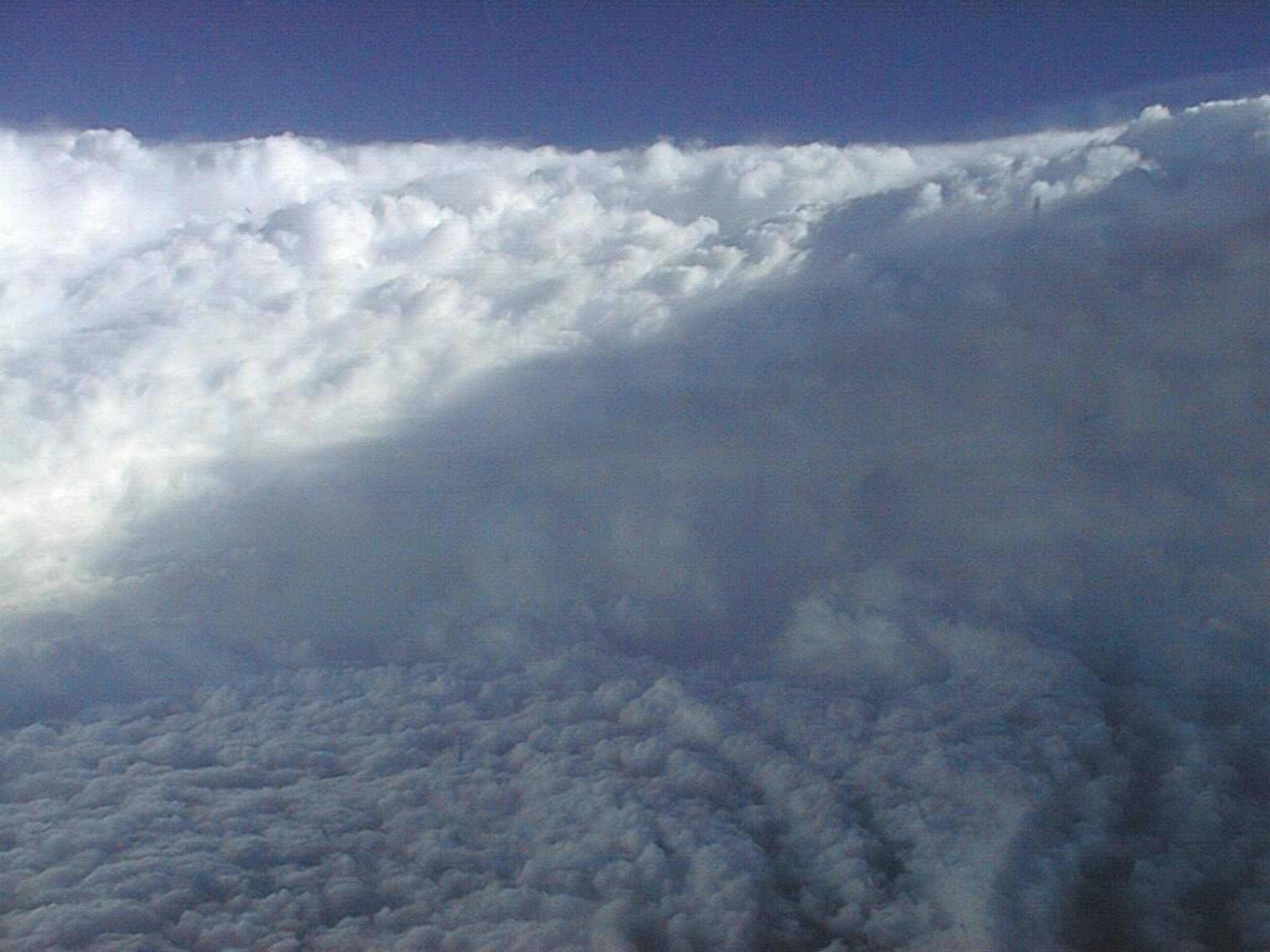
The View from Space



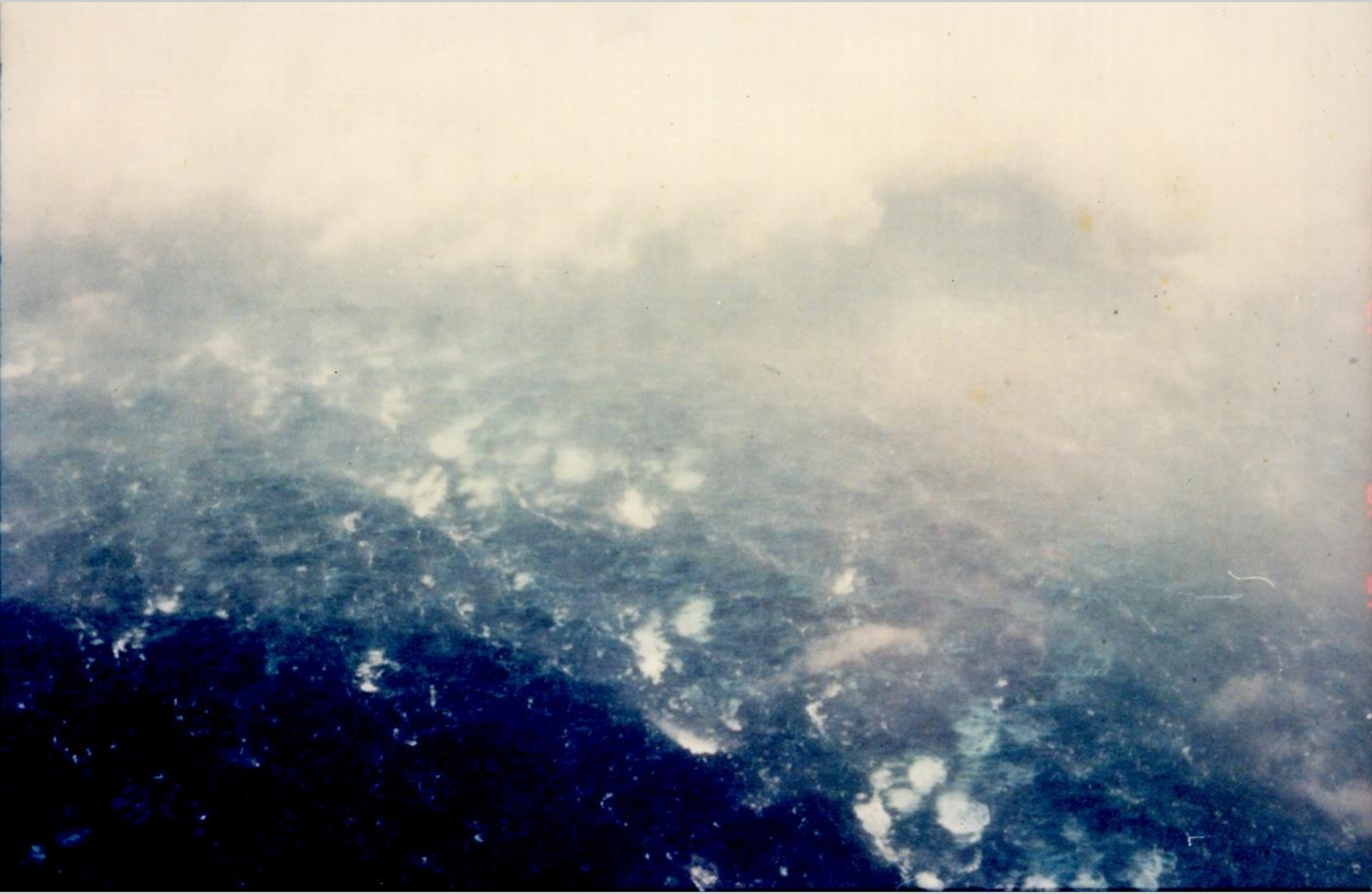
Igor, 2010



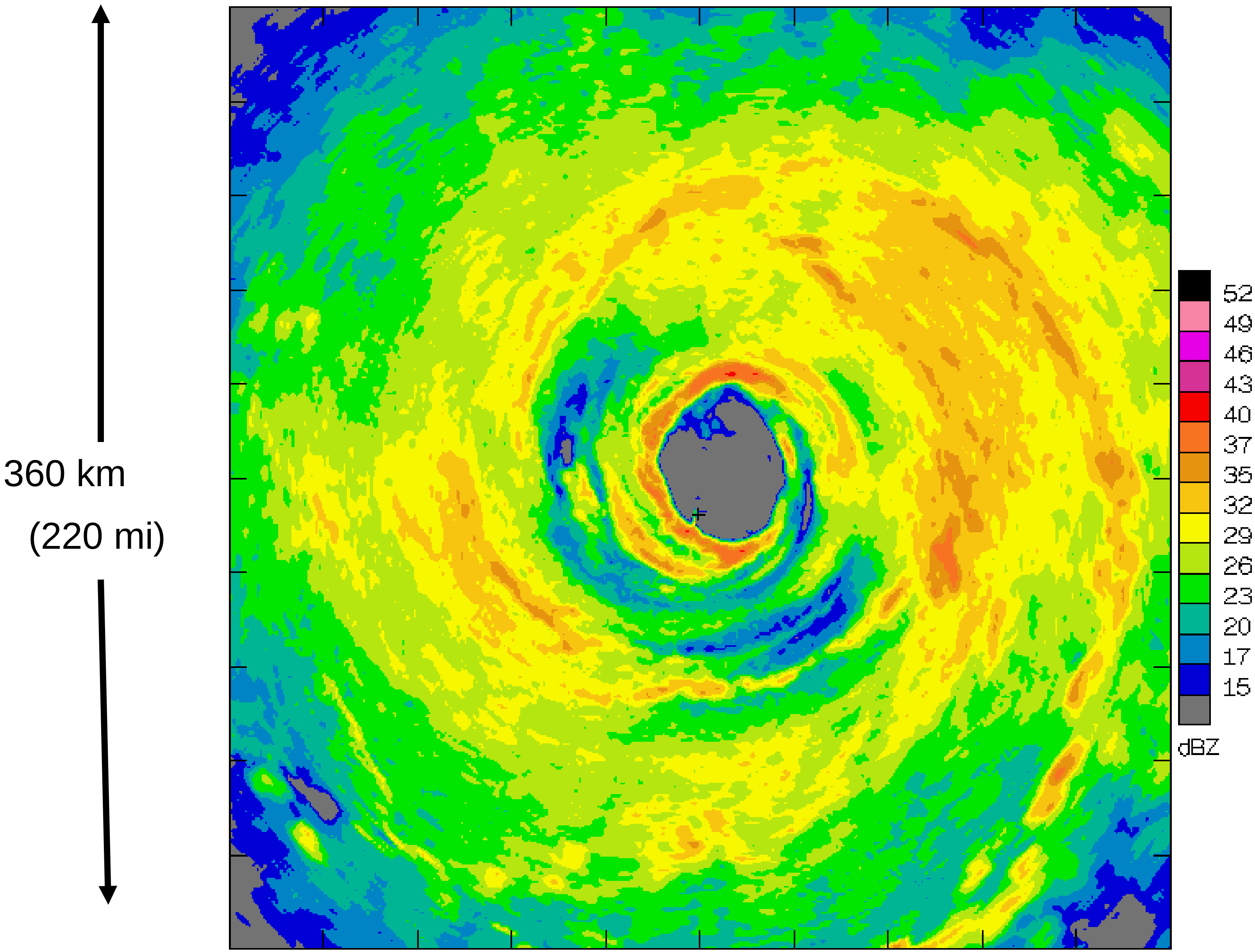

UNITED STATES DEPT OF COMMERCE
UNITED STATES DEPT. OF COMMERCE



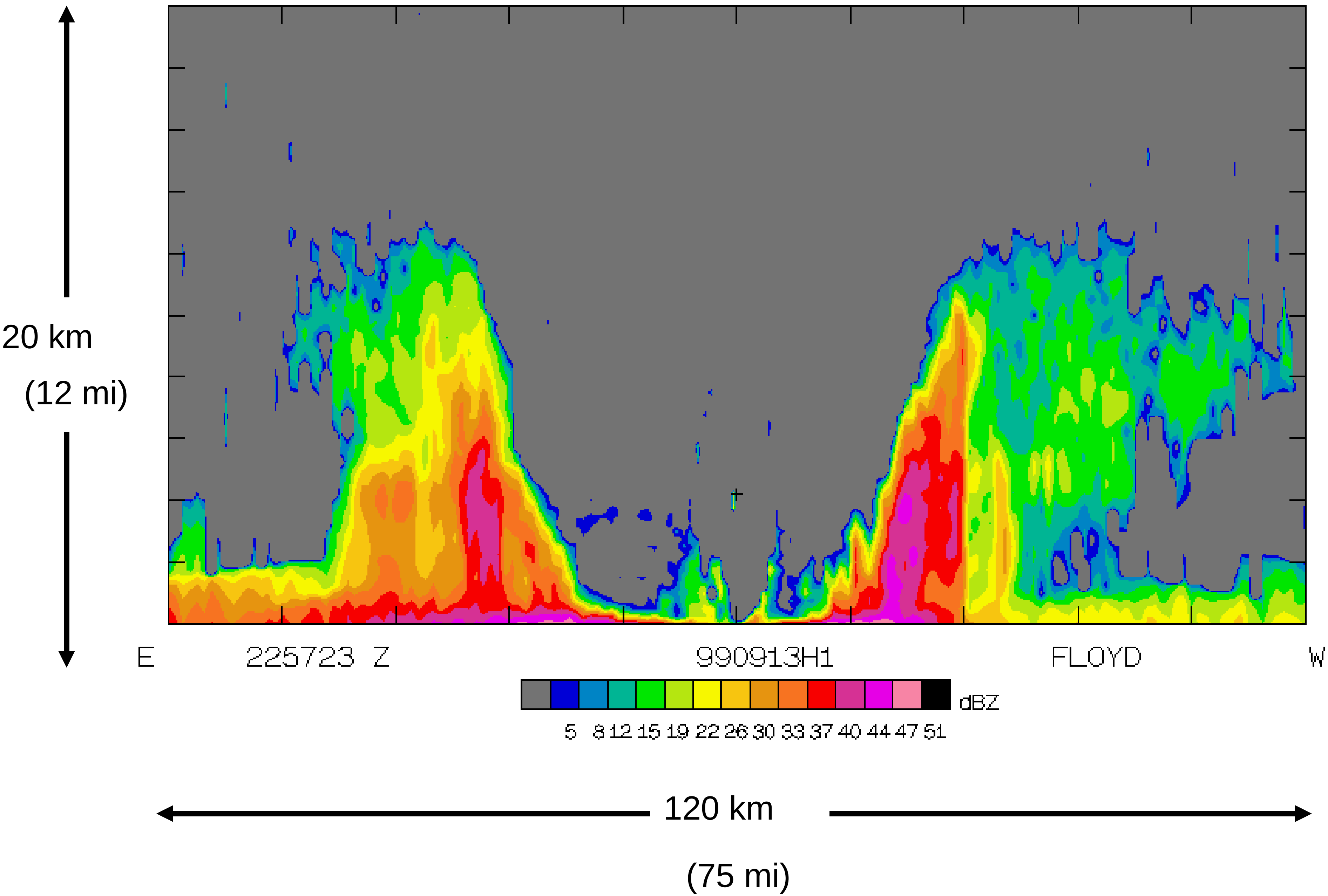
View of the eye of Hurricane Katrina on August 28th, 2005, as seen from a NOAA WP-3D hurricane reconnaissance aircraft.

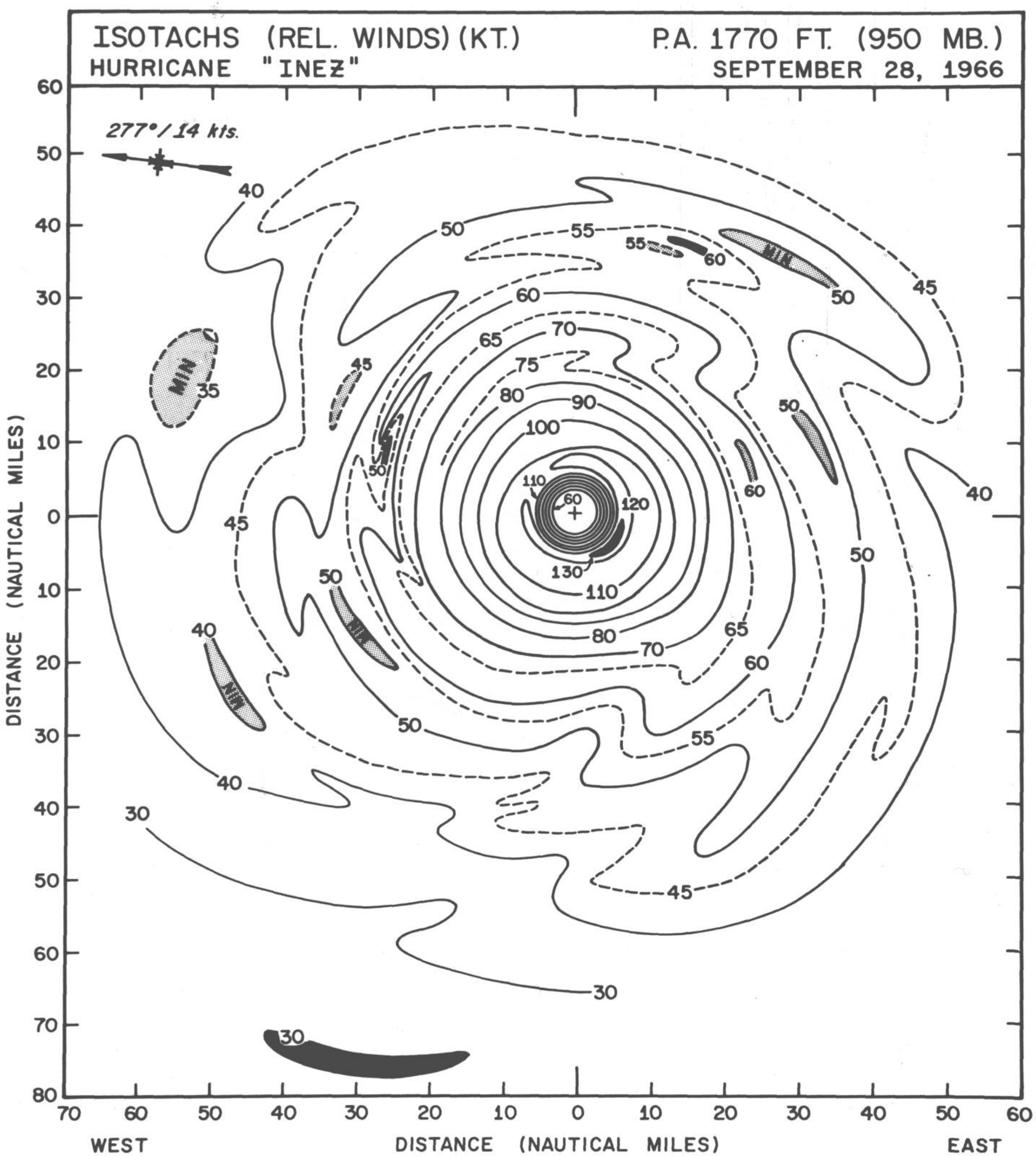


Airborne Radar: Horizontal Map



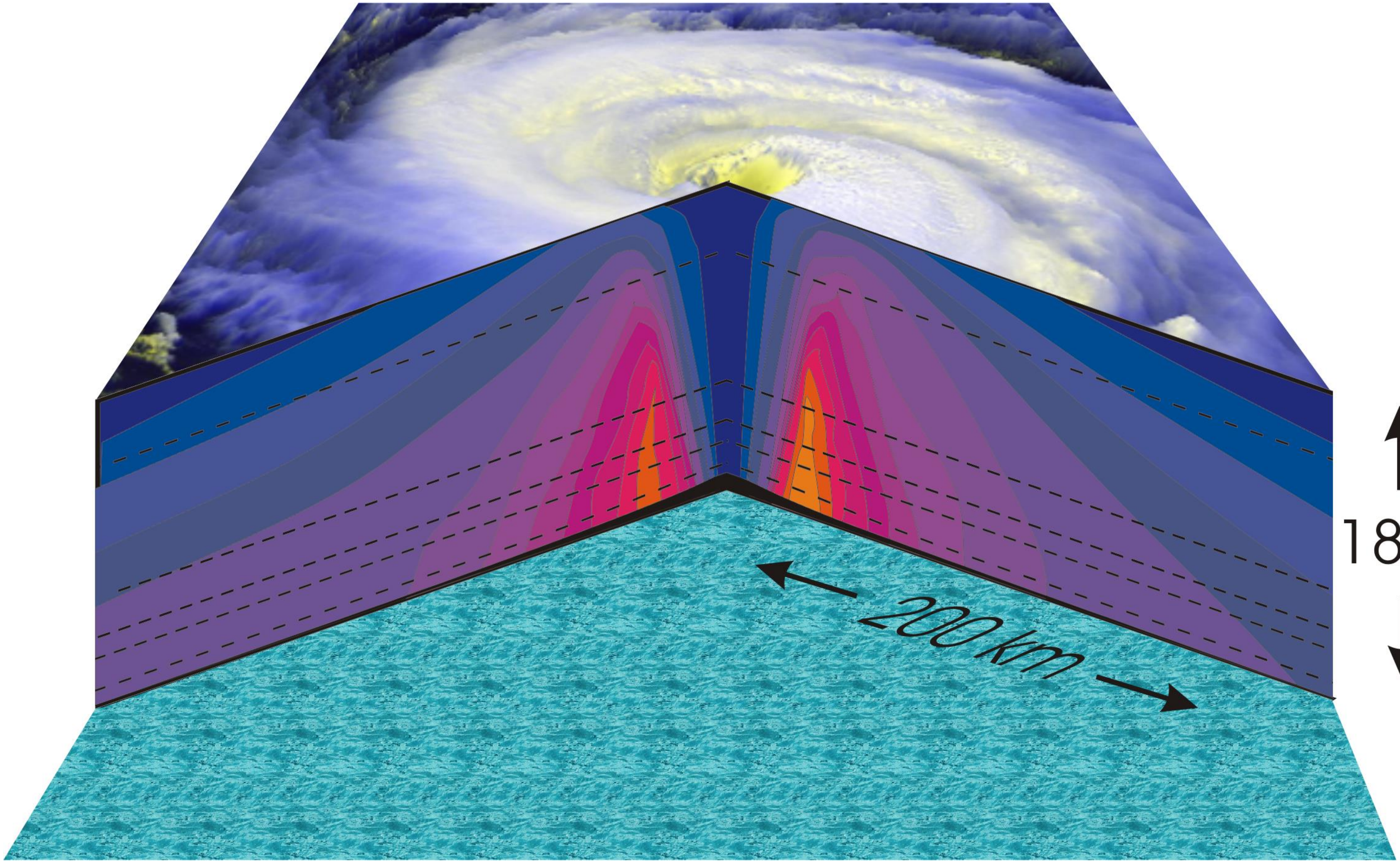
Airborne Radar: Vertical Slice





ISOTACHS (REL. WINDS) (KT.)
HURRICANE "INEZ"
P.A. 1770 FT. (950 MB.)
SEPTEMBER 28, 1966
277°/14 kts.
DISTANCE (NAUTICAL MILES)
WEST
EAST
MIN

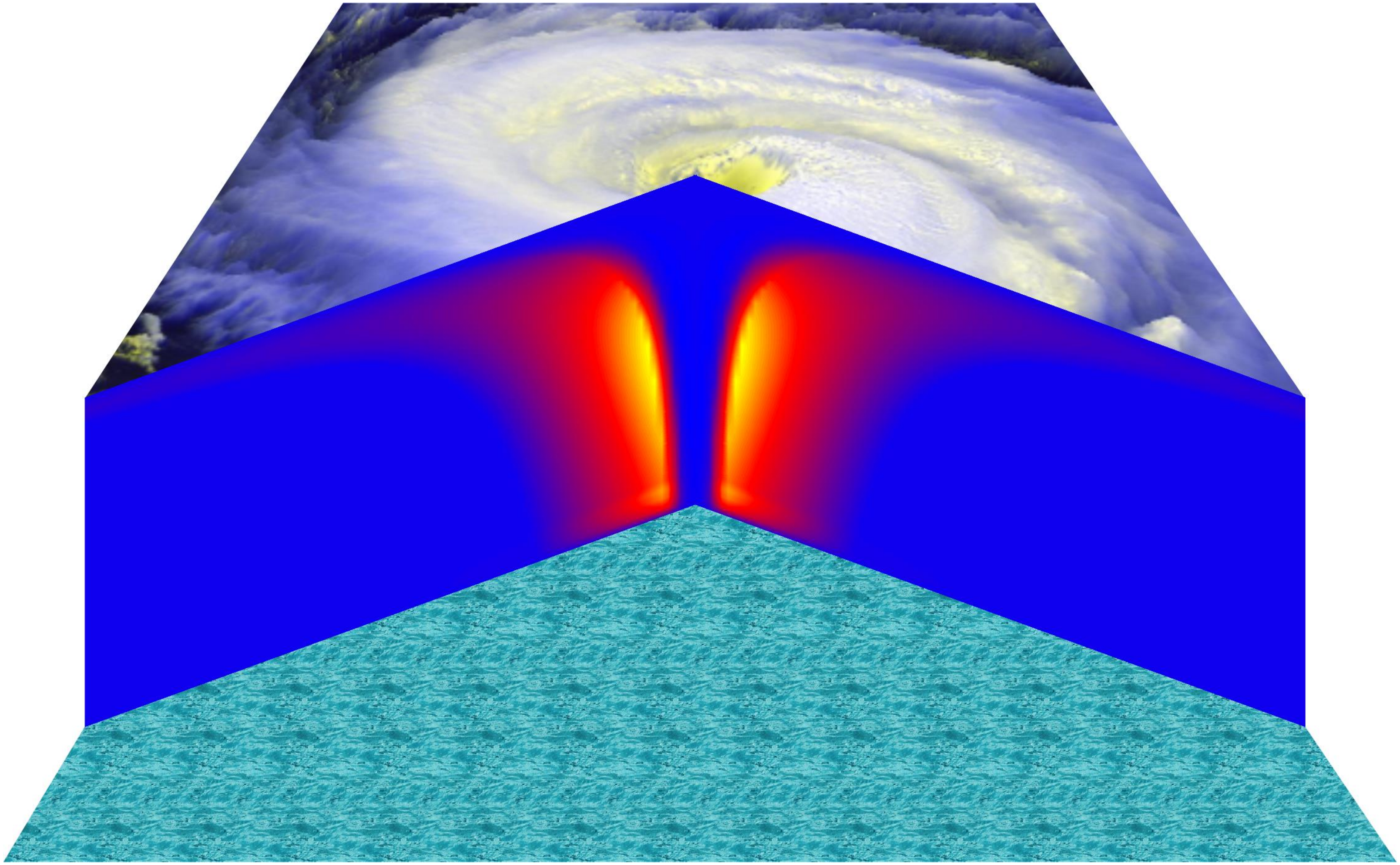
Hurricane Structure: Wind Speed



Azimuthal component of wind

< 11 mph - > 145 mph

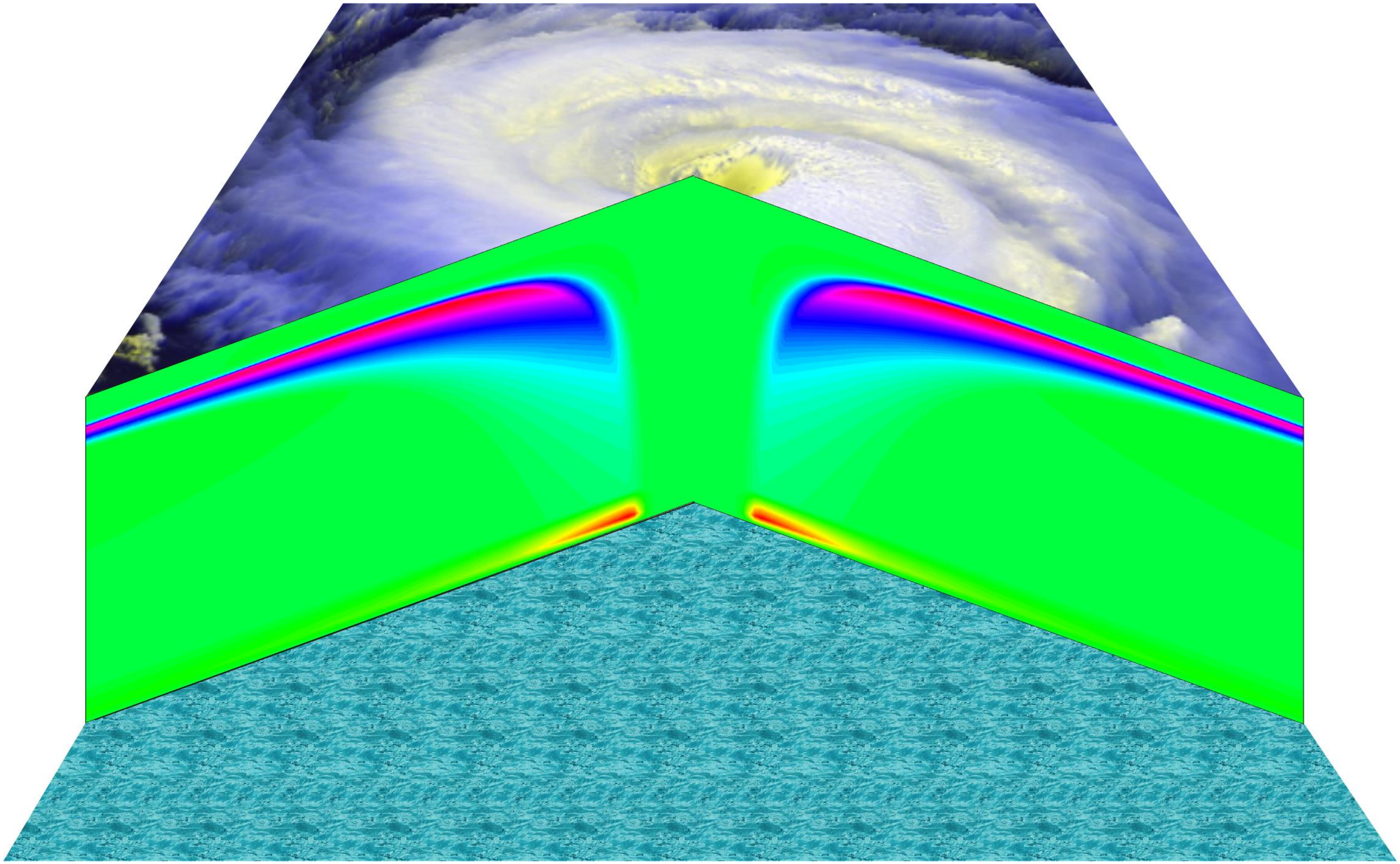
Vertical Air Motion



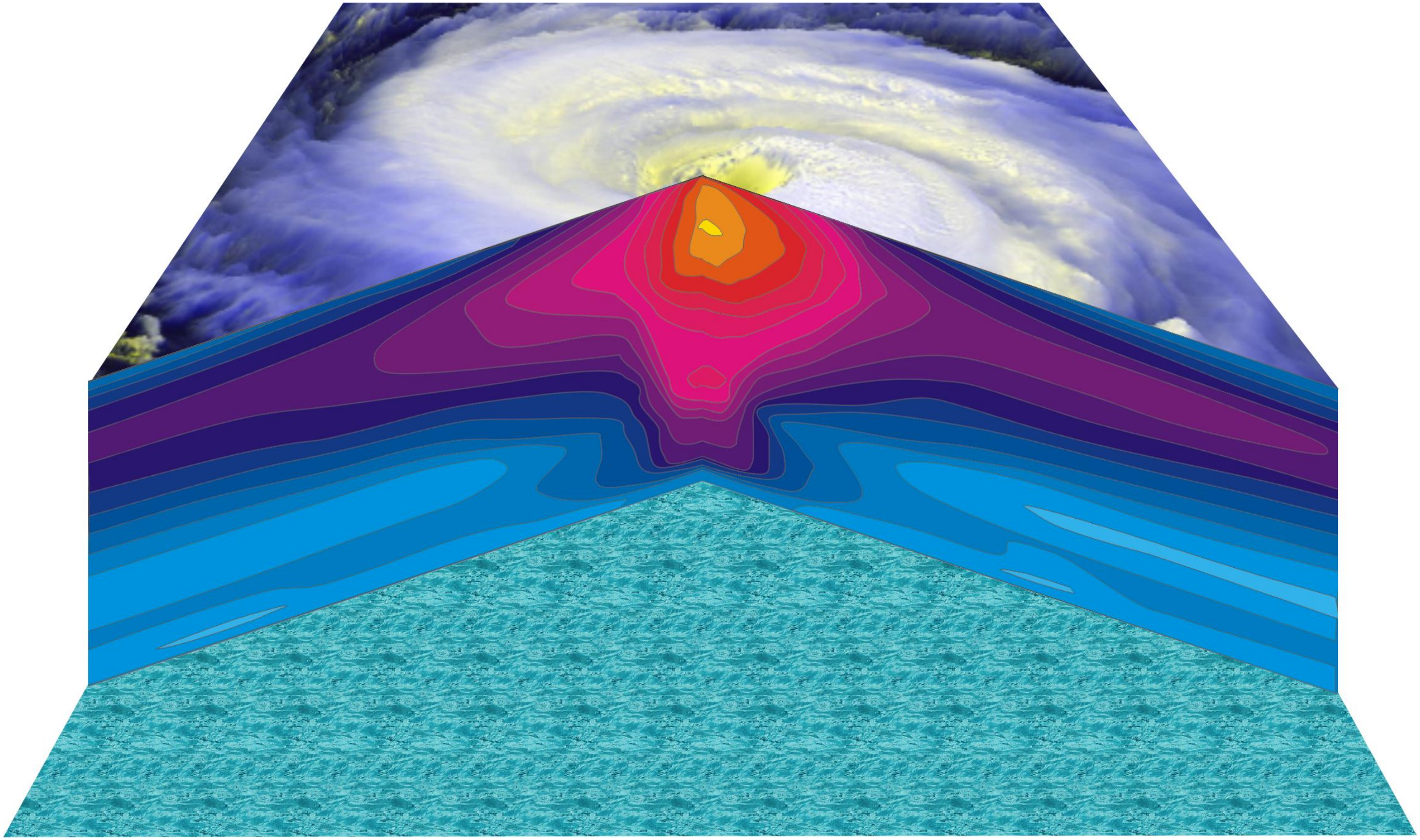
Updraft Speed

Strong upward motion in the eyewall

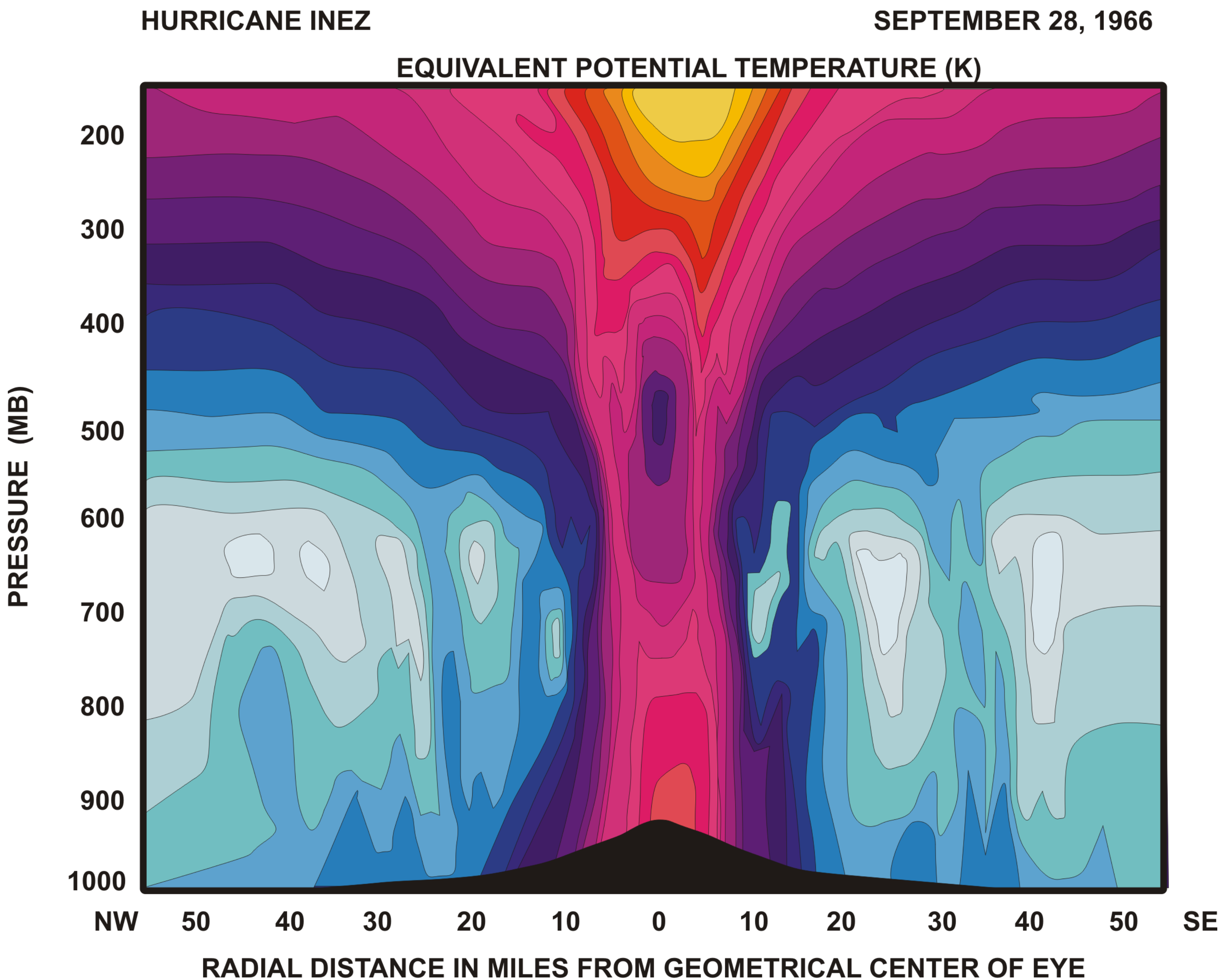
Radial wind



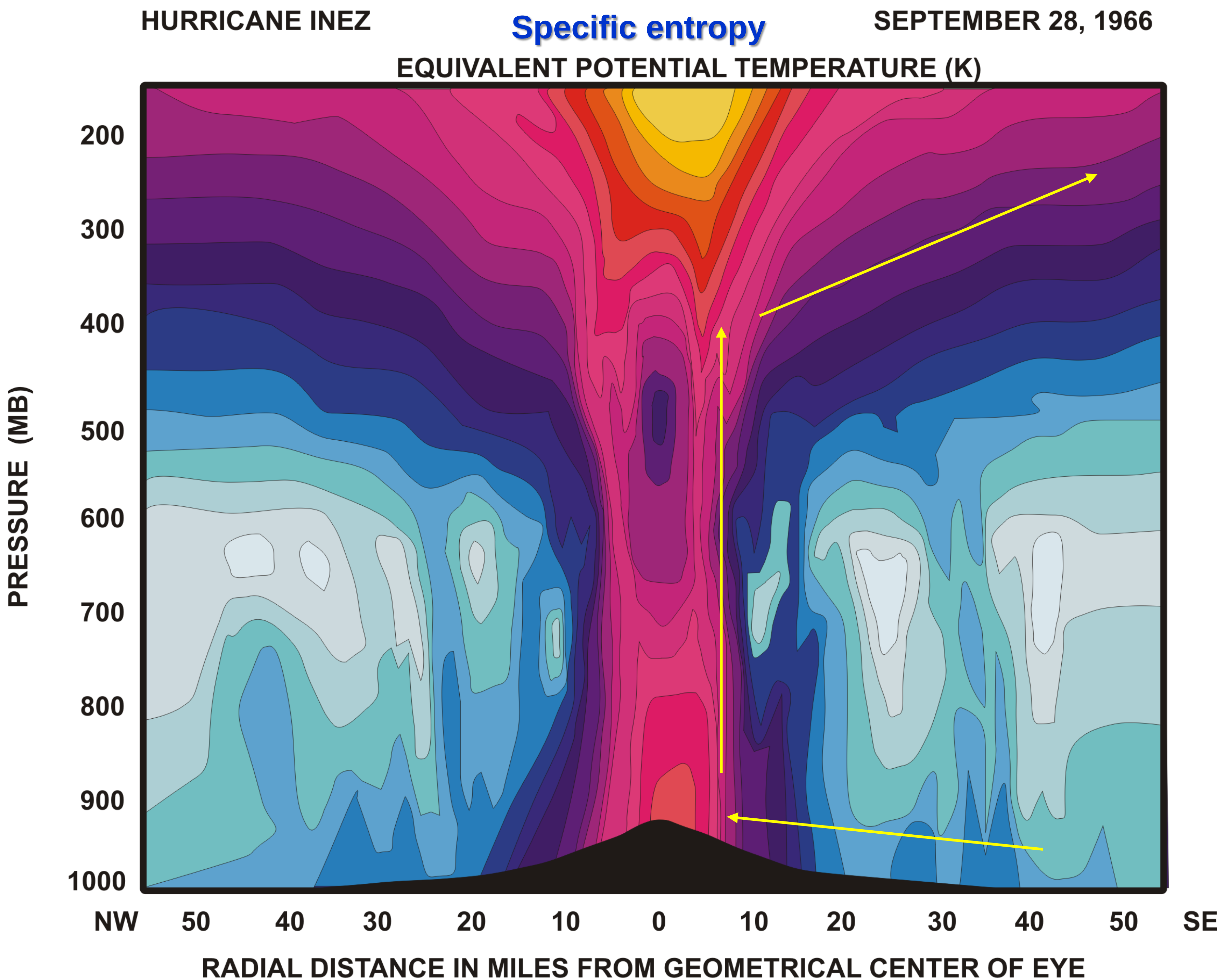
Hurricane Temperature Perturbations



No temperature difference - > 16°C (29°F) warmer

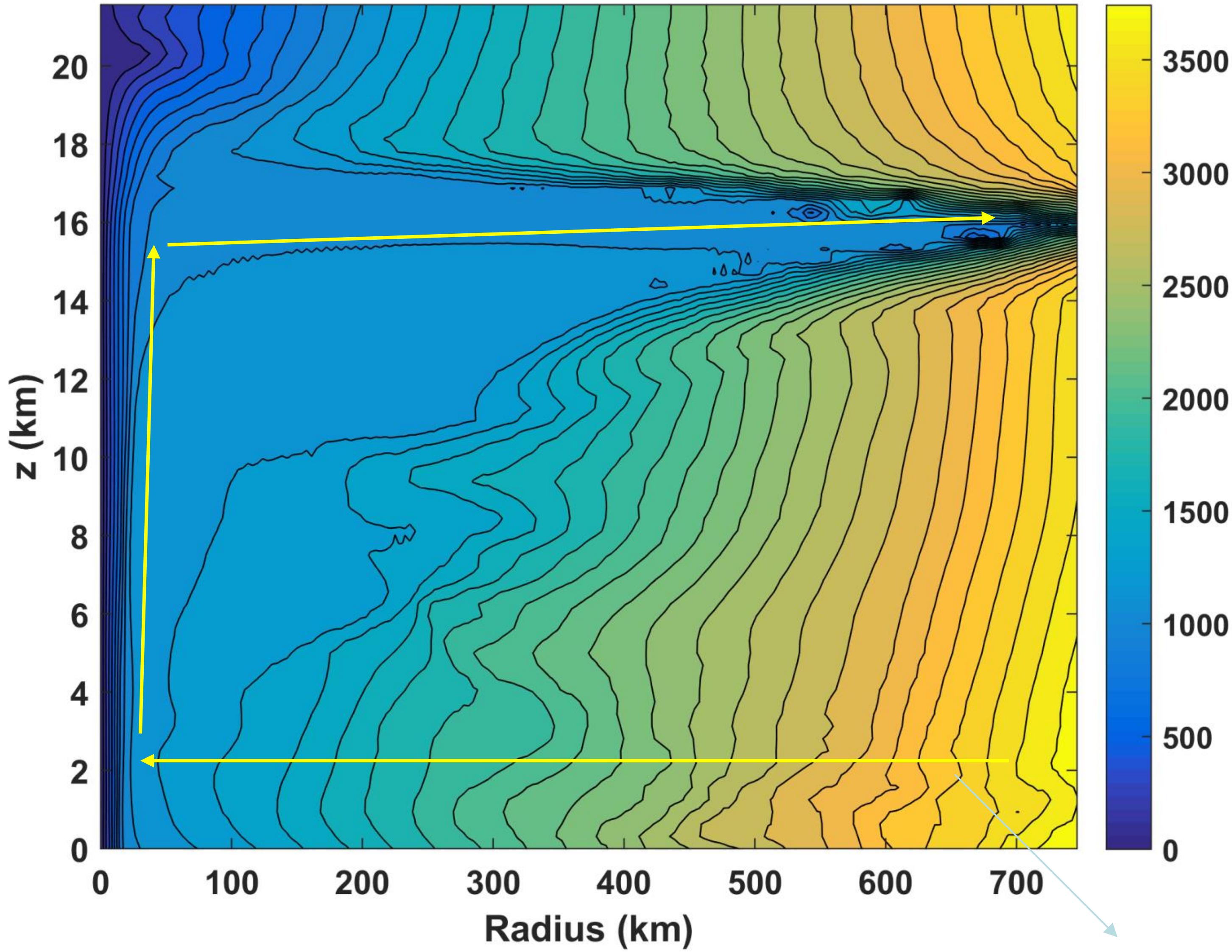


HURRICANE INEZ
SEPTEMBER 28, 1966
EQUIVALENT POTENTIAL TEMPERATURE (K)
PRESSURE (MB)
200
300
400
500
600
700
800
900
1000
NW
50
40
30
20
10
0
10
20
30
40
50
SE
RADIAL DISTANCE IN MILES FROM GEOMETRICAL CENTER OF EYE

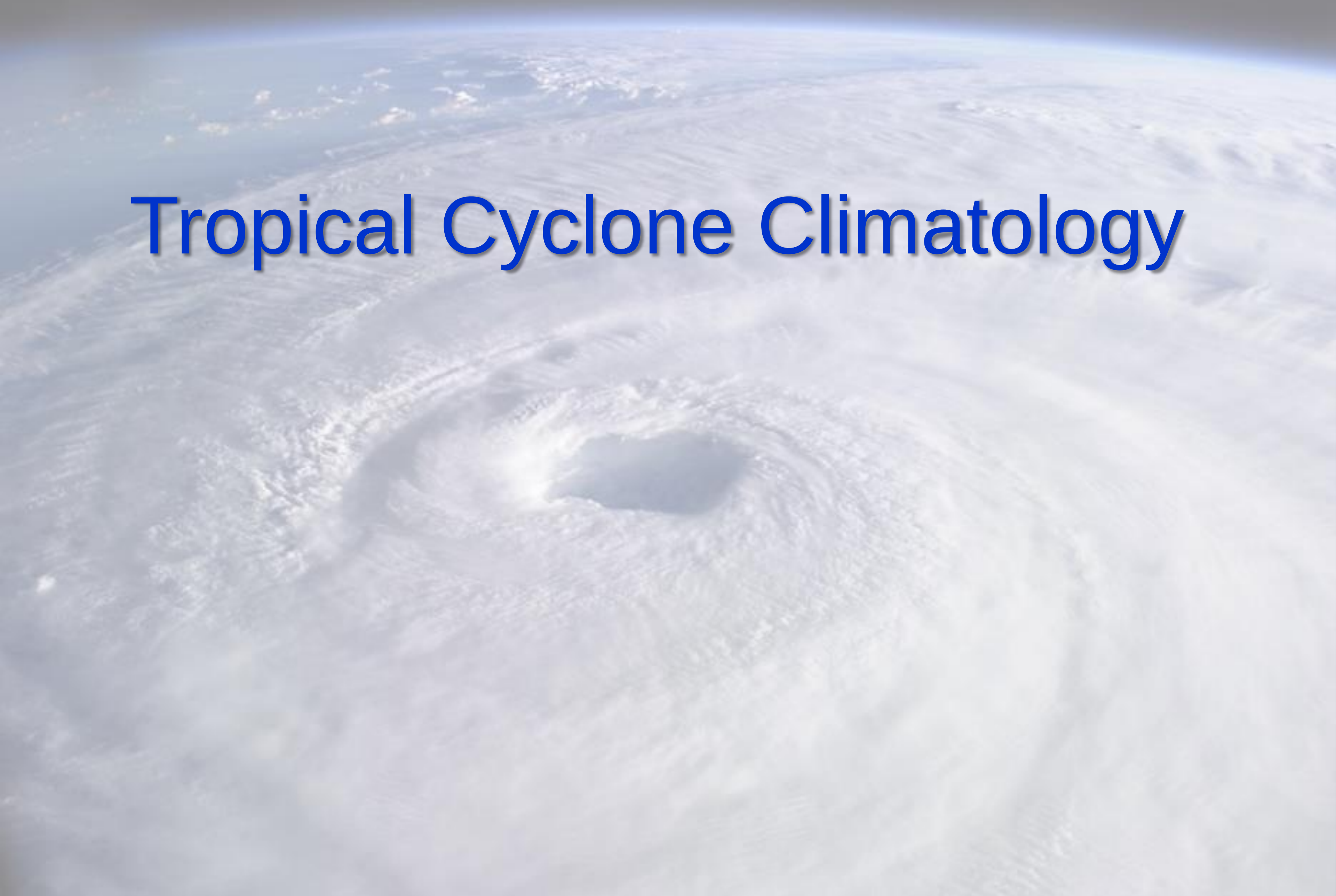

HURRICANE INEZ
Specific entropy
SEPTEMBER 28, 1966
EQUIVALENT POTENTIAL TEMPERATURE (K)
PRESSURE (MB)
200
300
400
500
600
700
800
900
1000
NW
50
40
30
20
10
0
10
20
30
40
50
SE
RADIAL DISTANCE IN MILES FROM GEOMETRICAL CENTER OF EYE

Absolute angular momentum per unit mass

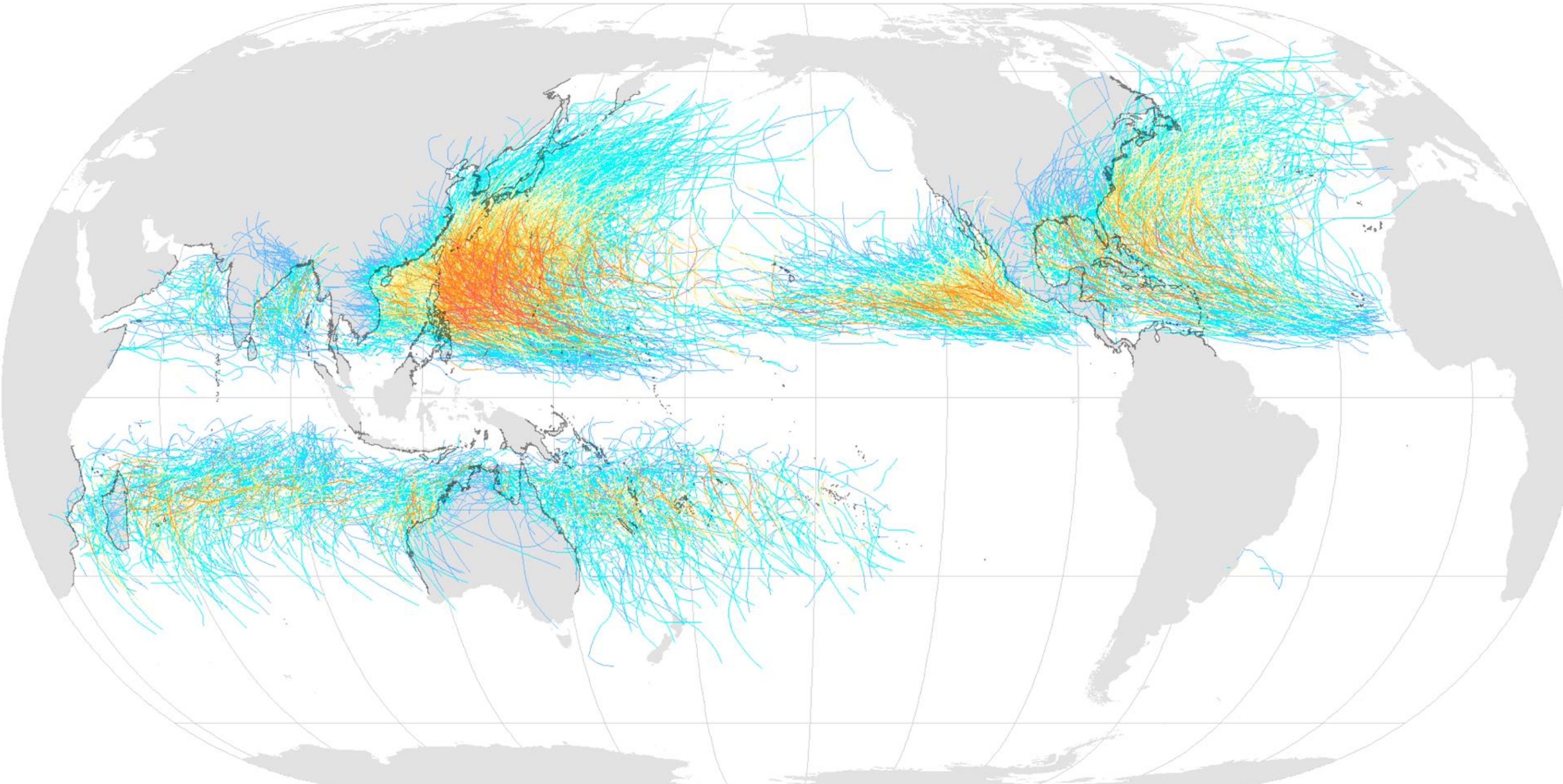
$$M = rV + \frac{1}{2} f r^2$$



Tropical Cyclone Climatology

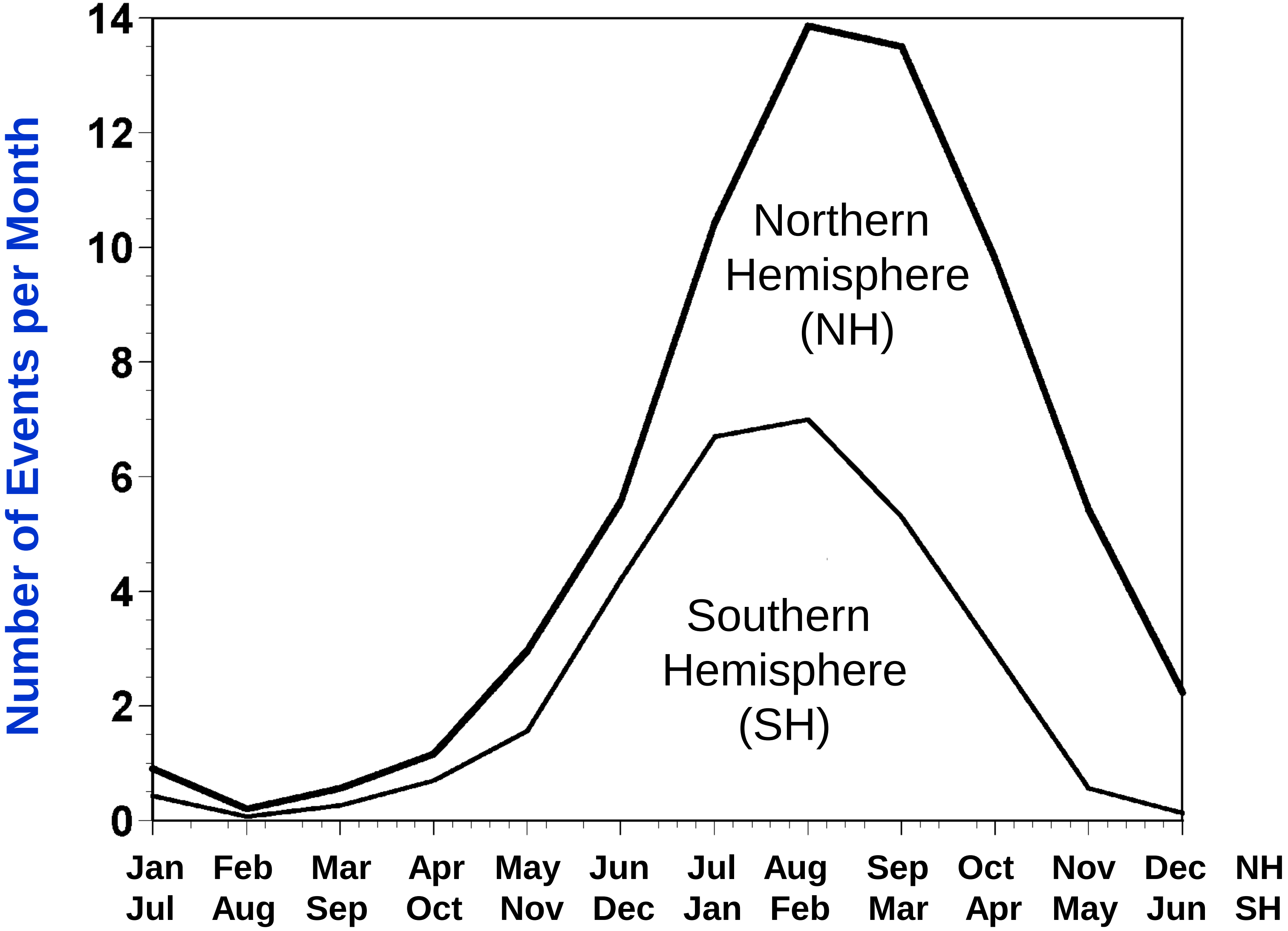


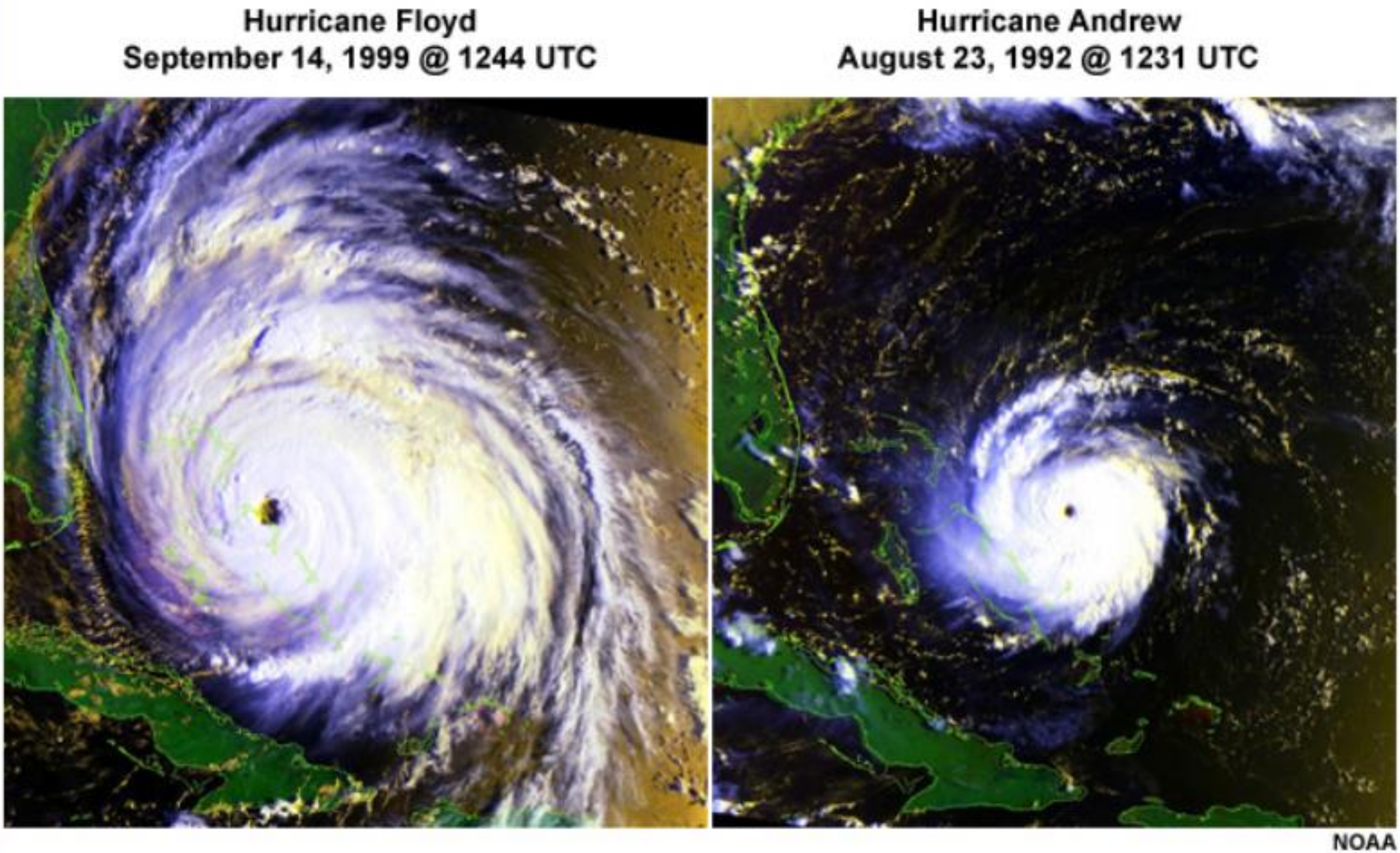
Tropical Cyclones, 1945–2006



Saffir-Simpson Hurricane Scale:

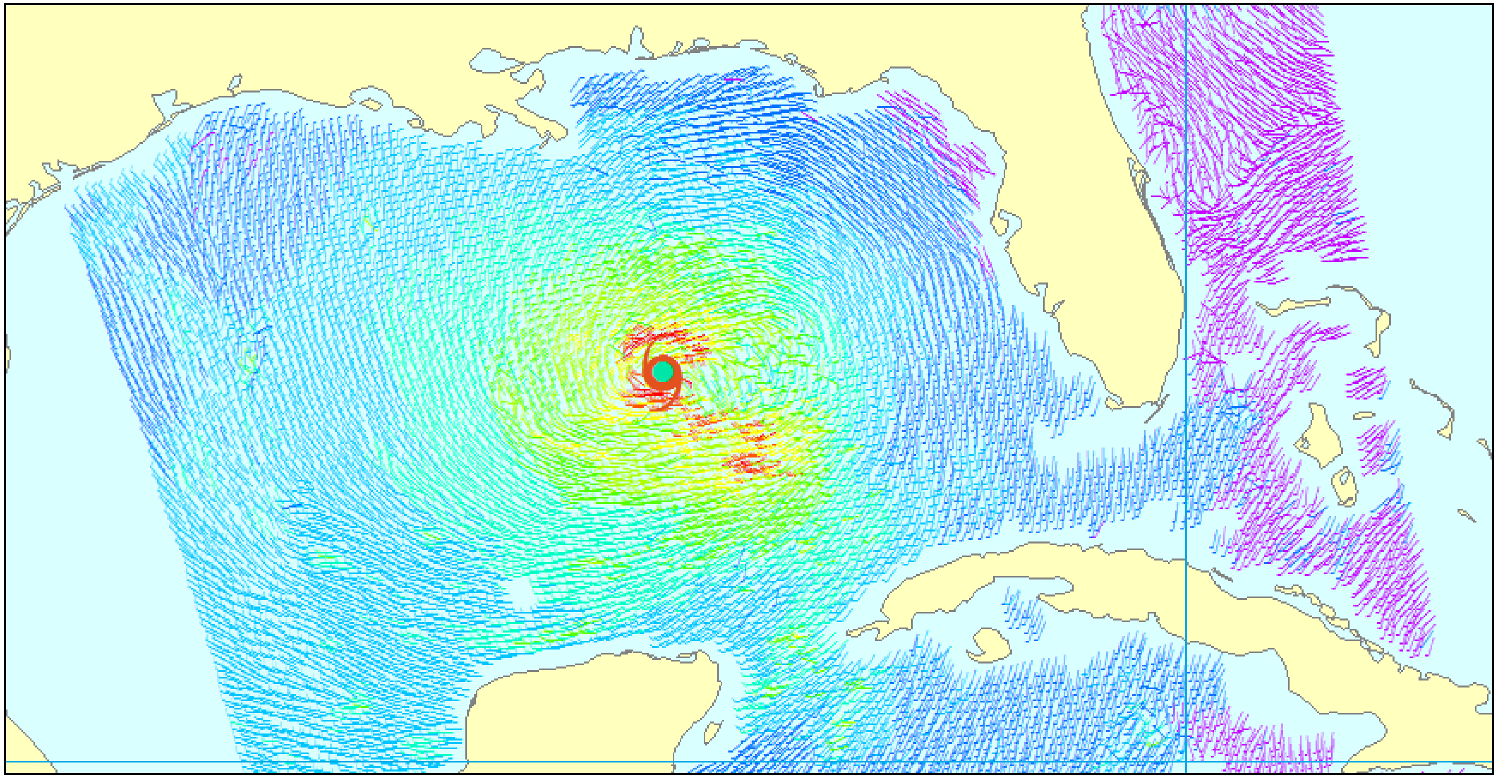
Annual Cycle of Tropical Cyclones

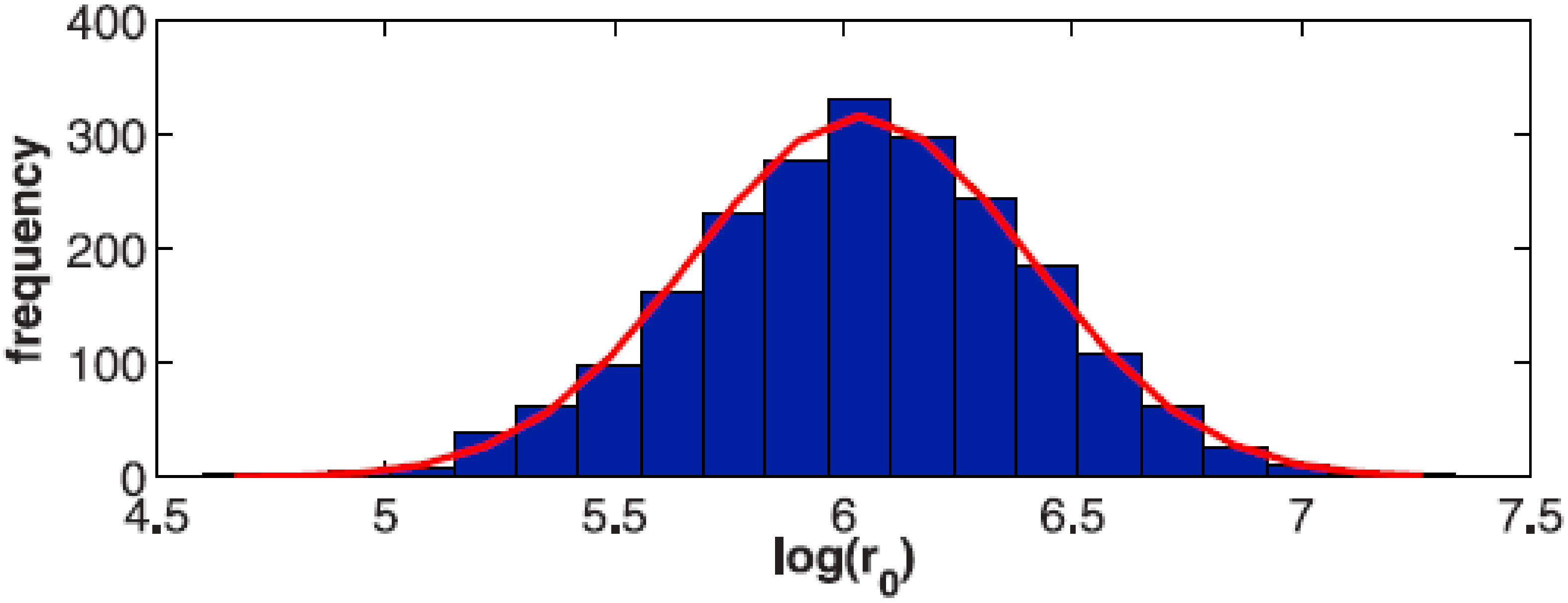




The spiral rainbands of Hurricane Floyd (left, 1999) versus the more compact Hurricane Andrew (right, 1992)

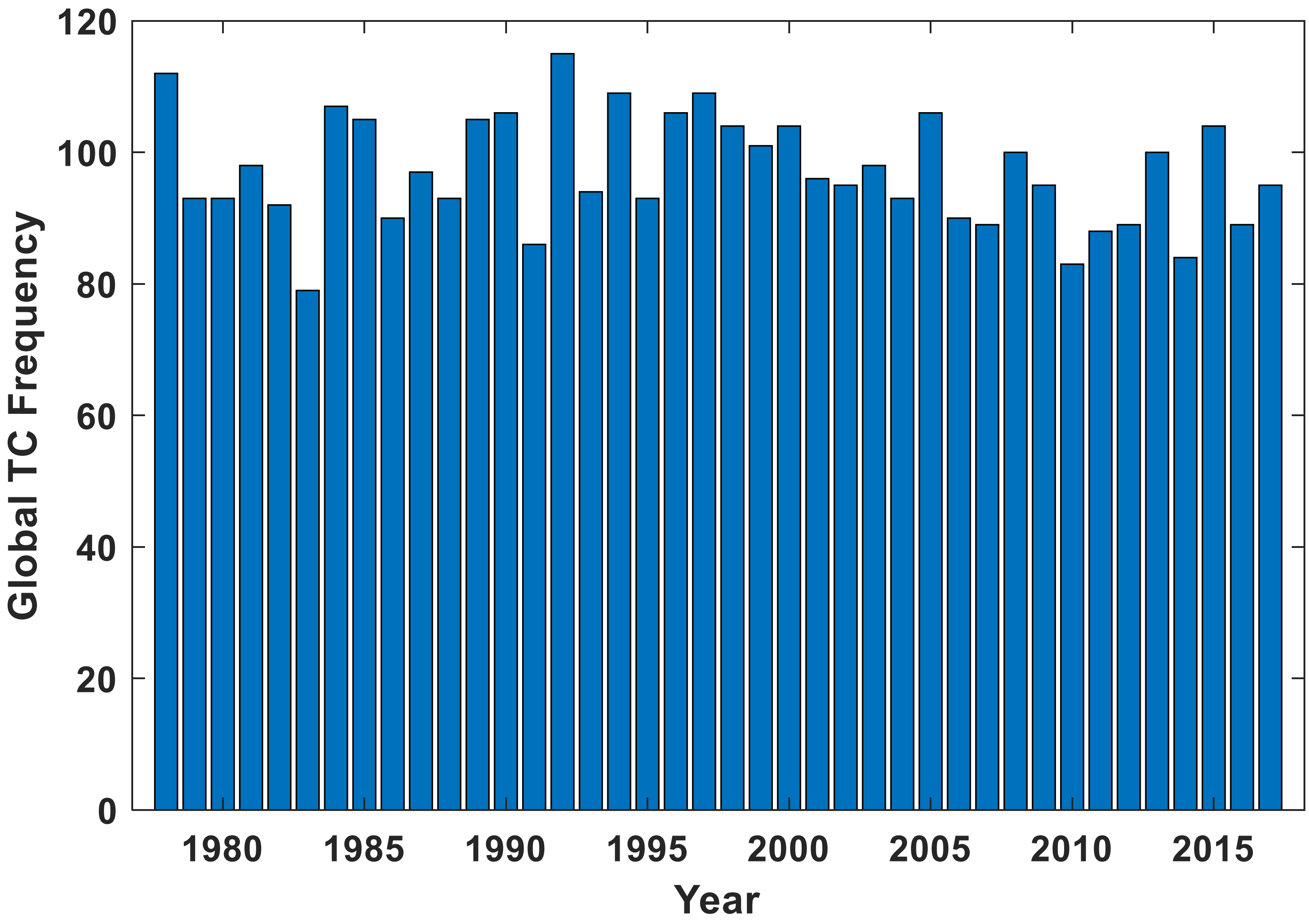
Climatology of Tropical Cyclone Size





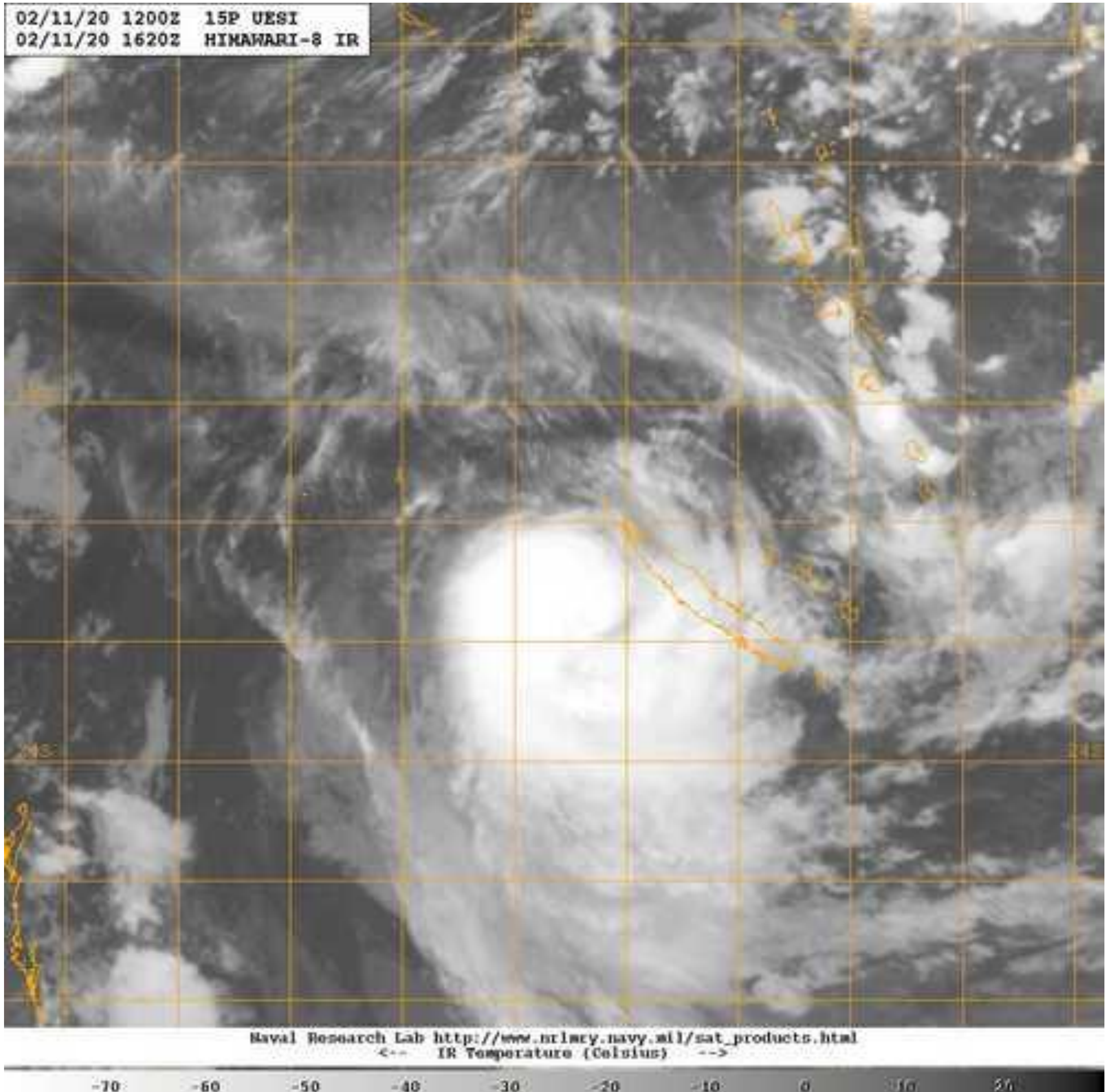
Outer radius very nearly follows a log-normal distribution with a median value of about 420 km (Courtesy Dan Chavas)

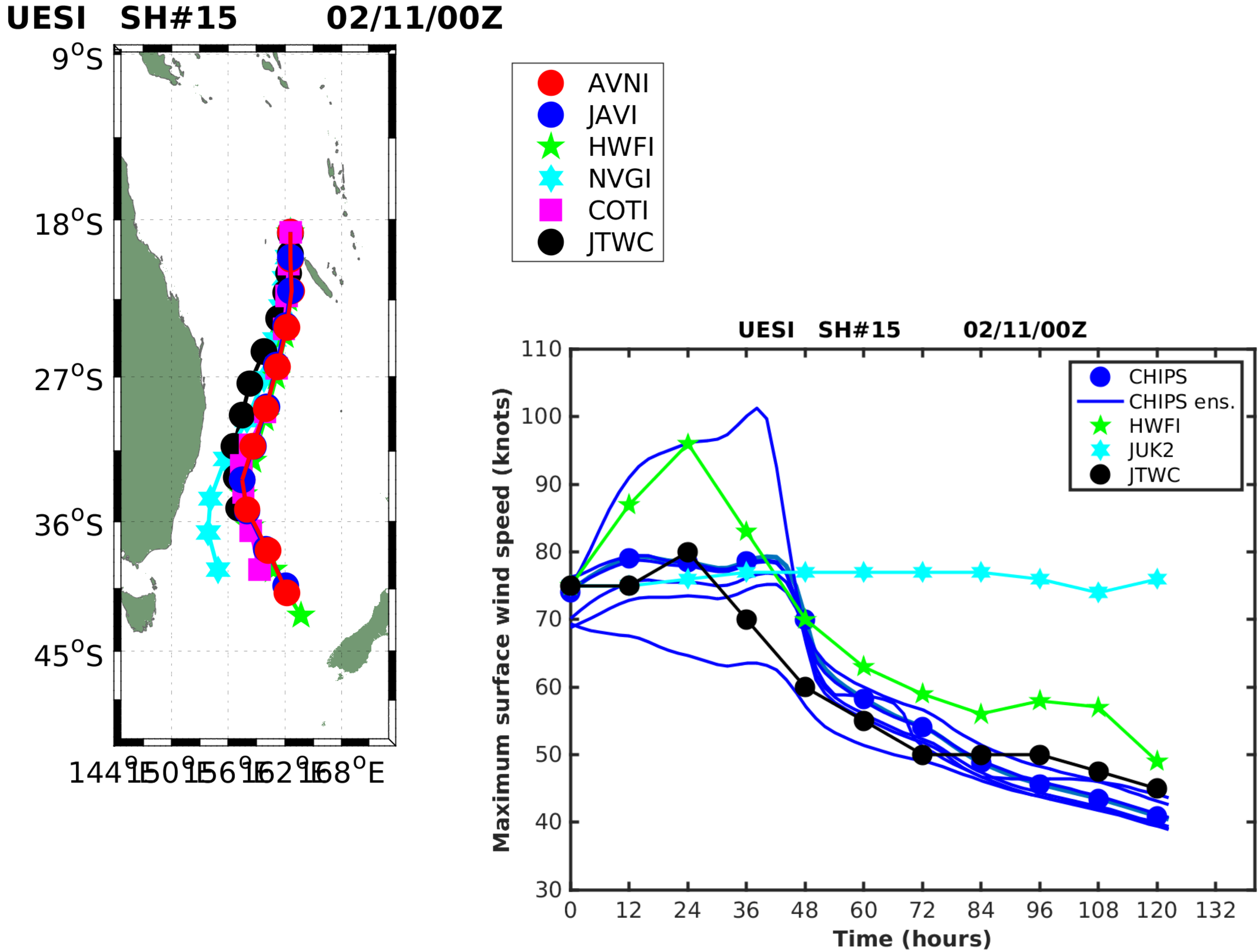
Global Tropical Cyclone Frequency, 1978-2017



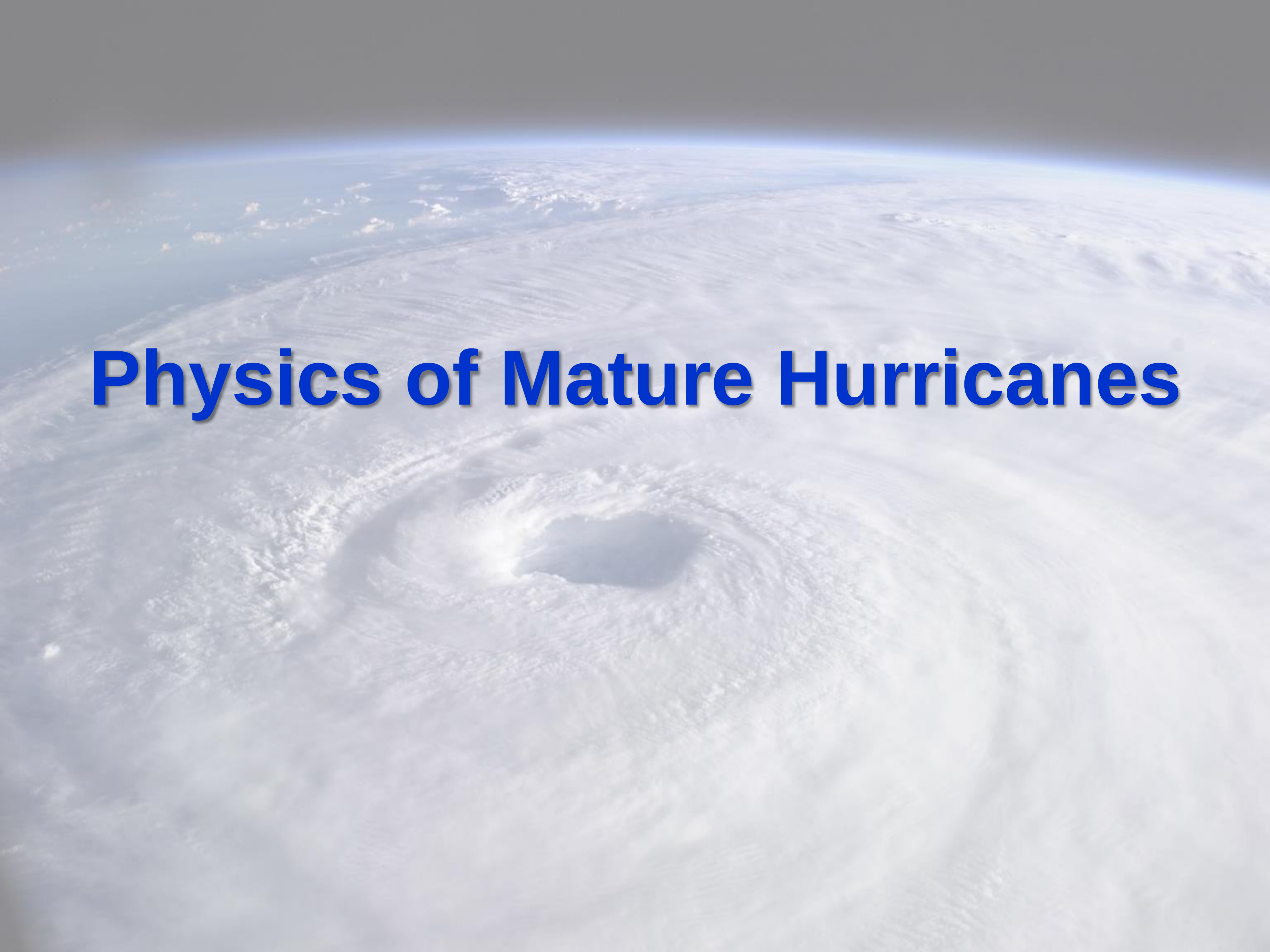
Data Sources: NOAA/TPC and NAVY/JTWC

Tropical Cyclone Uesi, February 11 2020 7 AM EST

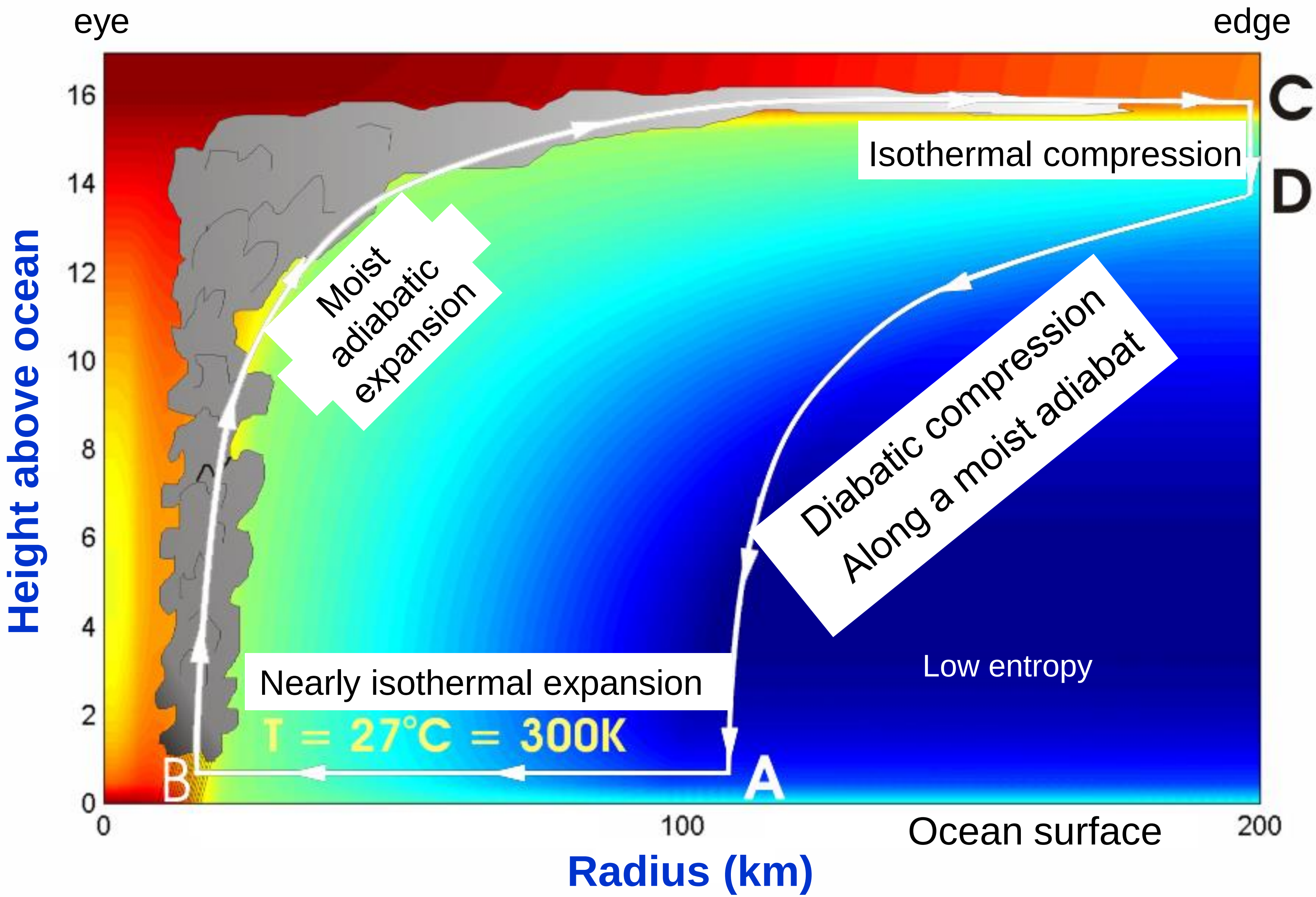




UESI SH#15 02/11/00Z
9°S
18°S
27°S
36°S
45°S
144°E 150°E 156°E 162°E 168°E
AVNI
JAVI
HWFI
NVGI
COTI
JTWC
UESI SH#15 02/11/00Z
Maximum surface wind speed (knots)
Time (hours)
CHIPS
CHIPS ens.
HWFI
JUK2
JTWC


Physics of Mature Hurricanes

Cross-section through a Hurricane & Energy Production



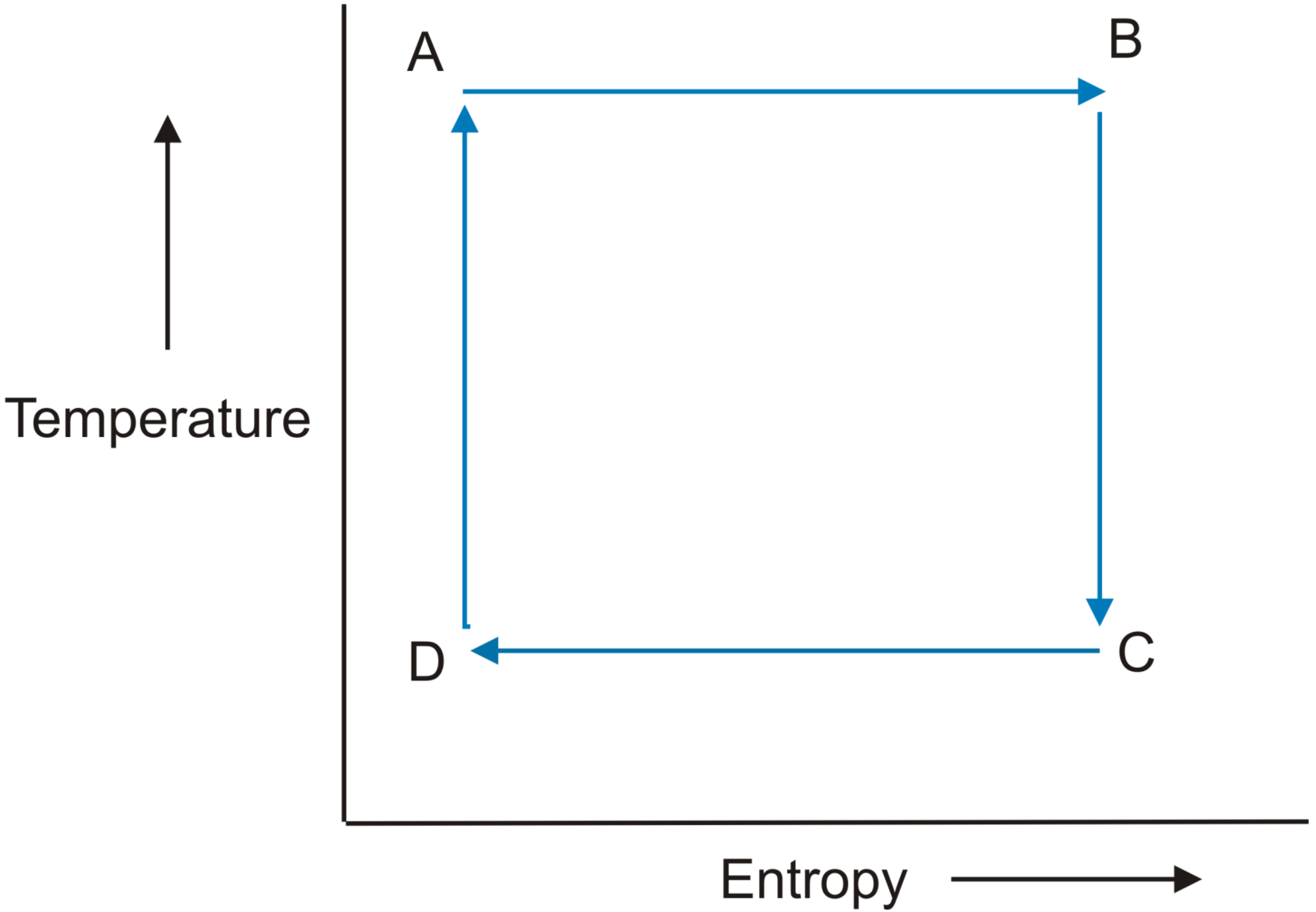
Carnot Theorem: Maximum efficiency results from a particular energy cycle:

- 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:

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


A
B
C
D
Temperature
Entropy

Total rate of heat input to hurricane:

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

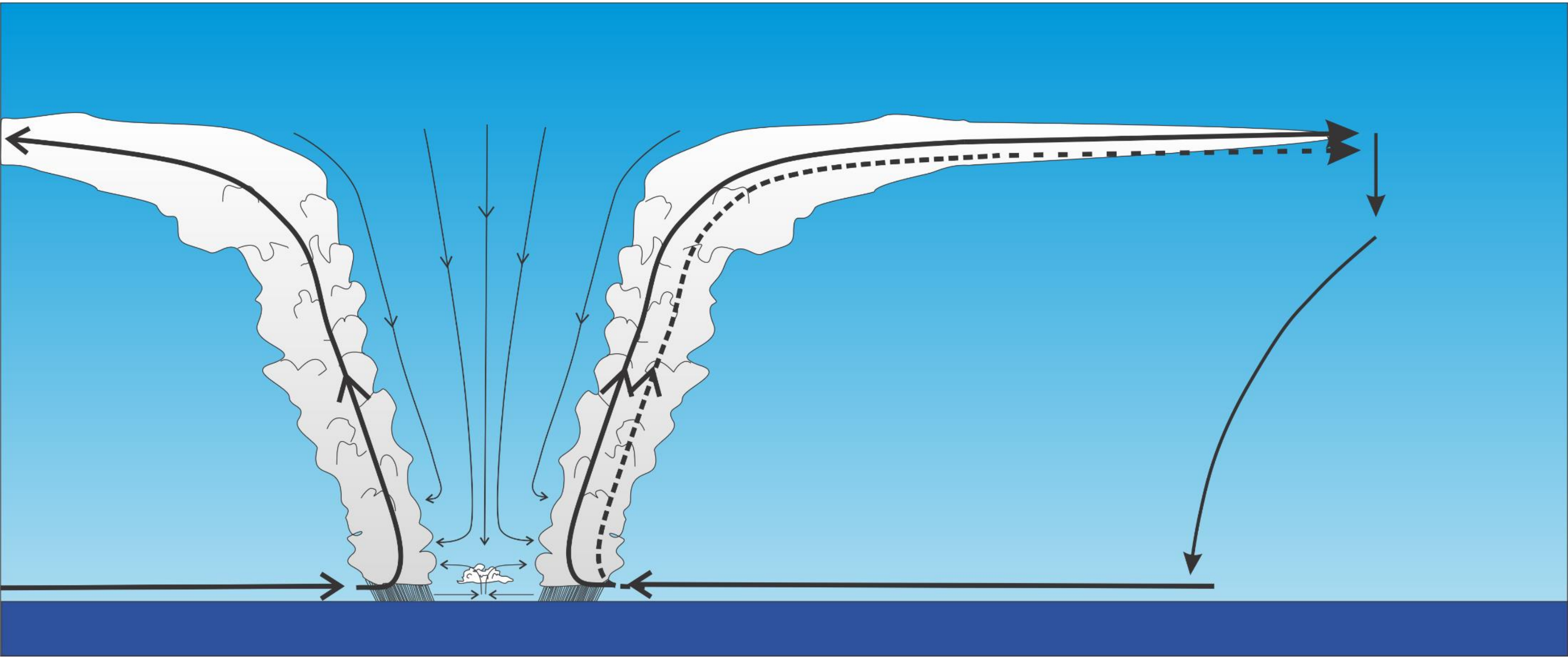
Surface enthalpy flux

Dissipative heating

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

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

Differential Carnot Cycle



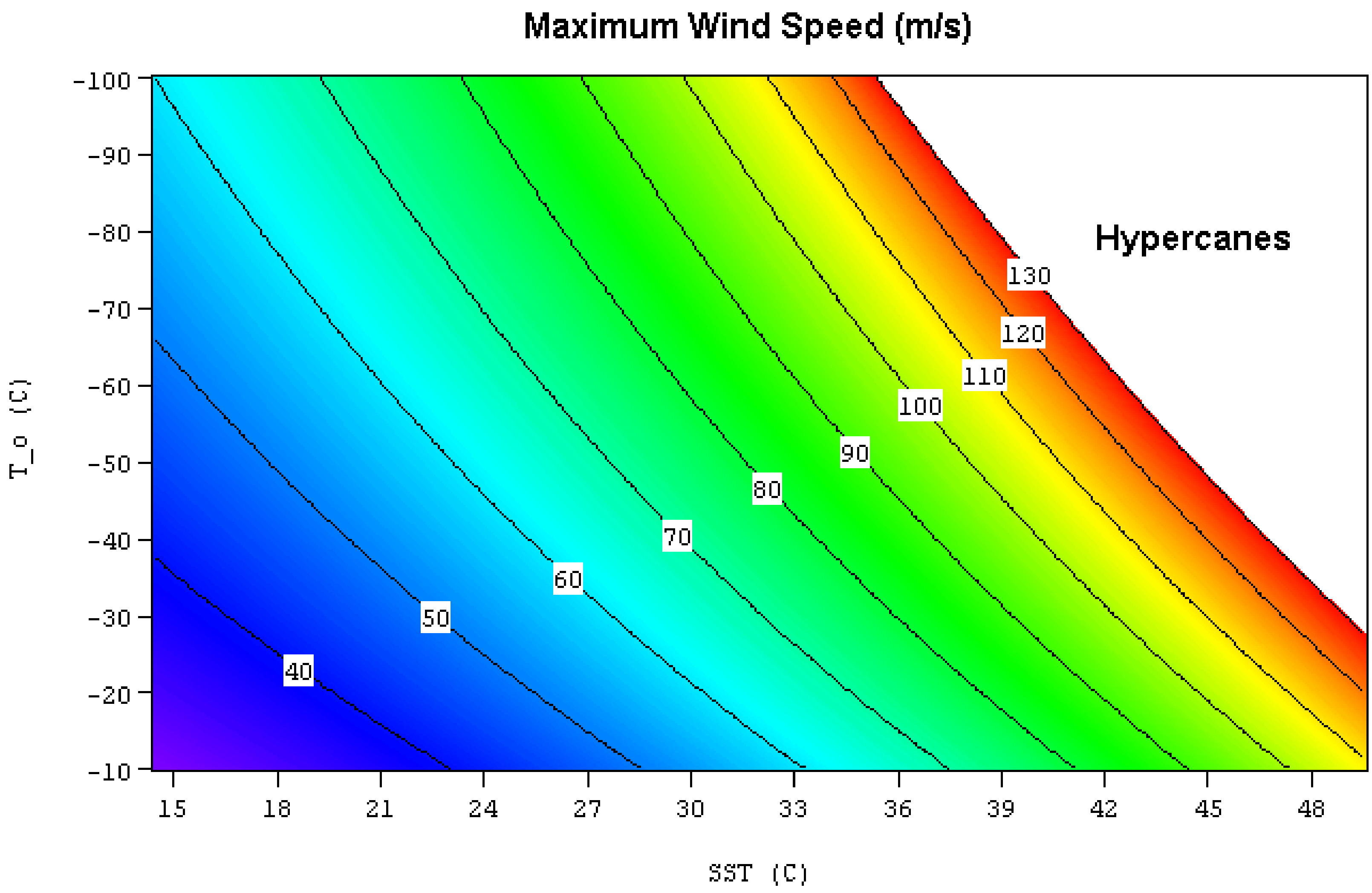
$$D = \frac{T_s - T_o}{T_s} \dot{Q}$$

$$\rho \left[C_D \, |\mathbf{V}_{max}|^3 \right] = \frac{T_s - T_o}{T_o} \rho \left[C_k \, |\mathbf{V}_{max}| \left(k_0^* - k \right) \right]$$

Internally determined

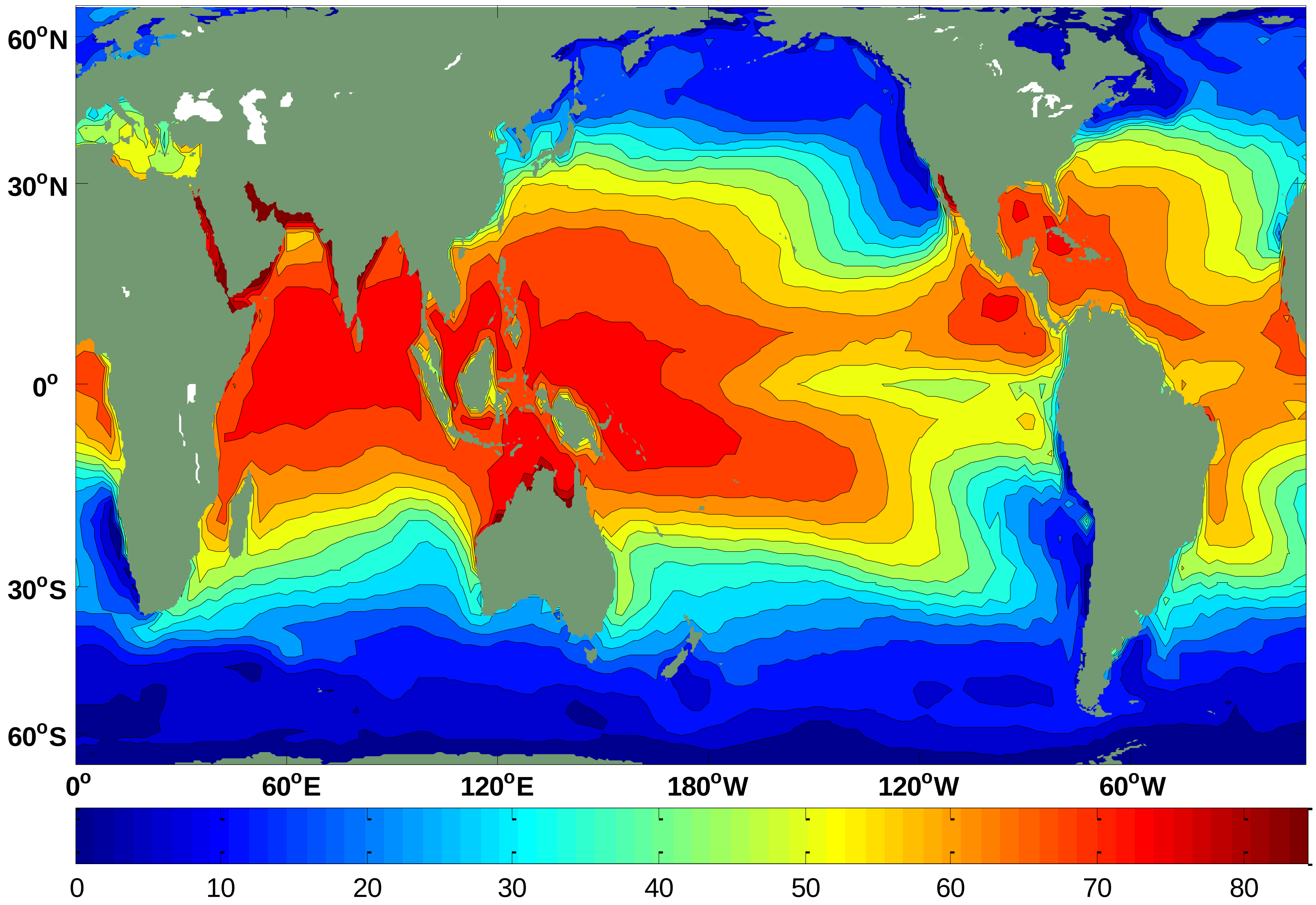
$$\rightarrow \quad |V_{max}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left(k_0{}^* - k \right)$$

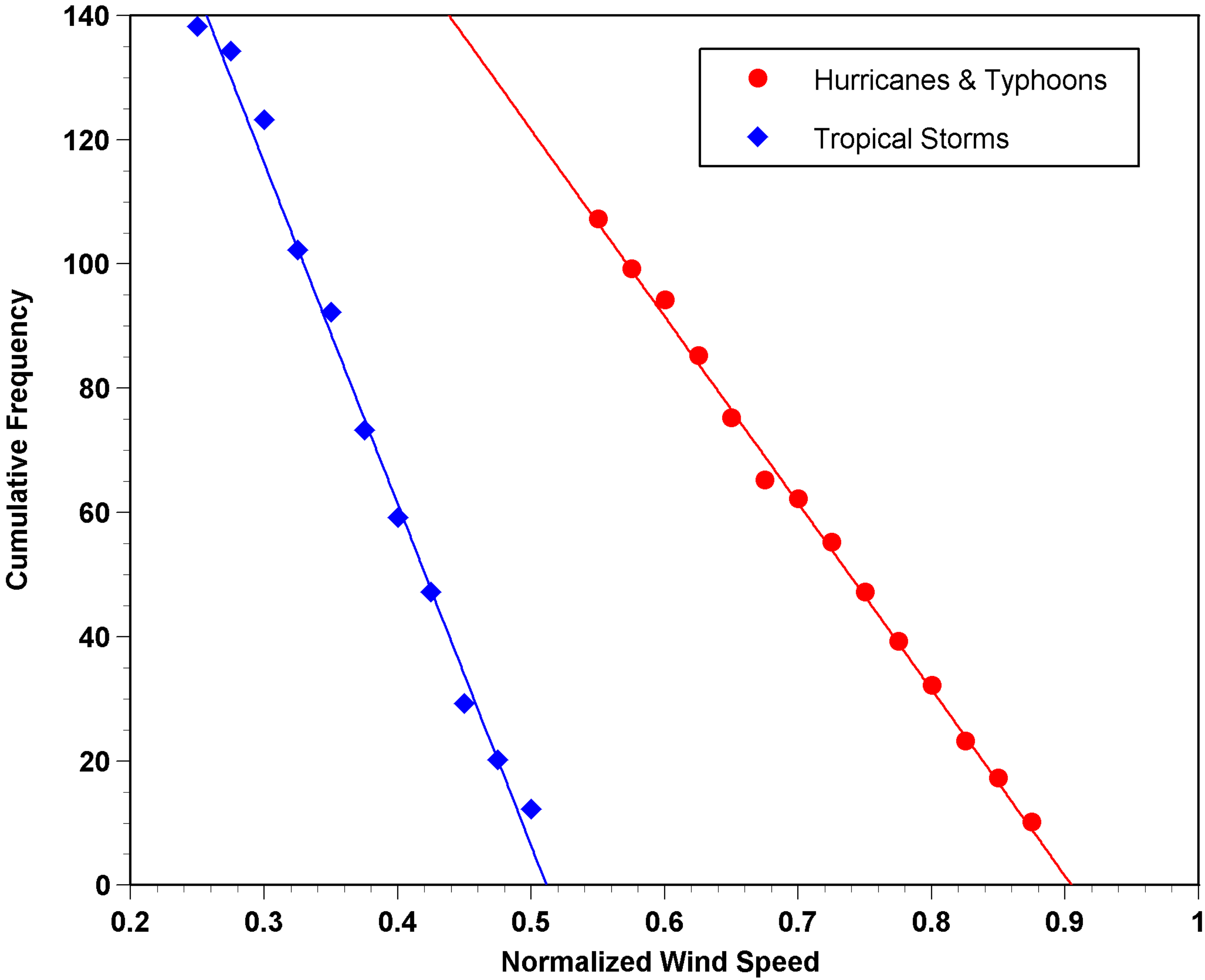
Note that this is valid between *ANY* two streamlines in the region of ascent



$\mathcal{X} = 0.75 \quad C_k/C_D = 1.2$

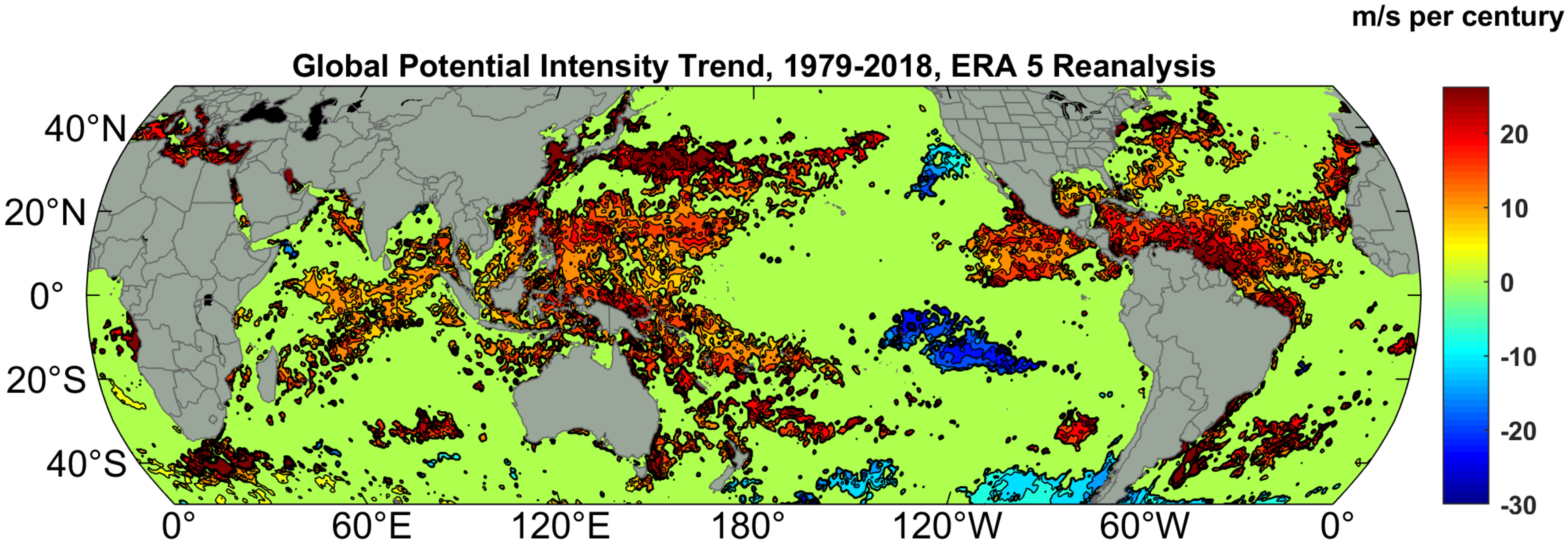
Annual Maximum Potential Intensity (m/s)




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

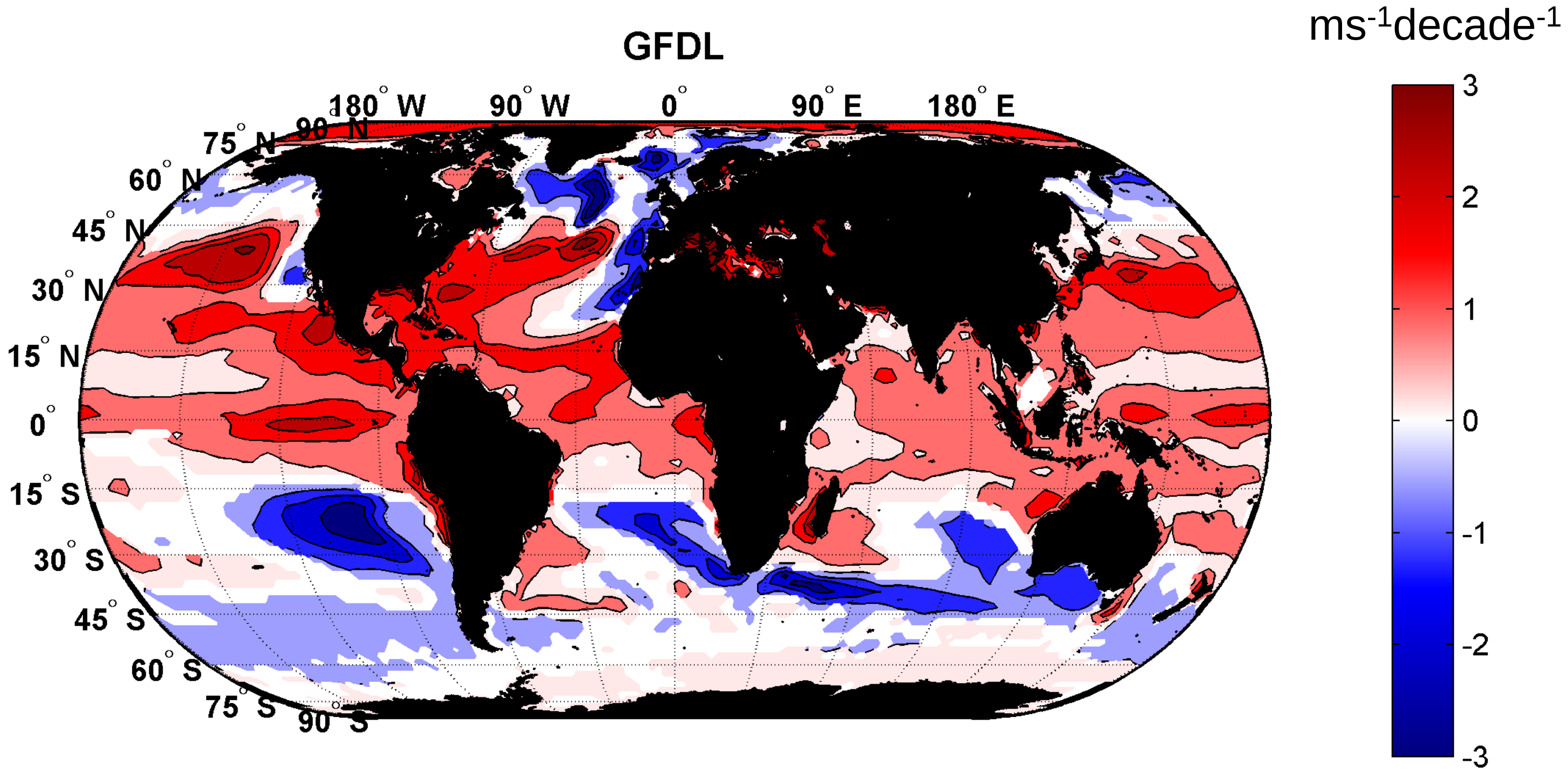
Hurricanes and Climate Change

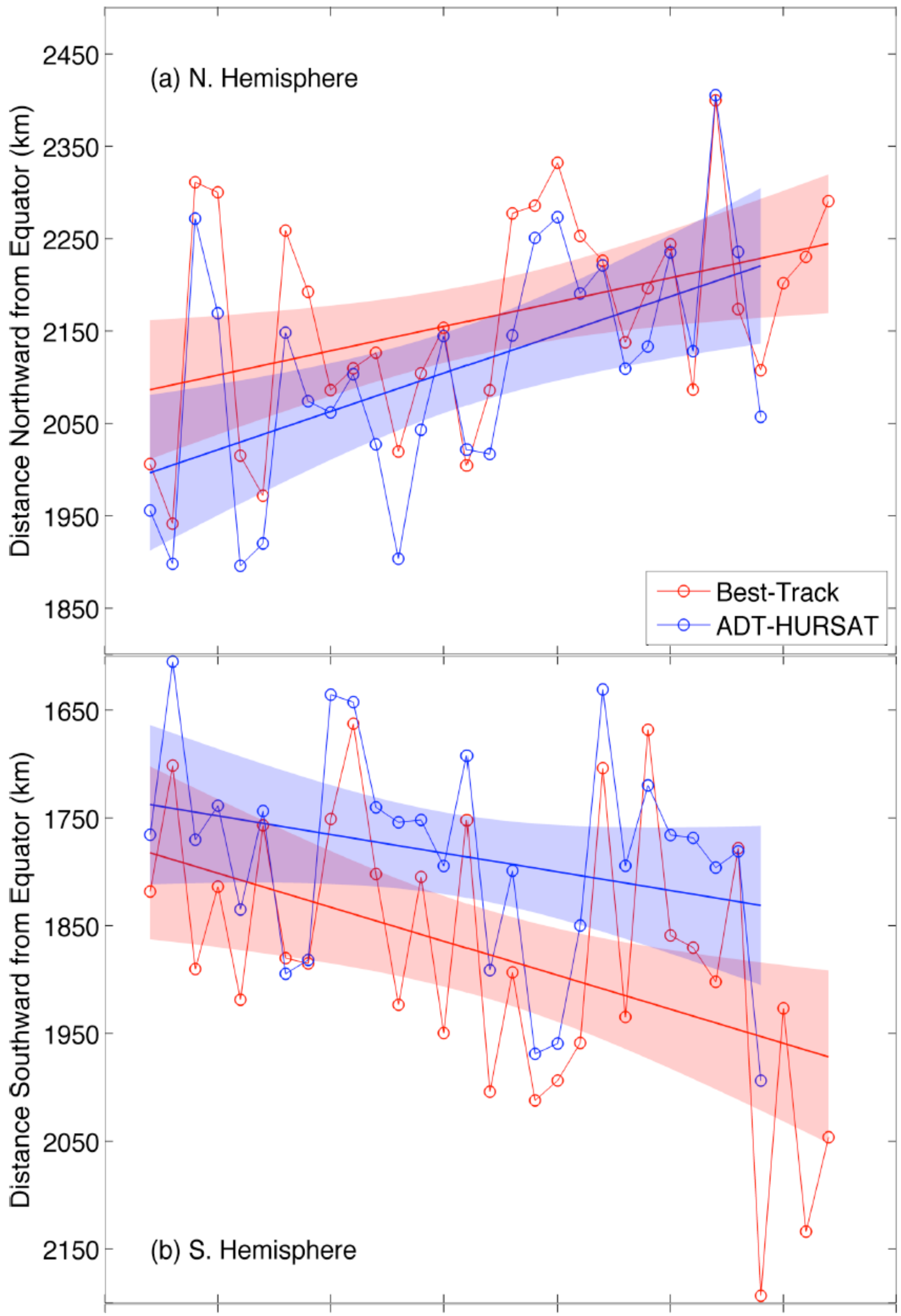
Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis



(Trend shown only where p value < 0.05)

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



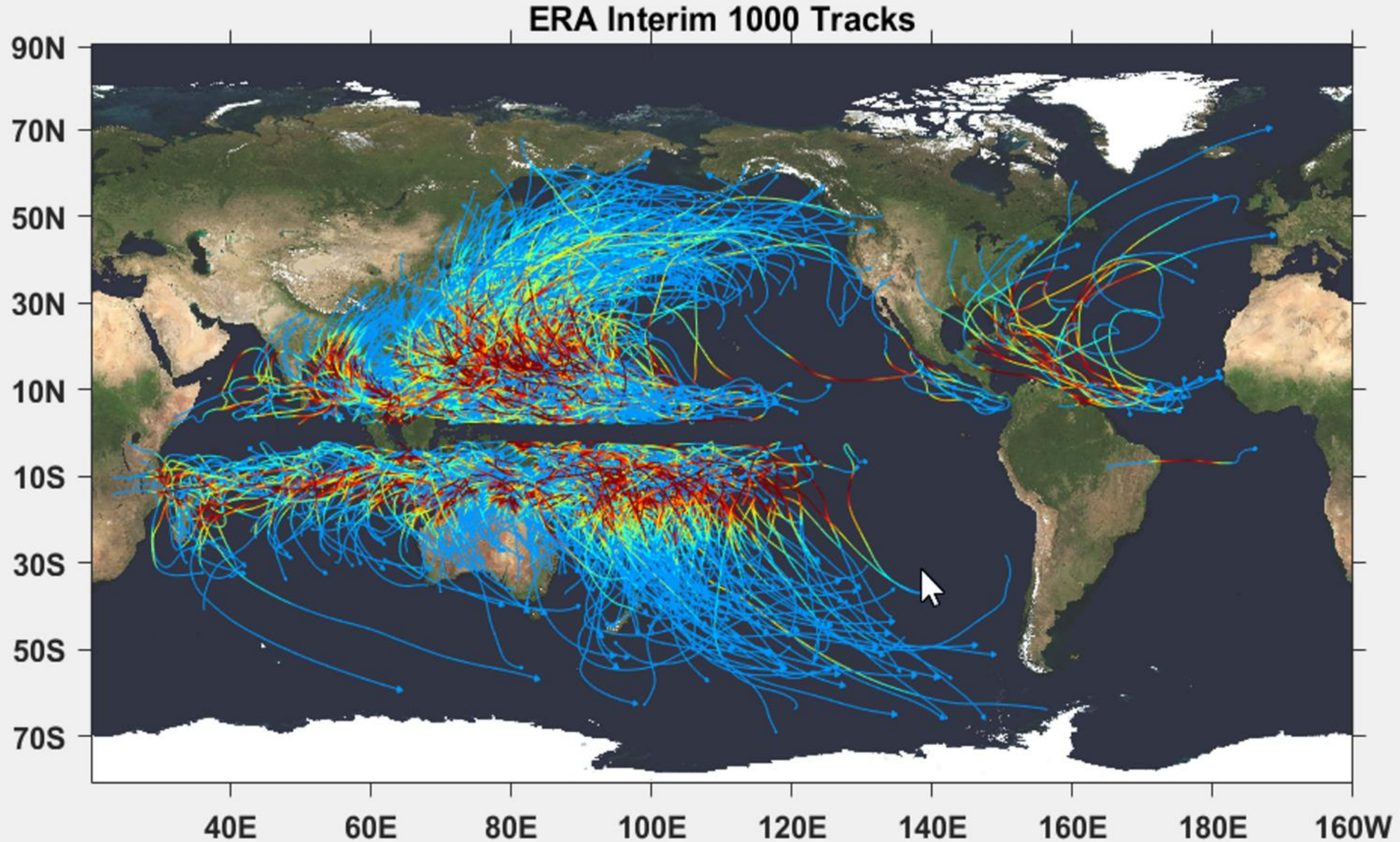


Time series of the latitudes at which tropical cyclones reach maximum intensity.

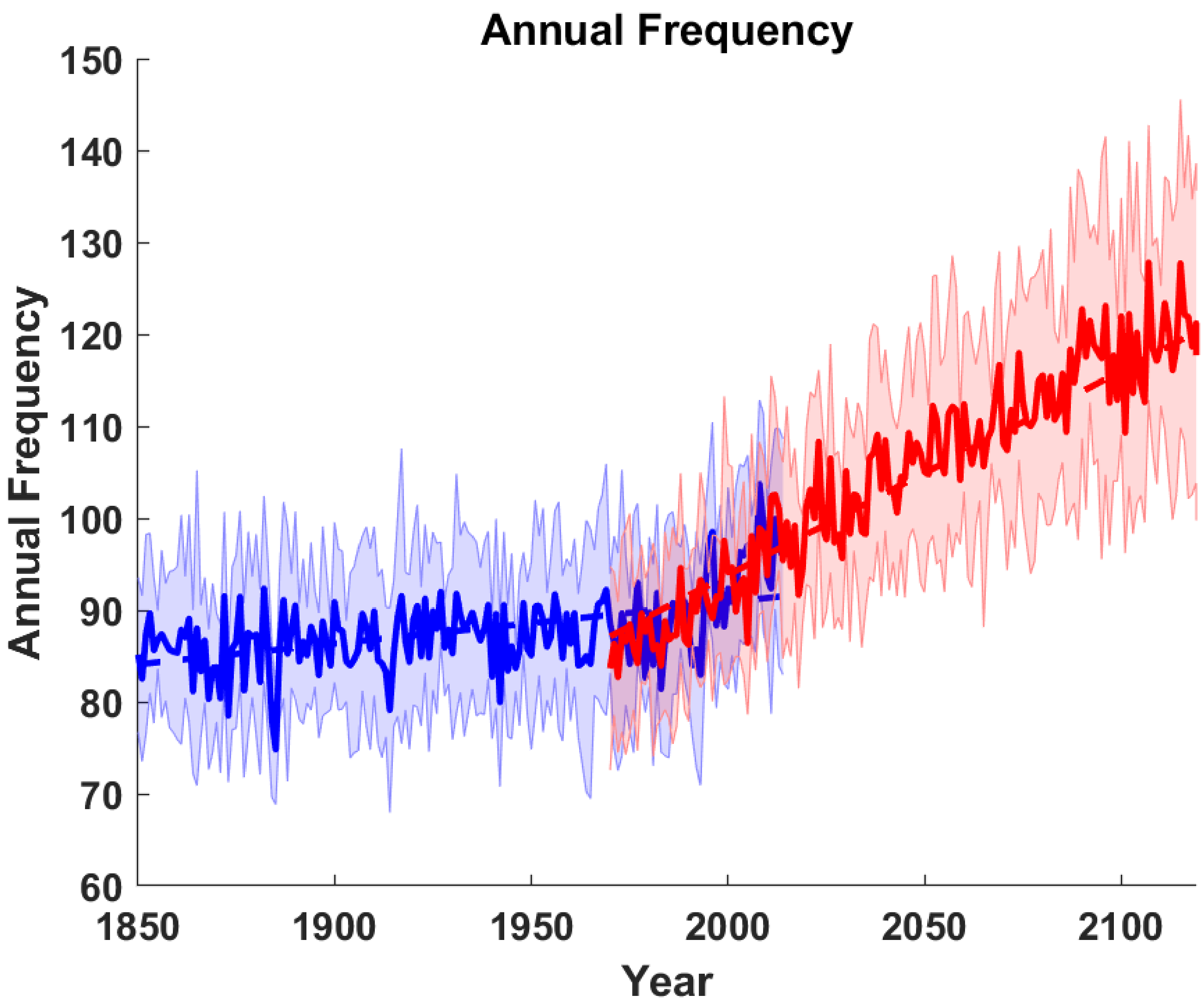
From *Kossin et al. (2014)*

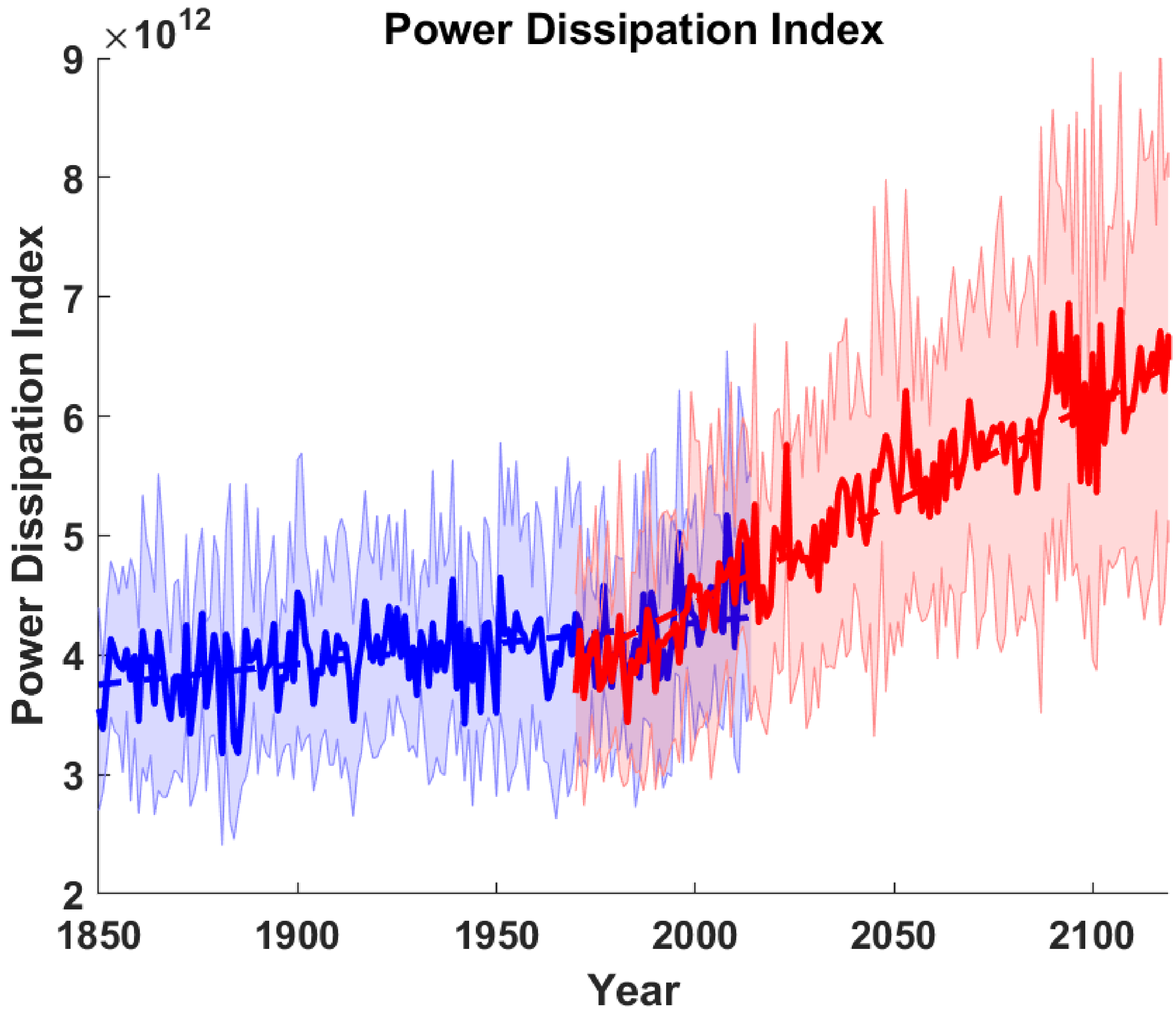
“Downscaling” hurricanes from global analyses and models

- Embed detailed hurricane forecast model in global climate analyses or climate models
- Generate thousands of synthetic hurricane tracks consistent with global climate
- Use these synthetic hurricanes to estimate hurricane risk


ERA Interim 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E
60E
80E
100E
120E
140E
160E
180E
160W

Downscale 9 climate models with observed forcings, 1850-2015 and with CO_2 increasing at 1% per year from 1970 to 2120




Power Dissipation Index
×10^12
9
8
7
6
5
4
3
2
Power Dissipation Index
1850
1900
1950
2000
2050
2100
Year