

An aerial photograph of a hurricane, showing a dark, circular eye surrounded by a thick, swirling ring of white clouds. The surrounding ocean is visible as a deep blue, with the hurricane's outer bands extending across the horizon. The image is taken from a high altitude, likely from a satellite or a high-altitude aircraft, providing a clear view of the storm's structure.

# **Hurricanes, the Ocean, and Climate Change**

# Program

- **Overview of hurricanes**
- **Hurricanes and the ocean**
- **Effects of climate change**

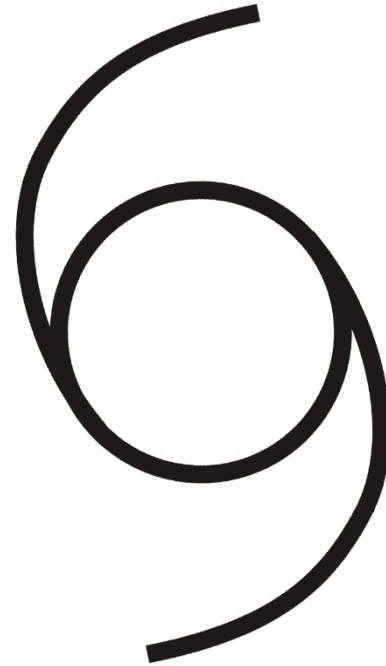
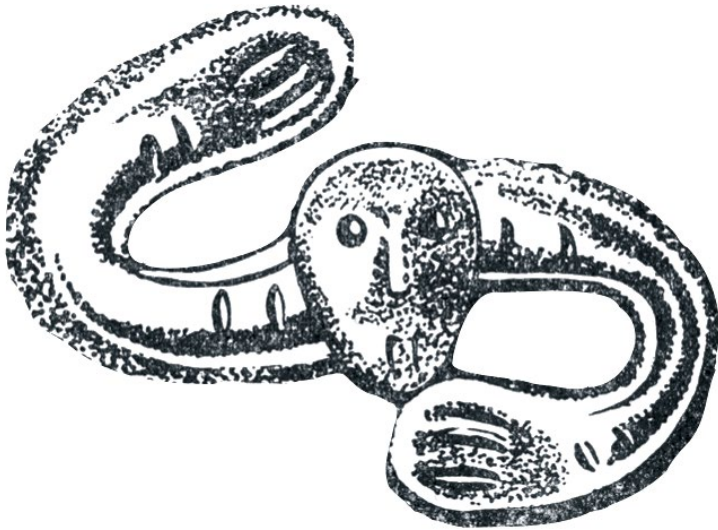


# Overview: What is a Hurricane?

**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



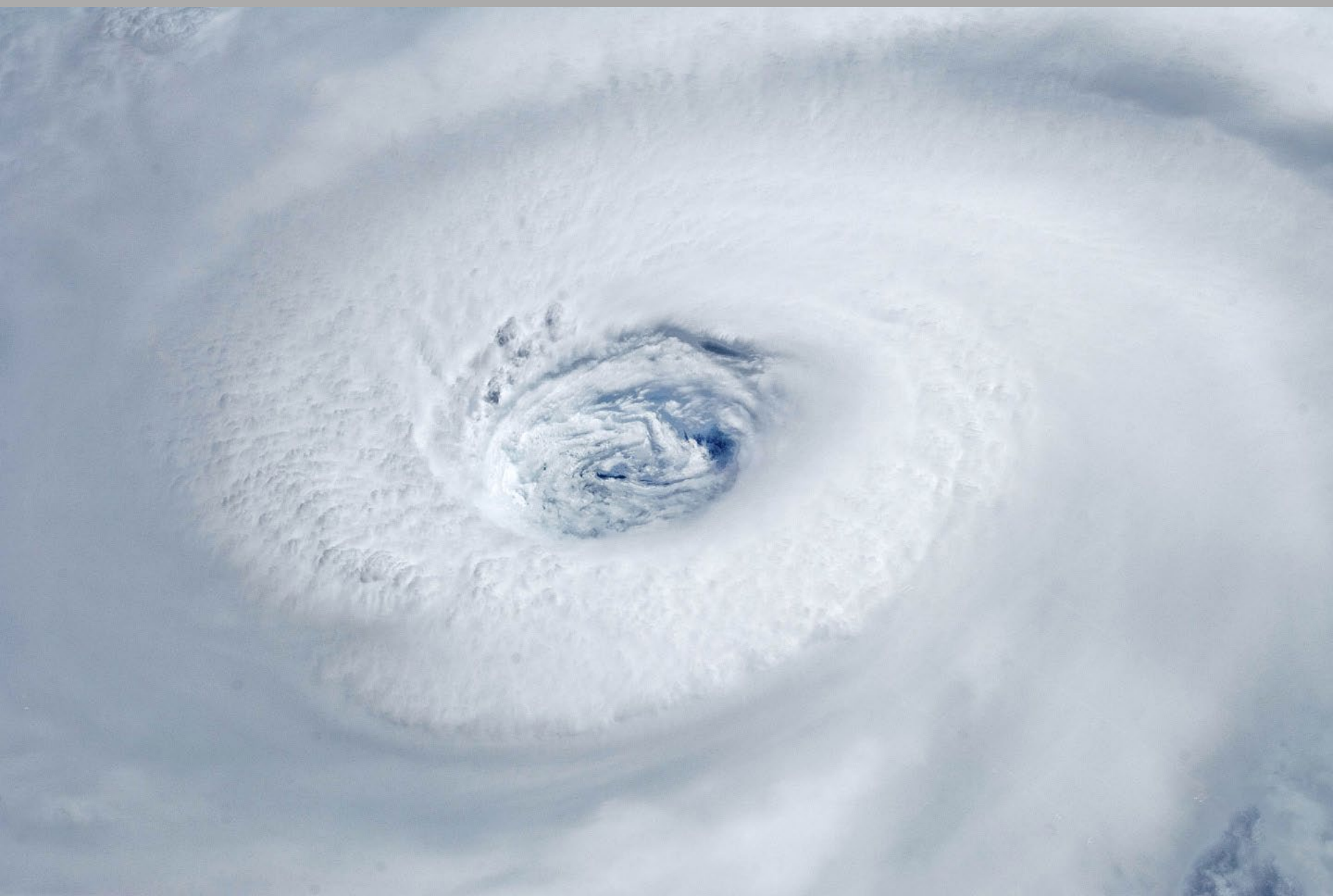
# The View from Space



Hurricane Erin, 20 August 2025



Igor, 2010





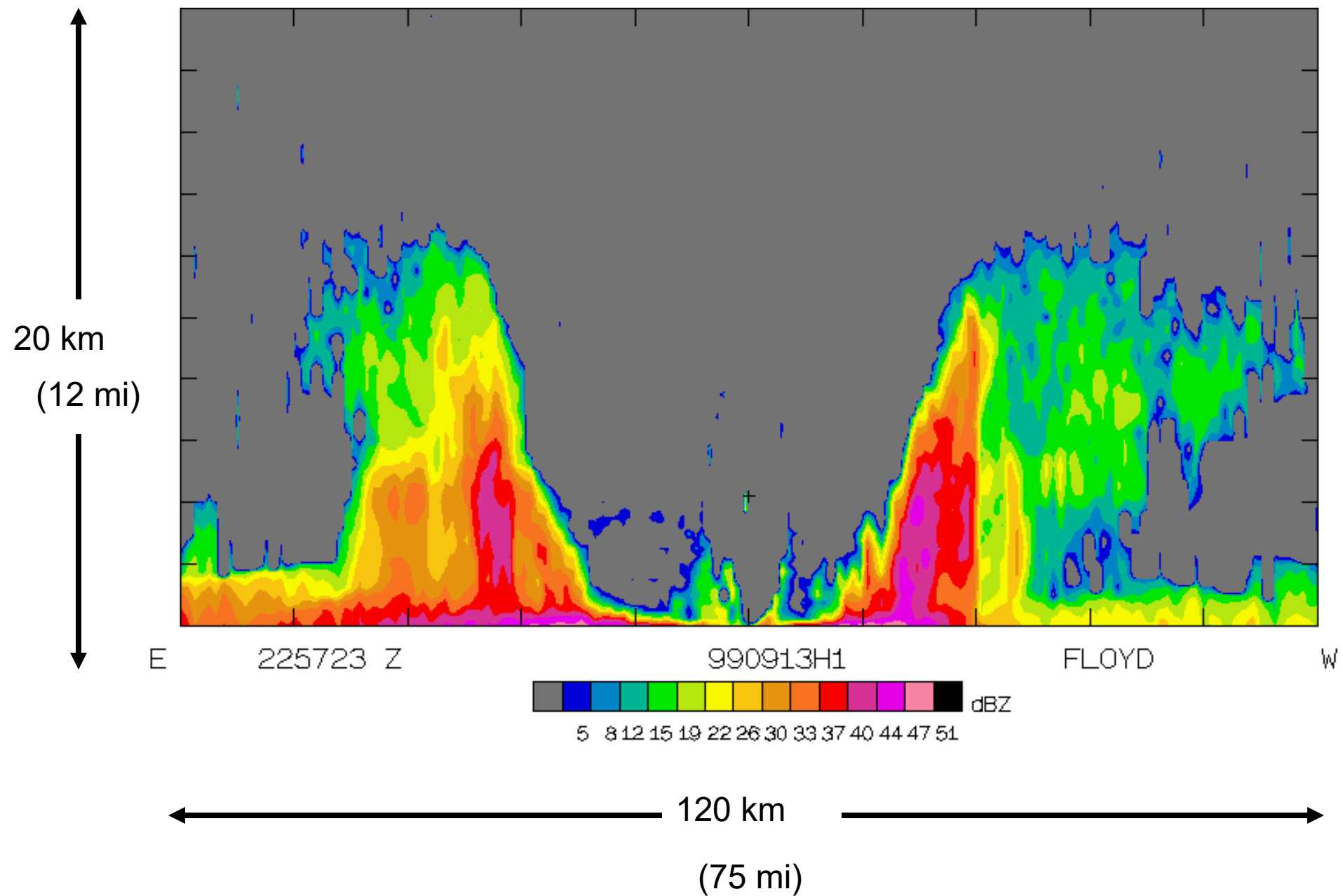






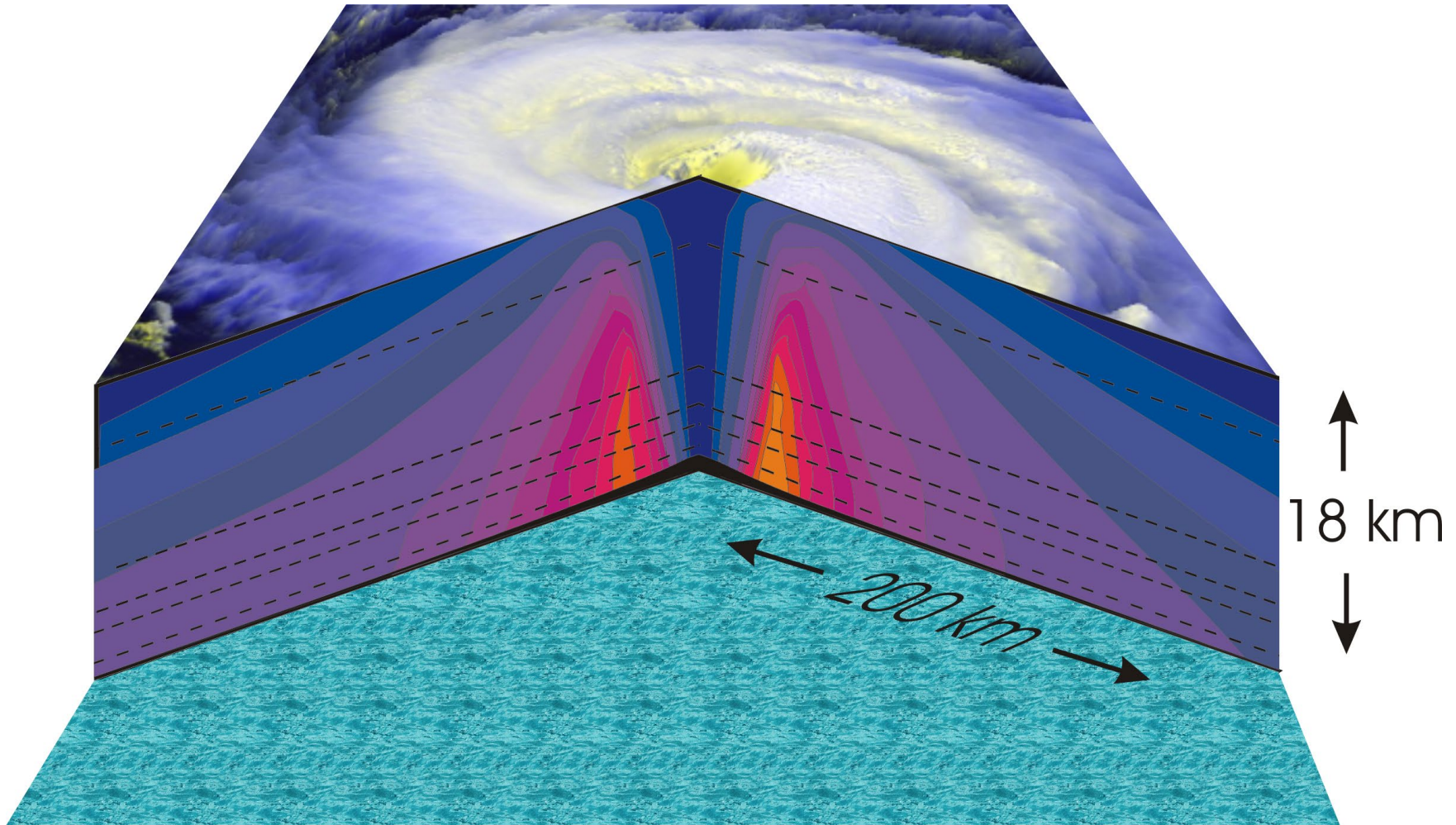
*View of the eye of Hurricane Katrina on August 28<sup>th</sup>,  
2005, as seen from a NOAA WP-3D hurricane  
reconnaissance aircraft.*

# Airborne Radar: Vertical Slice





# Hurricane Structure: Wind Speed



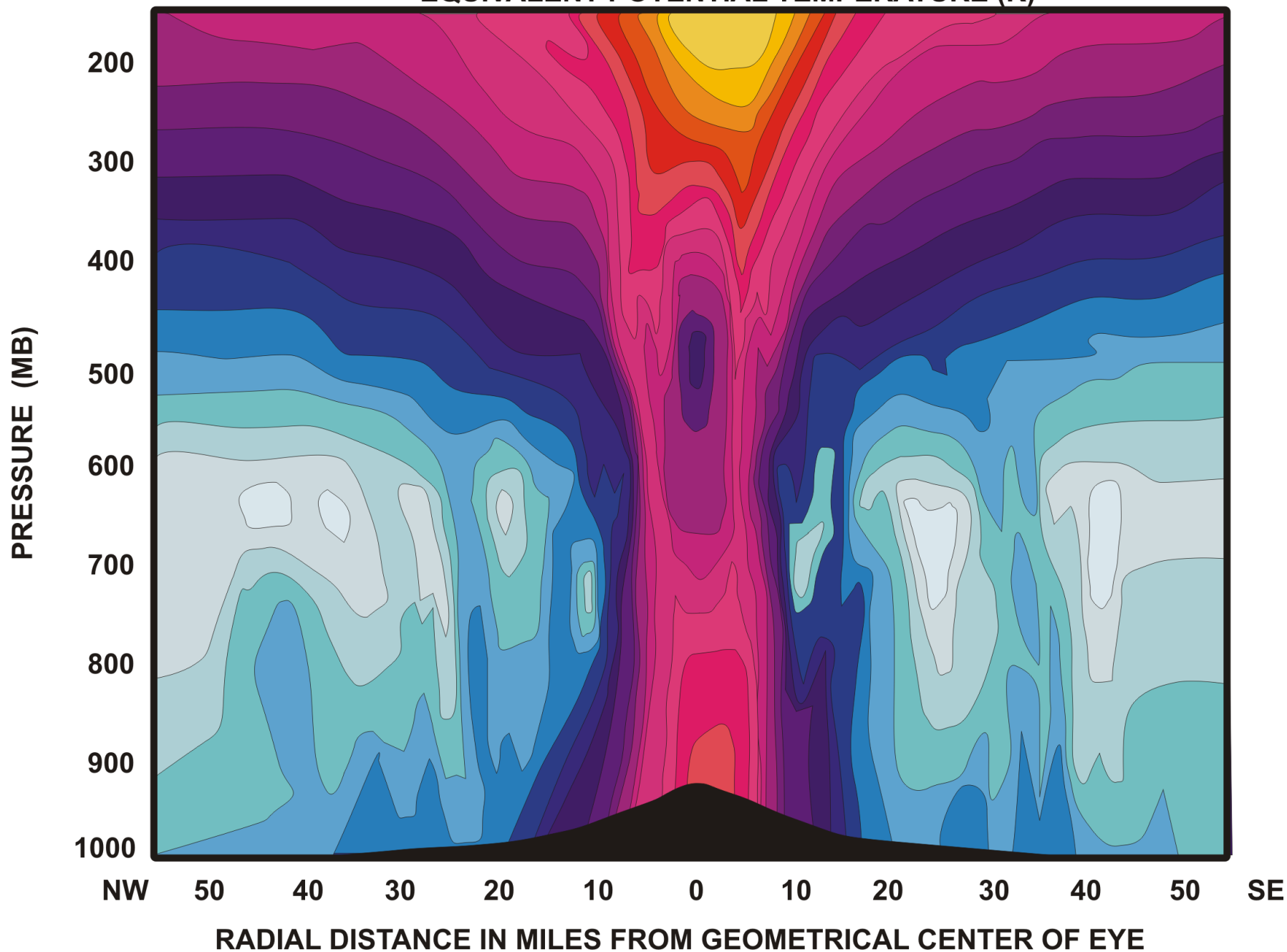
Azimuthal component of wind

< 11 mph - > 145 mph

HURRICANE INEZ

SEPTEMBER 28, 1966

EQUIVALENT POTENTIAL TEMPERATURE (K)

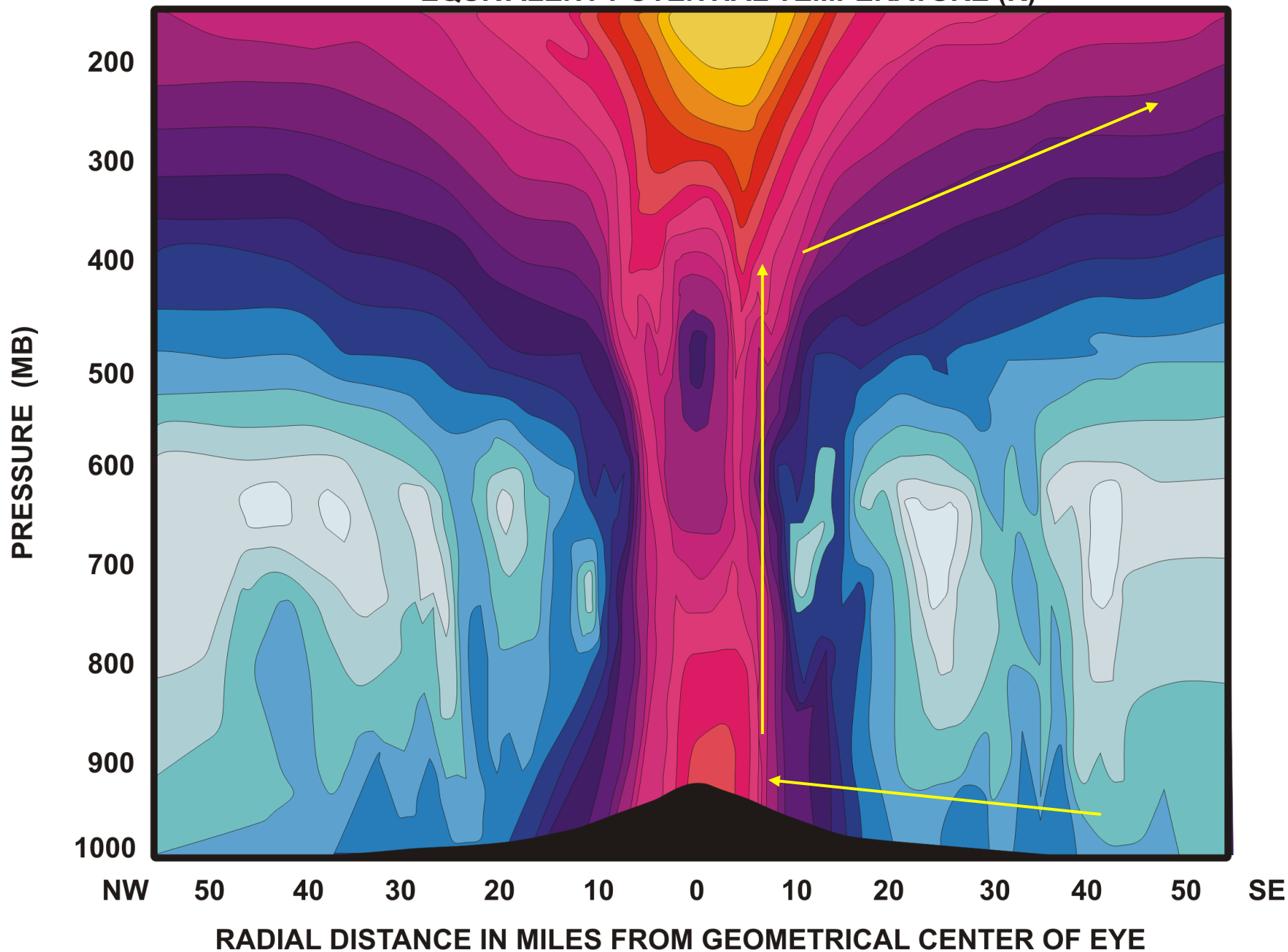


HURRICANE INEZ

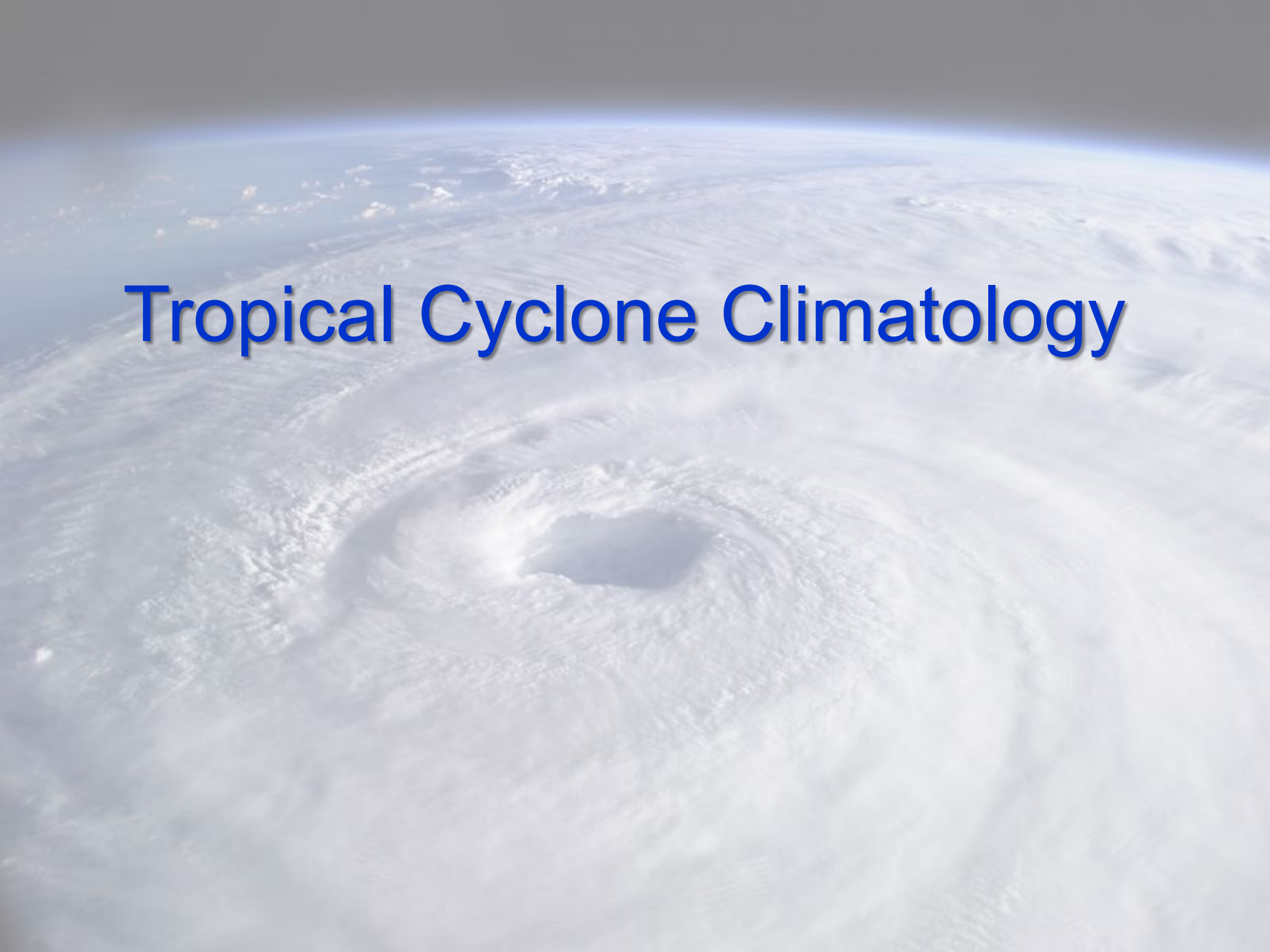
**Specific entropy**

SEPTEMBER 28, 1966

EQUIVALENT POTENTIAL TEMPERATURE (K)

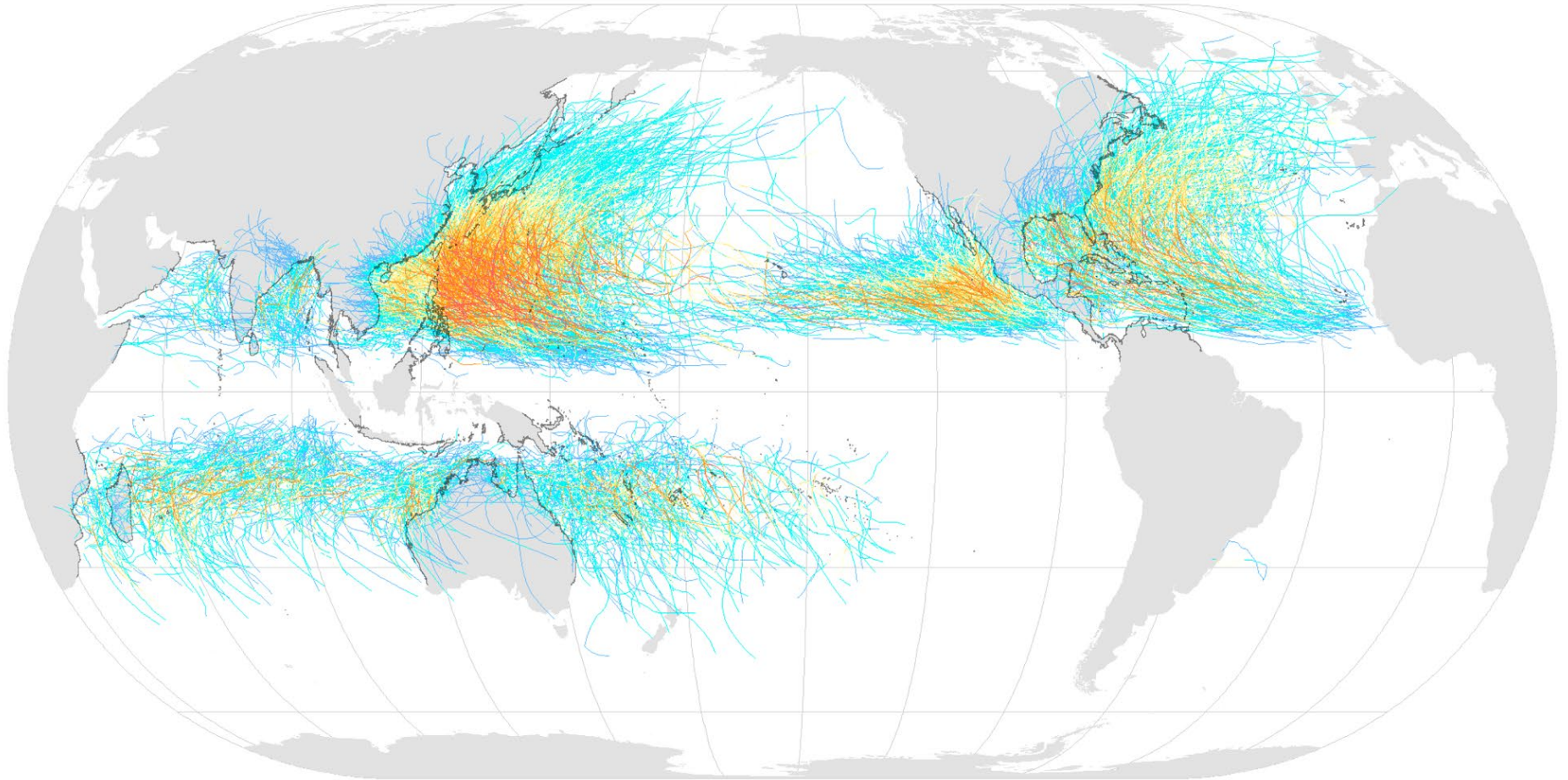


# Tropical Cyclone Climatology

A satellite image of a tropical cyclone, showing a well-defined eye and spiral cloud bands. The text "Tropical Cyclone Climatology" is overlaid in blue.



# Tropical Cyclones, 1945–2006



Saffir-Simpson Hurricane Scale:

tropical  
depression

tropical  
storm

hurricane  
category 1

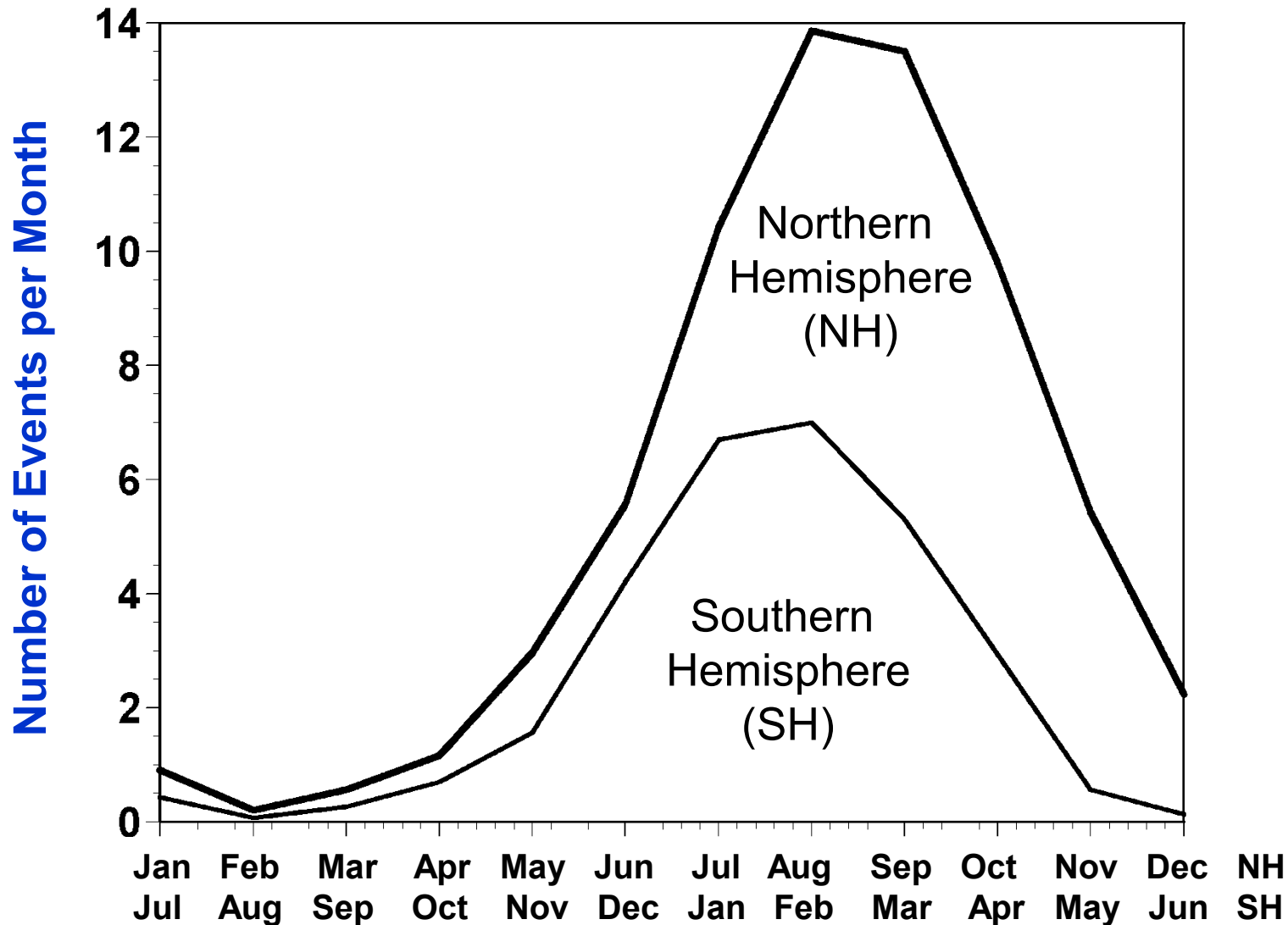
hurricane  
category 2

hurricane  
category 3

hurricane  
category 4

hurricane  
category 5

# Annual Cycle of Tropical Cyclones

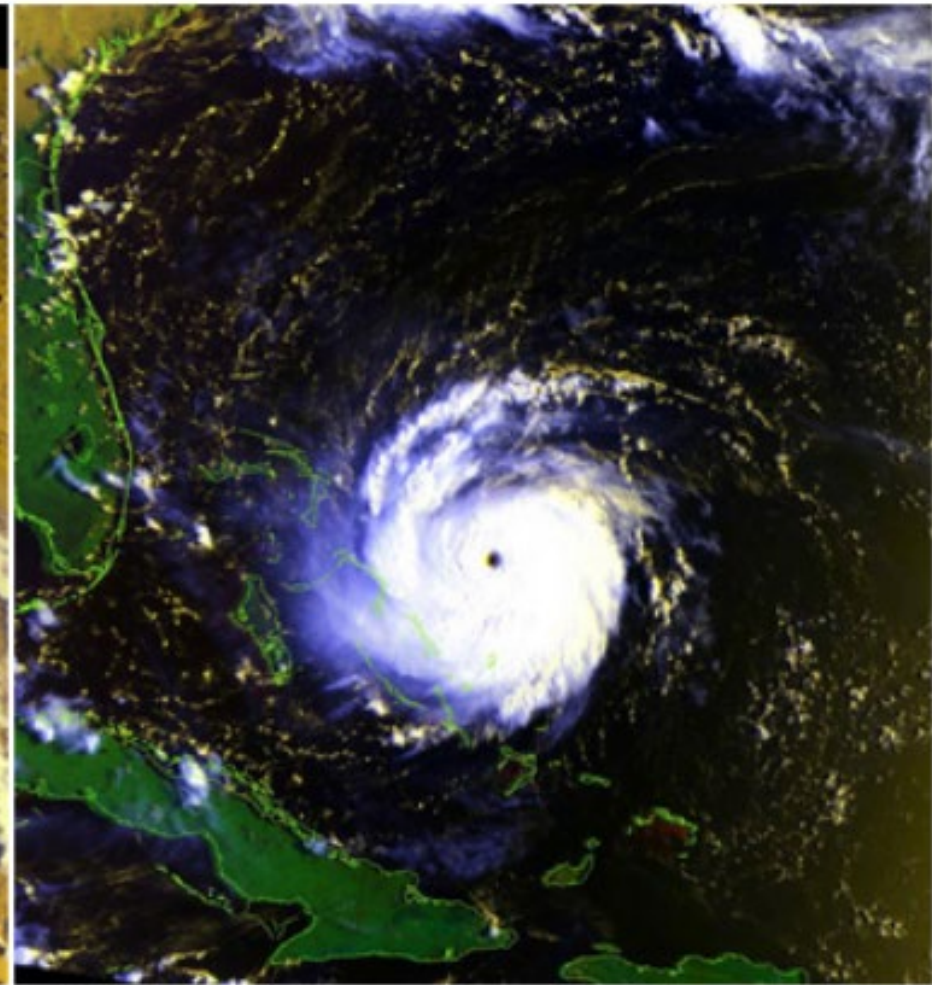




**Hurricane Floyd**  
**September 14, 1999 @ 1244 UTC**



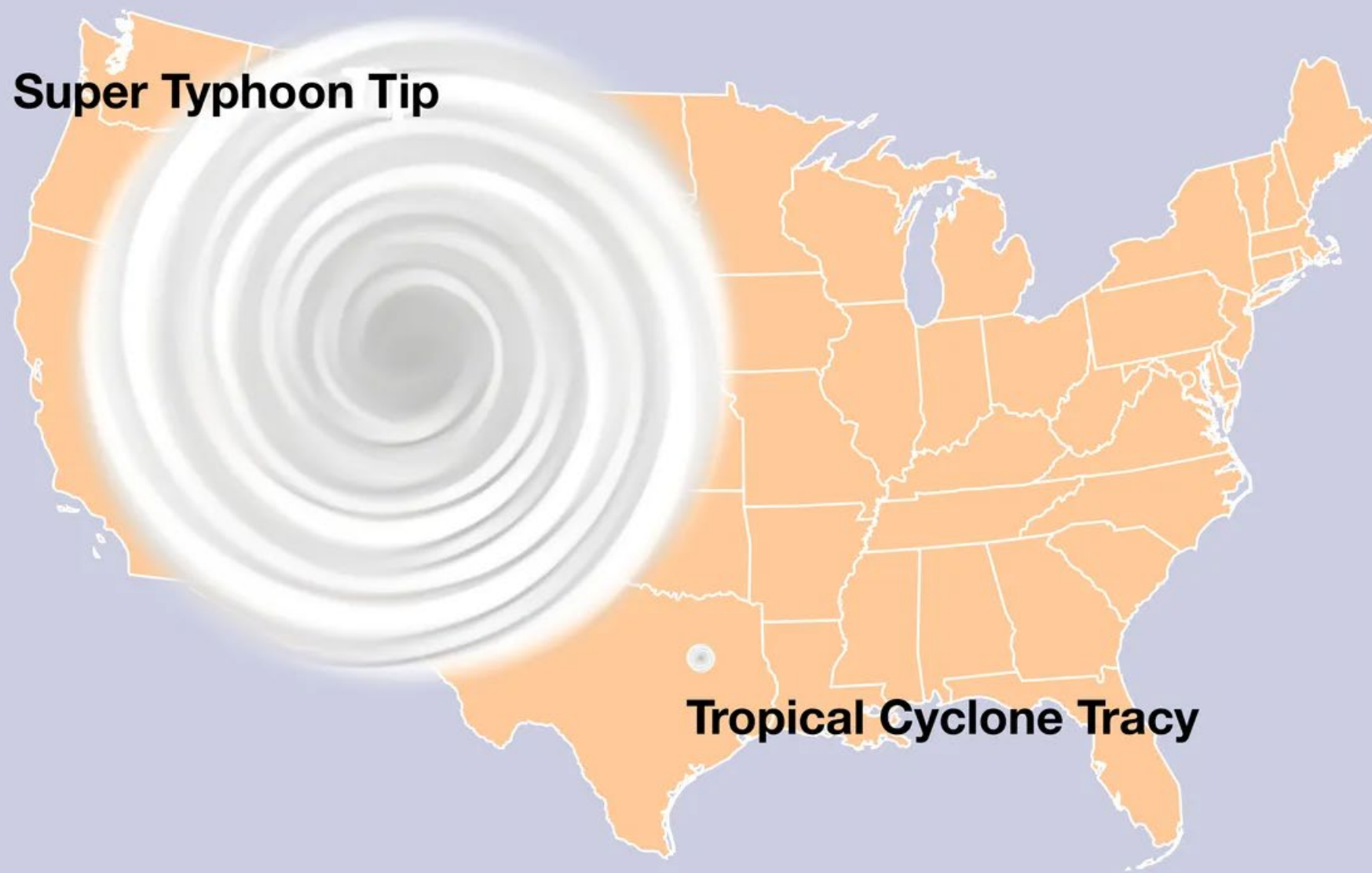
**Hurricane Andrew**  
**August 23, 1992 @ 1231 UTC**



NOAA

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

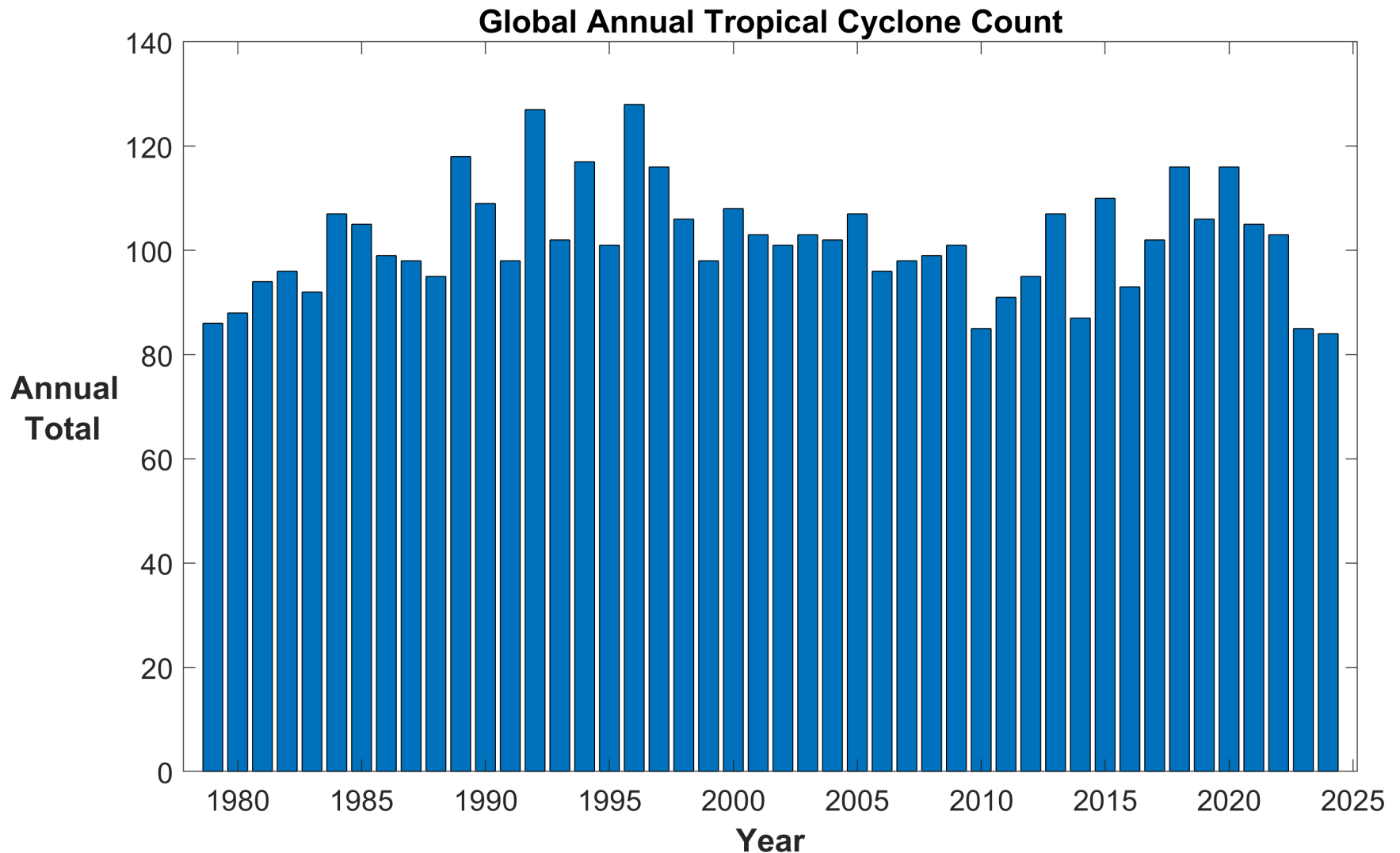
**Super Typhoon Tip**



**Tropical Cyclone Tracy**



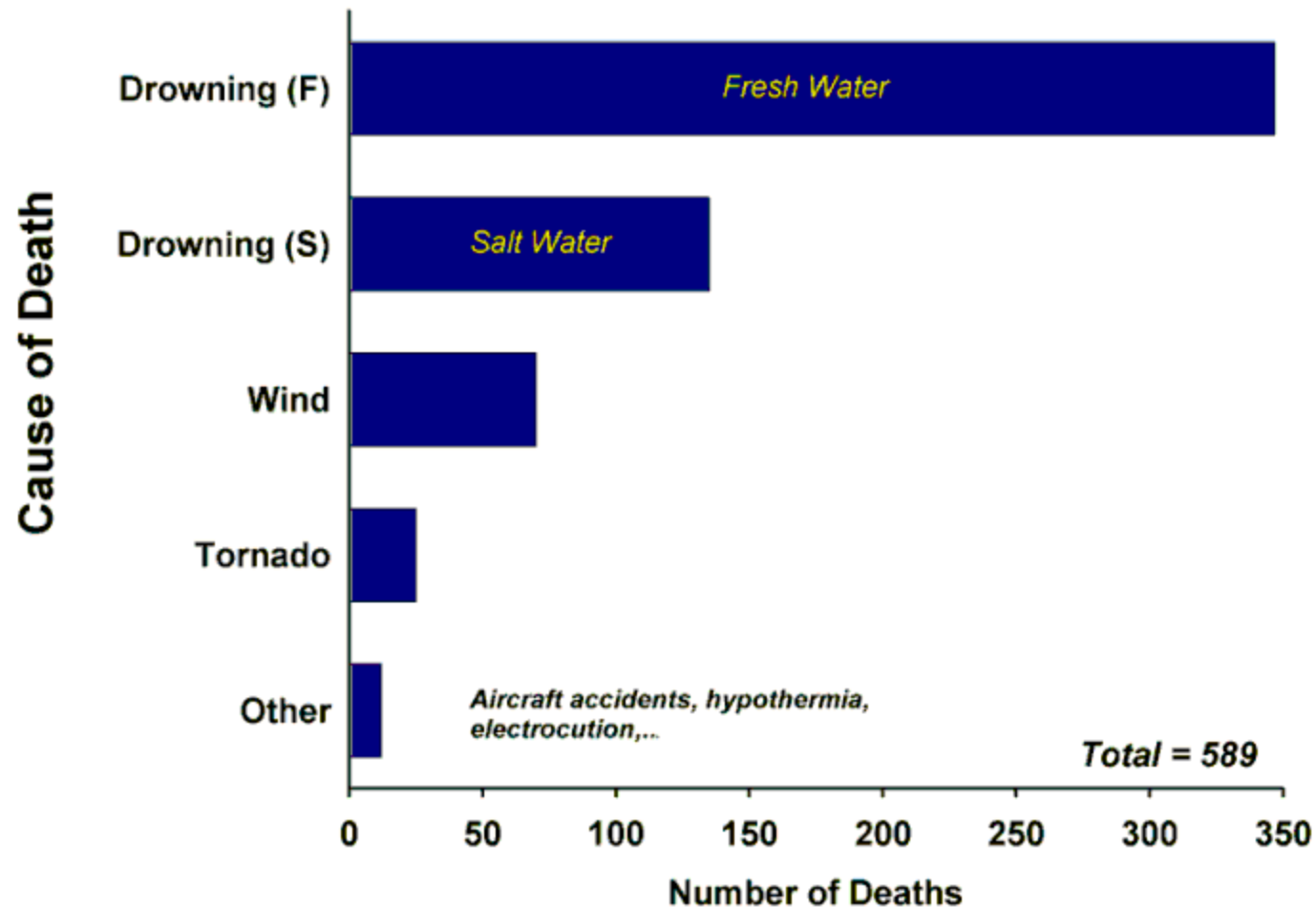
# Global Tropical Cyclone Frequency, 1979-2024



# 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

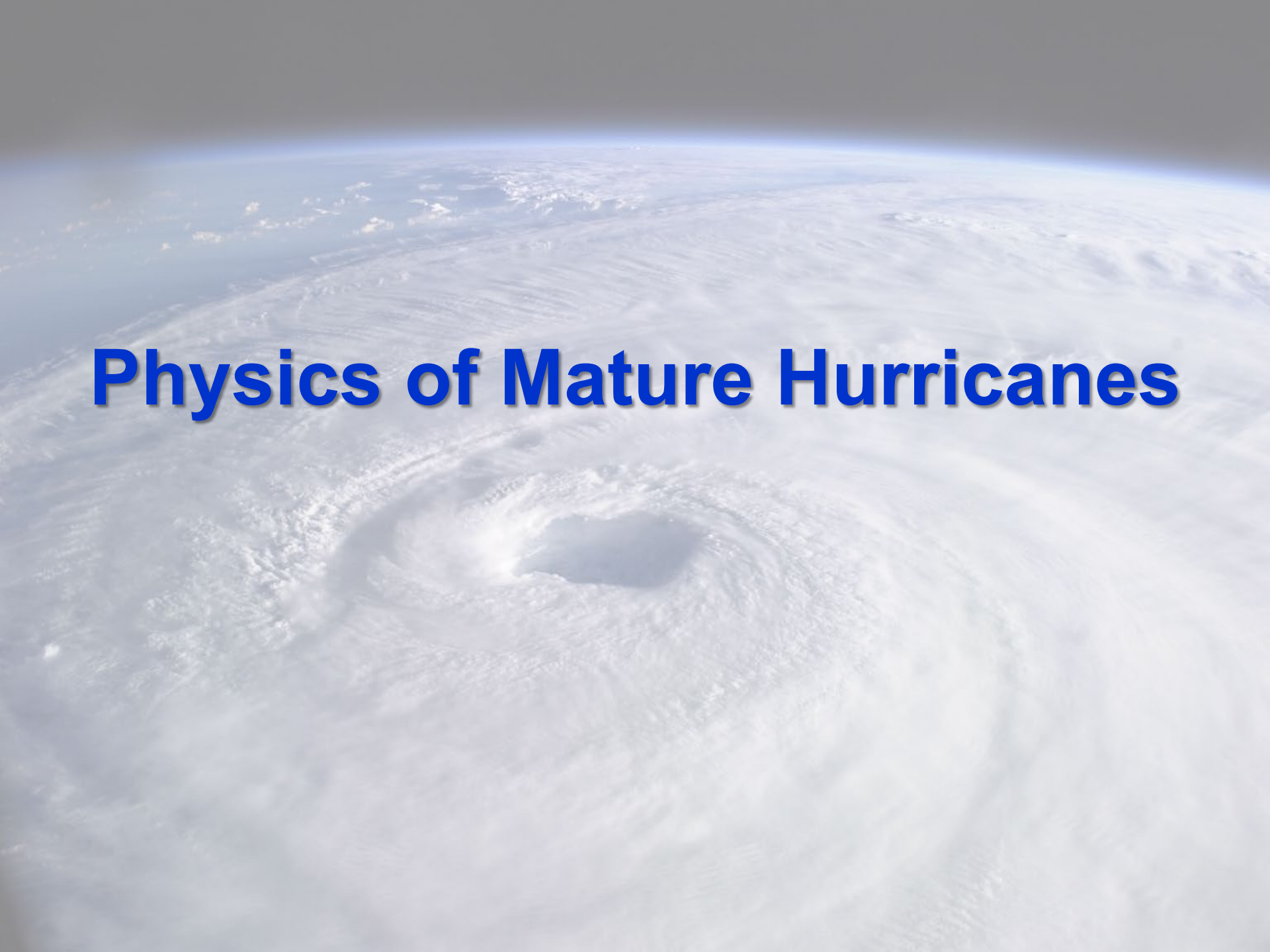
## U. S. Hurricane Mortality (1970-1999)



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

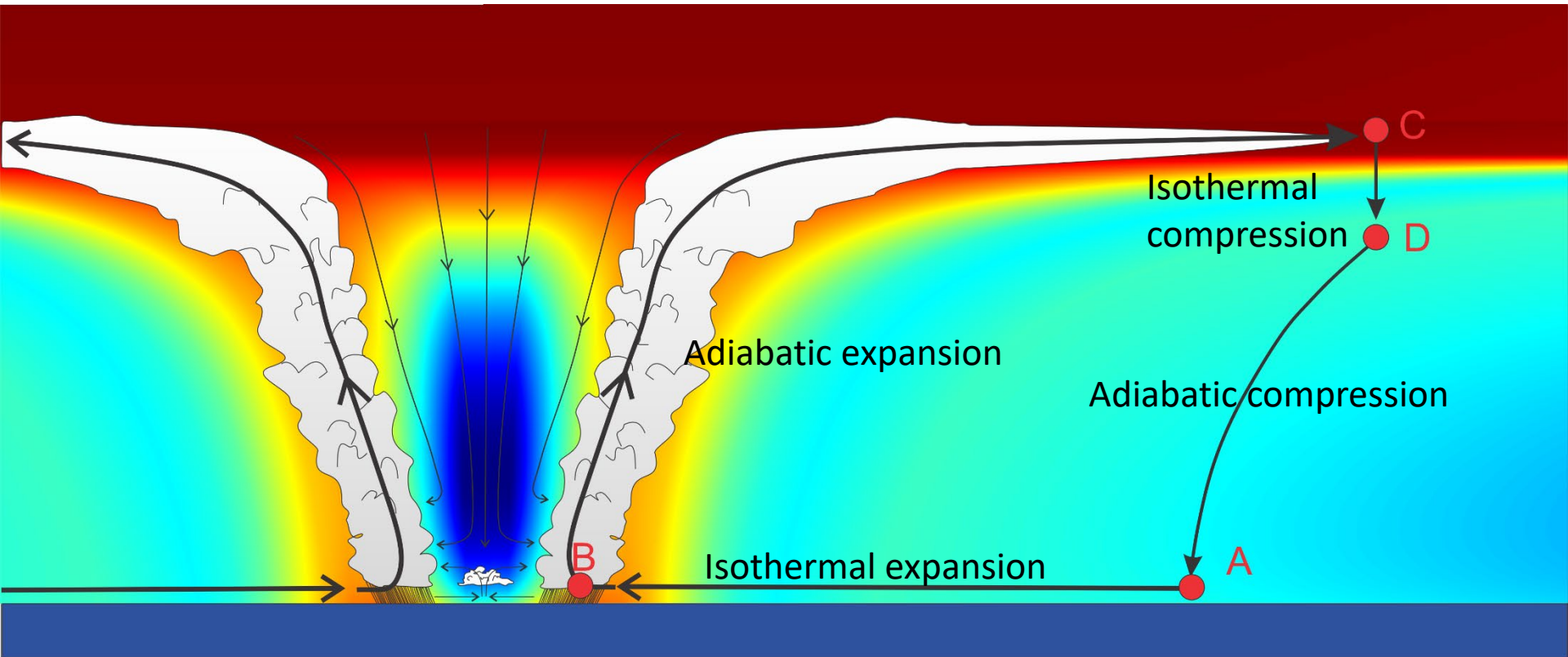




A satellite image of a mature hurricane, showing a well-defined eye and spiral cloud bands. The text "Physics of Mature Hurricanes" is overlaid in the center.

# **Physics of Mature Hurricanes**

# Thermal cycle of a mature hurricane



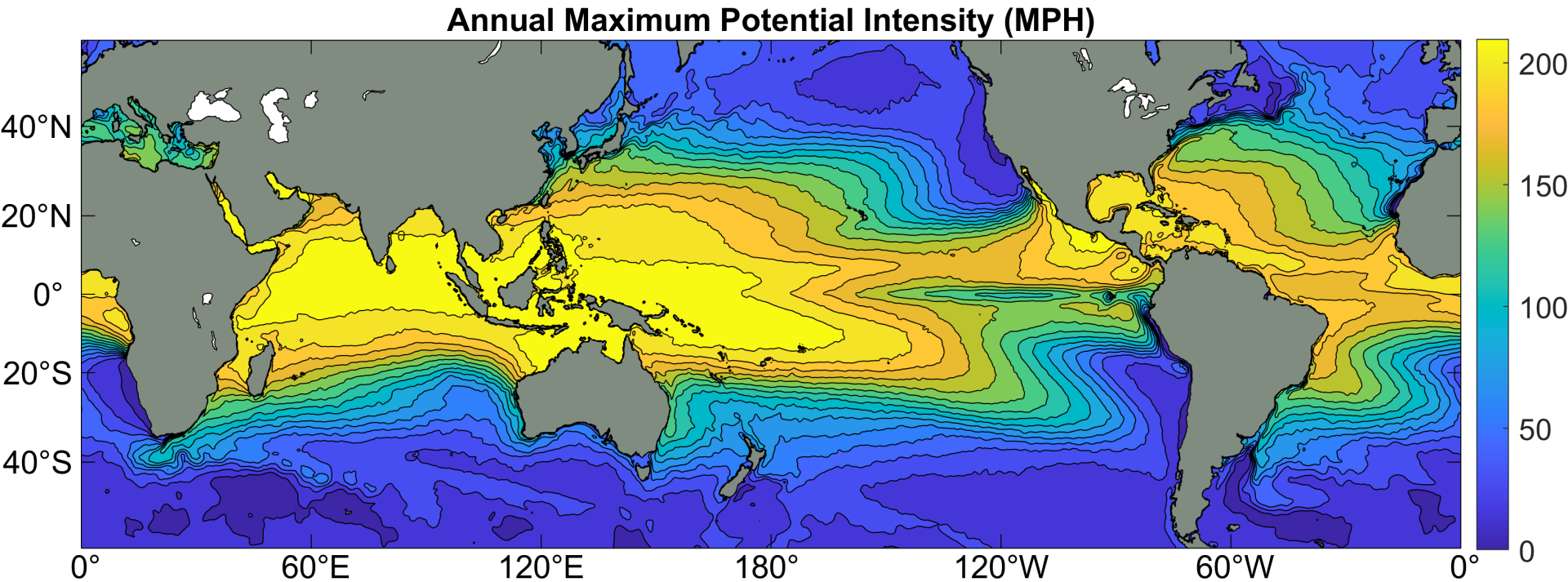
A nearly perfect Carnot Engine in nature!

# Potential Intensity

- Rate of air flow through the Carnot Cycle tells us how fast wind energy is generated
- Wind energy is dissipated mostly by friction between air flow and the surface
- Equating dissipation with generation gives us a wind speed called the *potential intensity*
- Potential intensity turn out to be a good upper bound on the intensity of real hurricanes

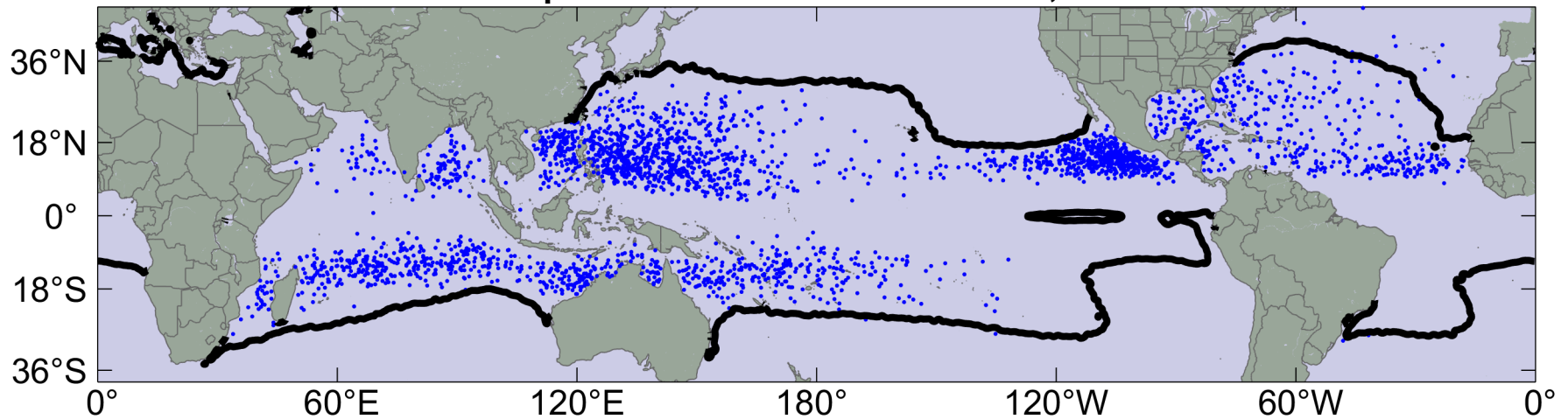


# Annual Maximum Potential Intensity (miles per hour)



# Hurricanes only form where potential intensity is large enough

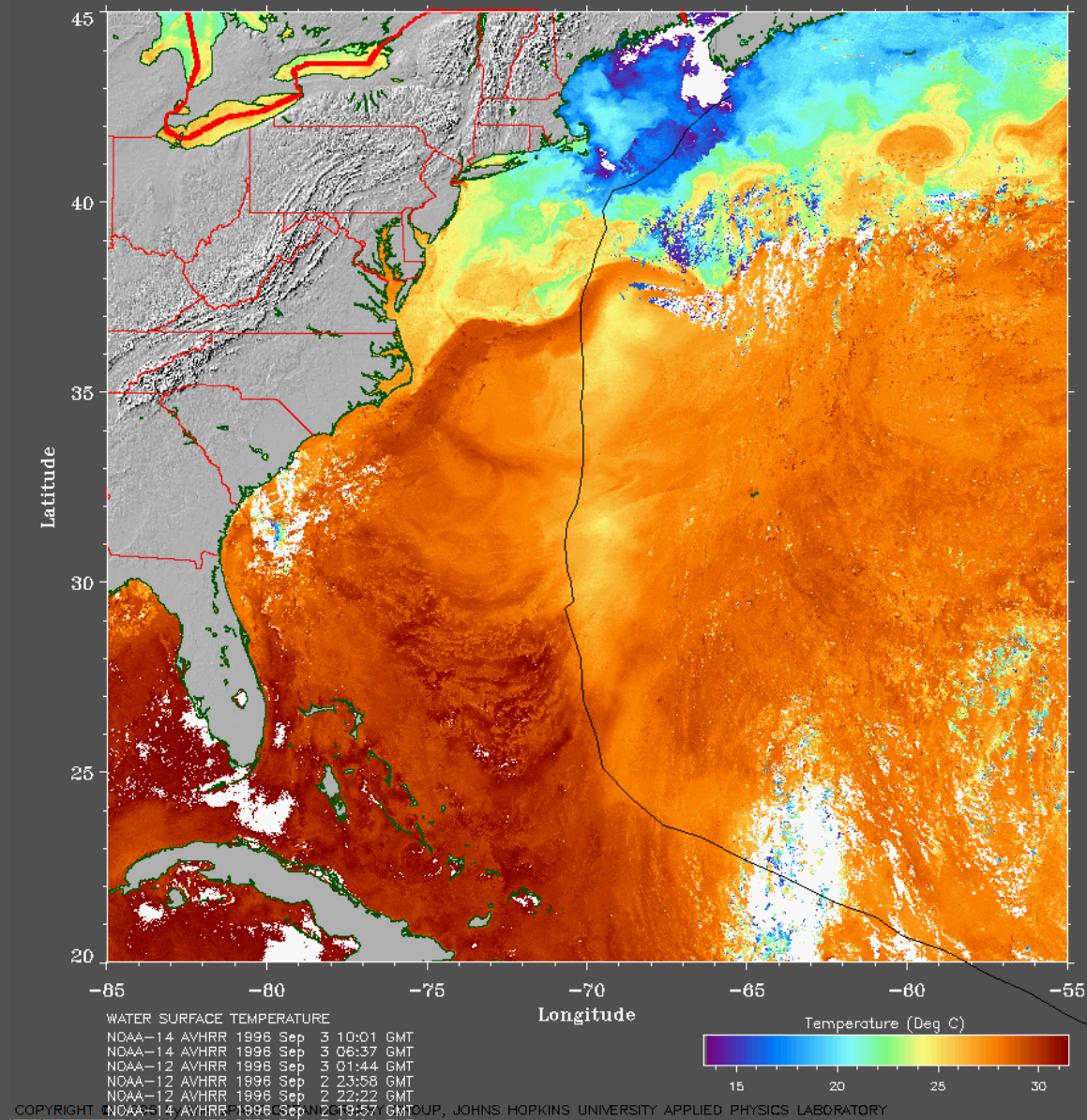
Genesis points and  $PI=60 \text{ ms}^{-1}$  contour, 1979-2018



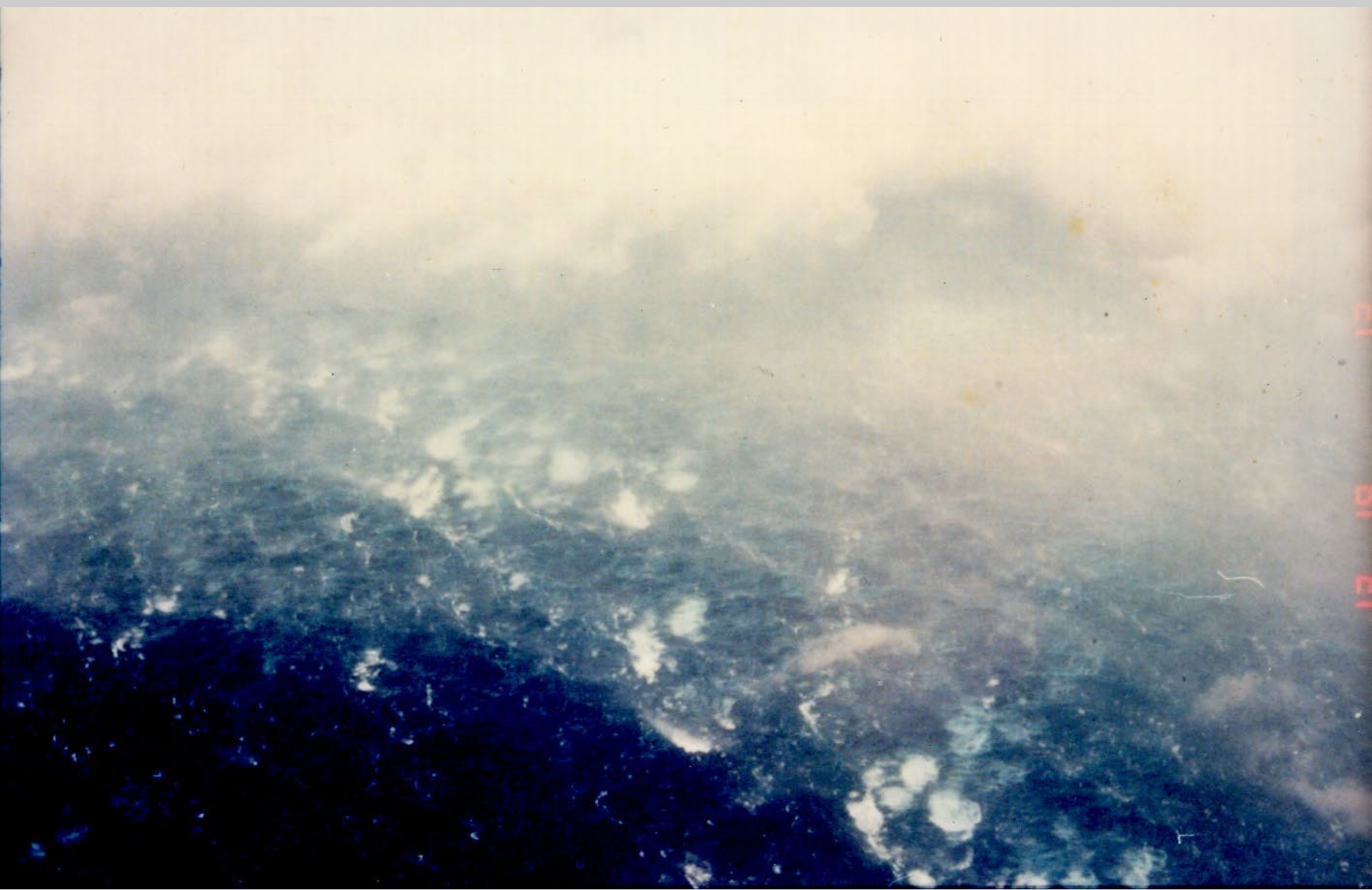
Blue dots are locations of hurricane formation, 1979-2018

Black contour is contour of 130 MPH potential intensity

# Strong Mixing of Upper Ocean





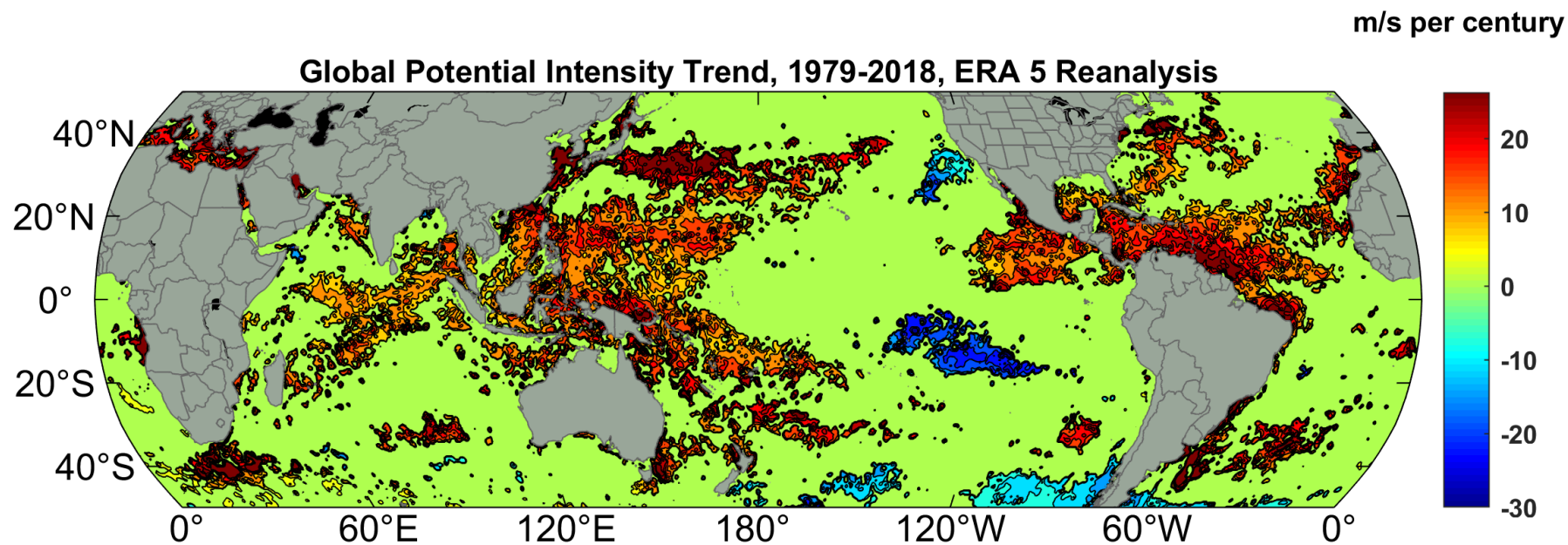




# Hurricanes and Climate Change

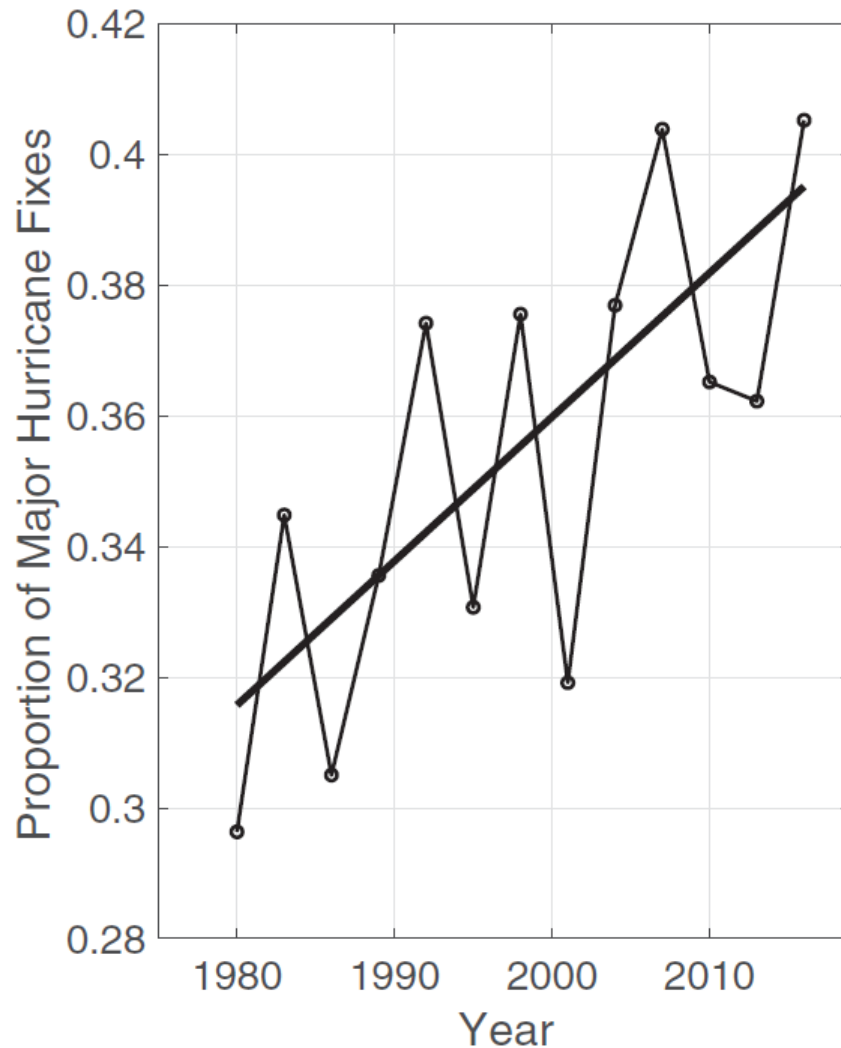


## Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis



(Trend shown only where p value < 0.05)

## Satellite-derived proportion of major hurricane fixes



Time series of fractional proportion of global major hurricane estimates to all hurricane estimates for the period 1979–2017. Each point, except the earliest, represents the data in a sequence of 3-y periods. The first data point is based on only 2 y (1979 and 1981) to avoid the years with no eastern hemisphere coverage. The linear Theil–Sen trend (black line) is significant at the 98% confidence level (Mann–Kendall  $P$  value = 0.02). The proportion increases by 25% in the 39-y period (about 6% per decade).

Kossin et al., *PNAS*, 2020

# Expected Responses to Global Warming

- Increased intensity of hurricanes
- Increased magnitude of storm surges
- Increase in hurricane rainfall
- Frequency could decline



# Summary

- Hurricanes are nature's heat engine, powered by heat flowing from the ocean to the atmosphere
- Only the ocean can support hurricanes; heat cannot flow through land fast enough to power these storms
- Hurricanes mix cold water to the surface, limiting their own strength
- Climate change is making hurricanes stronger and wetter, but not necessarily more frequent