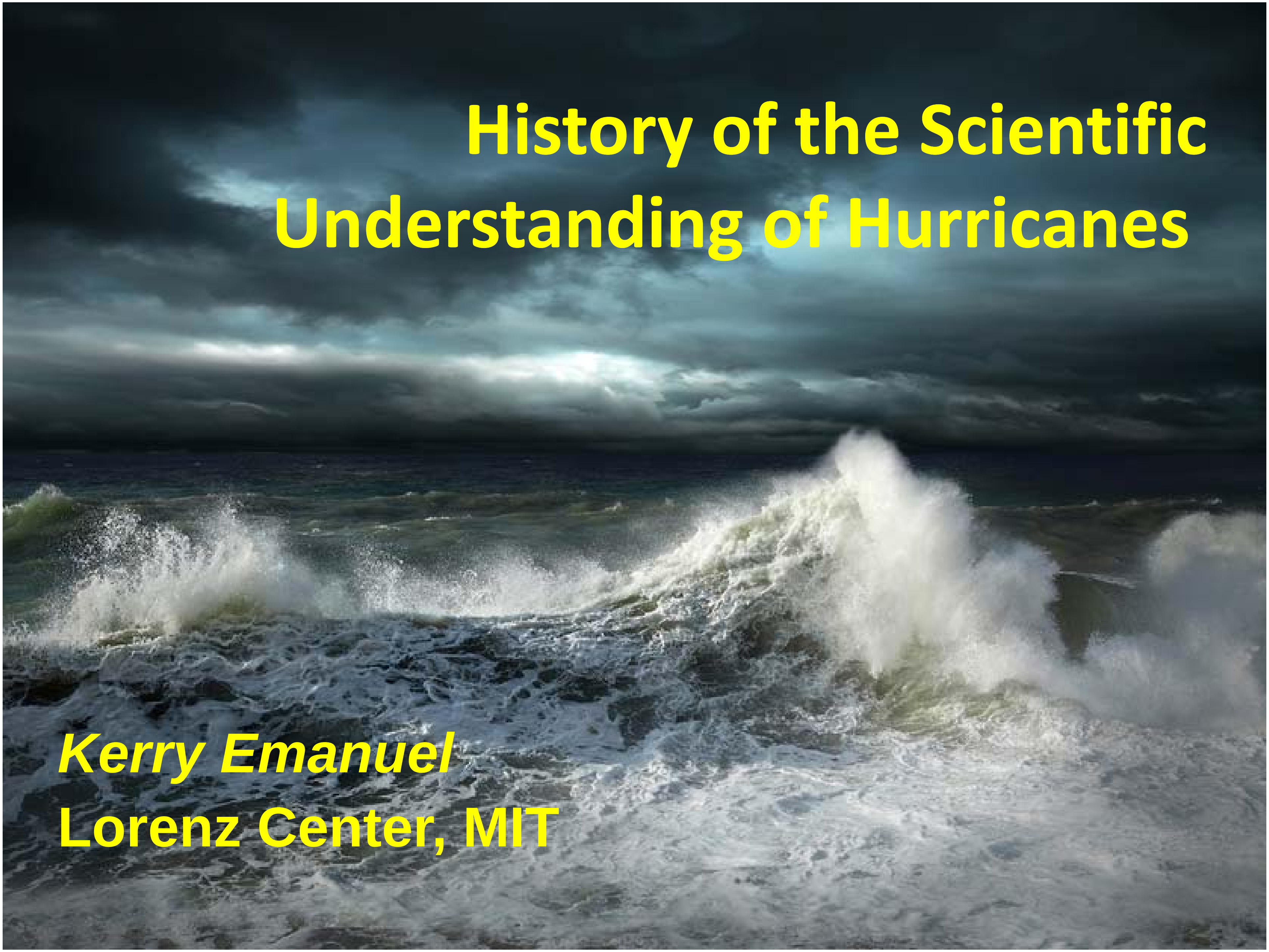
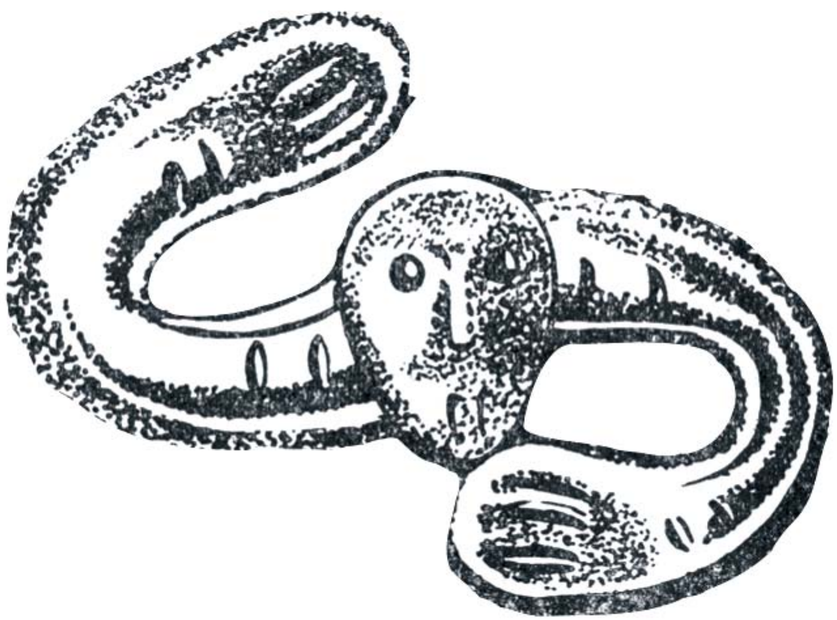
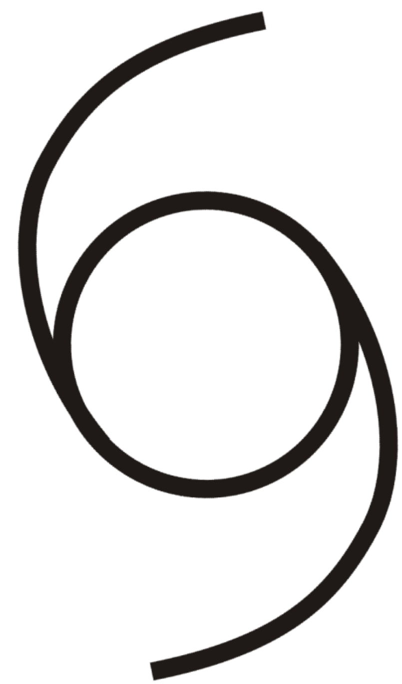

History of the Scientific
Understanding of Hurricanes
Kerry Emanuel
Lorenz Center, MIT

Four Eras

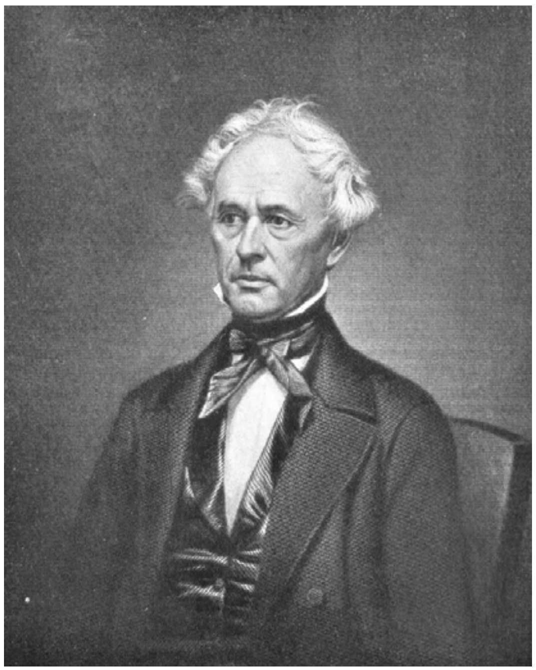
- Early inferences
- The Post-War era
- The 1960s-70s
- 1980s - Present

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, beginning with Columbus





Scientific research into hurricanes might be said to have begun in 1821, when **William C. Redfield**, a saddler by trade, rode across southern Connecticut to examine the damage wrought by a hurricane, and determined that the storm had to have been rotating.



William C. Redfield
1789-1857

After the Hurricane, Ogden Milton Pleissner

Early weather map, constructed by William Redfield, showing the winds around a winter storm in New England in 1839

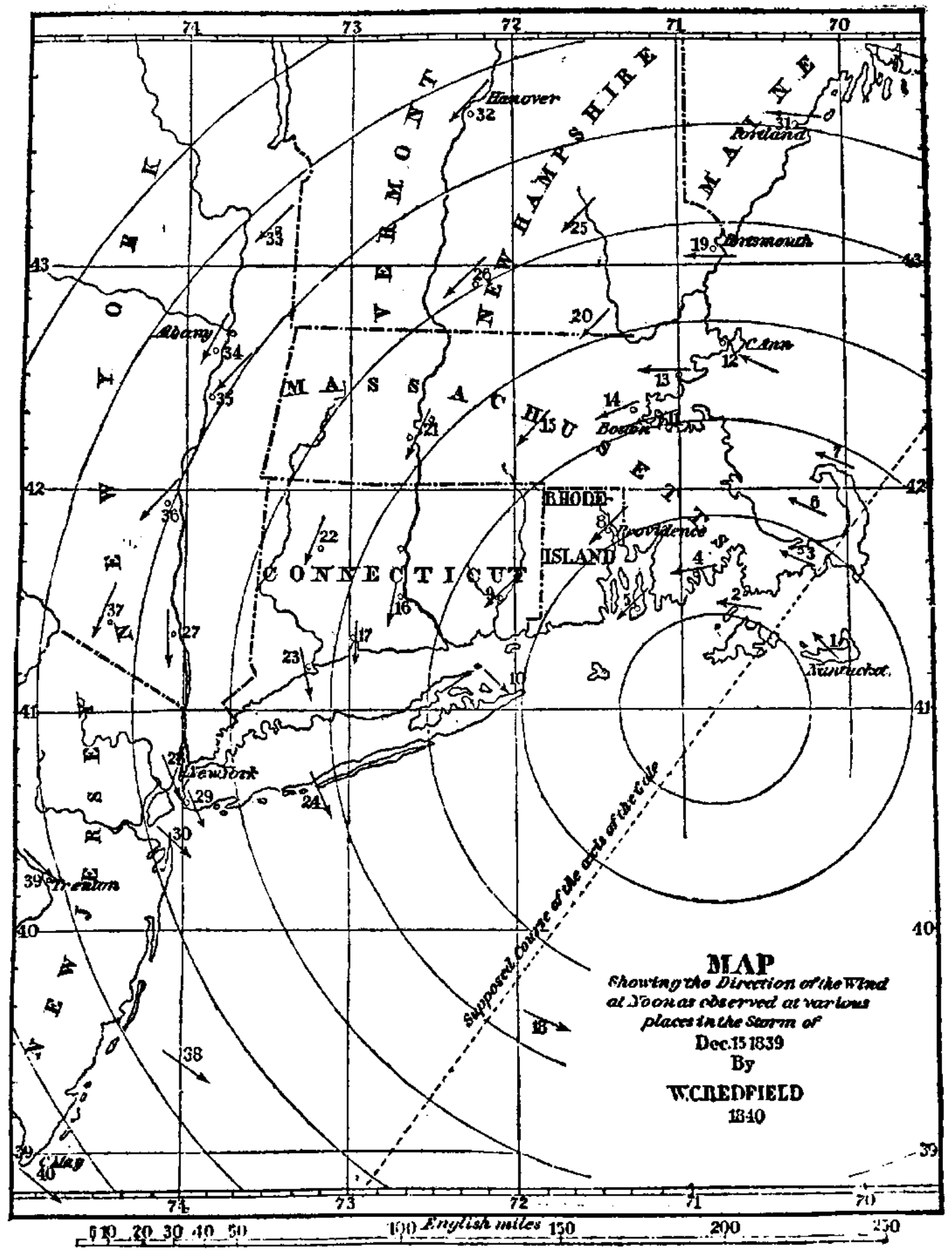
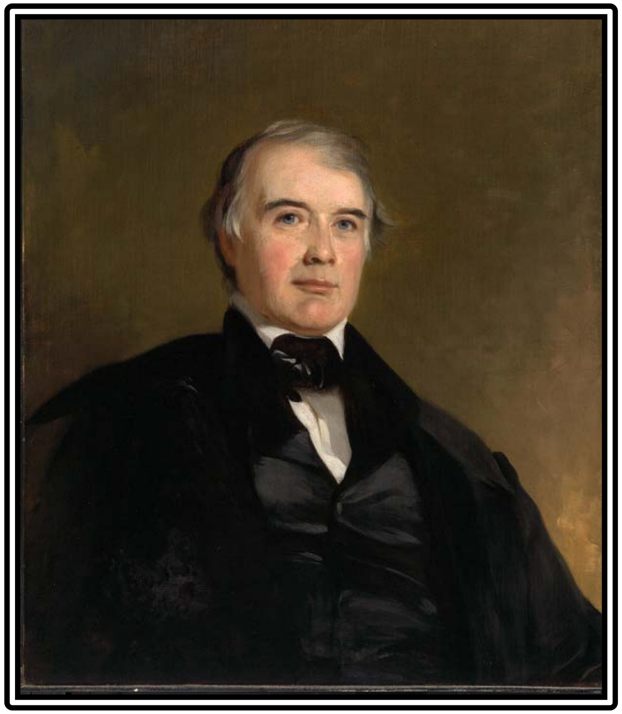


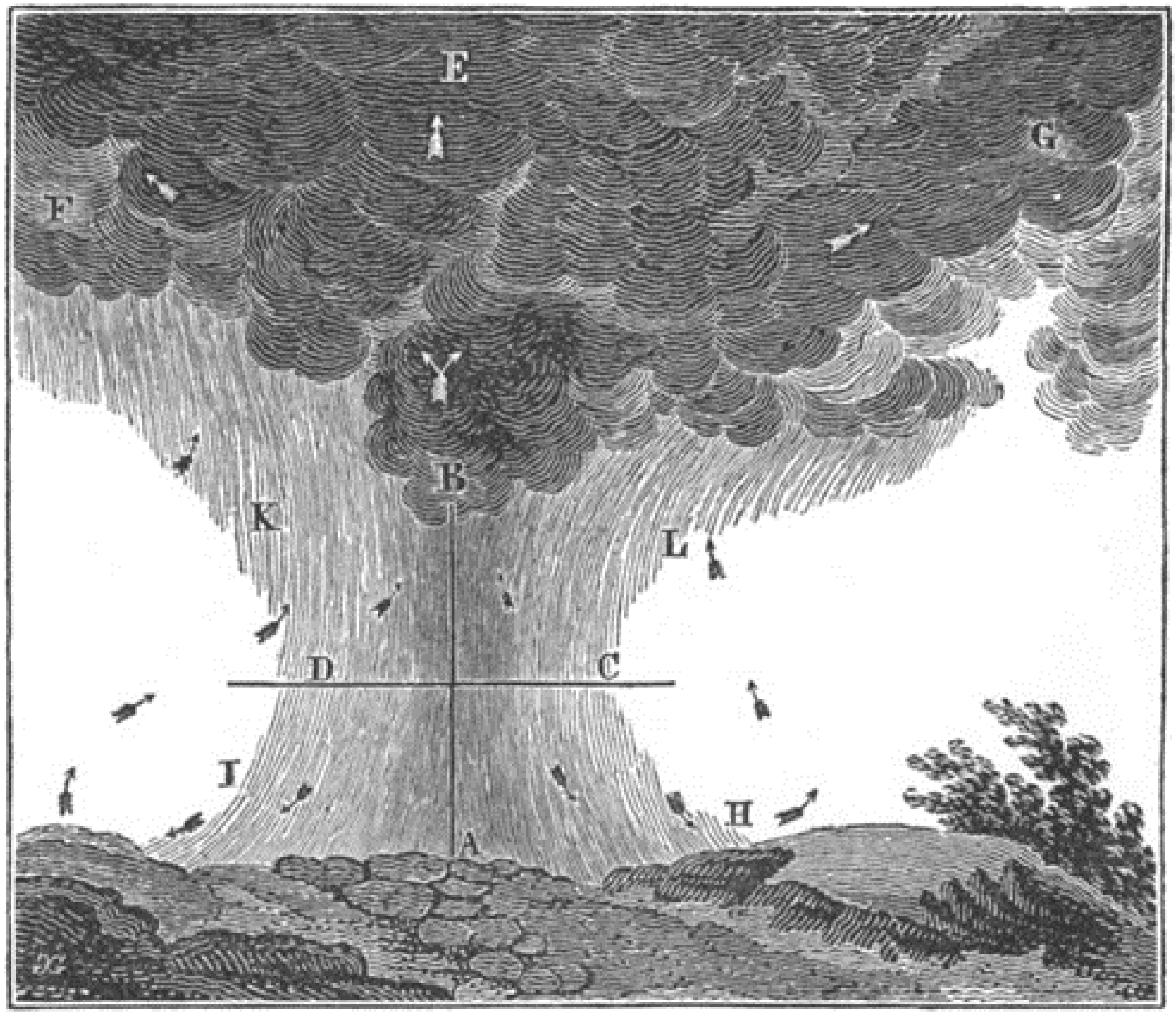
FIGURE 4. The vertical nature of storms (Redfield, 1843), from Redfield, "Observations on the storm of December 15, 1839," *Trans. Am. Phil. Soc.*, **8** (1843). Arrows indicate wind direction, corresponding to eight and in some cases to sixteen points of the compass. Numbers next to arrows refer to observation stations. Superimposed concentric circles indicate an average inward inclination of about 6° for the direction of the wind. Note that the southeast portion of the storm contains no wind data, a fact that Loomis later emphasized in his critique of Redfield's view of storms.

James Pollard Espy
1785-1860



Developed a theory of convection emphasizing the importance of adiabatic expansion and latent heating, publishing in 1841 a synthesis *The Philosophy of Storms*

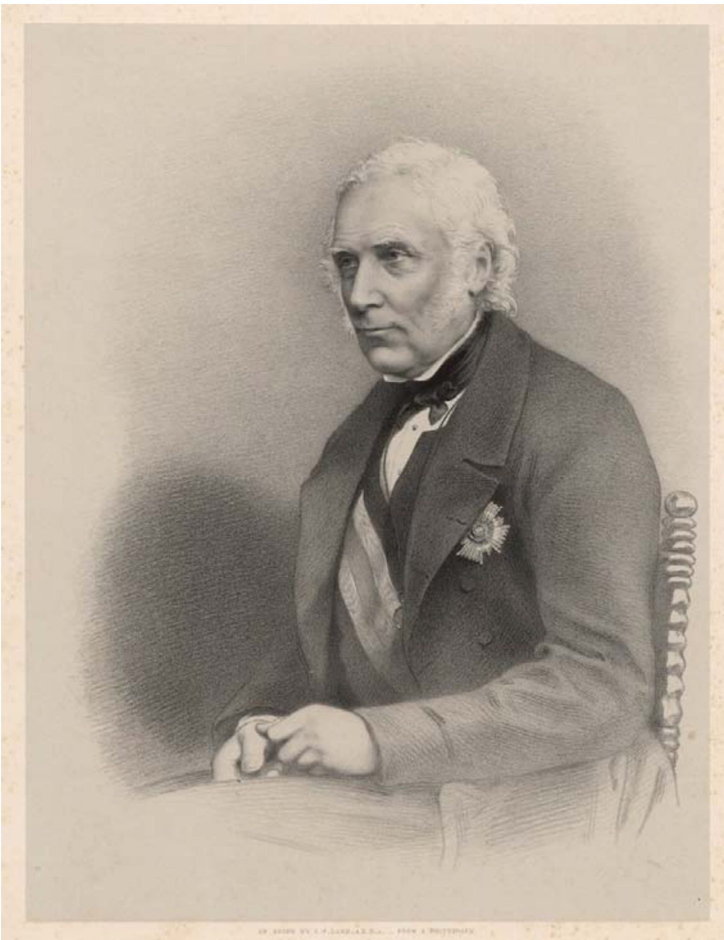
He debated Redfield, insisting that physics dictated that air should flow radially into storms, not around them.



From James Pollard Espy: *Second report of the joint committee on meteorology of the American philosophical society and Franklin Institute*. In: *Journal of the Franklin Institute* 21(6), June 1836

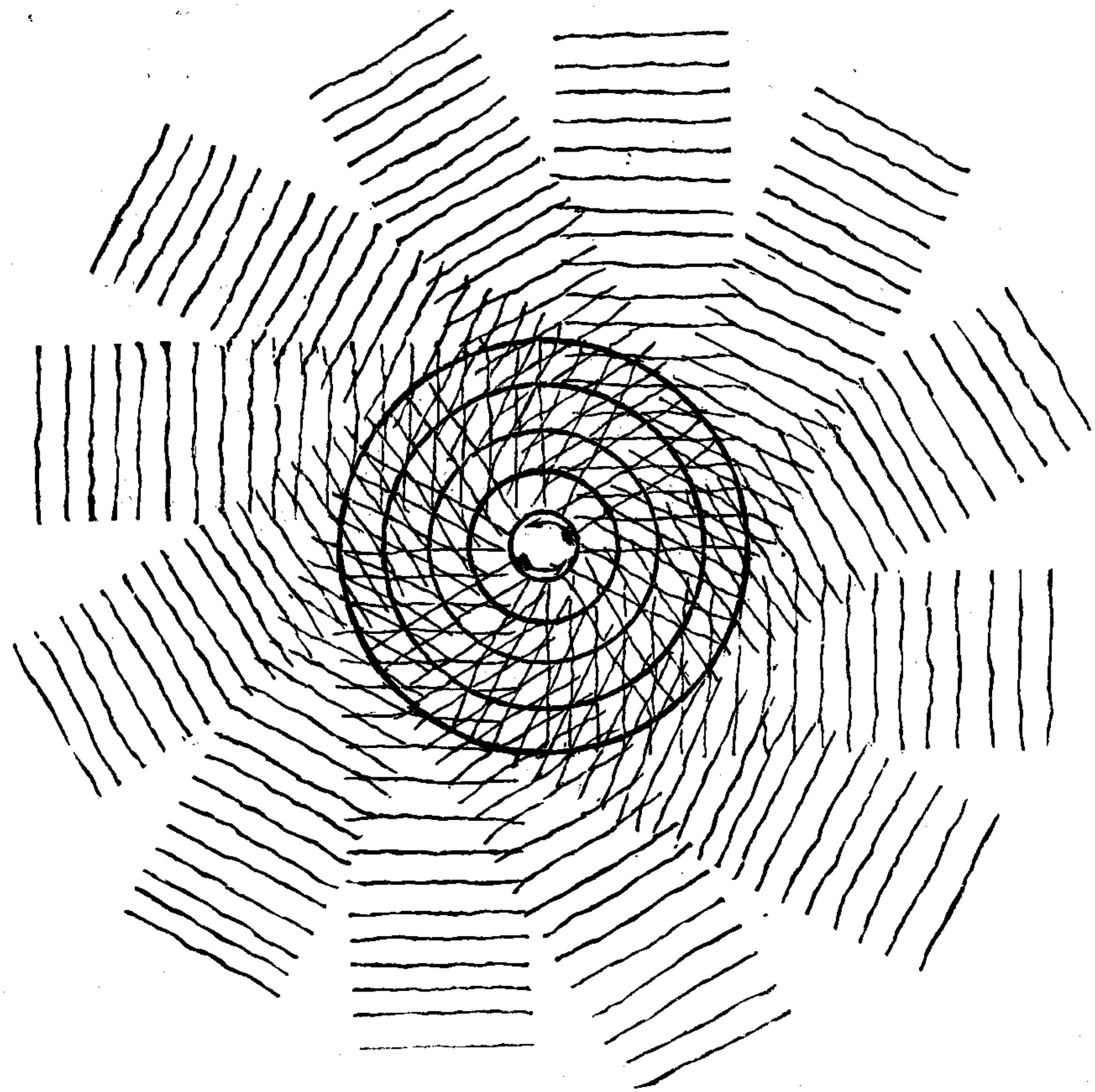
Sir William Reid

1791-1858



- Governor of Bermuda, 1839 to 1846
- Wrote first comprehensive analyses of hurricane, *The Law of Storms*, in 1838
- Practical guide to signs of approaching hurricanes

Cross-Sea and Swell raised by a Storm North of the Equator.



For the Northern Hemisphere.

Henry Piddington
1797-1858

A portrait sketch by Colesworthey Grant published in 1839 in the *India Review*

- British sea captain in the India and China trade
- Noting circular winds around a calm center recorded by ships caught in storms, coined the name *cyclone* in 1848
- In 1844 he published *The Horn-Book for the Law of Storms for the Indian and China Seas* -- first practical guide for sailors to avoid hurricanes.

Plate 117

Storm Card.

NORTHERN HEMISPHERE.

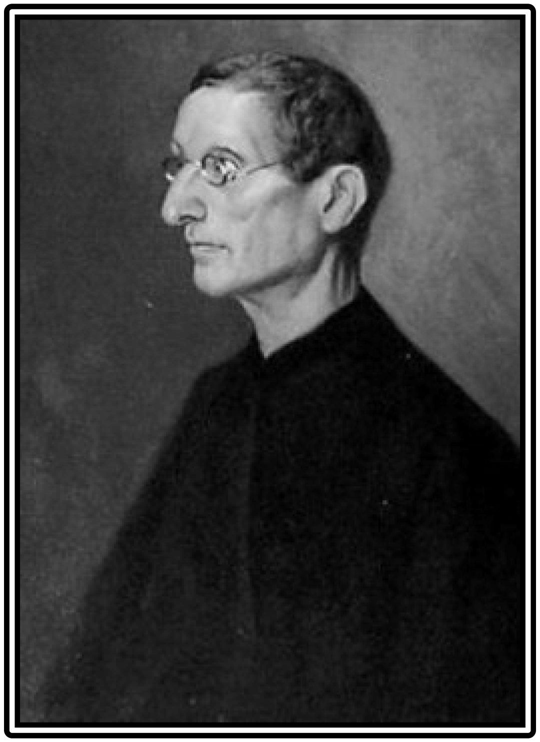
ABBREVIATIONS.

Nd.—northward.	*ch.*—change.
Ed.—eastward.	*h.*—heave-to.
Sd.—southward.	*Str.*—starboard
Wd.—westward.	*P.*—port.

REMARKS.

The courses here given are for the wind two points on the starboard quarter, but if sea and wind permit, bring the wind broad on the quarter. If in either of these positions there be danger of broaching-to, run before the wind until more moderate, and then bring wind on starboard quarter. A ship hove-to having the wind steady, is on the storm-track. Run before the wind, note the course, and keep it.

Benito Viñes
1837-1893



- Jesuit priest in Havana, head of Meteorological Observatory at El Colegio Belen, 1870
- Established network of observations in the Caribbean
- First to recognize importance of upper level winds in steering hurricanes
- Published *Practical hints in regard to West Indian hurricanes* in 1885.

WWII and Post-War Years

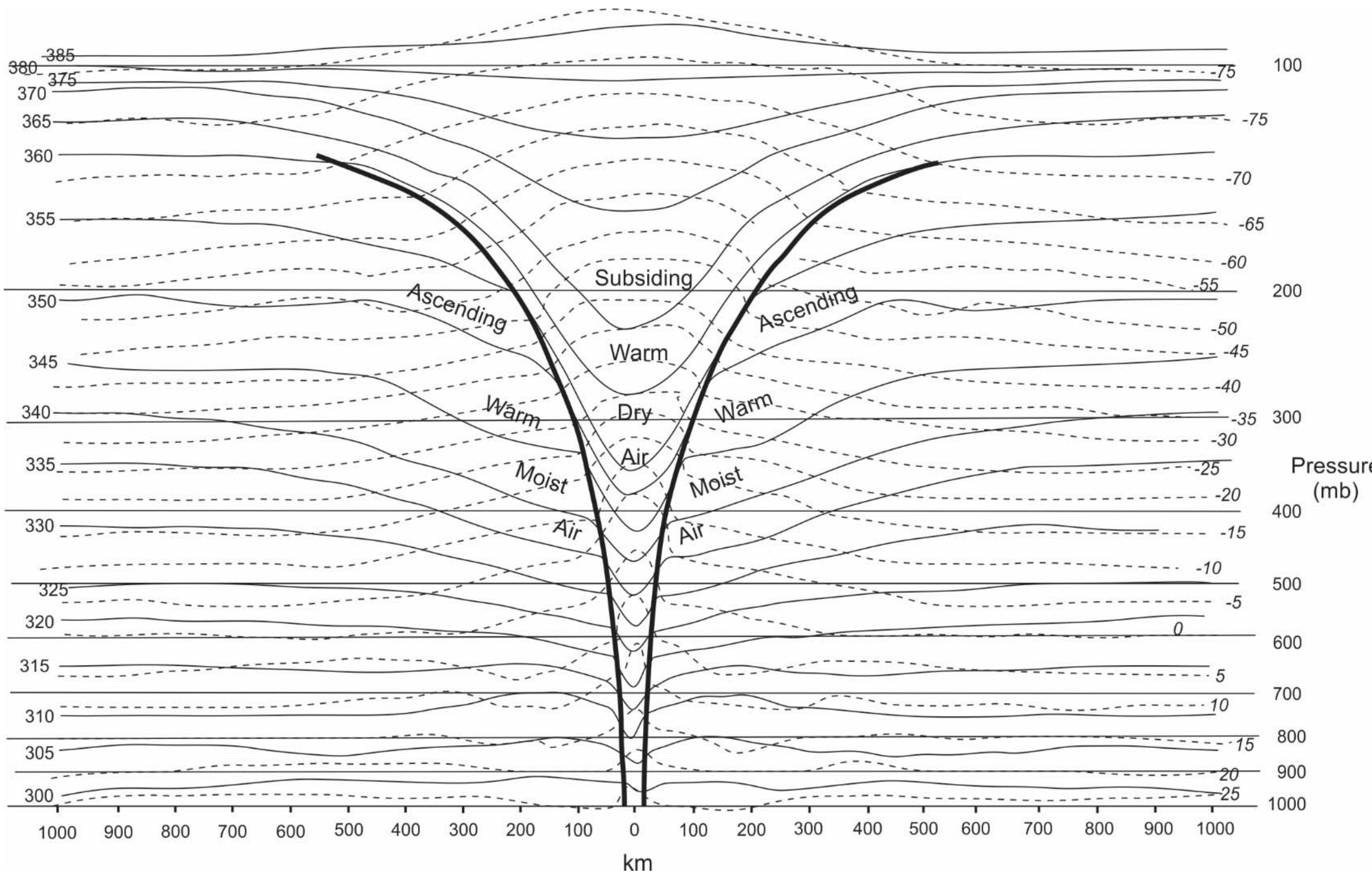
- 27 July 1943: Army Air Corps Colonel Joseph Duckworth took an Air Force AT-6 trainer from an airfield in Texas and became the first aviator to penetrate the eye of a hurricane.
- Shortly thereafter, routine hurricane reconnaissance began in the North Atlantic and western North Pacific

AT-6

Radar

Radar image of Typhoon Cobra captured from one of
the ships of Admiral Halsey’s Third Fleet, east of the Philippines.
This was only the second tropical cyclone captured on radar.

The Post-War Research Boom



Palmén, 1948, based on a single radiosonde ascent through the eye of a hurricane in 1944

Herbert Riehl, 1950: Recognized that latent heat is an *internal* conversion, and not the source of energy for a hurricane. He emphasized that the flow of enthalpy from the ocean to the atmosphere is the energy source for a hurricane

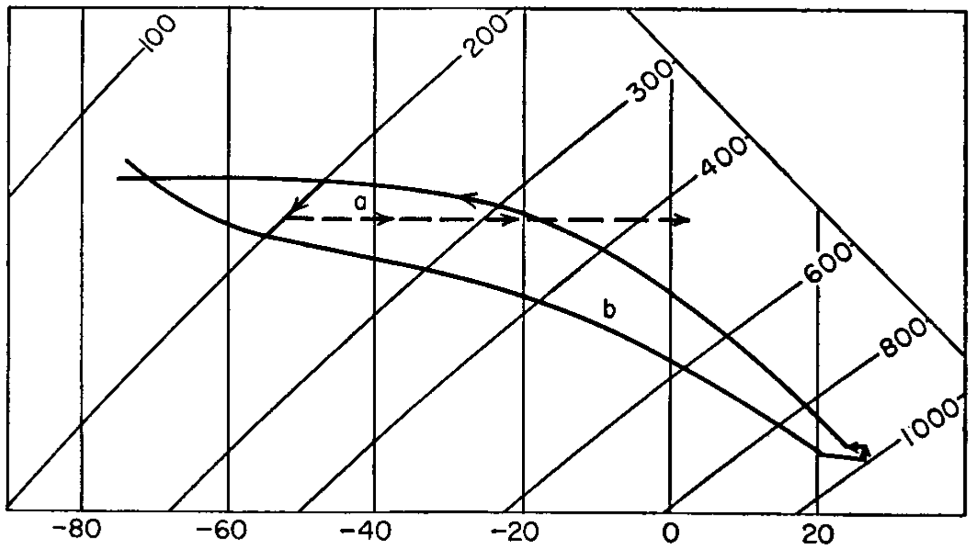


Fig. 11.34. Tephigram showing energy cycle in mature hurricane (53).

Ernst Kleinschmidt, 1951: "*The heat removed from the sea by the storm is the basic energy source of the typhoon*" (translation from German)

$$V^2 = 2E\frac{q^2}{1-q^2}$$

E=Energy from tephigram above
q= Fraction of angular momentum lost in transit to eyewall

Riehl and Malkus, 1960: Again recognizing that hurricanes are powered by heat fluxes from the sea, they came close to deriving a bound for the surface winds:

Empirical relation between increase in equivalent potential temperature and drop in pressure in PBL air in transit to eyewall:

$$\delta p_s = -2.5 \delta \theta_e$$

Conservation of equivalent potential temperature:

$$V \frac{\partial \theta_e}{\partial s} = C_k V \frac{\left(\theta^*{}_{e0} - \theta_e\right)}{h}$$

Combine:

$$\frac{\partial p_s}{\partial s} = -2.5 C_k \frac{\left(\theta^*{}_{e0} - \theta_e\right)}{h}$$

Work done against friction in PBL:

$$V \frac{\partial p_s}{\partial s} = \frac{-C_D}{h} \rho V^3$$

Had they combined above two:

$$V^2 = 2.5 \frac{C_k}{C_D} \frac{\left(\theta^*{}_{e0} - \theta_e\right)}{\rho}$$

Some other notable contributions, 1948-1958:

Rossby, 1948: "Beta drift" of closed isopleths of vorticity on a sphere

Bergeron, 1954: Reasoned that cold convective downdrafts should lead to initial cold-core cyclone aloft; surface fluxes would later "invert" the cyclone

1955: Troika of 3 damaging U.S. hurricanes in 1954 (Carol, Edna, and Hazel) leads to the establishment of the National Hurricane Research Program, led by Robert Simpson

Late 1950s: Rapid progress in numerical solution of the vorticity equation

Then something strange happened!

From 1958-1969, research reverted to Espy's idea that tropical cyclones are modes of release of conditional instability. Work of Riehl, Malkus, Kleinschmidt and Bergeron cast aside; surface fluxes omitted.

Miller, 1958: Estimated pressure drop from compressional heating in eye

Kasahara (1961), Rosenthal (1964), Kuo (1965), Yamasaki (1968): First attempts to numerically simulate tropical cyclones regarded them as modes of release of conditional instability and did not include surface heat fluxes. They recognized they had failed.

Charney and Eliassen, 1964: "*Conditional Instability of the Second Kind*" (CISK): Rotation inhibits release of CAPE; needs Ekman boundary layer

J. Charney and A. Eliassen, *J. Atmos. Sci*., 1964: Conditional Instability of the Second Kind

- Significant departure from earlier theoretical development
- Emphasized thermodynamic interaction of vortex with cumulus convection, rather than with the ocean
- Energetically inconsistent, but largely displaced Riehl-Malkus-Kleinschmidt view during 1970s and 80s

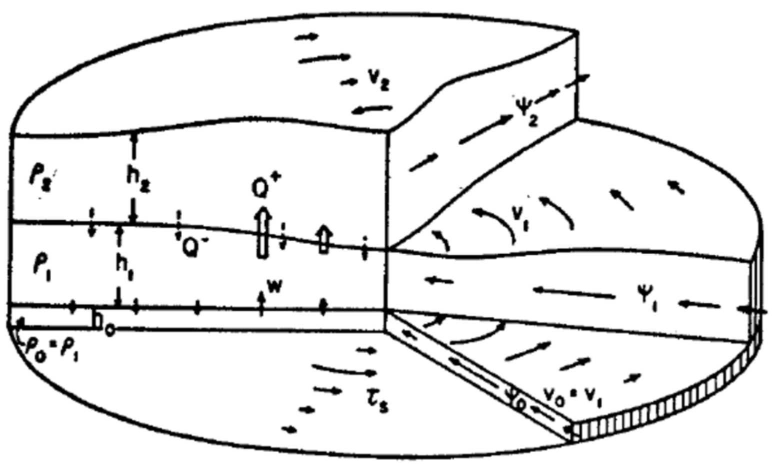
V. Ooyama, *J. Atmos. Sci*., 1969:

- Regarded as first successful numerical model of tropical cyclone; included surface fluxes
- Sensitivity experiments demonstrated the critical importance of surface enthalpy fluxes
- Nevertheless, results interpreted by some as supporting CISK theory, because Ooyama started from a very unstable initial condition and showed that it was linearly unstable to vortex amplification

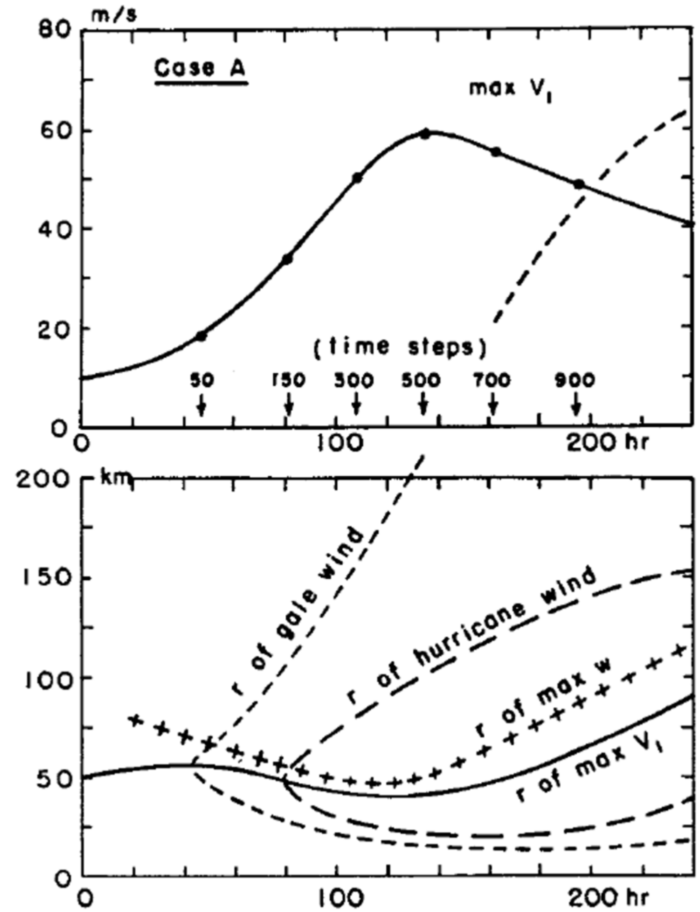
Ooyama's 1969 Model

First successful numerical simulation of a tropical cyclone by Vic Ooyama in **1969**.

Model Structure



Time evolutions of maximum wind speed, and radius of maximum winds



1960s-1970s:
Rapid technological development

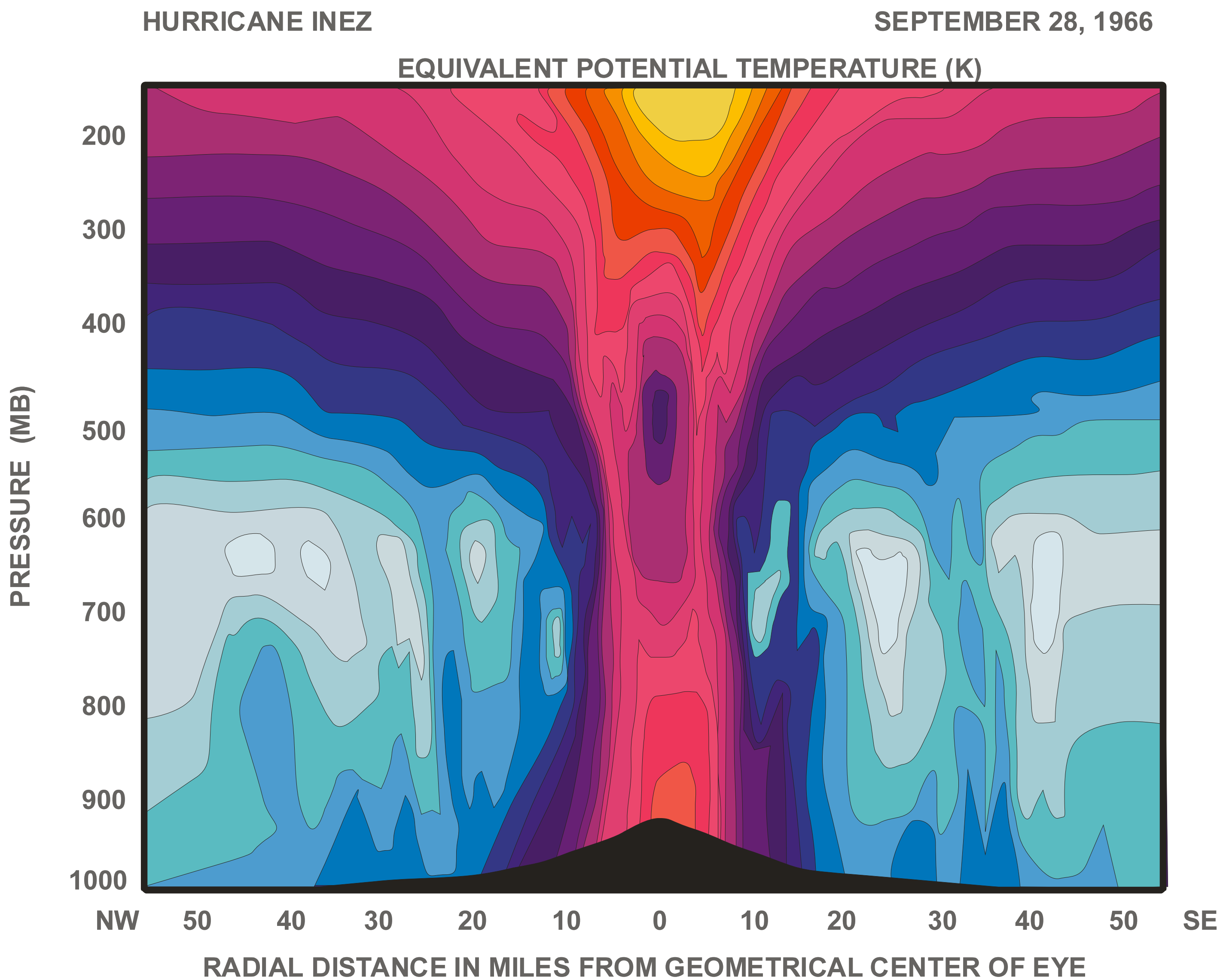
Hurricane Esther of 1961, as photographed from *TIROS III*. This was first tropical cyclone to have been discovered from space.

Airborne Reconnaissance

WV-2, 1964

NOAA WP-3Ds
Mid 1970s

Cross-section of equivalent potential temperature through Hurricane Inez of 1966, from aircraft and dropsondes



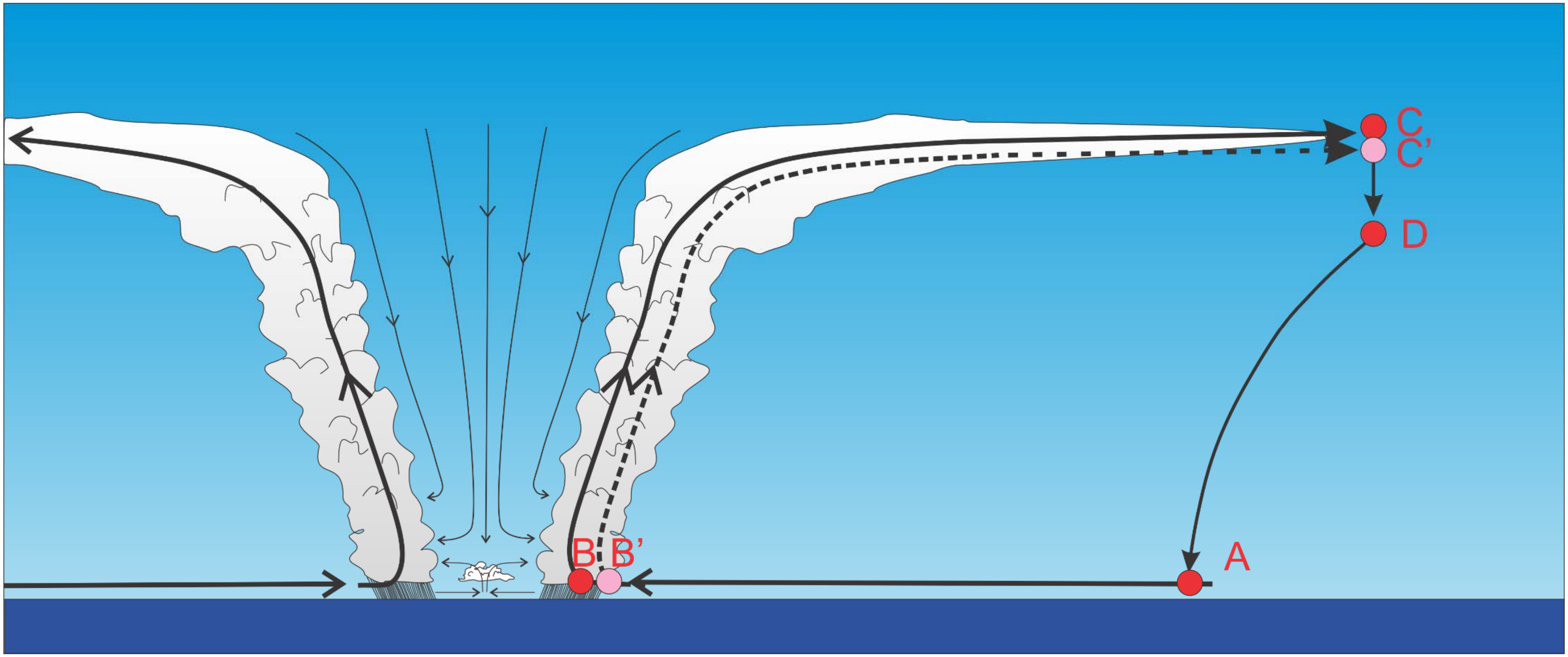
1970s-1980s:
Slow return to idea of flux-powered vortex:

S. Rosenthal, *J. Atmos. Sci*., 1978: Accidentally turned off cumulus parameterization in numerical model but found that vortex amplified anyway; sensitive to surface fluxes

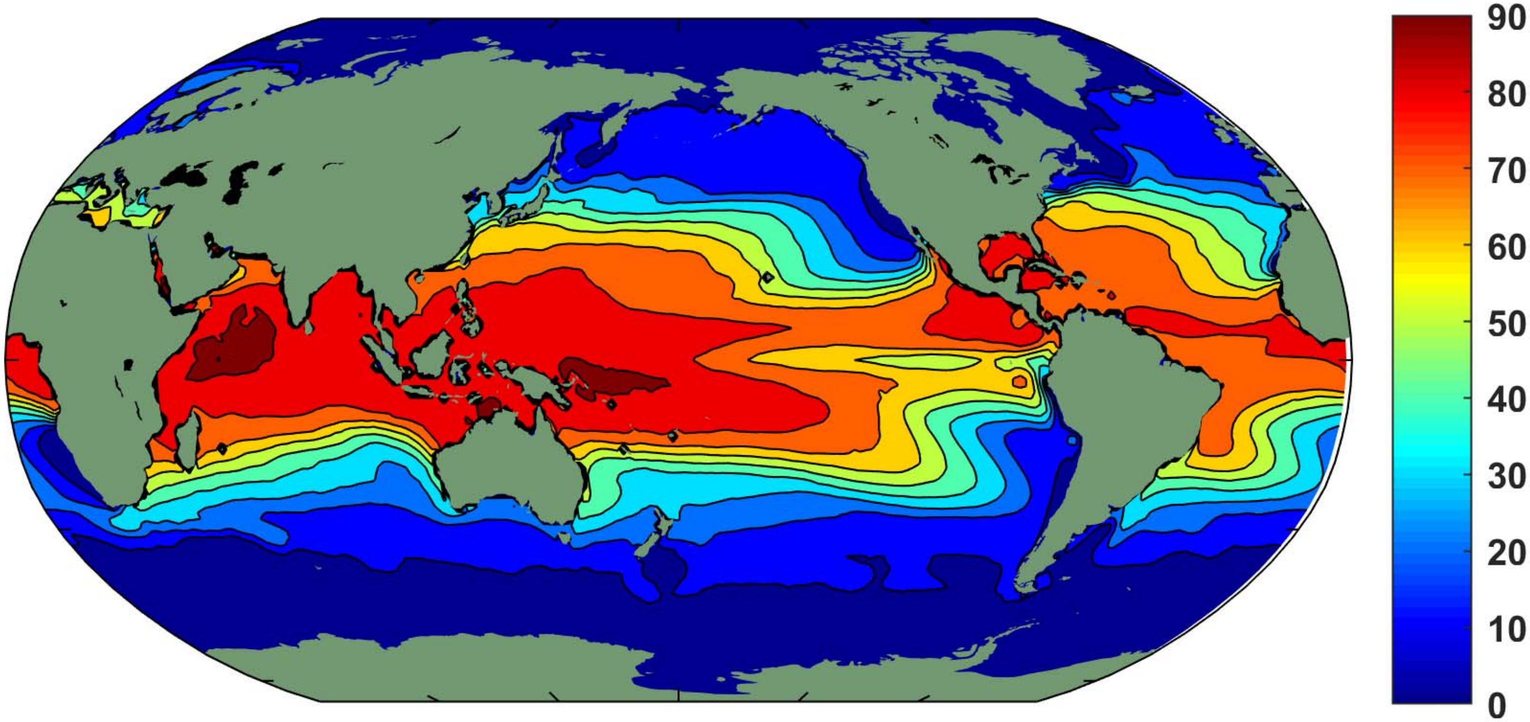
D. Lilly, late 1970s: Developed theory of steady axisymmetric hurricane, motivated by Rosenthal results, but did not publish this work

1985: K. Emanuel and R. Rotunno worked on steady state theory and discovered earlier work of Lilly

Differential Carnot Cycle

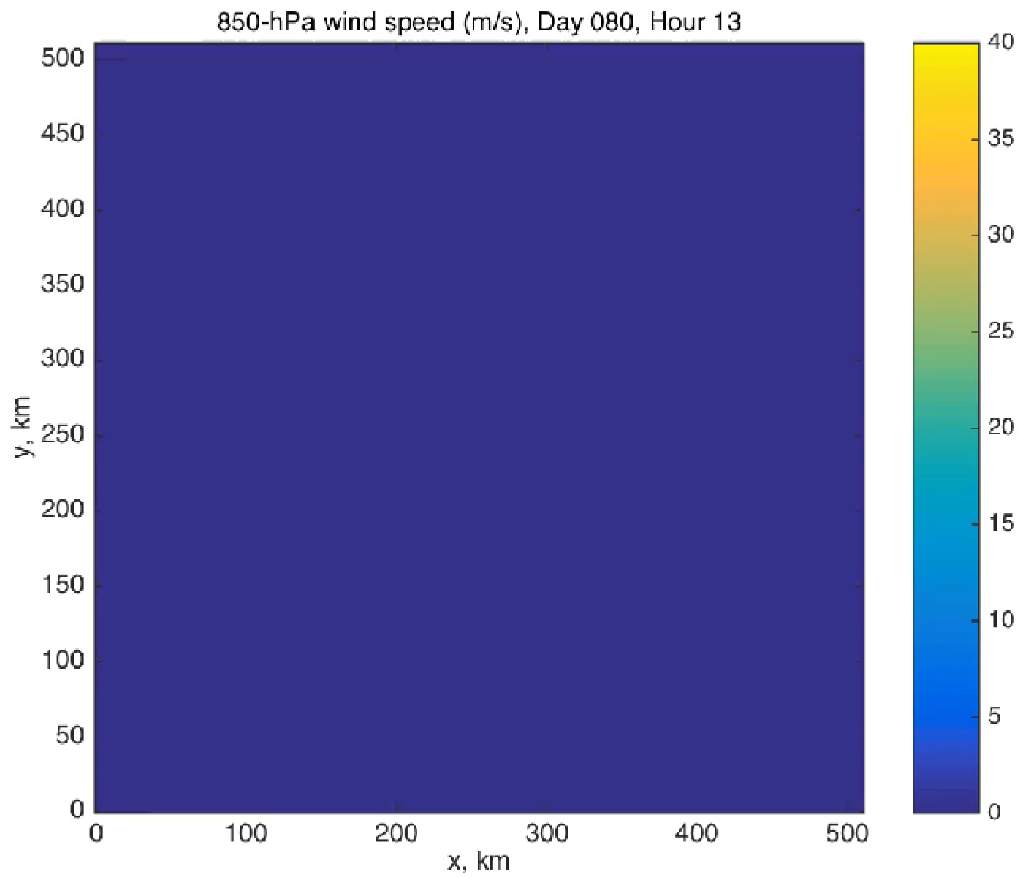


$$|\mathbf{V}_s|^2 = \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}\left(k_0^* - k\right)$$



Annual maximum of the potential intensity (m/s) using
ERA-Interim data averaged over 1979–2016.

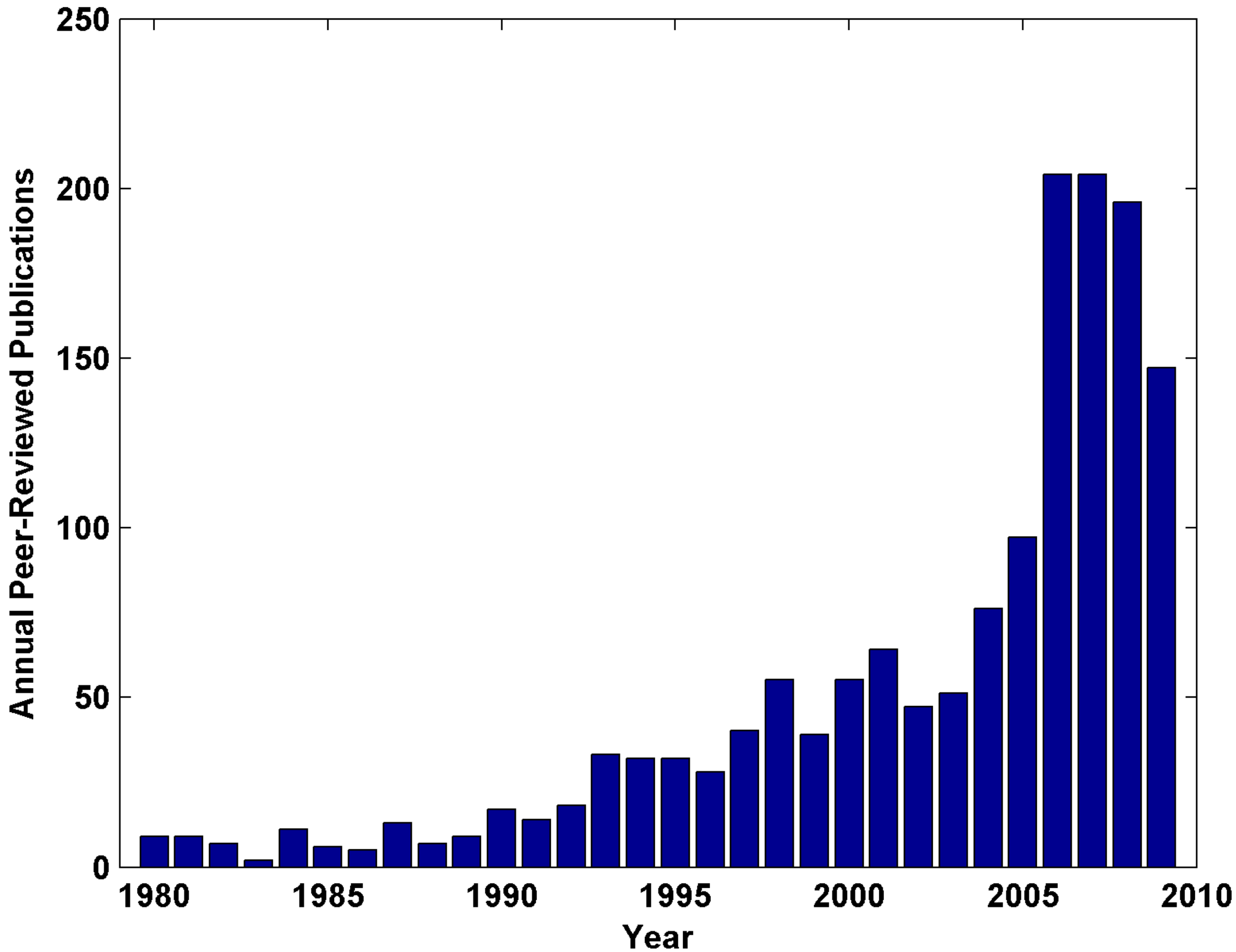
Explicit numerical simulation of rotating radiative-convective equilibrium



Courtesy Tim Cronin

Yet most contemporary textbooks and even some research papers continue to state that tropical cyclones are driven by latent heat release

1980s to Present: Rapid Advances in Basic Understanding, Measurement Technology, and Forecasting Skill



Annual Number of Peer-Reviewed Articles with “Hurricane” or “Tropical Cyclone” in their Titles, according to *Meteorological and Geoastrophysical Abstracts*

Theory:

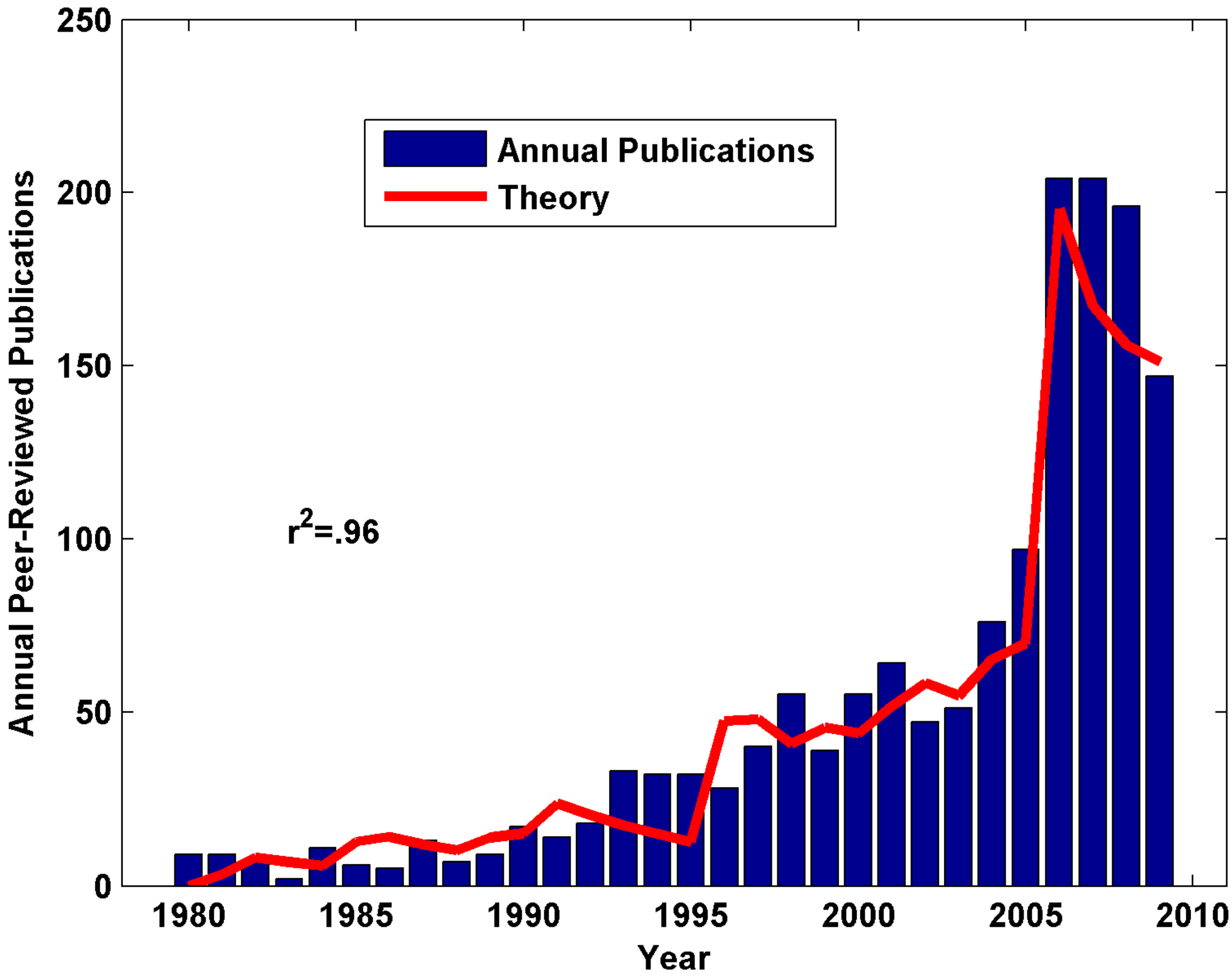
Interest Stimulation

$$\frac{\partial PRP}{\partial t} = 0.08\left(N_{Atl} - 6\right)^{5/2} - \frac{PRP}{6\ years}$$

Scientist Attention Span

$$PRP = Annual\ \ peer - reviewed\ \ publications$$

$$N_{Atl} = Number\ of\ \ Atlantic\ TCs\ per\ \ year$$



250
200
150
100
50
0
1980
1985
1990
1995
2000
2005
2010
Year
Annual Peer-Reviewed Publications
Annual Publications
Theory
r²=.96

Basic Research Highlights:

- Rejection of CISK
- Return to older view of Kleinschmidt and Riehl
- Development of physically consistent potential intensity theory
- Conclusive demonstration of ocean feedback on hurricane intensity
- Refinement of theory of tropical cyclone motion

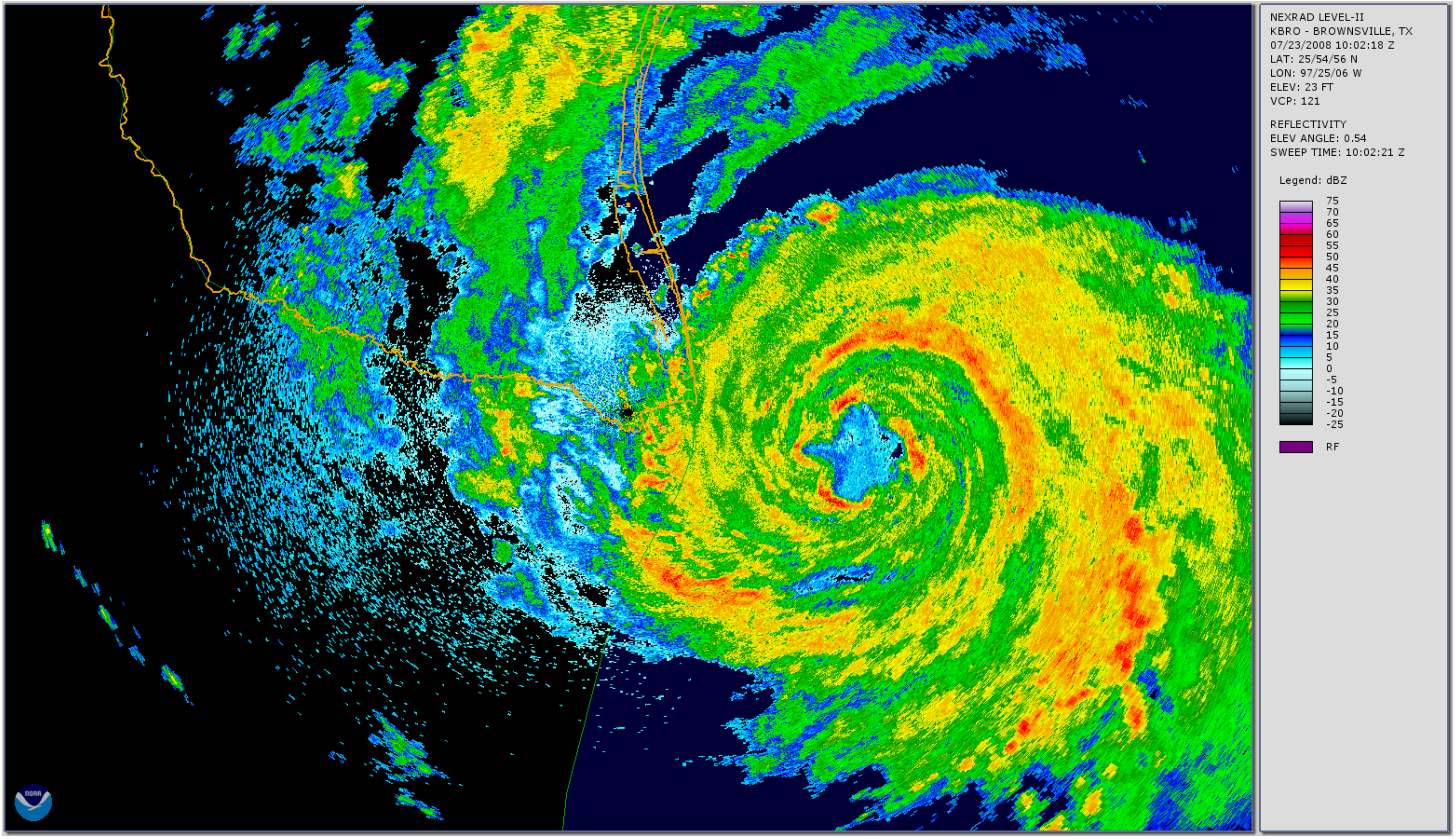
- Quantification of structure of vertical motions
- Secondary eyewalls: Discovery and dynamics
- Identification of eddy PV (angular momentum) fluxes in outflow layer as an influence on intensity change
- Further quantification of vertical shear effects on storm motion, structure, and intensity
- Further quantification of ENSO effects on NH TCs
- Modulation of TC activity by the Madden-Julian Oscillation

- Reemergence of interest in vortex Rossby waves
- Progress in understanding TC genesis through large-scale field experiments
- Accelerated research in extratropical transition
- Importance of surface effects: waves and spray
- Identification and understanding of superintensity

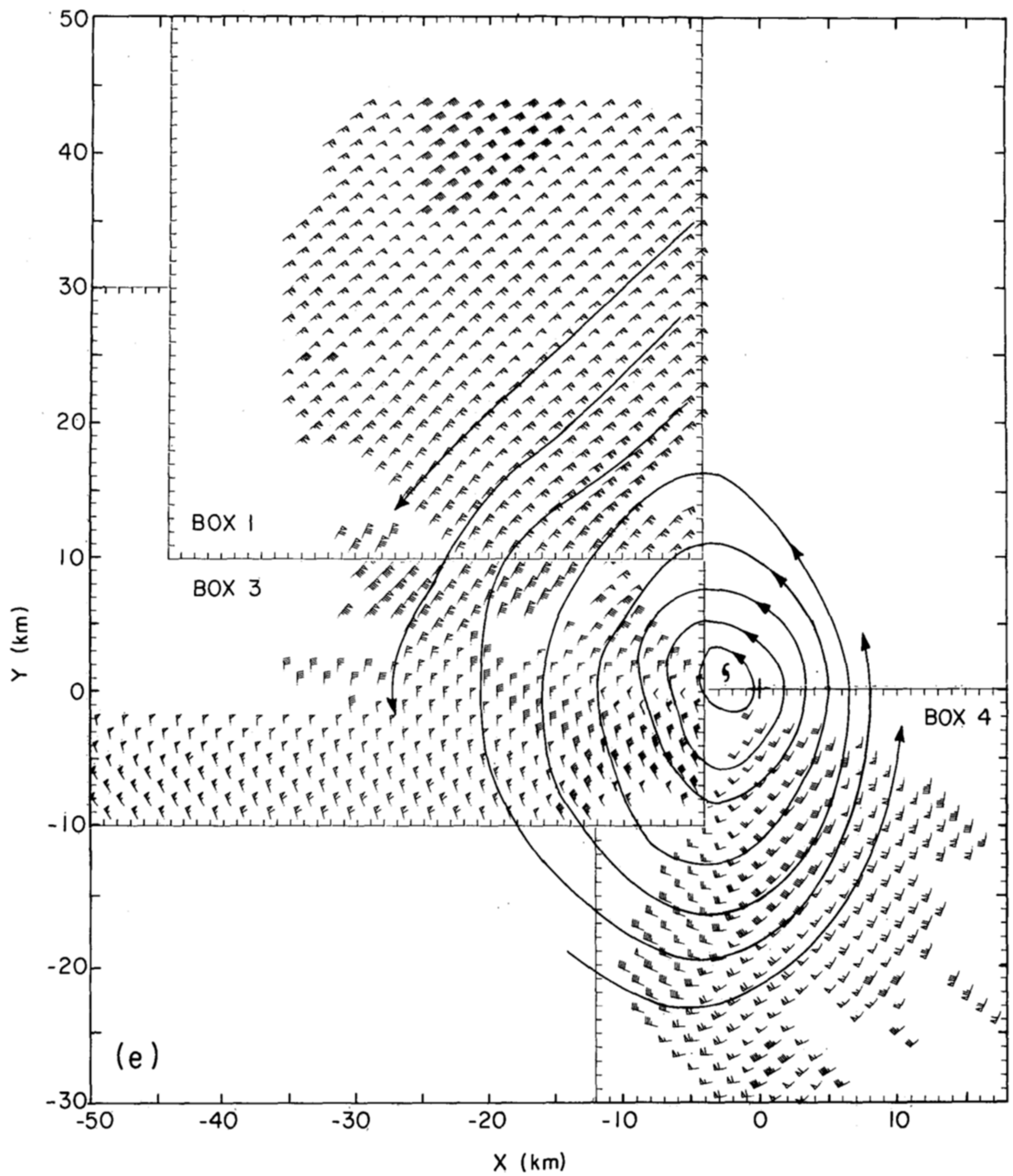
- Development of paleotempestology
- Emergence of research on long-term climate change effects on hurricanes
- Identification of physical and biological feedbacks of hurricanes upon climate

Advancing Measurement Technology

Radar



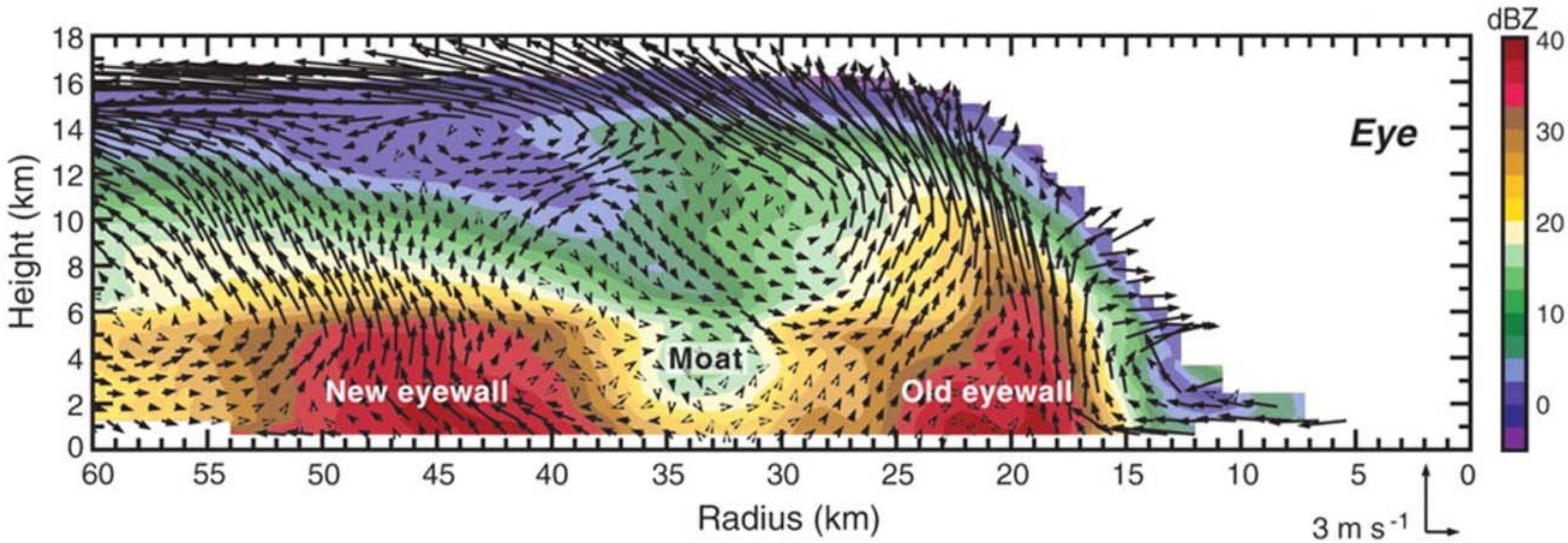
NOAA/NEXRAD image from Brownsville, Texas, showing Hurricane Dolly approaching the Texas–Mexico border on 23 Jul 2008. The radar reflectivity scale (dBZ) is given at the right.



Hurricane Debby, 1982

First Doppler winds in a hurricane: Marks and Houze, *BAMS*, 1984

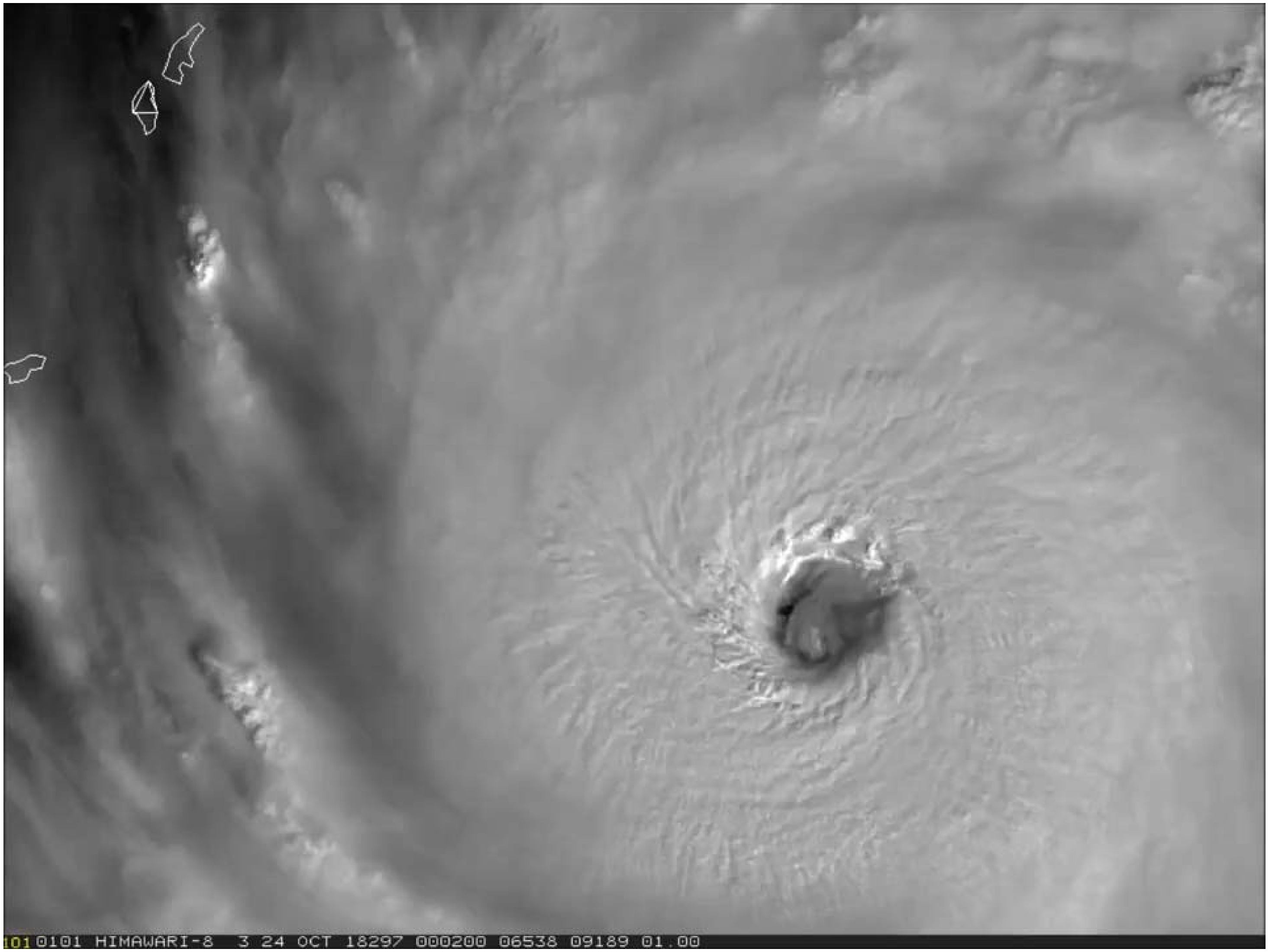
Doppler winds are now routinely collected by aircraft in Atlantic tropical cyclones



Drones!

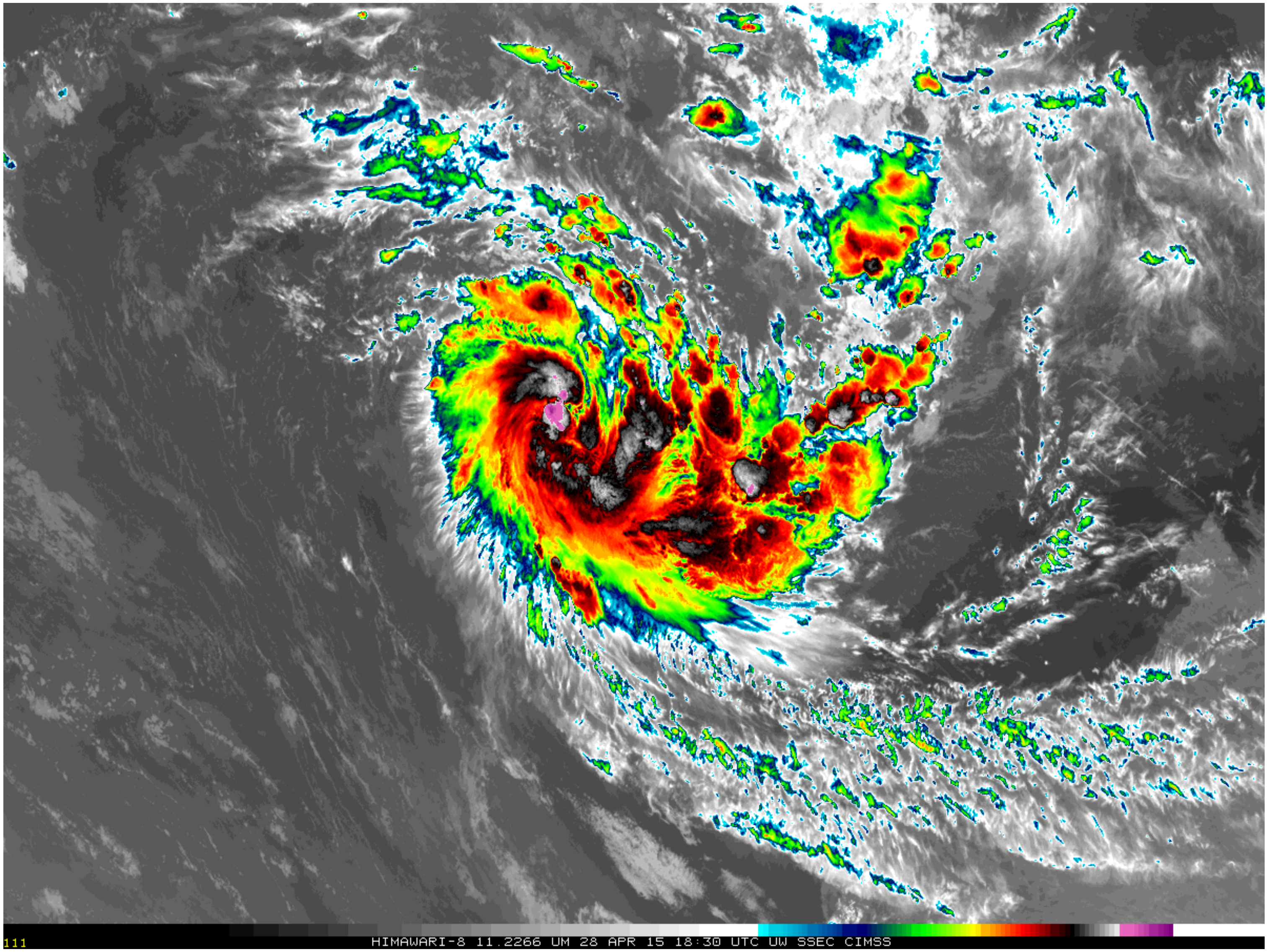
Joseph Cione shows a Coyote drone, soon to be dropped into a hurricane from the P-3 behind them. (NOAA/AOML)

Satellite Imagery: Unprecedented resolution

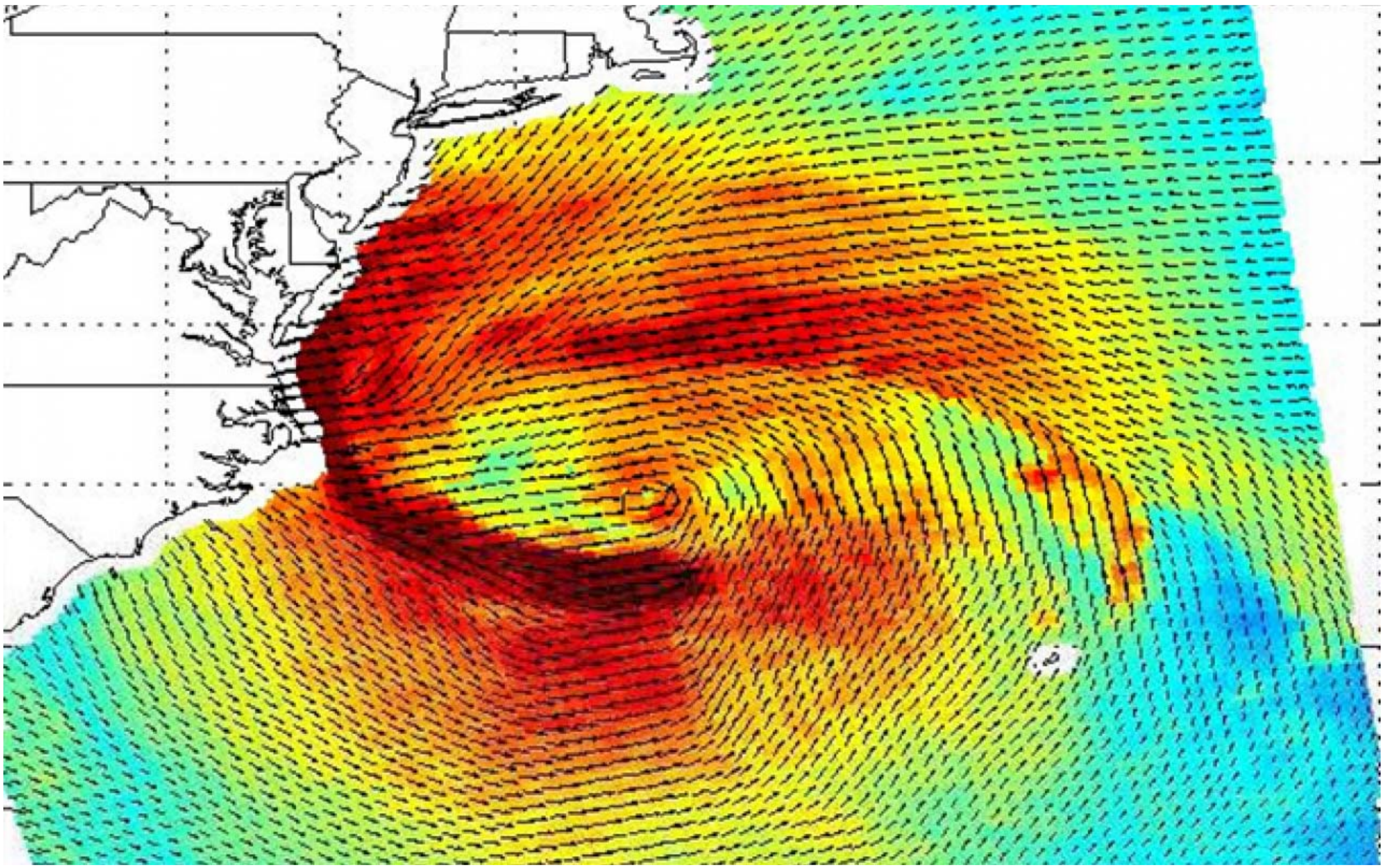


Typhoon Yutu on 24 October 2018

Himawari image of Depression 24S northwest of Australia, 1830 UTC 28 April 2015



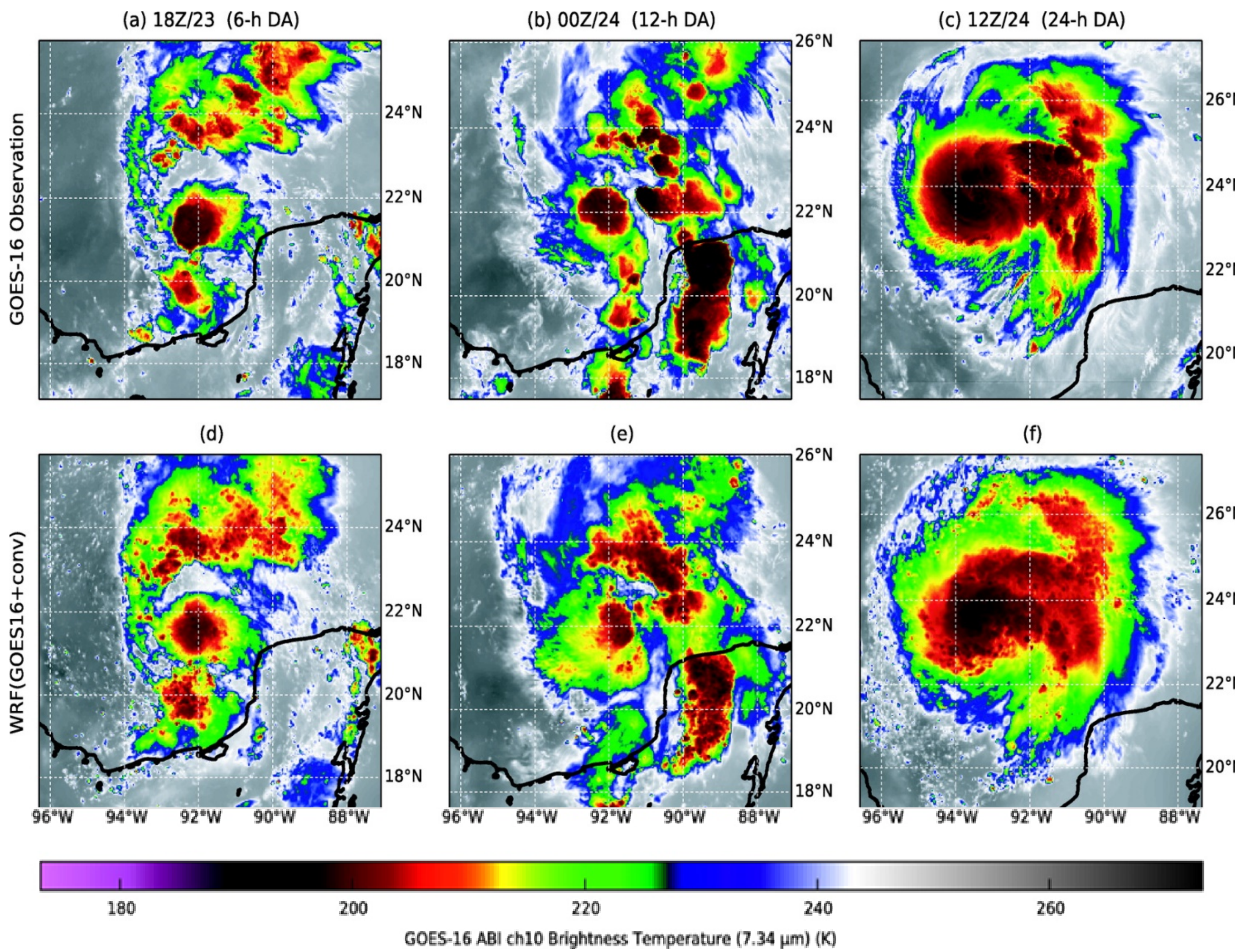
Scatterometer winds in Hurricane Sandy, 04 GMT 29 October 2012



Numerical Simulation:

Observed Brightness Temperature, TC Harvey of 2012

WRF-simulated Brightness Temperature



Zhang, F., M. Minamide, R. G. Nystrom, X. Chen, S.-J. Lin, and L. M. Harris, 2019: Improving Harvey forecasts with next-generation weather satellites: Advanced hurricane analysis and prediction with assimilation of GOES-r all-sky radiances. *Bull. Amer. Meteor. Soc.*, **100,** 1217-1222, doi:10.1175/bams-d-18-0149.1.

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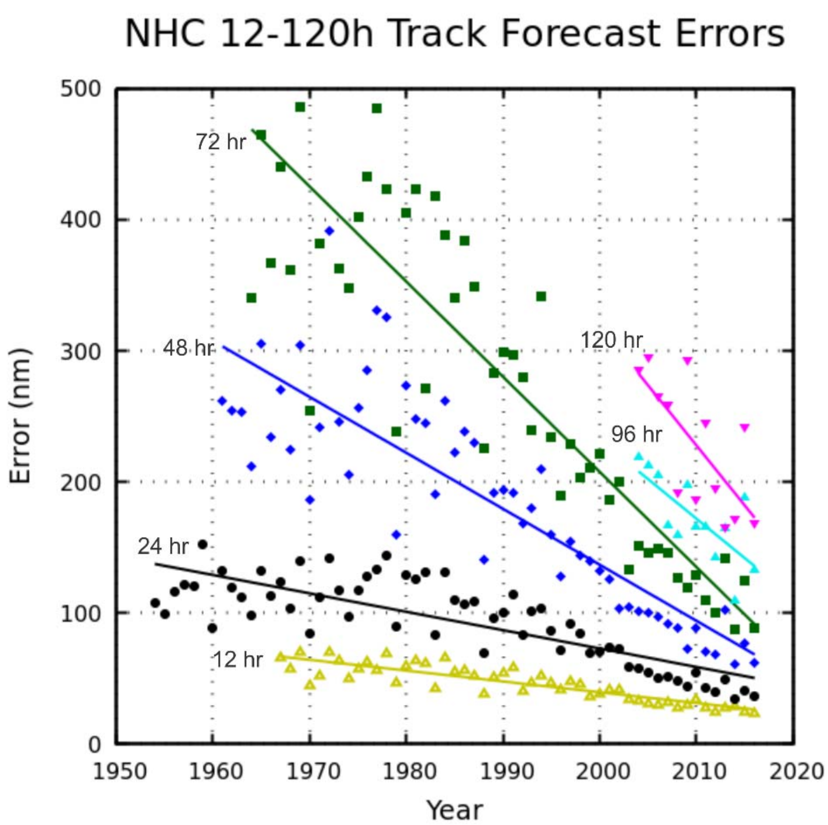
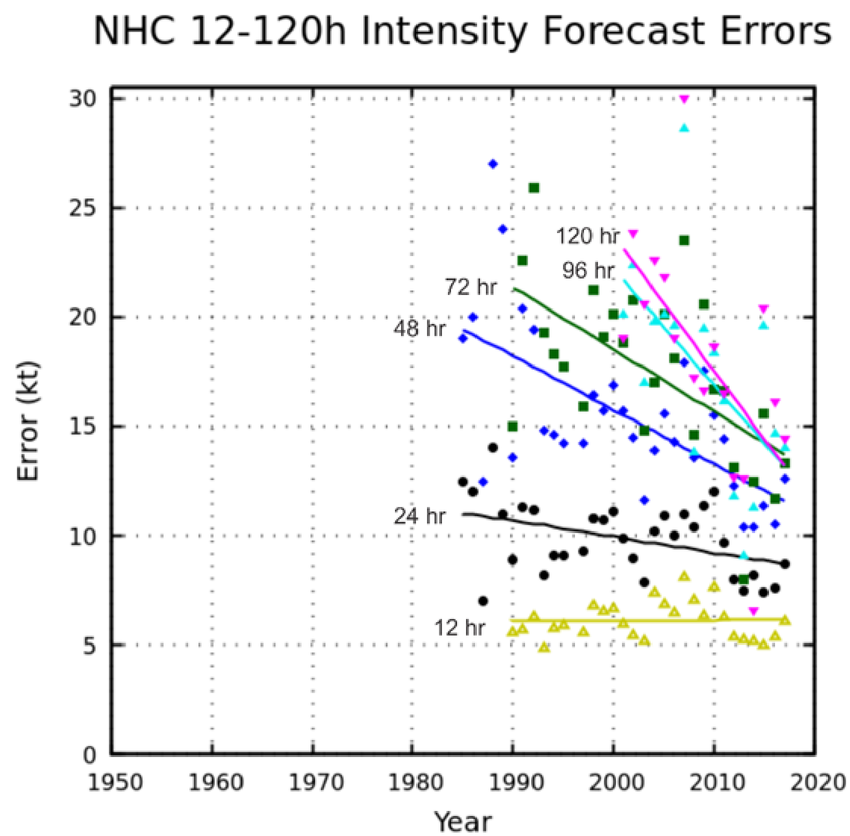
Forecasting



Track



Intensity

Note: Not easy to rule out the hypothesis that *all* of the improvement in the intensity skill came from improvements in track forecasts

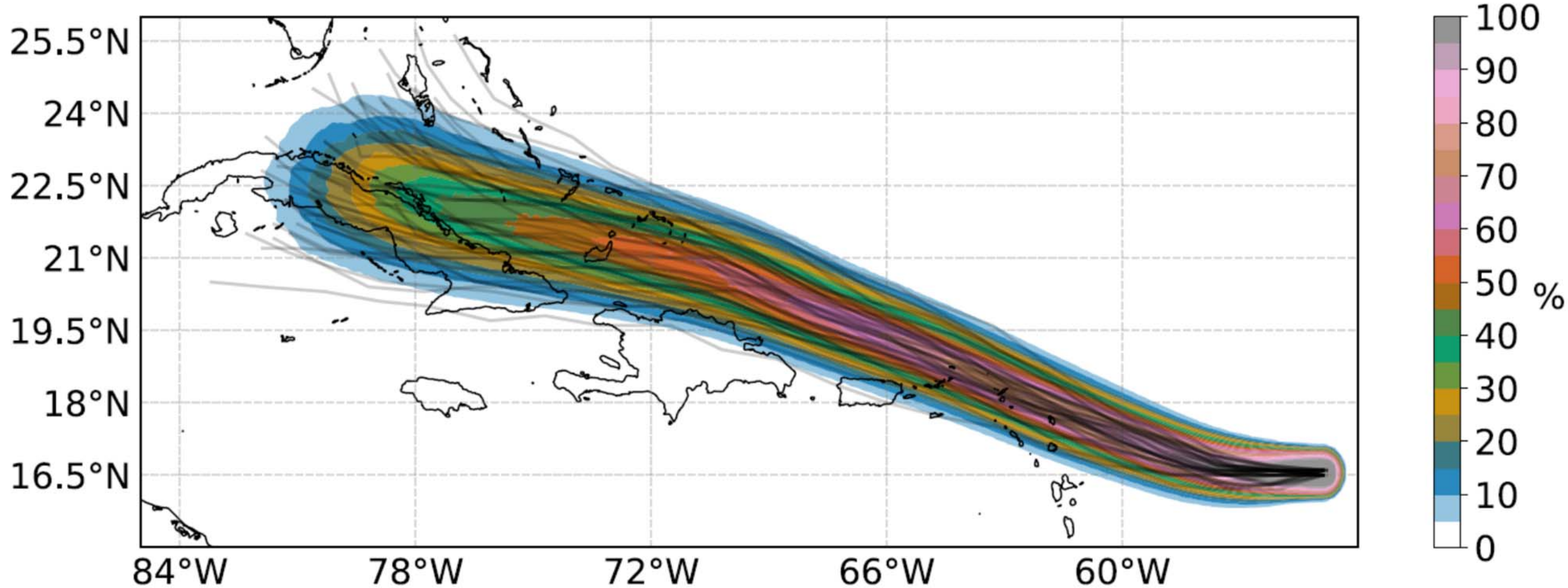
A Look Ahead

The Future of TC Observations:

Solar-powered stratospheric UAV

Dual-scanning X-band Doppler (~15 kg)

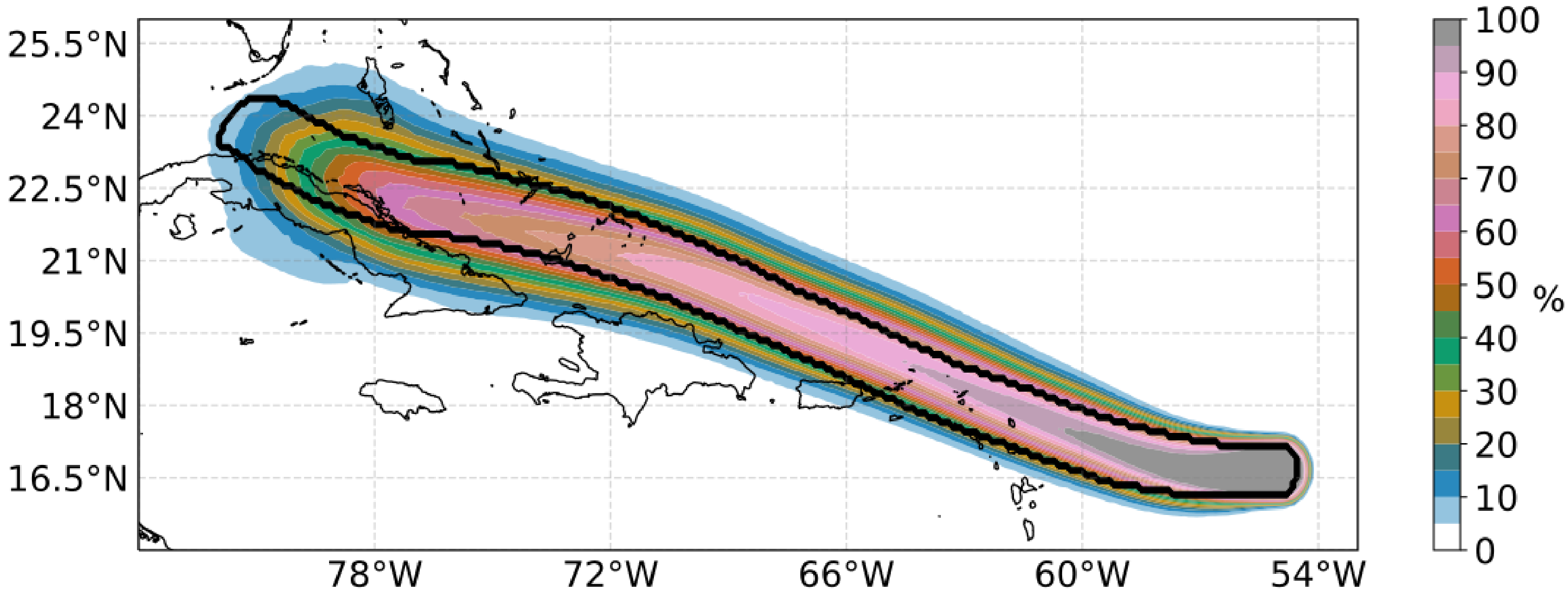
Forecasting: We will move away from track and intensity to pointwise probabilities of wind, surge, and freshwater flooding



50-km strike probability (color), for Hurricane Irma in the Atlantic Basin, using 1000 synthetic tracks generated from the ECMWF ensemble. Forecast initialized on September 5th, 2017, 00z. Overlaid lines (black) depict TC centers from the ECMWF ensemble.

Courtesy Jonathan Lin, MIT

Probabilistic Winds

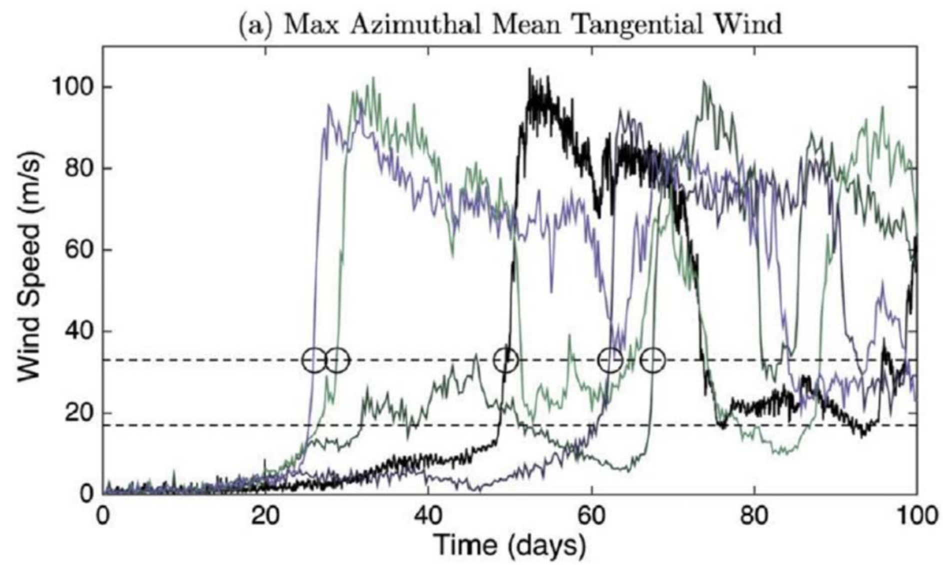


Probability of wind exceeding 64-kts over a 5-day period (color), for Hurricane Irma in the Atlantic Basin, using 1000 ensemble members bootstrapped from the ECMWF ensemble. Forecast initialized on September 5th, 2017, 00z. Black contour depicts extent of the observed 64-kt winds.

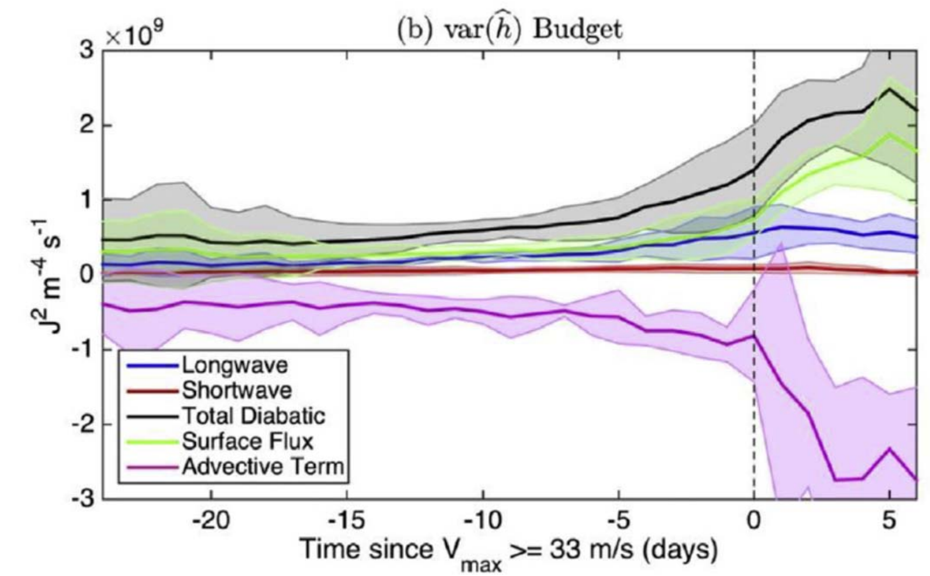
Courtesy Jonathan Lin, MIT

Will We Finally Crack the Genesis Problem?

5-member ensemble of radiative-convective equilibrium simulations



Individual terms in the budget of the variance of vertically integrated moist static energy



Tang et al, 2020: *Tropical Cyclone Research and Review* **9**, 87-105

Summary

- The history of the scientific understanding of tropical cyclones is rich and very interesting!
- In the 1960s and 1970s, research into the basic energy source of tropical cyclones took a step backward, with researchers either ignorant of or unwilling to acknowledge progress made in the 1950s
- Tropical cyclone research greatly accelerated in the 1980s and 1990s and there has been much progress in basic understanding as well as the ability to measure and forecast hurricanes
- Basic understanding of such issues as secondary eyewalls, spiral rainbands, the control and predictability of hurricane intensity, and genesis remain challenging for the future