Hurricane Research and Modeling from 1960 to 1980 and a Look to Future Hurricane NWP

Richard A. Anthes

EMC/MMM/DTC Joint Hurricane Workshop
22-23 February 2010

Disclaimer and Apologies

- My talk will not be a comprehensive, balanced history
- It will be based largely on my work and the work of my students, colleagues and friends
- It will focus largely on modeling studies, neglecting very important observational studies based on research aircraft and other observing systems
- Apologies to those I don't mention, or mention only briefly (e.g. W. Gray, A. Arakawa, K. Ooyama, G. Holland, W. Frank, R. Houze, H. Hawkins, R. Sheets, Y. Kurihara, R. Tuleya, M. Yanai, P. Black, T.N. Krishnamurti, S. Rosenthal, W. Schubert, B. Miller, R. Elsberry, Y. Ogura, S. Syono, H. Sundqvist, W. Schubert, P. Webster, F. Sanders, R. Burpee, E. Zipser, L. Shapiro, M. Yamasaki, H. Willoughby, C. Neumann, and many others)

Topics I will discuss

- Joanne and Bob Simpson contributions
- Hot towers and cumulus parameterization
- Linear studies of hurricane formation
- Early hurricane models → MM5
- Future

Two NWP Milestones

- 1922-L.F. Richardson, *Weather Prediction by Numerical Processes*.
- 5 March 1950-1st computer forecasts of weather (Charney, Fjørtoft, Freeman, Smagorinsky, Platzman) on ENIAC

Kristine Harper, 2008: *Weather by the Numbers,*
-- *The Genesis of Modern Meteorology*.

Early Hurricane Models

- Kasahara, 1961
- Ooyama, 1964
- Ogura, 1964
- Yamasaki, 1968
- Rosenthal, 1970
- Anthes, Rosenthal and Trout, 1971

Age-old Hurricane Facts
A lot was known in the 50s and 60s!

- Hurricanes are driven by the latent heat of condensation of water vapor.
- The sensible and latent heat addition from the underlying ocean is an <u>essential</u> process in hurricane formation and maintenance.
- Hurricanes cause upwelling, mixing, and cooling of the ocean surface over which they pass

Palmén, Riehl, Malkus-1940s and 50s

Hurricane formation favored by

- High ocean temperatures (>26ºC) and heat content (Palmén, 1948; Riehl, 1954)
- Preexisting cyclonic disturbances
- Low vertical wind shear
- High absolute vorticity in lower troposphere
- Low static stability (conditional instability-high sfc θe or moist static energy)
- Moist environment

Summarized by Gray, 1968, 1979; Anthes, 1982

Bob and Joanne Simpson

- Bob born 1912
- 1940-43-USWB in TX and New Orleans
- 1945-74
  - Hurricane forecaster in Miami
  - Founding Director NHRL
  - Director NHC

- Joanne born 1923
- 1951-60-WHOI
- 1960-64-UCLA
- 1965-74-Director NOAA EML Miami
- 1974-79-U VA
- 1979- NASA GSFC

Robert H. Simpson

- 1945-planned and conducted one of first research missions through eye of hurricane
- 1973-Saffir-Simpson damage potential scale
- Published more than 65 reviewed papers
- 1962-DoC gold medal
- 1973-Gold medal of France
- 1990-AMS Cleveland Abbe Award
- 2002-Editor of ***Hurricane! Coping with Disaster***

Joanne Simpson

- ~150 reviewed papers
- AMS Meisinger Award 1962
- LA Times Woman of Year 1963
- DoC Gold medal 1972
- AMS Rossby Award 1983
- NAE 1988
- President AMS
- Honorary Member AMS
- Many AMS, NRC committees
- Editor many journals

Washington Star
Sept. 19, 1947

STAR, Washington, D. C.
SEPTEMBER 19, 1947.

Hurricane-Hunter's Plane Flies Into 150-Mile Wind for Data

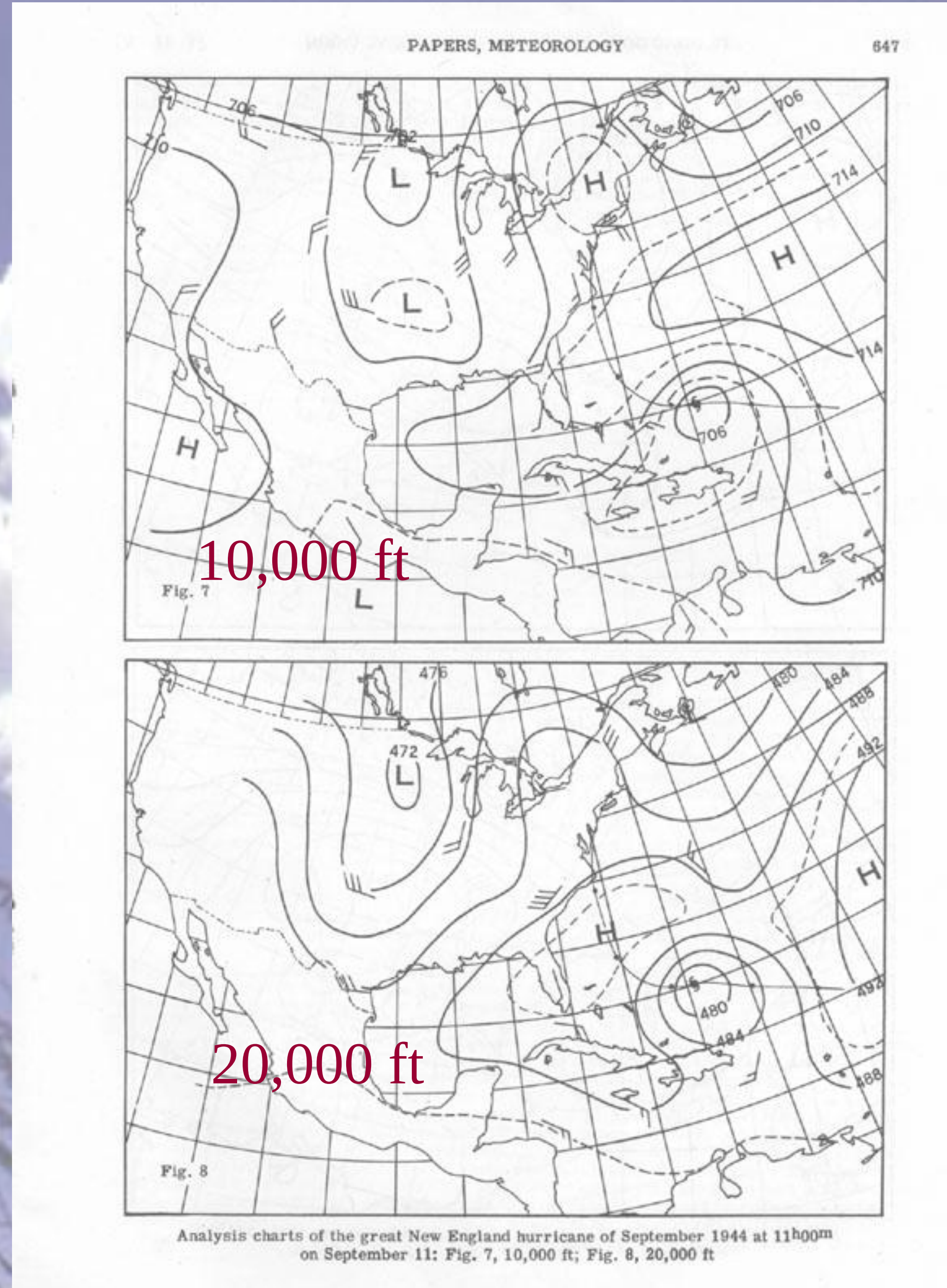
Robert Simpson, ace hurricane hunter for the Weather Bureau, points out the path of the Florida storm on a map.
—Star Staff Photo.

Hurricane Forecasting before models

Simpson, R.H., 1946: On the Movement of Tropical Cyclones. Transactions, AGU, 27, 641-655.

Top: 10,000 ft p analysis
Bottom: 20,000 ft p analysis

Note scarcity of data.



A Blind Date With "MARGE"

By ROBERT H. SIMPSON

Meteorologist in Charge, U. S. Weather Bureau, Honolulu

I LEFT GUAM AT DAWN and flew some 800 miles to keep a blind date with "Marge," a spirited, wily Micronesian lass of unusual fascination. This date had been arranged for me by Lt. Col. Bechtel, who, with a twinkle in his eye, had promised I would not be disappointed. And he was a man who knew, for Marge was one of those "evil spirits of the tropics," which in the Pacific is known as a typhoon and in the Atlantic as a hurricane; and Bechtel is commanding officer of the Air Force's 54th Strategic Recon Squadron, whose officers and men had been chasing after Marge for almost a week.

"Marge" was a product of the Caroline Islands. During her "adolescence" she had harassed Guam before moving northwestward to become a really big storm. On this day, Aug. 15, she reached her peak development and put on her grandest show of strength.

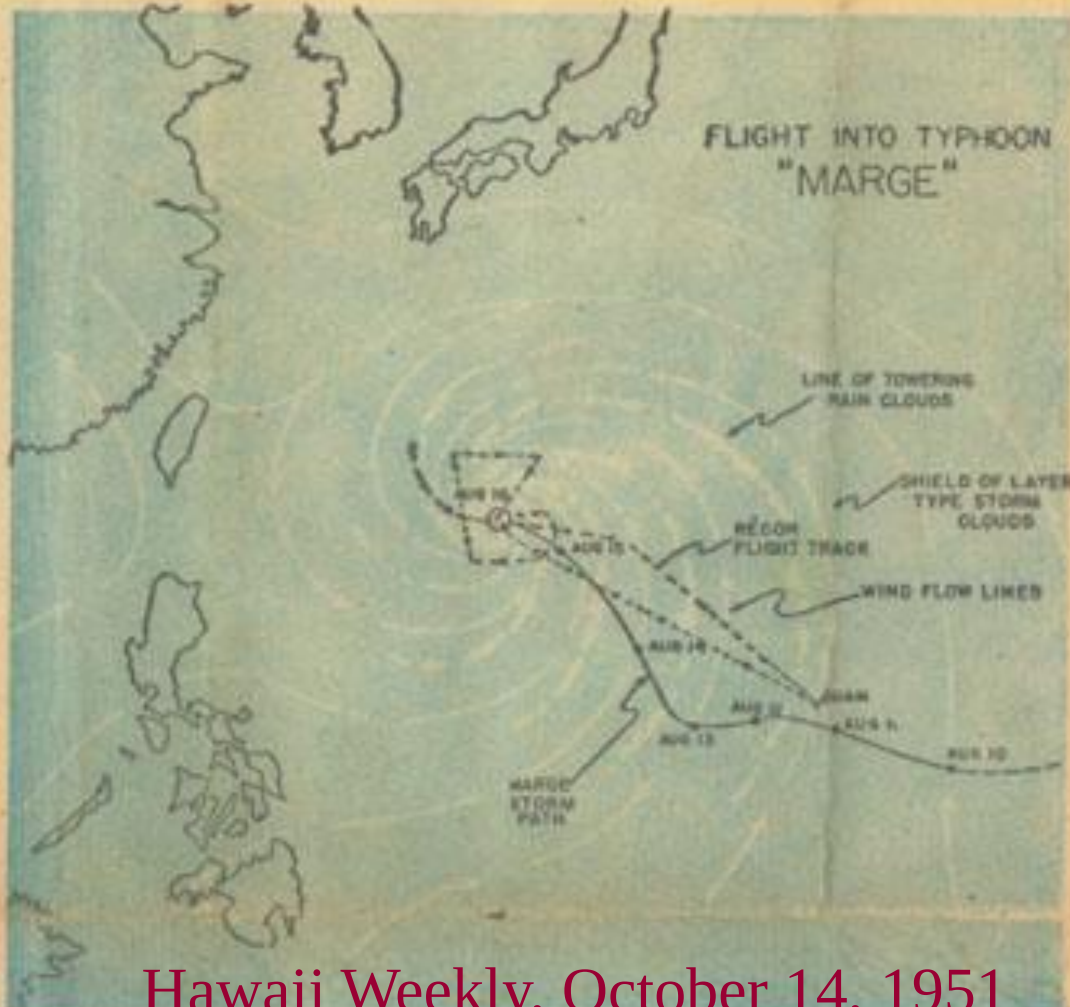
Our RB-29 slowly climbed to altitude at 10,500 feet beneath an overcast of high clouds which even at a distance of 800 miles was a part of the great shield of storm clouds created by Marge. From the cockpit Maj. Arthur Brashear, plane commander, pointed to the telltale sea condition below, which also gave evidence of Marge's presence. In addition to the whitecaps from a strong southwest wind, one could see long swells emanating from the northwest, remnants of the great waves generated near the storm center.

* * * *

Soon our radar, reaching out scores of miles ahead, told us we were approaching the first of several lines of rain clouds. These lines of towering clouds are associated with all large typhoons and follow the spiral path of the winds toward the storm center.

Between these lines of rain clouds the air was clear beneath the plane and we could see that winds were increasing and whipping up an angry sea. At flight level, the going was still smooth, however; just a few bumps now and then as we passed through cloud towers. As we approached closer to the center, the shield of clouds overhead lowered and gradually enveloped the plane. The plane was still in smooth air, but we could no longer see the pattern of wind on the sea. To locate the storm center we would have to depend upon electronic instruments. This proved to be no dilemma, however, for the plane was excellently equipped.

A few minutes later "Eye [illegible] miles, dead ahead" came over the intercom. This was Capt. Paul Sharp, our navigator, who had fixed the position of the eye by radar. Radar had reached out into "Marge's" rainy vortex and located each band of rain clouds which wound in about the eye of the storm like a spiral nebula. These spiral bands were recorded on a fluorescent grid in front of Capt. Sharp, who had detected the rainless edge of the eye and read from the grid its bearing and distance from the plane!



Hawaii Weekly, October 14, 1951

Typhoon Marge 0600 GMT Aug. 15, 1951.

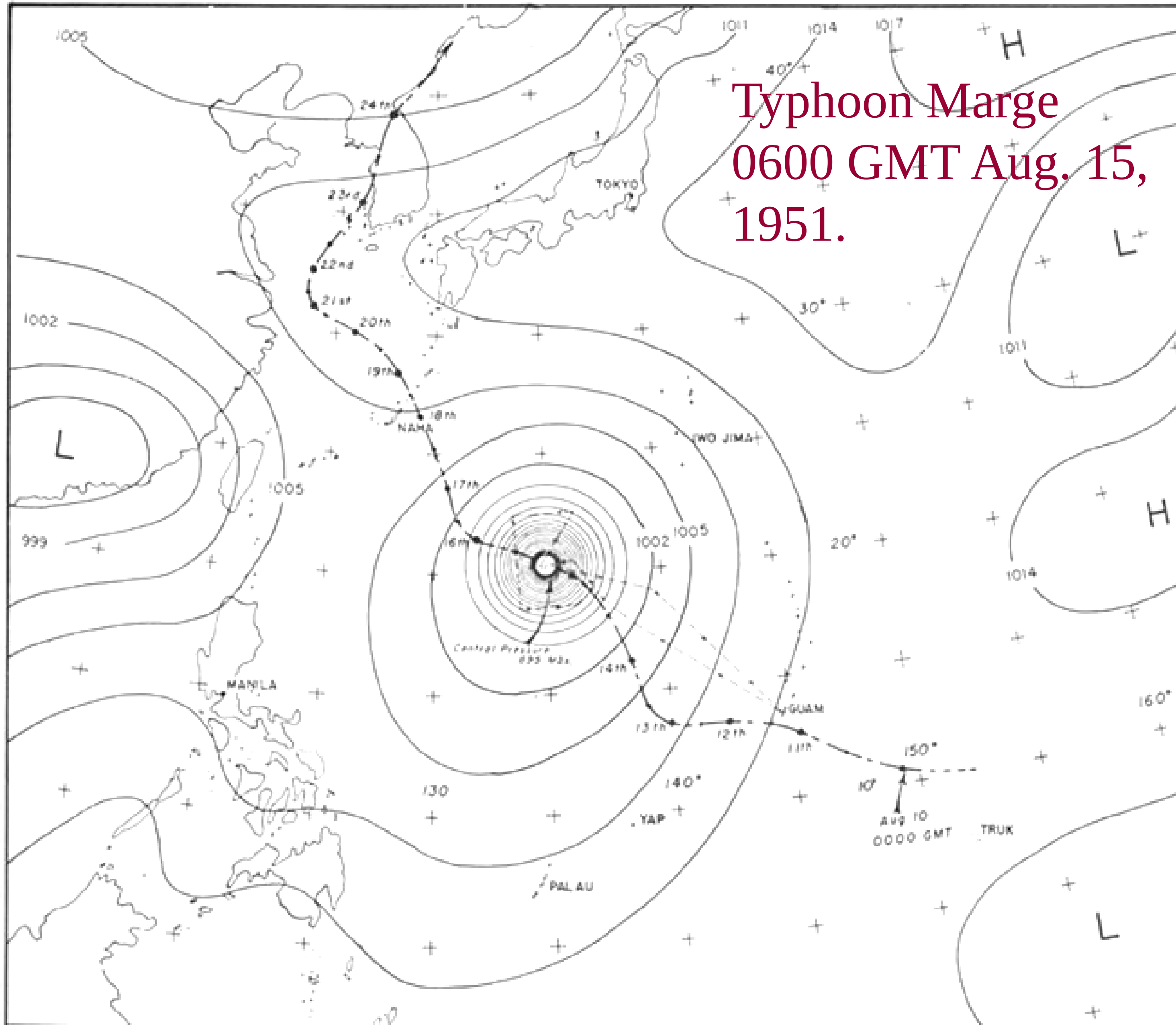


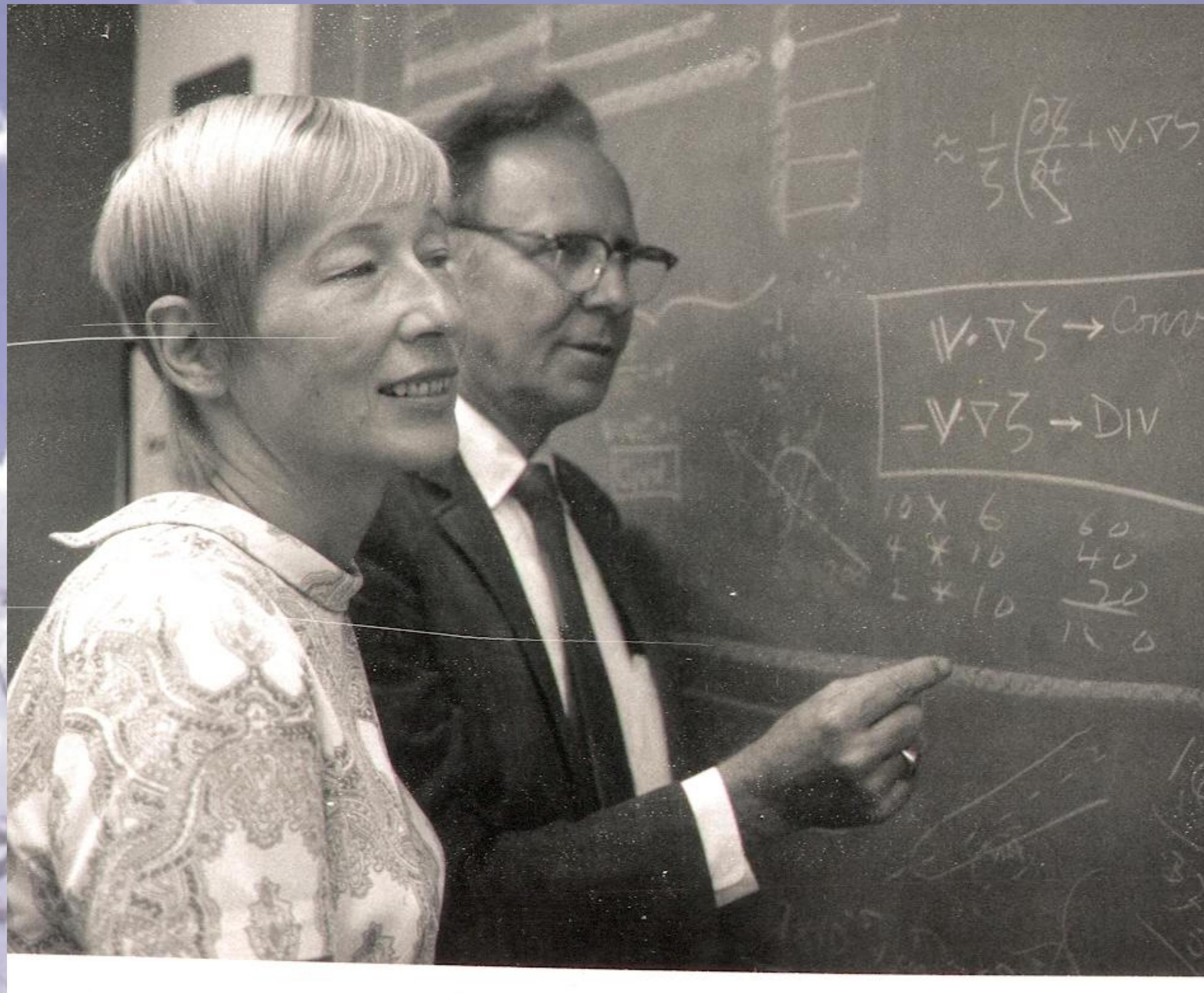
FIG. 1. Surface map showing Typhoon "Marge" at 0600 GMT, August 15, 1951. The heavy broken line is the path of the typhoon showing 12-hour positions. The light dash line is the track of the plane during its reconnaissance of "Marge."

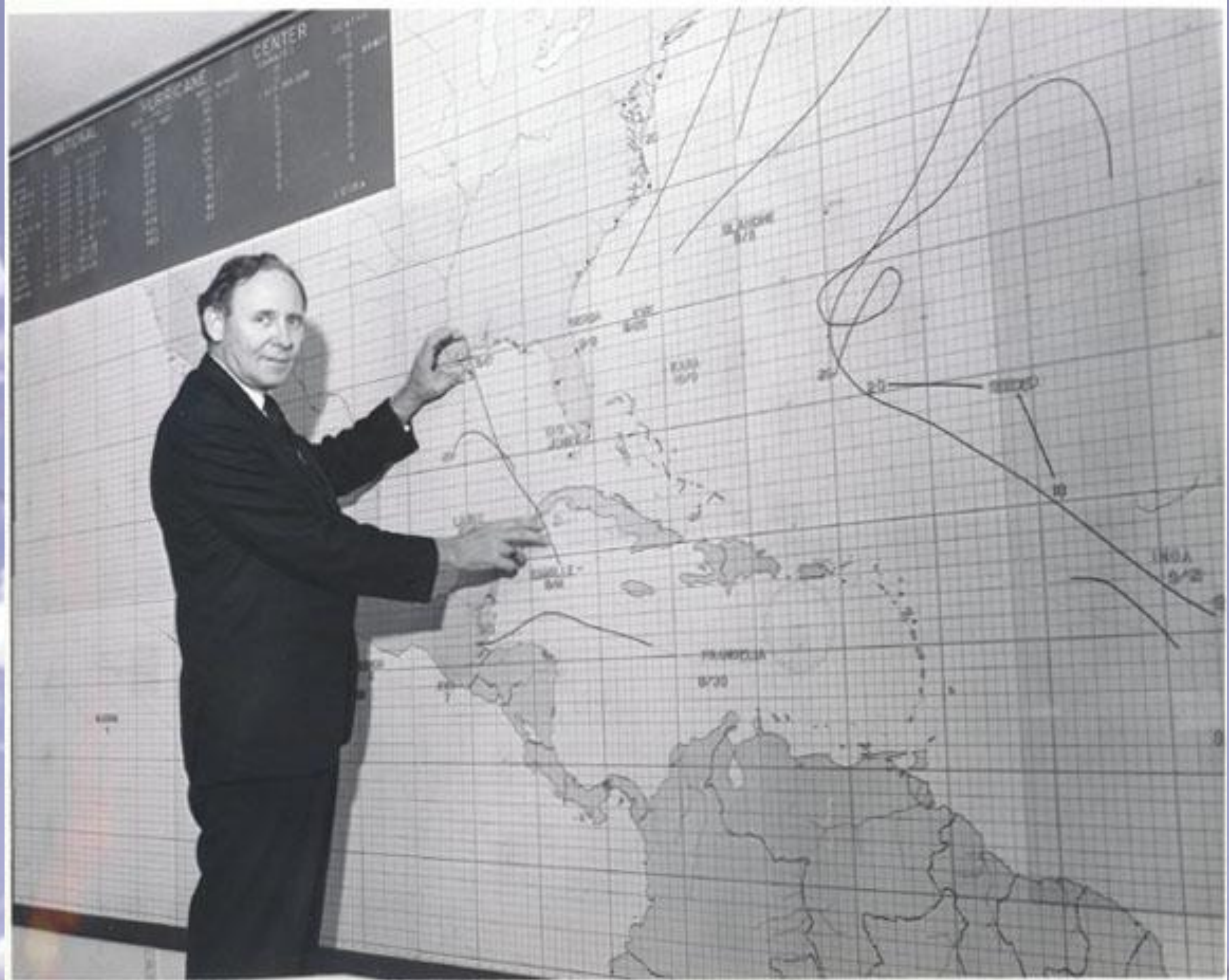
Inside the eye of Typhoon Marge

FIG. 7. Panorama of eye from 17,000-ft elevation at a point just west of the eye-center looking southwest. Time 1100 LST. Temperature 16°C. Walls of the eye rise vertically to a height of approximately 35,000 feet. The cloud rim of the eye is 40 miles in diameter. Sky overhead is cloudless.

Bob and Joanne, Roosevelt Roads, Puerto Rico, 1964

Joanne and Bob
1968
NHC
Miami





Bob discussing hurricane tracks at NHC in 1969

Joanne in aircraft

1970

Research on clouds over Florida and Caribbean

Hot Towers
A major topic of research and theory in the 50s and 60s!

Examples of Hot Towers

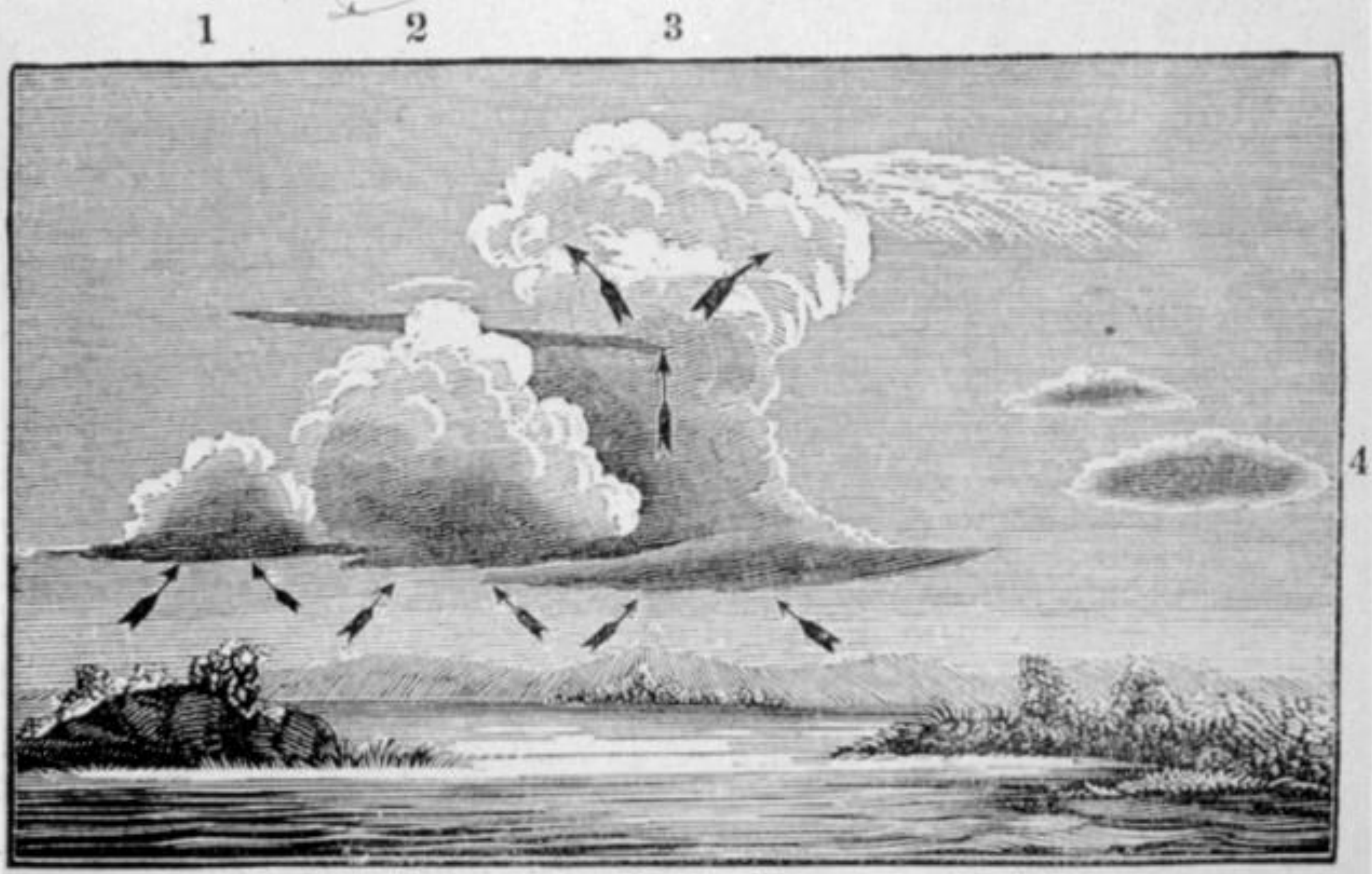
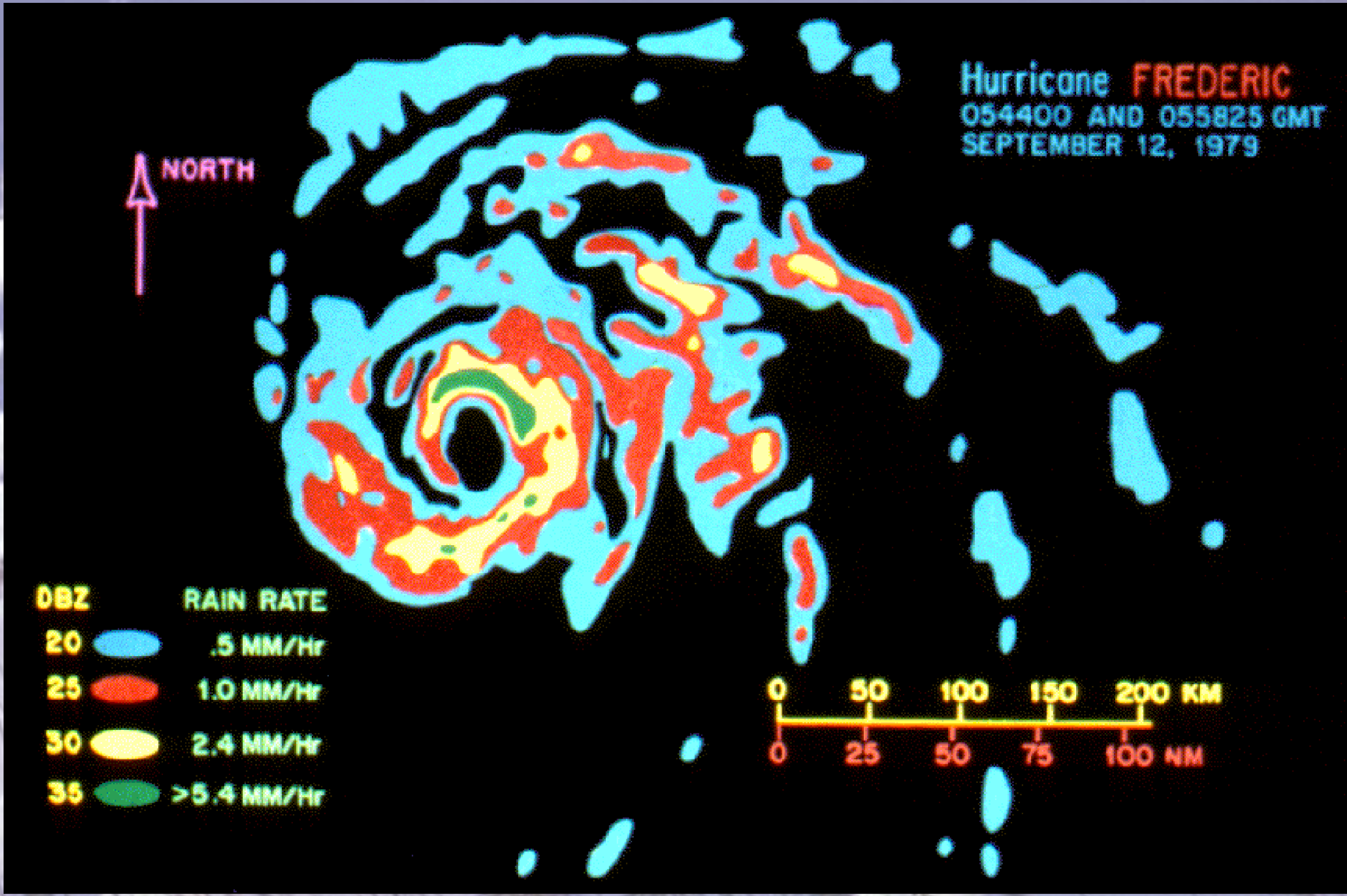


FIGURE 5. Formation of cumulus clouds by convection (Espy, 1841), from Espy, *Philosophy of Storms* (1841).

From Kutzbach, 1979, p. 24

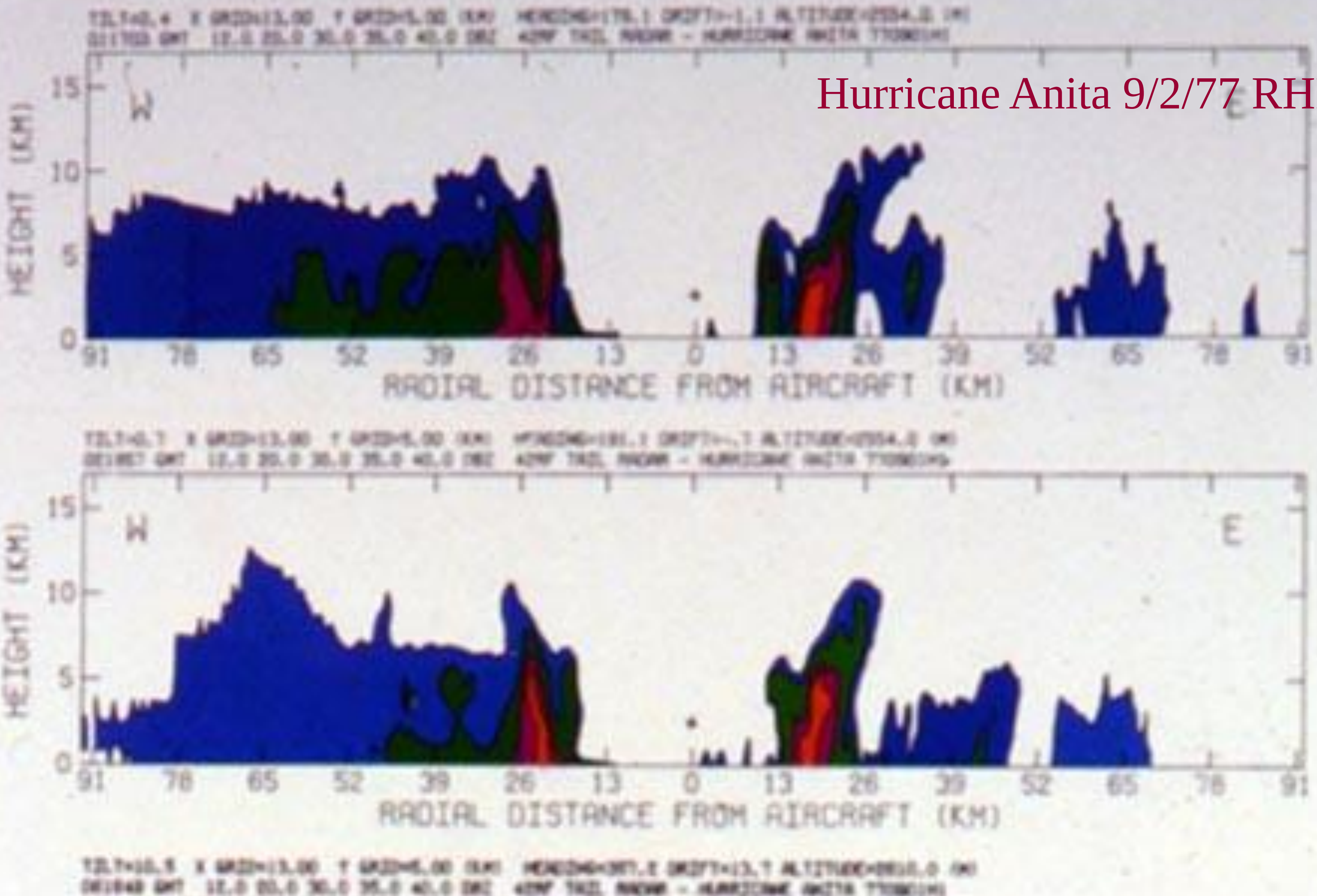
Sea-breeze front west coast Florida

Towering Cumulus Florida coast



Hurricane FREDERIC
054400 AND 055825 GMT
SEPTEMBER 12, 1979
NORTH
DBZ
RAIN RATE
20 .5 MM/Hr
25 1.0 MM/Hr
30 2.4 MM/Hr
35 >5.4 MM/Hr
0 50 100 150 200 KM
0 25 50 75 100 NM

Hurricane Anita 9/2/77 RHI



Countergradient heat flux by "warm towers."

Riehl and Malkus, 1958.

On the heat balance in the equatorial trough zone

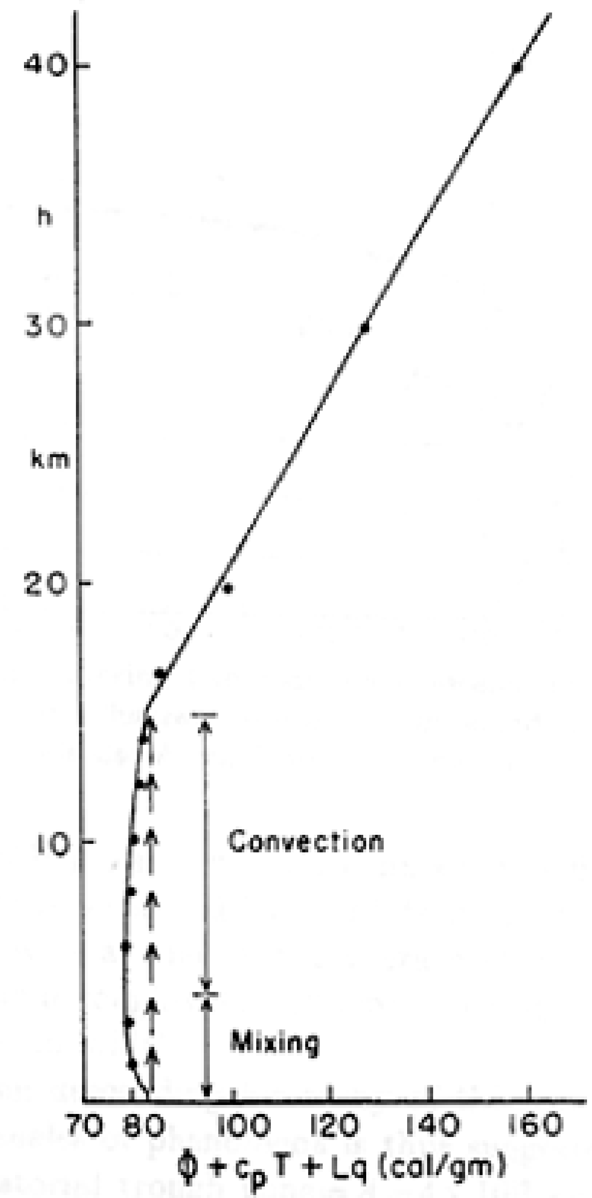


Fig. 19. Model of mean vertical distribution of $gz + c_p T + Lq$ in troposphere, stratosphere and ozonosphere; mechanisms of upward heat flow in troposphere, and limit of upward penetration of heat gained by atmosphere from ground.

“the moist adiabatic ascent does not take place by means of uniform and gradual ascent of the whole mass in the hurricane but, as postulated by Riehl and Malkus (1958) for the equatorial trough zone, it is largely concentrated in regions of rapidly ascending buoyant hot towers”

Malkus and Riehl, 1960: On the dynamics and energy transformations in steady-state hurricanes. Tellus.

Parameterization of Cumulus Convection in Hurricane Models

"If the details of the activity on these small scales are decisive for storm growth and maintenance, then the prospect for solving the large-scale hurricane problems and achieving predictive models recedes into the dim future. On the contrary, we shall conclude by offering the hope that the dynamic and thermodynamic effects of these small scales can be introduced or parameterized effectively in a relatively simple framework, without dwelling on their complex details.."

Riehl and Malkus, 1961: Some aspects of Hurricane Daisy, 1958. Tellus

"In a photographic mapping of cloud conditions over the tropical Pacific we found that penetrative cumulonimbus occurred only where low-level synoptic-scale convergence prevailed and were snuffed out instantly when divergence took over."

"In fact, dynamic factors have proved far more critical criteria for cloud growth in the tropics that has static stability, which in fact shows an inverse relation to convection."

Malkus and Williams, 1963: On the interaction between severe storms and large cumulus clouds. Meteor. Monographs, 5.

Cumulus Parameterization

- Relate interactions and feedbacks of cumulus convection and larger-scale hurricane circulation.
- Concept supported by separation of scales and the fact that the two scales of circulation were known to be closely related through static stability, low-level convergence, water vapor supply.

Cumulus Parameterization

- Linear theories
- Cooperation vs. Competition
- Conditional Instability of First Kind (CIFK)
- Conditional Instability of Second Kind (CISK)
- Reality

Linear Theories

- Assume small random perturbations in a conditionally unstable stagnant base state.
- Under these conditions, small-scale disturbances like cumulus clouds grow most quickly, overwhelming larger-scale circulations (Bjerknes, 1938)
- This is Conditional Instability of First Kind (CIFK)

CIFK in an early hurricane model.

Akira Kasahara
1961 J. Meteor.

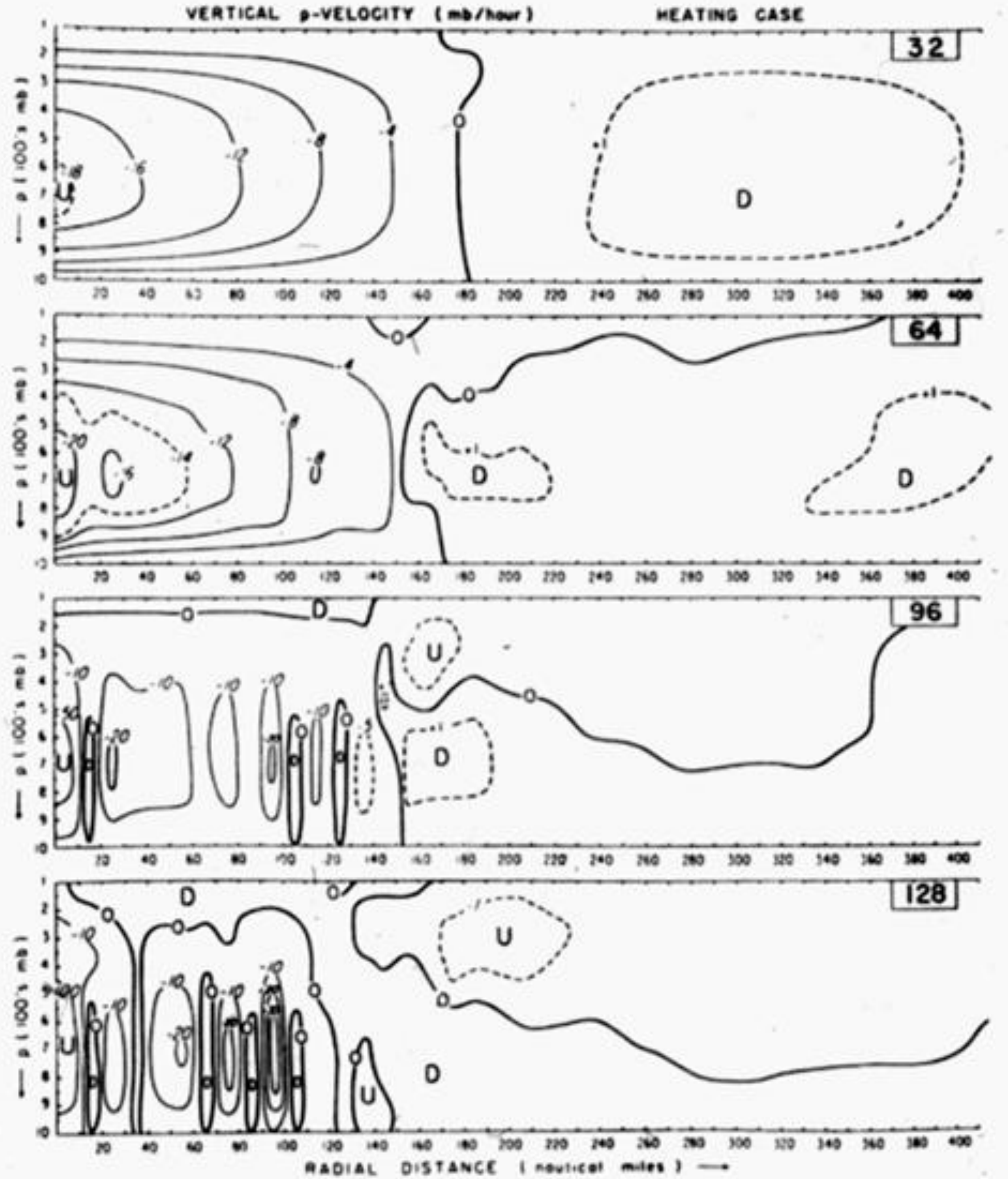


Fig. 8b. Same as fig. 8a, but for the heating case.

Linear Theories-
Not much relevance to hurricane formation

- Hurricanes develop from large-scale preexisting disturbances
- Stagnant base state irrelevant
- Development is nonlinear with evolving static stability
- Therefore can't explain hurricane development

Cooperation vs Competition

- Linear theories in a conditionally unstable atmosphere (CIFK) say that, given a wide range of scales in initial perturbations, the cumulus scales will always "win" over hurricane scales.
- To explain the existence of both scales, the idea of cooperation rather than competition was developed (Ooyama, 1964; Charney and Eliassen, 1964)

Conditional Instability of Second Kind (CISK)

- Name introduced by Charney and Eliassen (1964)
- With a suitable parameterization of cumulus clouds, the cumulus scales of motion can be suppressed and hurricane scale motions can grow in linear theory
- Generated huge arguments in the ’60s!

CISK

- CISK is not a parameterization
- CISK is not very relevant to hurricane formation, but the idea of cooperation between the cumulus and hurricane scales of motion is highly relevant.

H.L. Kuo (1965) Cumulus Parameterization

“The cumulus clouds exist momentarily. They dissolve by mixing with the environmental air at the same level, so that the heat and moisture carried up by the cloud are imparted to the environmental air”

“Thus our model is similar to the deep cumulus towers described by Riehl and Malkus (1961”

Kuo (1965) Parameterization

- Influenced by notion of “hot towers”
- Not good physical explanation of actual interactions.
- But it works pretty well because it adjusts the large-scale atmosphere toward a moist adiabatic structure, has a reasonable vertical distribution of heating and moistening, and conserves energy.

So, are “hot towers” relevant to hurricanes?

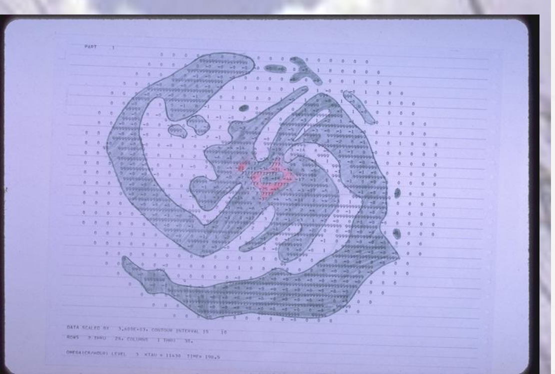
Reality

- Many other features and detailed processes are important in determining the actual evolution of hurricanes
  - Preexisting large-scale disturbance
  - Large-scale environment (static stability, horizontal and vertical wind shear)
  - Sea surface temperature and fluxes from the ocean to the atmosphere
  - "Ekman pumping"
  - Compensating subsidence
  - Stratiform precipitation
  - Evaporation of cloud and rainwater
  - Ice processes
  - Radiation

Reality

- However, hot towers are critical to formation, intensification and maintenance of hurricanes. Without hot towers, hurricanes would not exist!

From NHRL Hurricane Model to Penn State/NCAR Mesoscale Model (MM5)



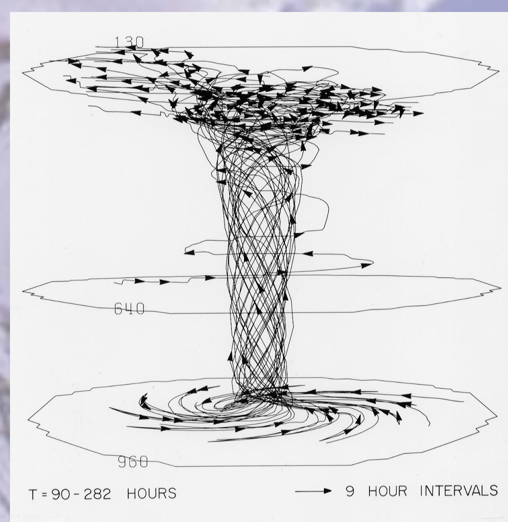


Figure 1: Particle trajectories calculated from a numerical model of an asymmetric hurricane. Labels of 3 levels in mb.

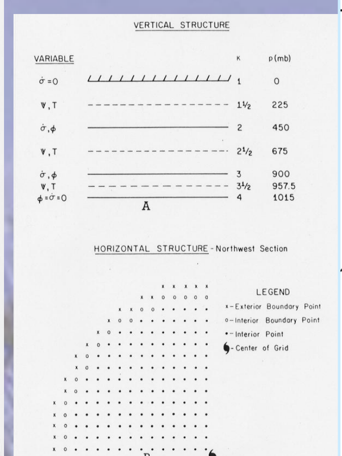
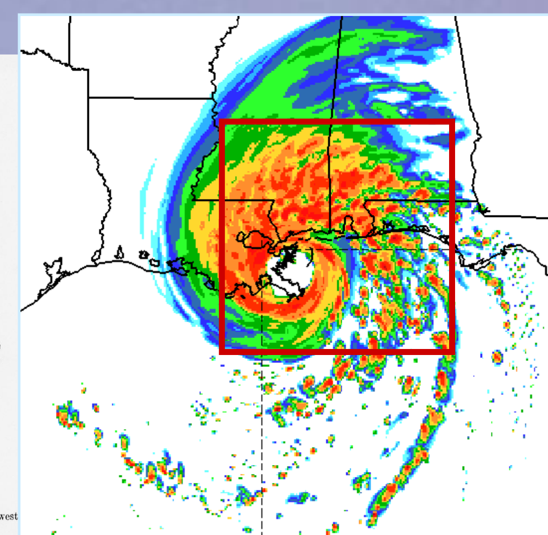
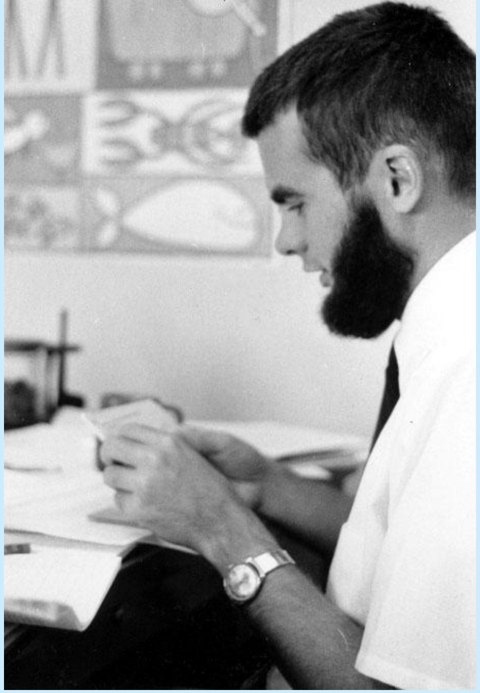
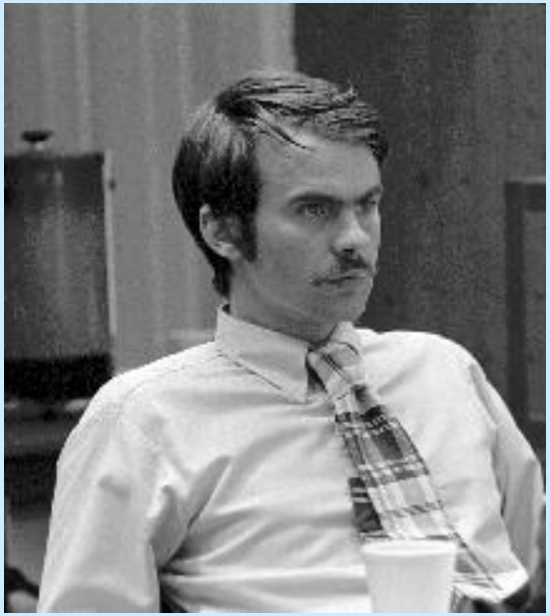


FIGURE 1.—(A) vertical information levels and (B) northwest quadrant of the horizontal grid.





1968



1975

Alan ?, Russ DeSouza, Xavier (Bill) Proenza

El Yunque rain forest 7-31-65

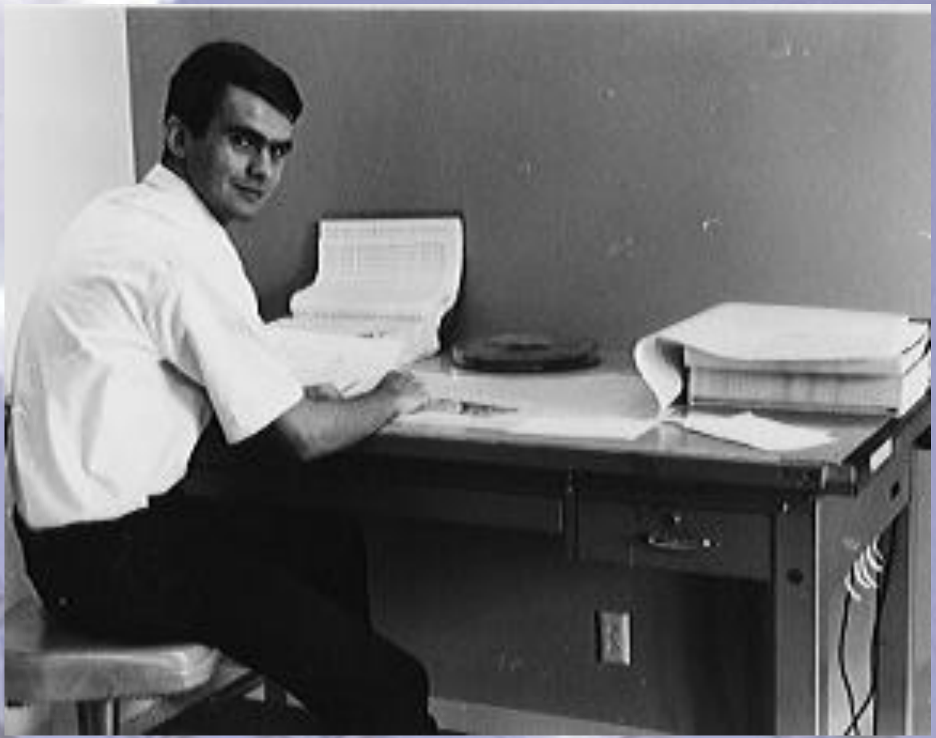
Jim Koss and Rick

July 1967

August 1965

History of MM5

MM5 is the fifth generation version of the Penn State-NCAR mesoscale model. It was probably the most widely used mesoscale model in the world for many years. It began with the development of a 3-D hurricane model in the late 1960s at NOAA's National Hurricane Research Laboratory in Miami, Florida.



MM5 Developers in 1999

Nelson Seaman, Dave Stauffer, Tom Warner, Rick Anthes, George Grell, Jimy Dudhia, Bill Kuo. June 1999

1969--NHRL Miami

- Working on 3-level, 3-D hurricane model
- Constant f, unstaggered grid
- Kuo (H.-L.) cumulus parameterization
- Bulk PBL model with constant Cd
- Constant sea temperature
- Begin 2-D analog

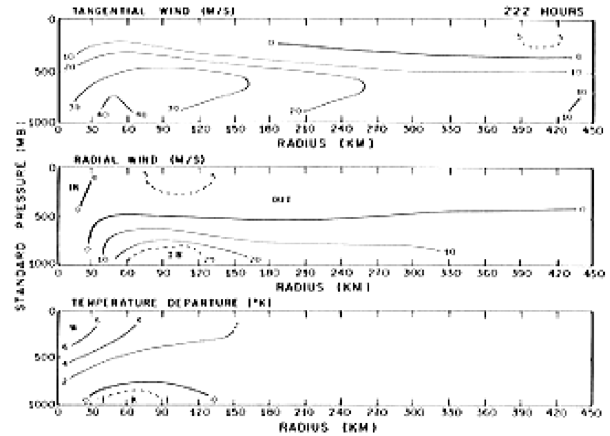


FIGURE 7.—Azimuthal mean vertical cross sections for the tangential wind, the radial wind, and the temperature anomaly at 222 hr for the asymmetric model experiment.

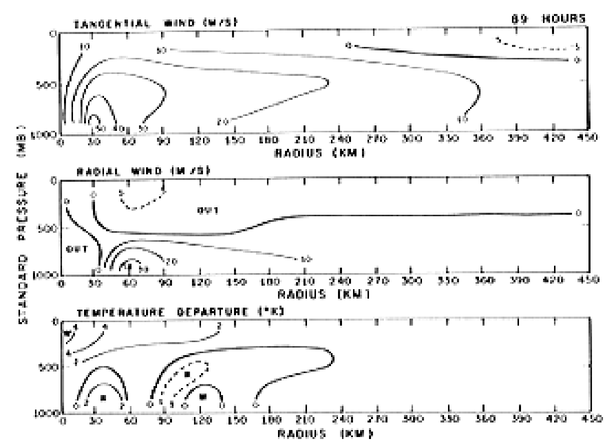
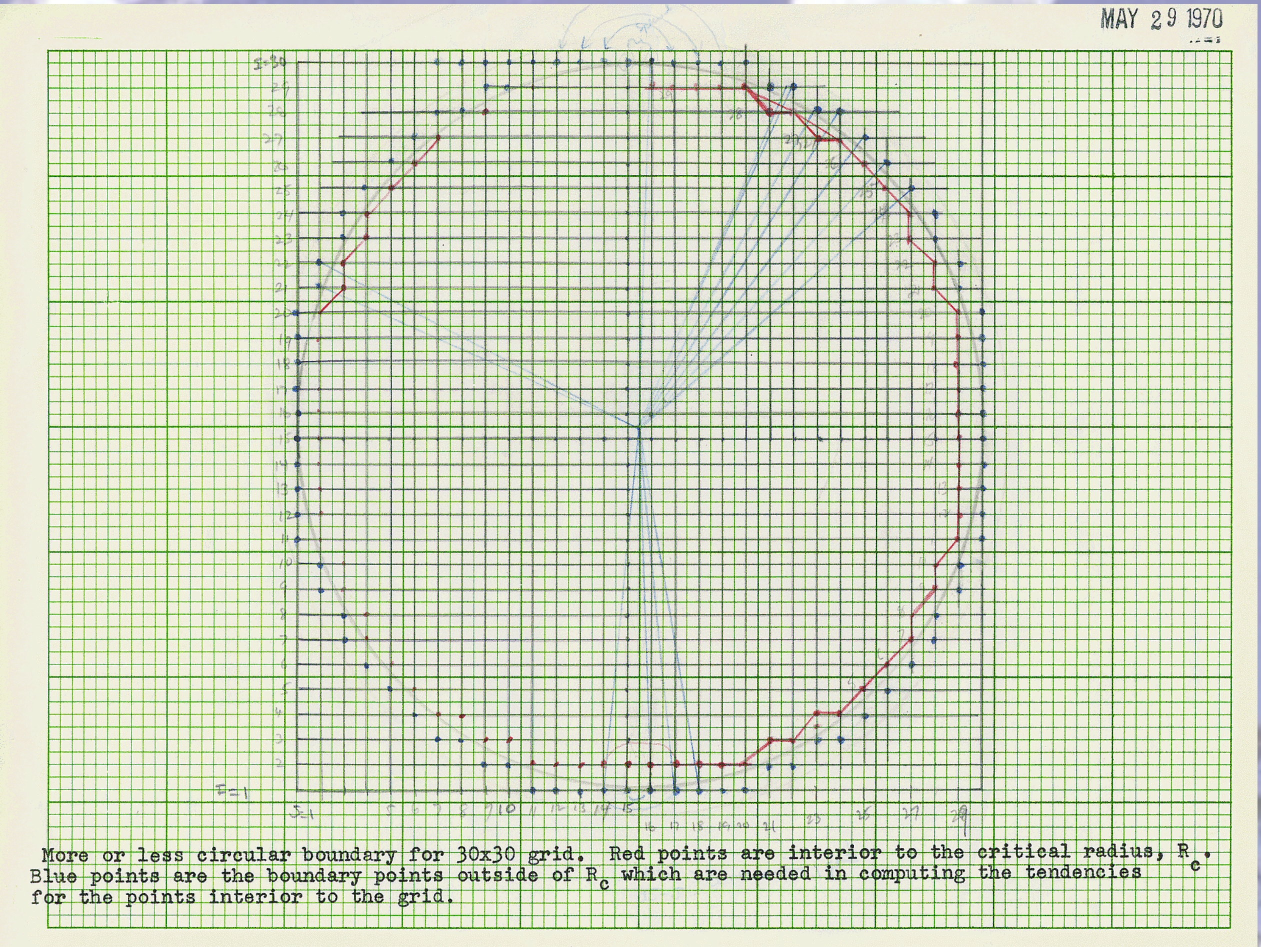


FIGURE 8.—Vertical cross sections for the tangential wind, the radial wind, and the temperature anomaly at 89 hr for the symmetric model experiment.

1969--Early Grid structures



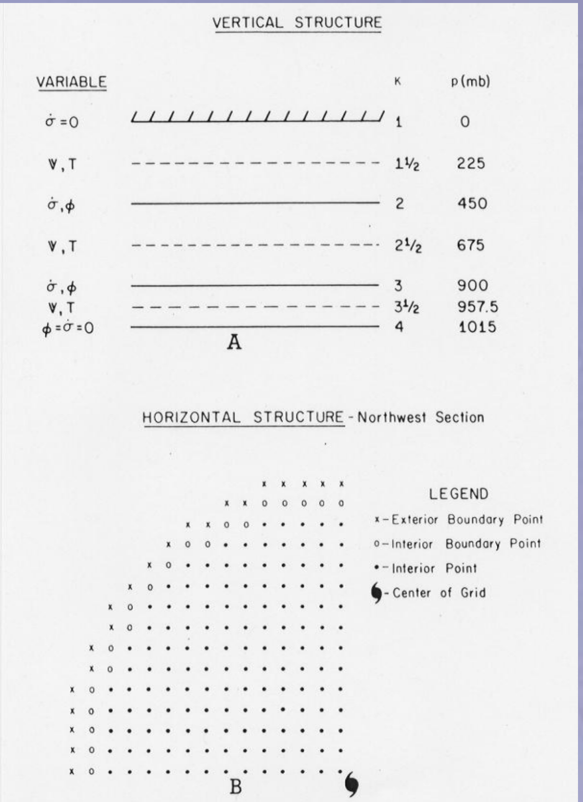
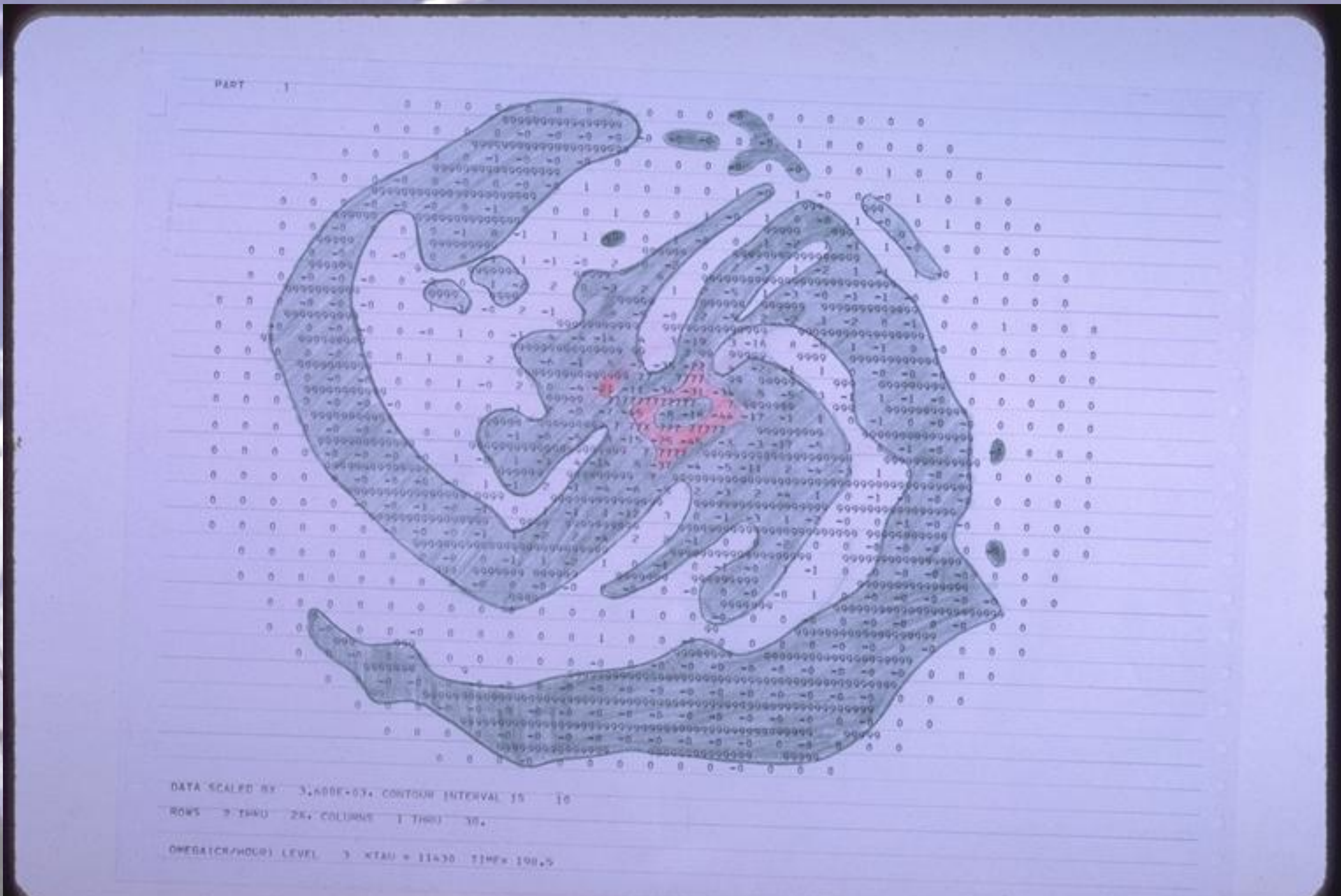


FIGURE 1.—(A) vertical information levels and (B) northwest quadrant of the horizontal grid.

1970--NHRL Miami

- Many 2-D and a few 3-D experiments
- Variation of horizontal diffusion, lateral boundary conditions, PBL, Kuo cumulus parameterization
- Staggered grids
- Eliminate corners of square grid
- Many "blow ups"
- Oct. 12-First stable and realistic hurricane simulation
- Grid 30 x 30 x 3 less 10% (corners)=2430 pts

Spiral Rainbands



3-D Trajectories

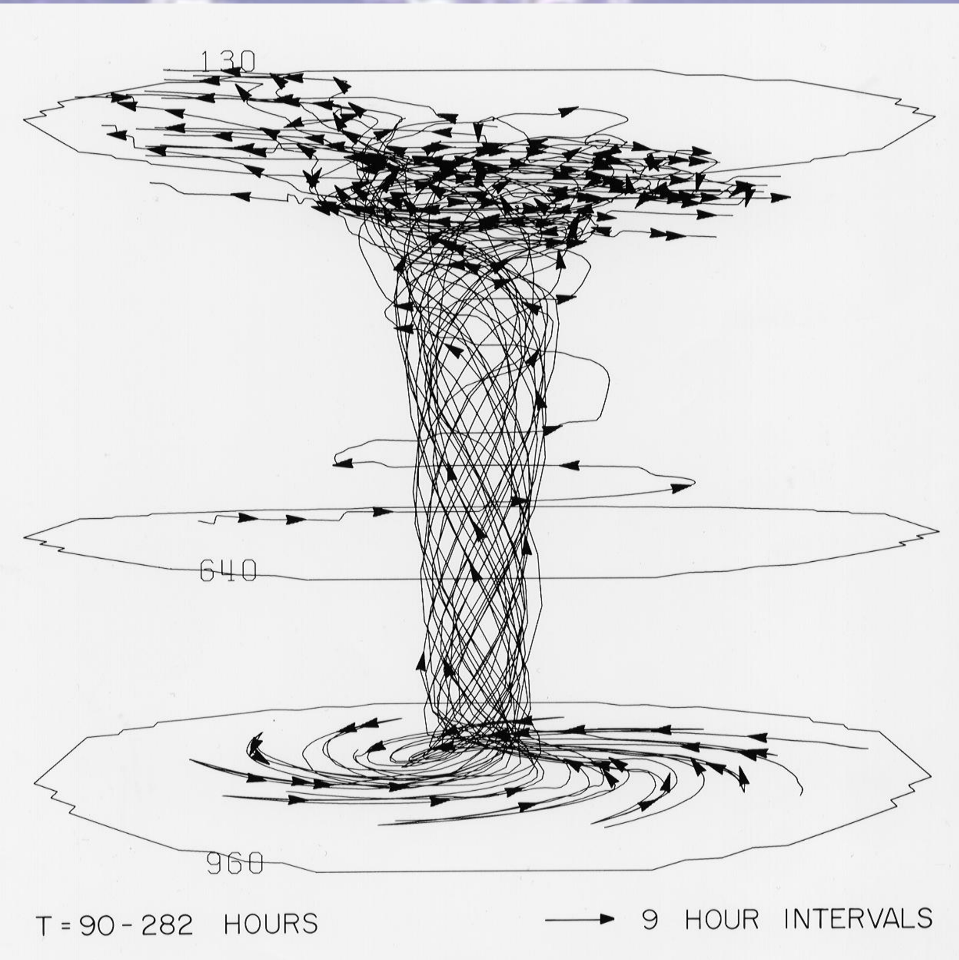
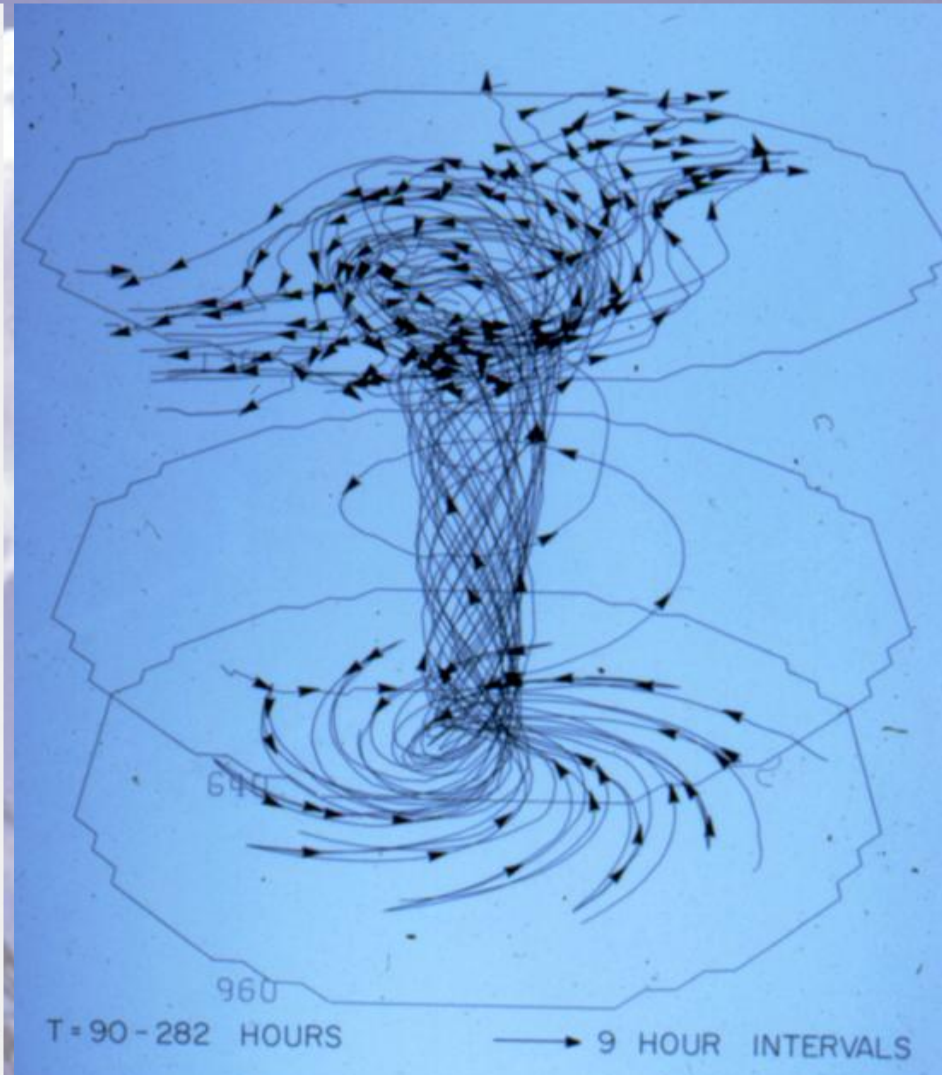
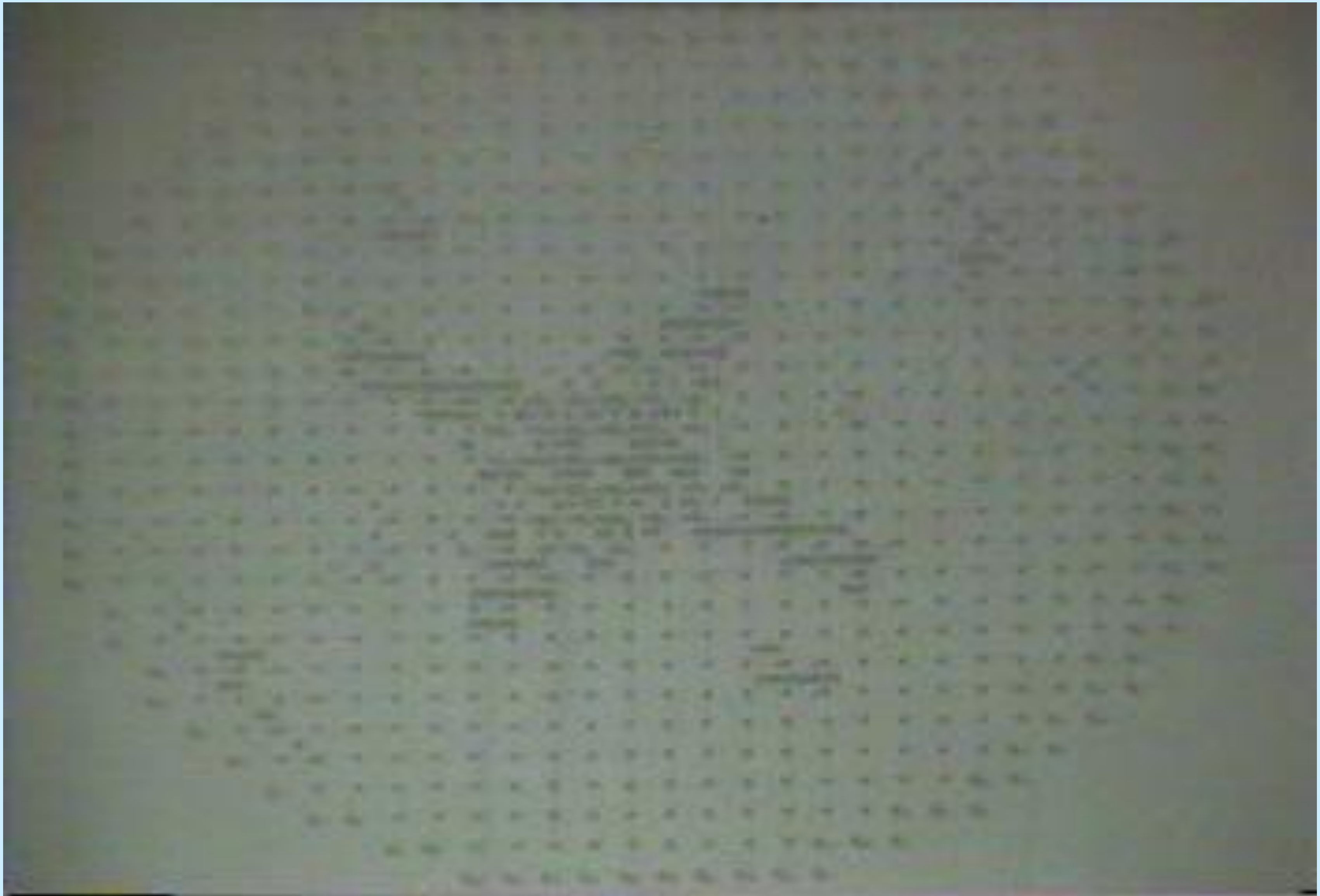


Figure 1: Particle trajectories calculated from a numerical model of an asymmetric hurricane. Labels of 3 levels in mb.

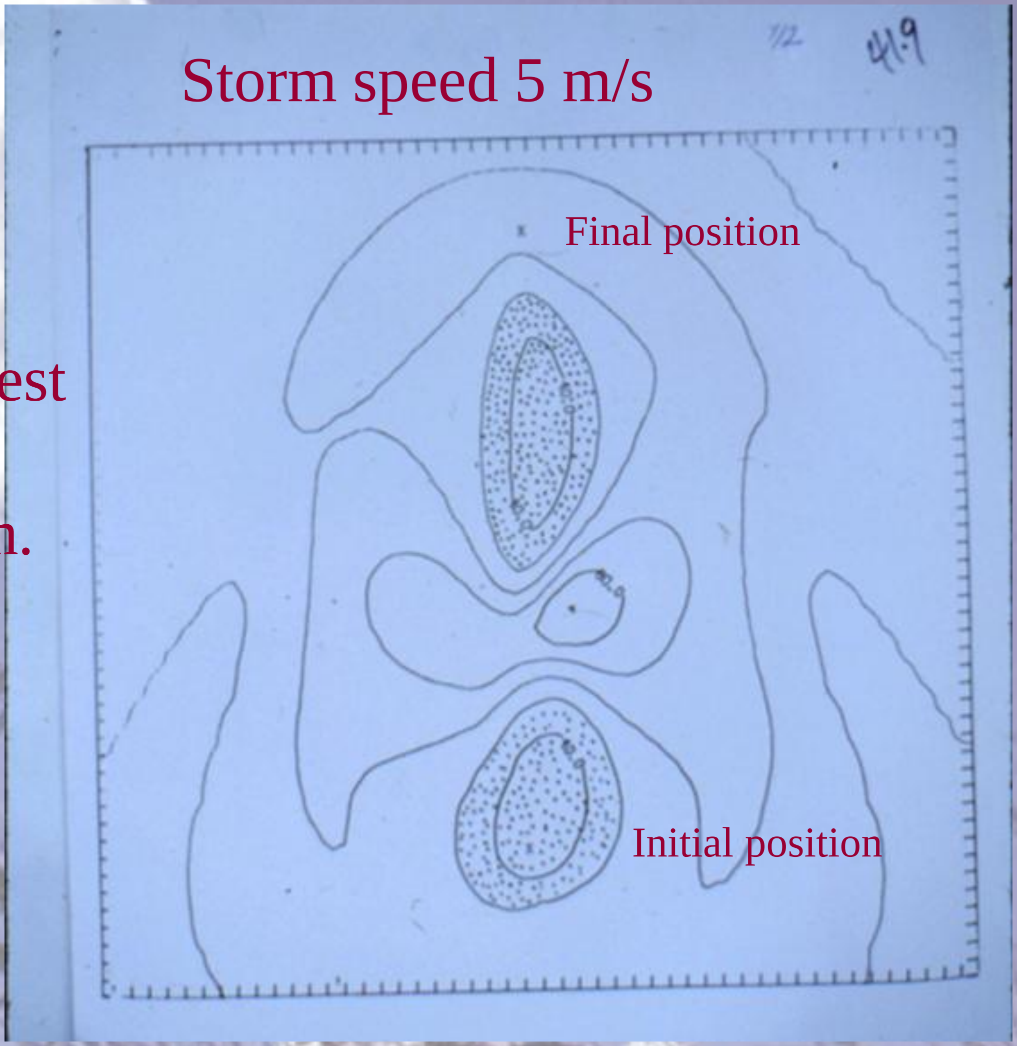


First model of tropical cyclone that produced spiral rainbands. Also one of earliest animations of atmospheric model output (Anthes, 1970)



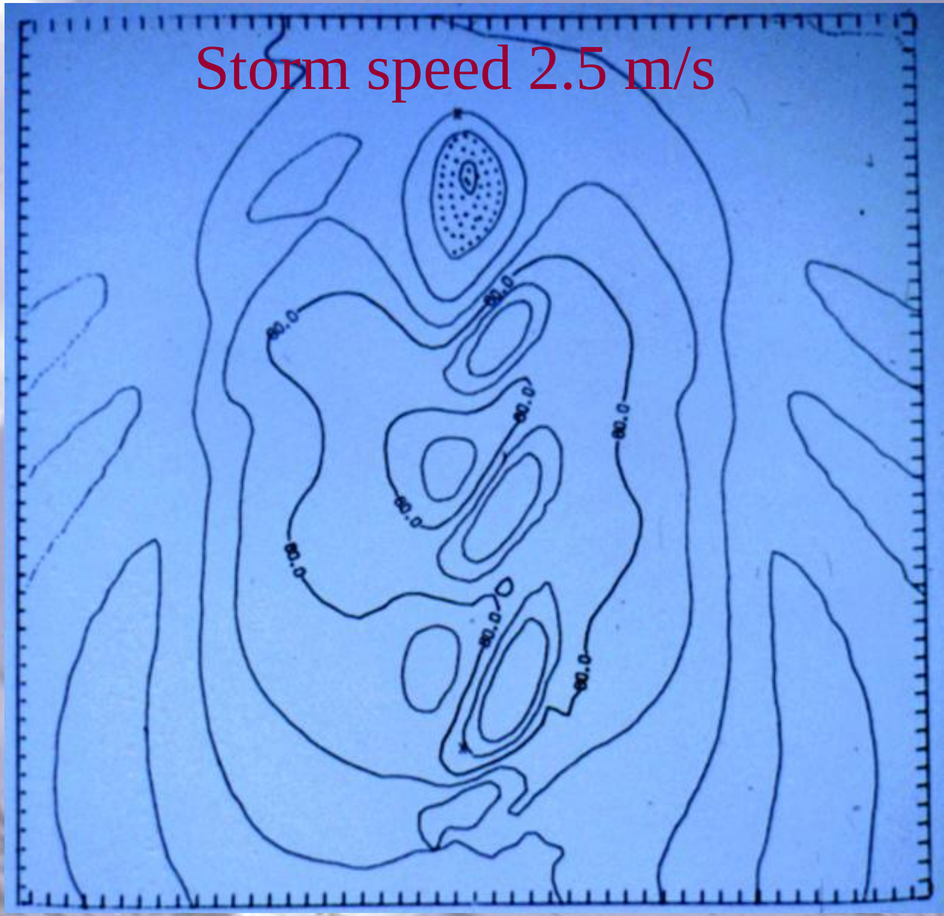
3-D Ocean Response to moving hurricane Chang and Anthes (JPO, 1978)

Thermocline depth at 41h in control experiment. Initial depth was 50m. Upwelled areas denoted by dotted lines (40 m lowest contour. Contour interval 5 m. Spacing between tick marks 20 km.



3-D Ocean Response to moving hurricane
Chang and Anthes (JPO, 1978)

Thermocline depth at 82h with slow moving (2.5m/s) storm. Initial depth was 50m. Upwelled areas denoted by dotted lines (40 m lowest contour. Contour interval 5 m. Spacing between tick marks 20 km.

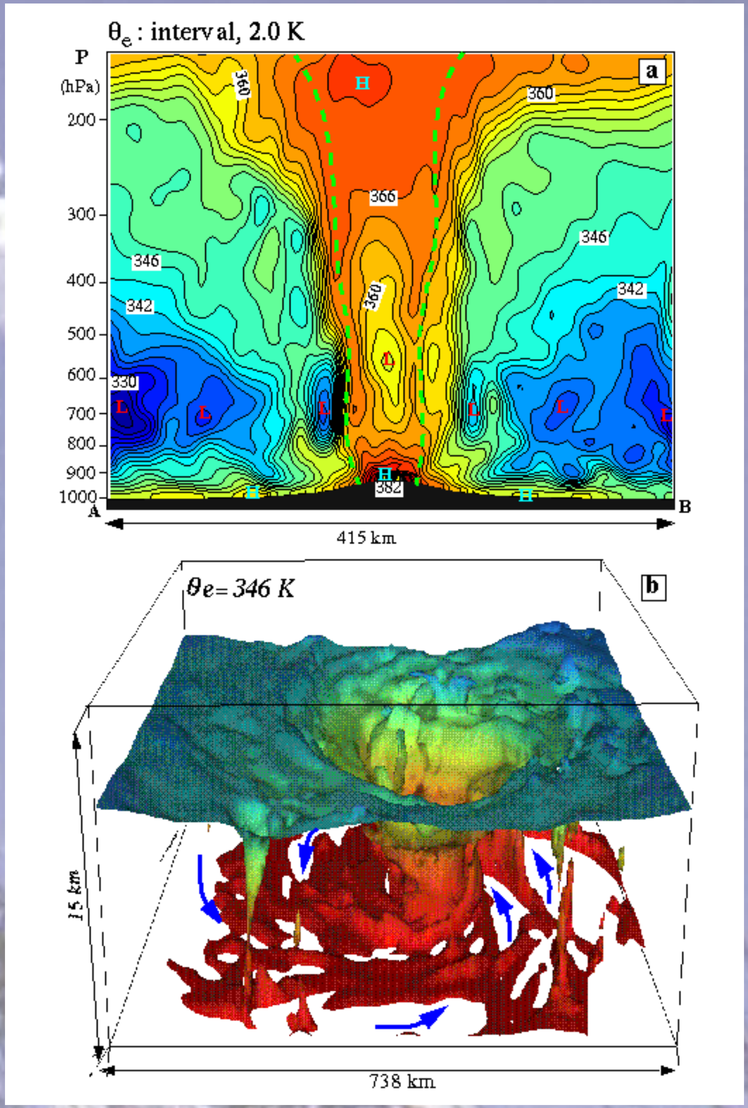


Computers and MM in 1976

- CDC 7600 5X faster than 6600
- IBM 370/195 same as 7600
- 3-D dry MM
- 6x40x40=9600 grid points
- DT=30s DX=20km
- Storage 140K 12-h run took 30 min on 7600

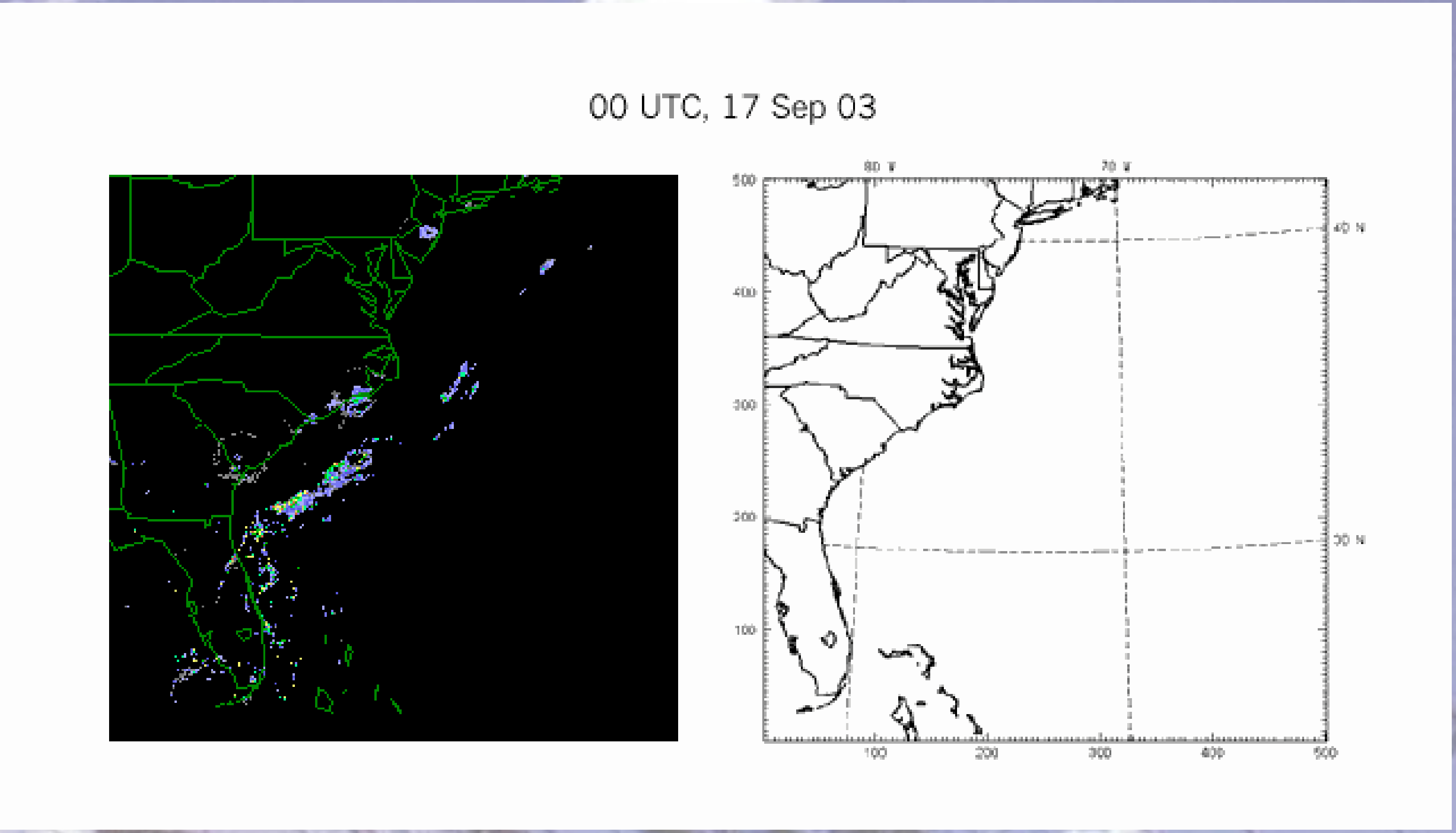
Da-Lin Zhang 1998
Hurricane Andrew Simulation

- Liu, Zhang and Yau (1997 MWR)
- Triply nested grid
  - A 82x64 54 km
  - B 124x94 18km
  - C 124x94 6km
  - 23 layers
- 661,020 grid points- 272 times as many as original hurricane model!



Hurricane Isabel 2003

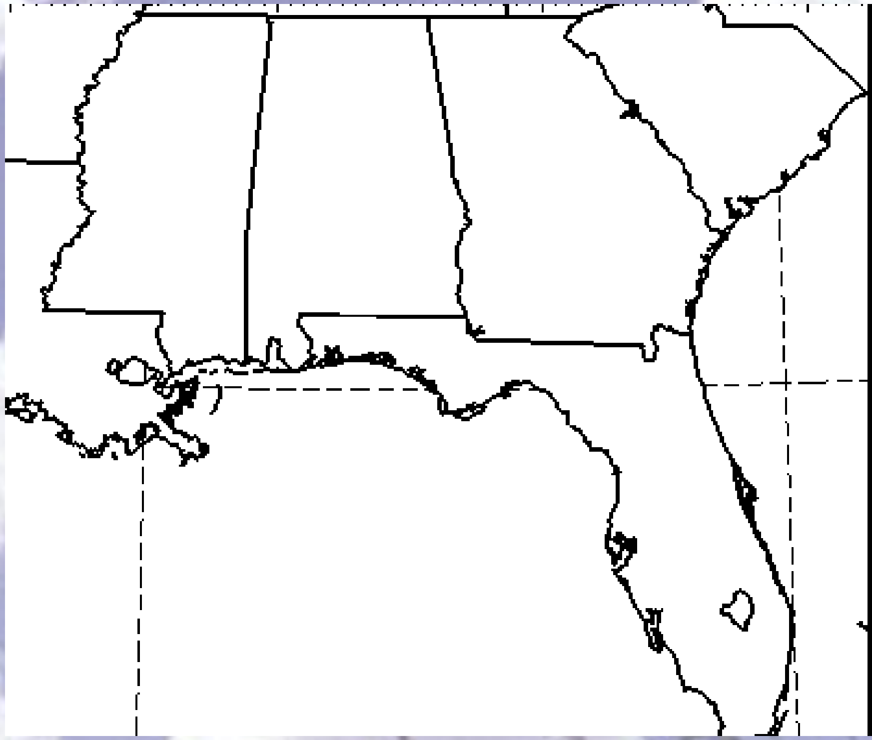
Composite Radar Observations   WRF initialized 00 UTC 17 Sept 03



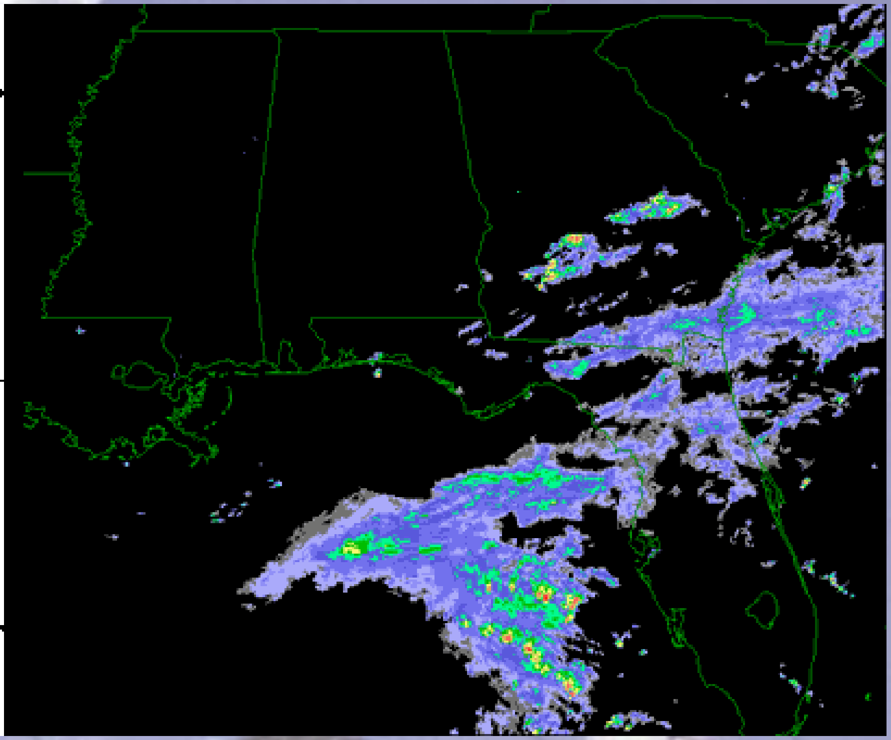
48 h forecast

Hurricane Ivan 2004

WRF initialized 00 UTC 15 Sept 04



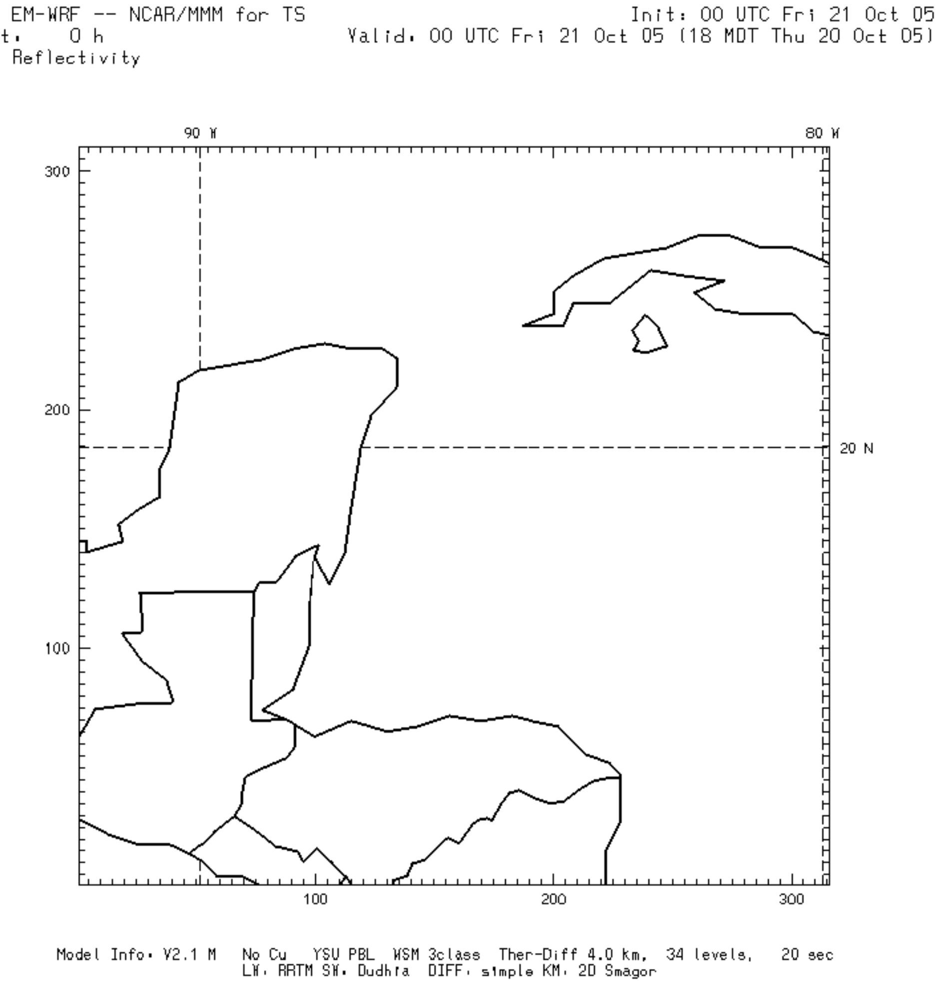
Composite Radar Observations

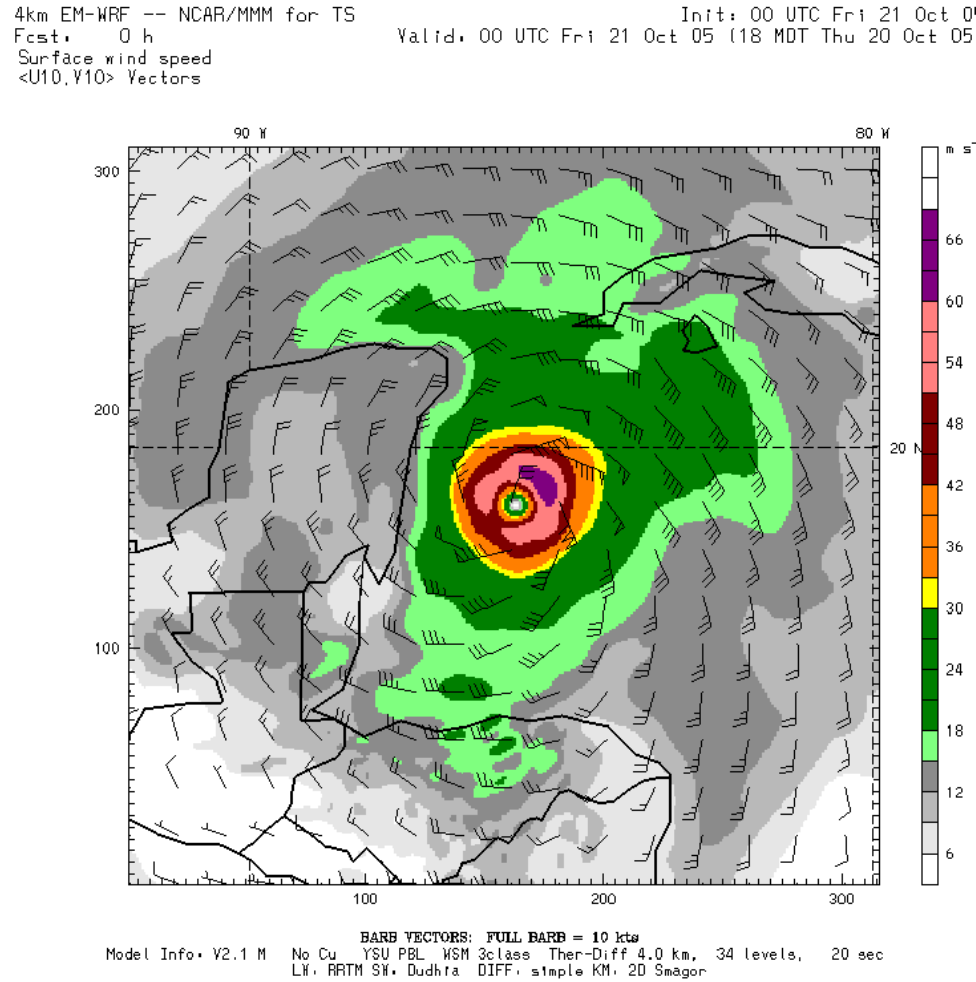


72 h forecast

WRF 4-km 4 –day forecast Hurricane Wilma 00 Z Fri Oct 21-00Z Tues Oct 25 2005

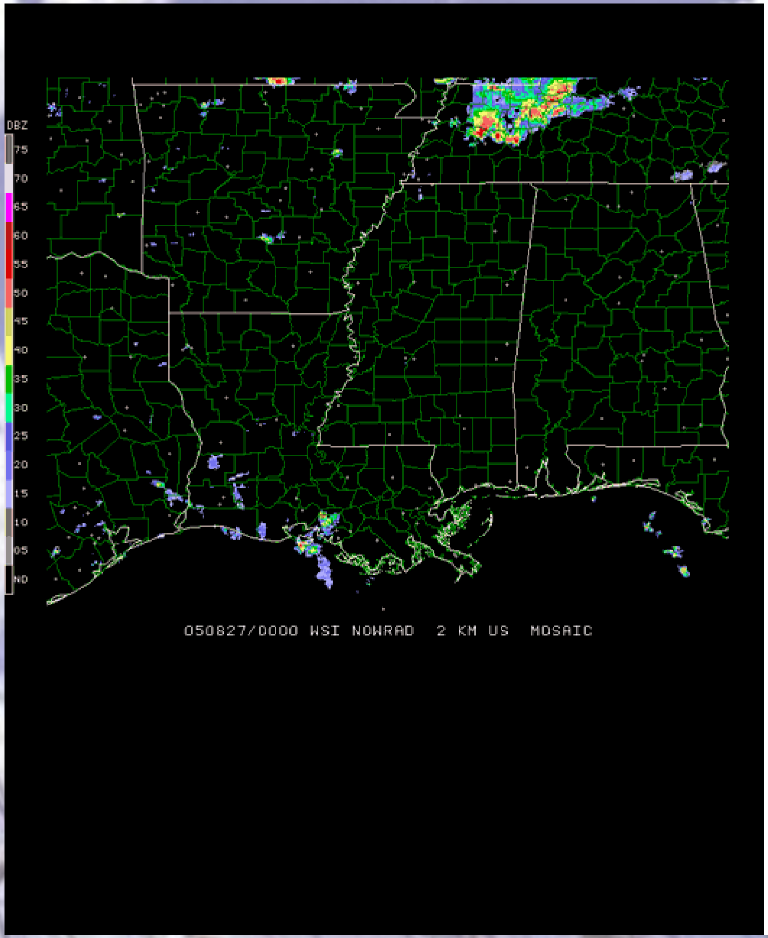
Rainfall (left) Sfc winds (right)



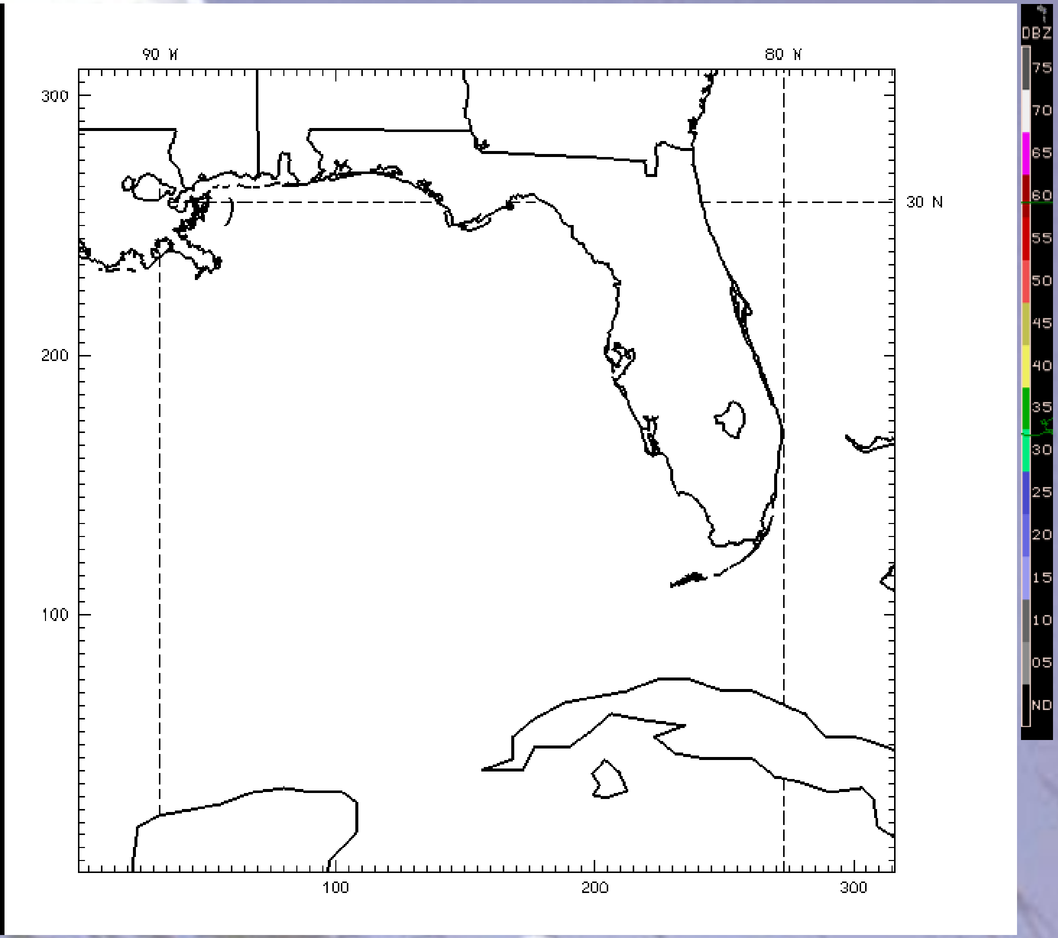


Hurricane Katrina 2005

Composite Radar Observations



WRF initialized 00 UTC 27 Aug

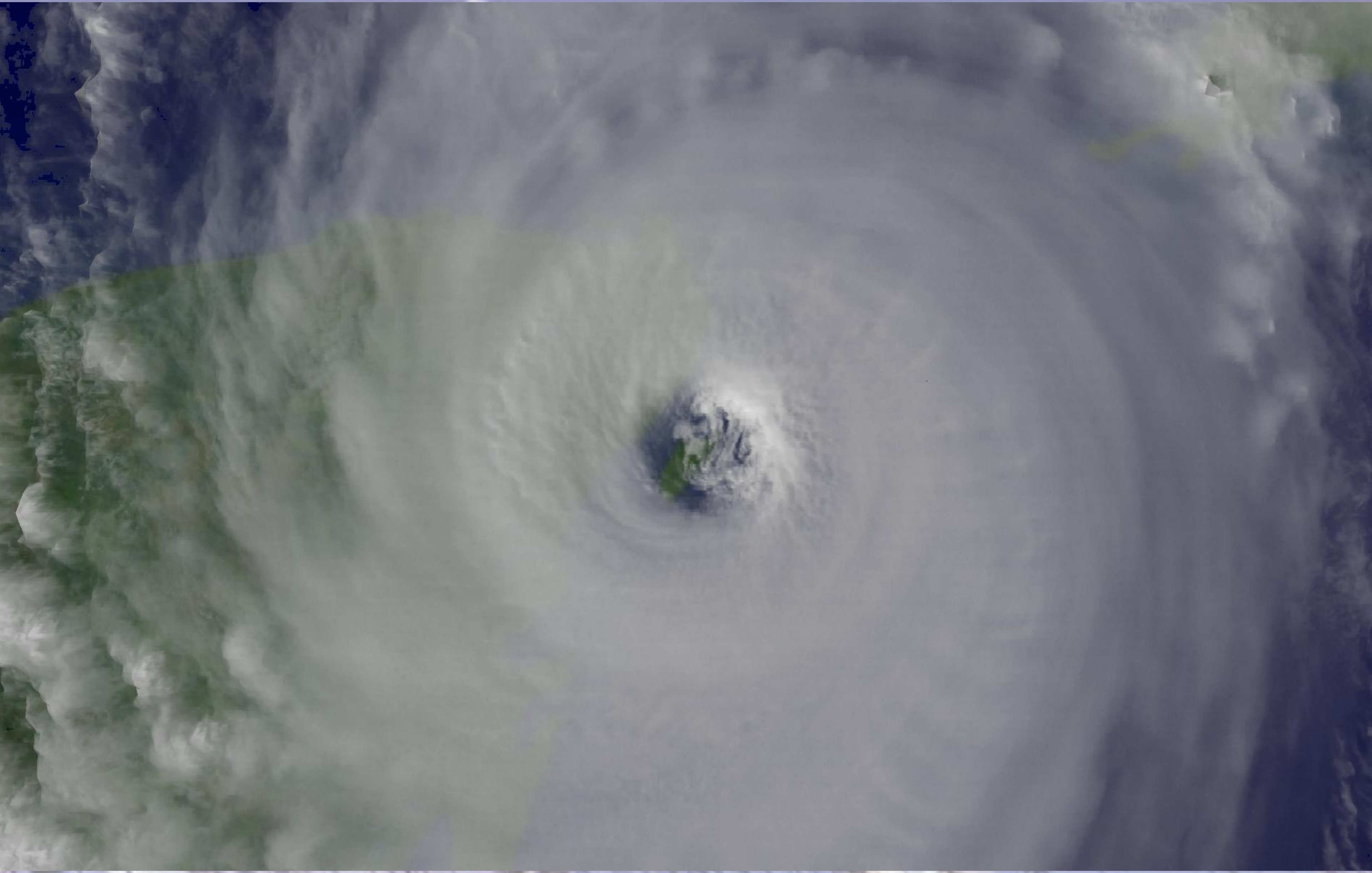


72 h forecast

Rick's Forecast

- Forecast models will contain interactive oceans, explicit cloud physics, resolve clouds, rainbands and eyewall ($\Delta s \sim 500$m)
- Track accuracy will continue to improve, especially beyond three days
- Tropical cyclogenesis will be routinely and correctly predicted by operational models
- A dramatic increase in accuracy of TC intensity forecasts is imminent (within 5 years)
- The relationship between TC formation and intensity and climate change will continue to be an important topic of research for many years.

Thank You!



Wilma 20:15 UTC Friday October 21, 2005