Hurricane Structure: Theory and Diagnosis

6 March, 2017

World Meteorological Organization Workshop

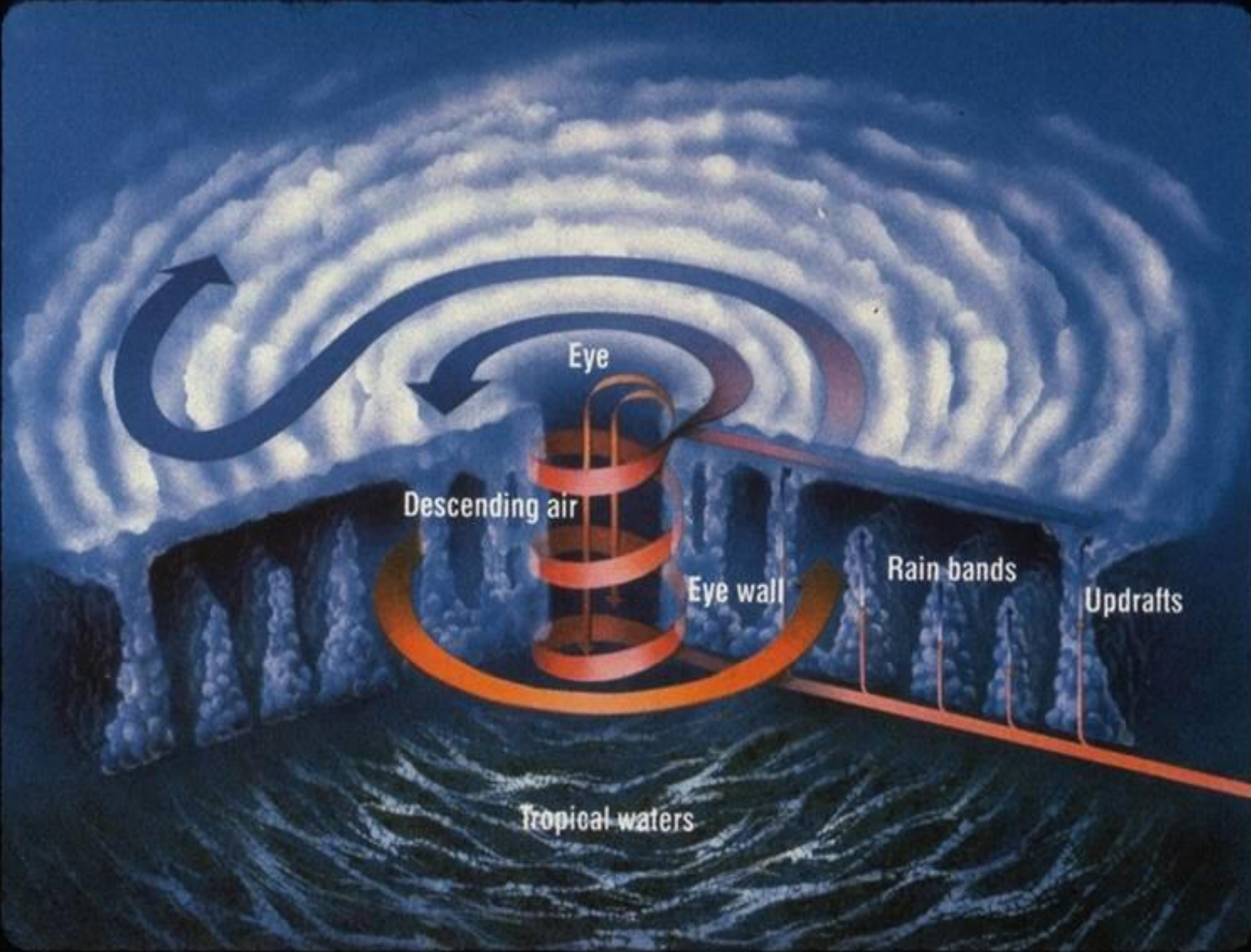
Chris Landsea

Chris.Landsea@noaa.gov

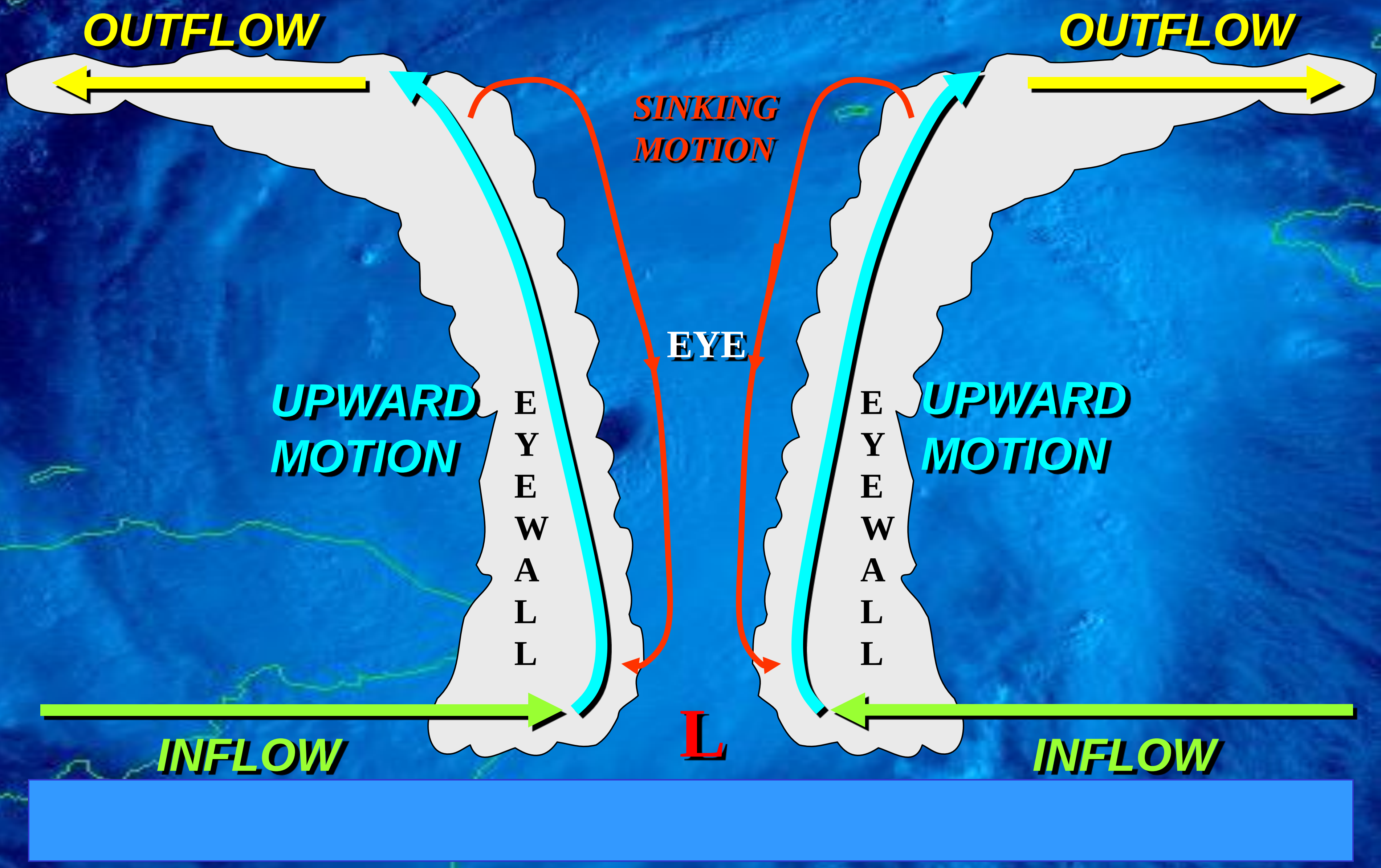
National Hurricane Center, Miami

Outline

- Structure of Hurricanes – Dynamical and thermodynamical
- How is size defined and measured?
- Exercise: Analyze size (tropical storm and hurricane force winds)


Eye
Descending air
Eye wall
Rain bands
Updrafts
Tropical waters

THE WARM CORE IS A CONSEQUENCE OF BOTH LATENT HEAT RELEASE AND WARMING BY SUBSIDENCE



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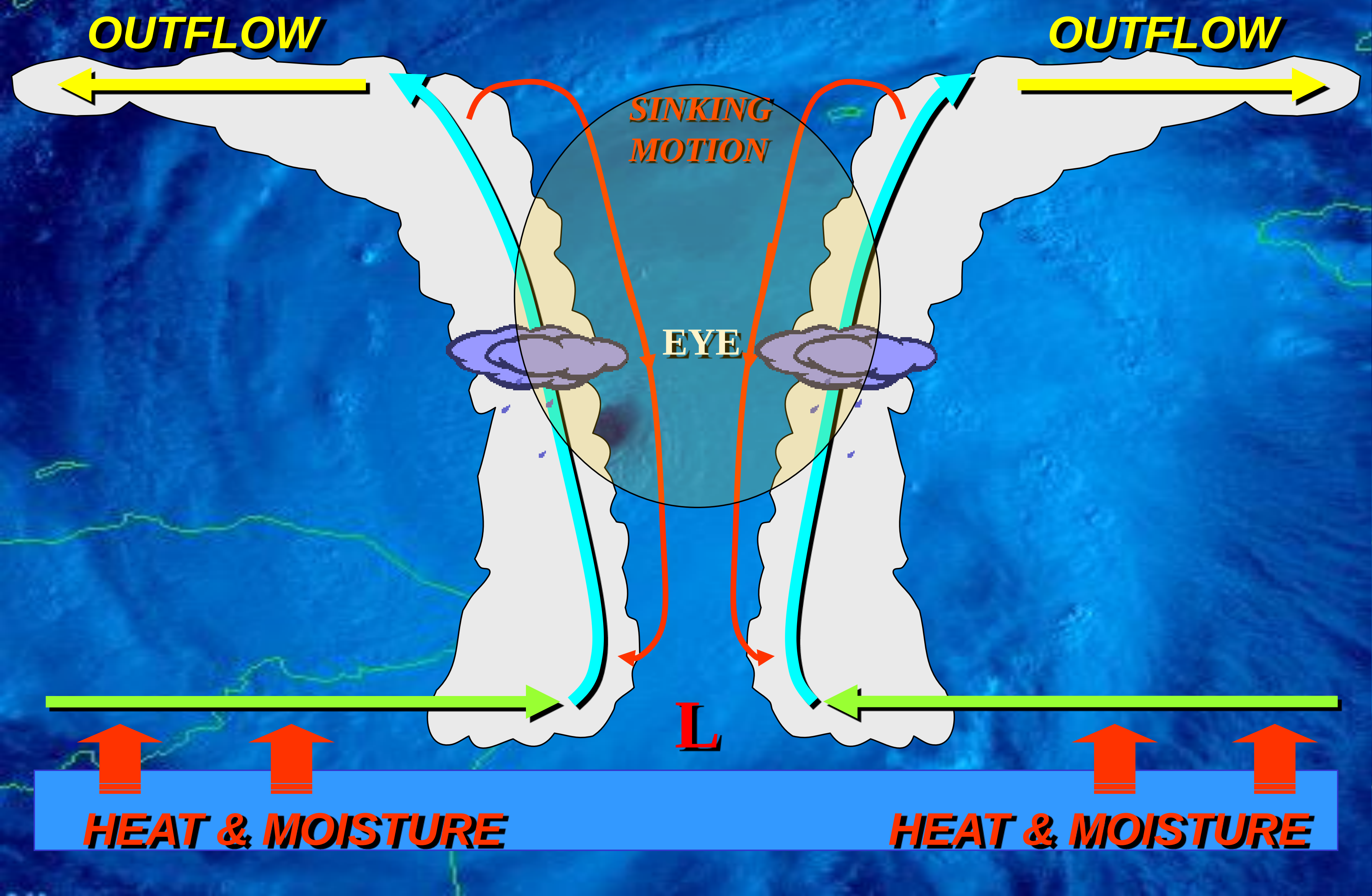
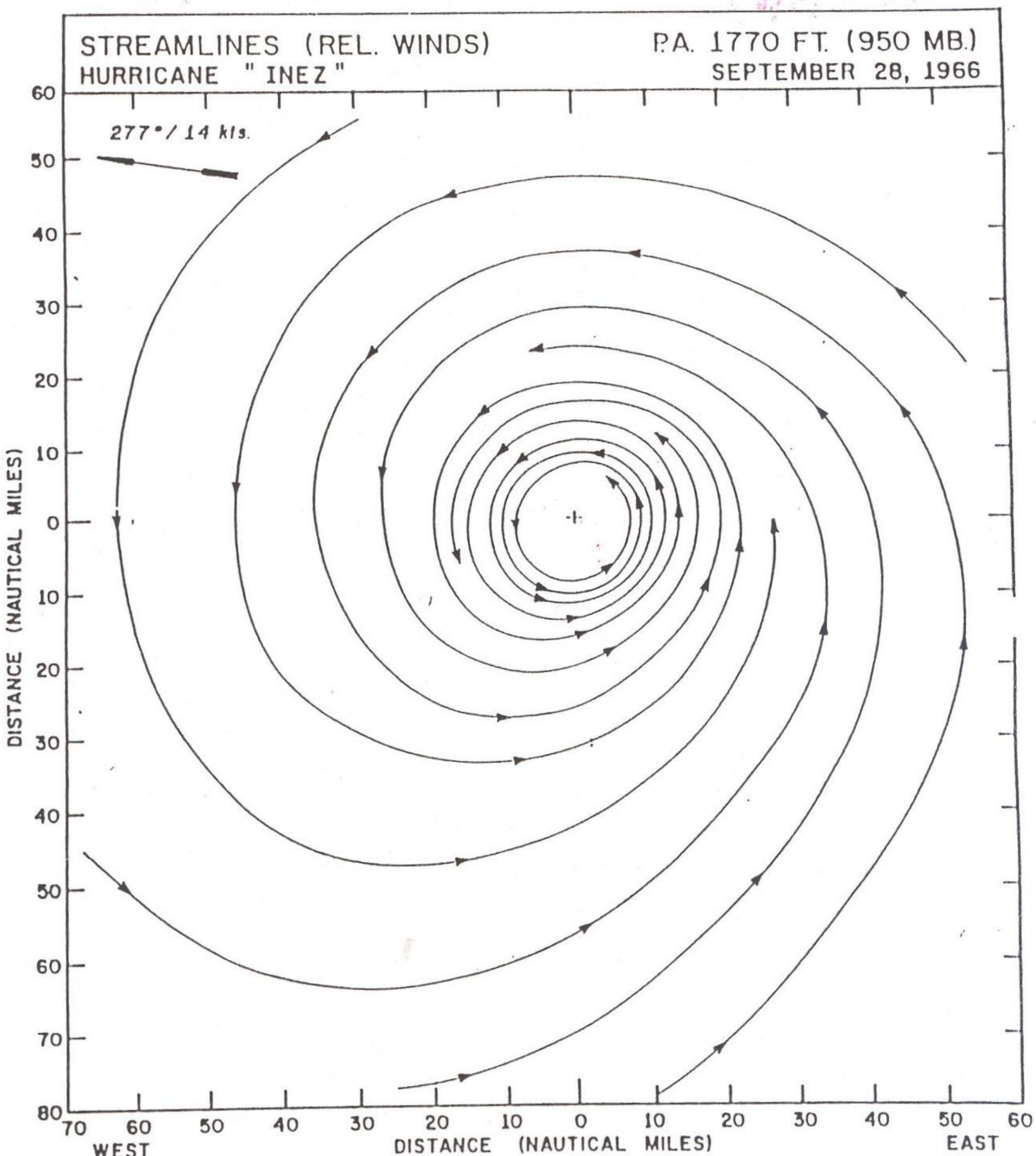
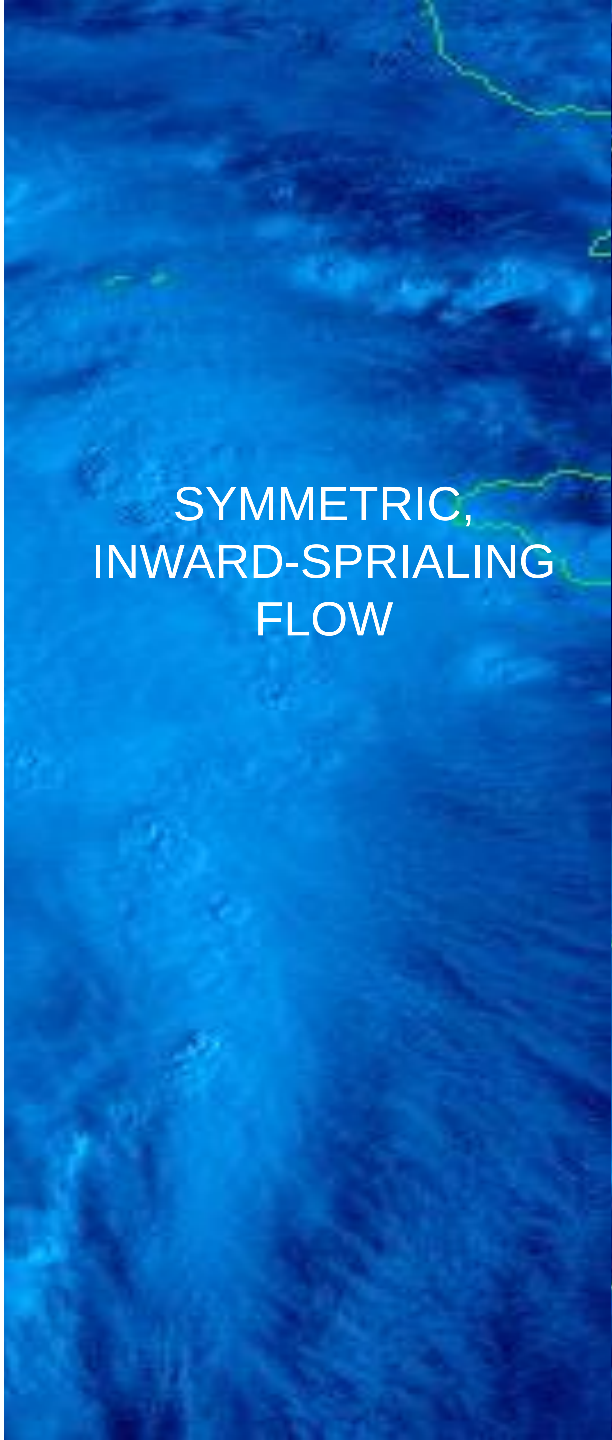




STREAMLINES (REL. WINDS)
HURRICANE "INEZ"
P.A. 1770 FT. (950 MB.)
SEPTEMBER 28, 1966
277°/ 14 kts.
DISTANCE (NAUTICAL MILES)
WEST
EAST
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60



SYMMETRIC,
INWARD-SPRIALING
FLOW

WIND SPEEDS ARE CLOSE TO SYMMETRIC – ONLY AFTER SUBTRACTING MOTION

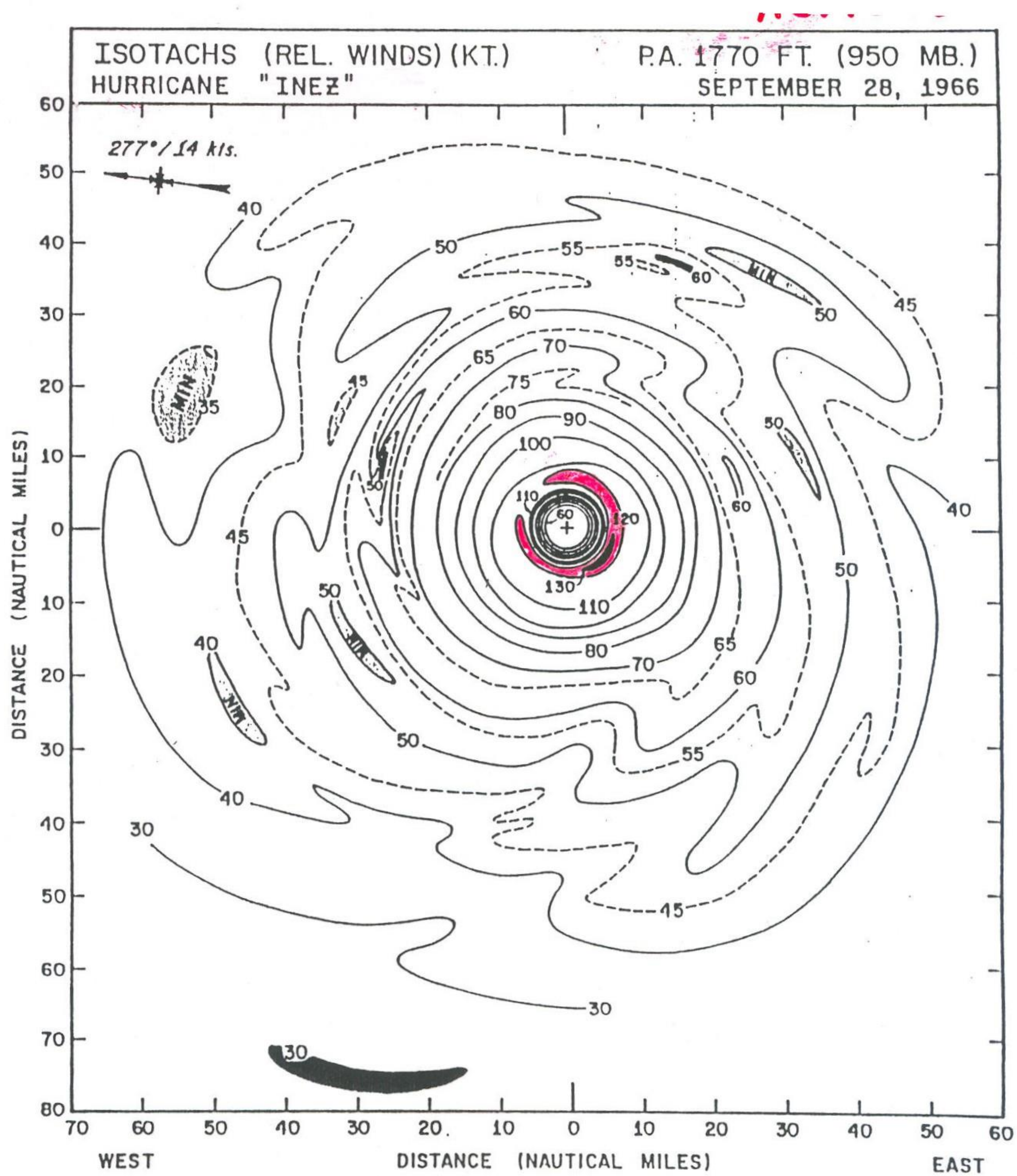
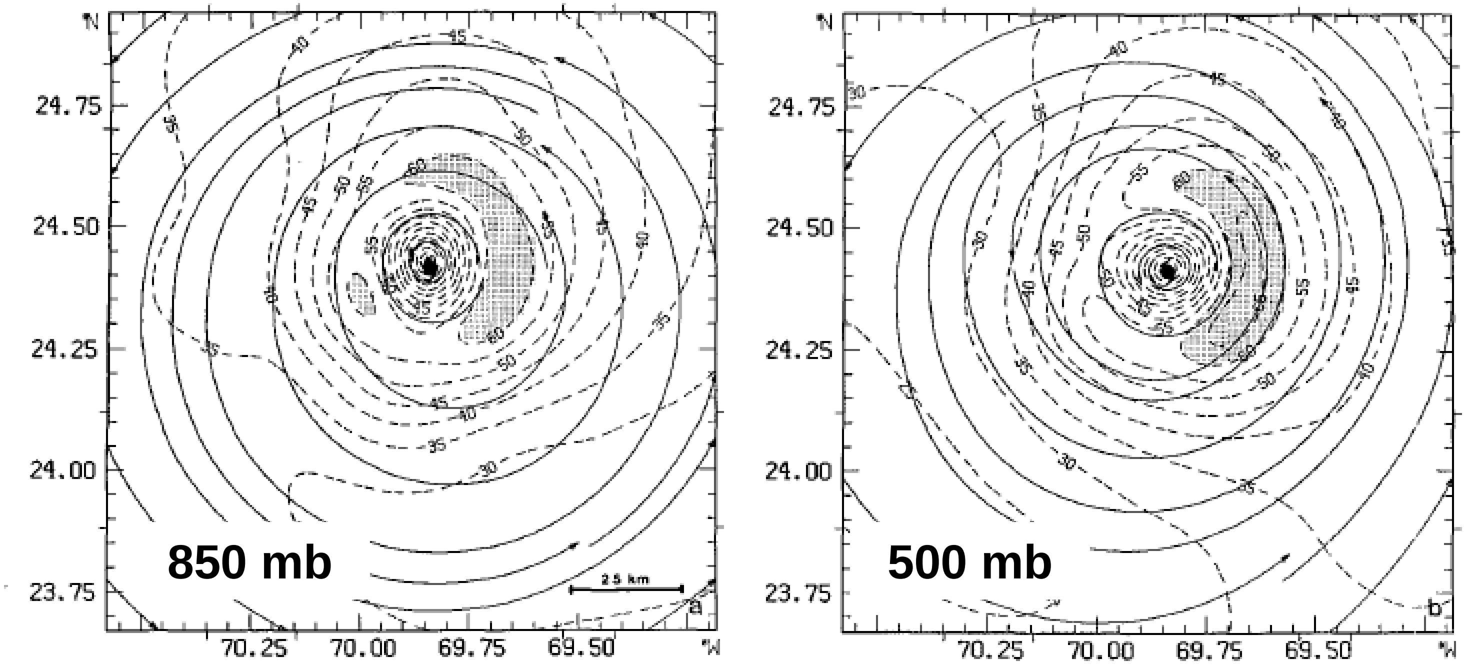
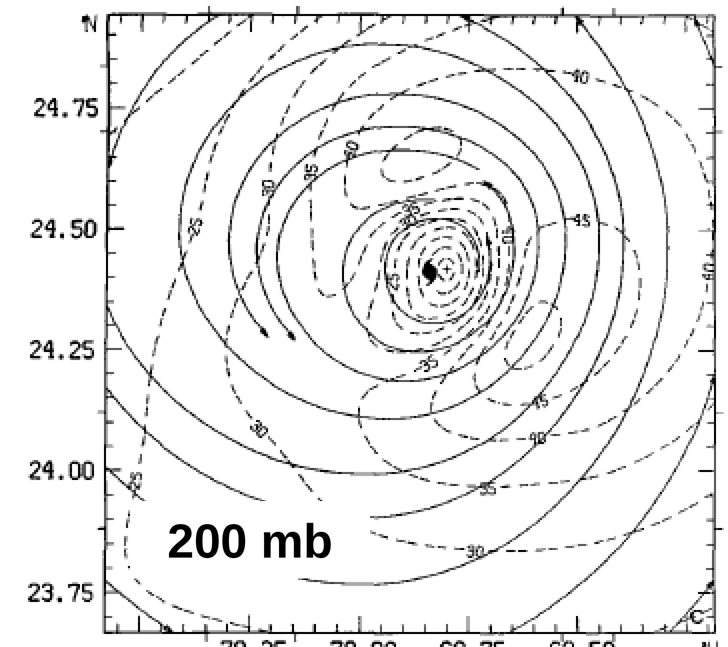


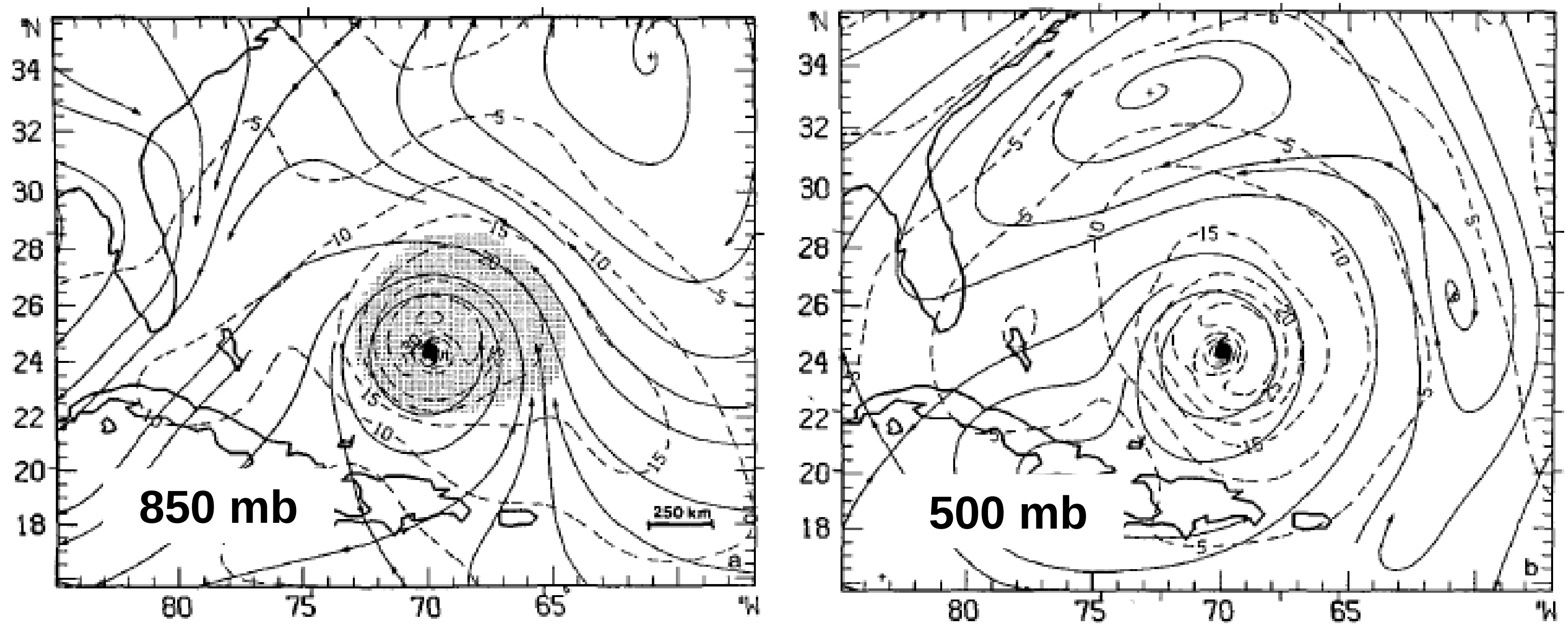
FIG. 2.4b. Low-level (950 mb) isotachs (kt) in Hurricane Inez (1966) (Hawkins and Imbembo, 1976).

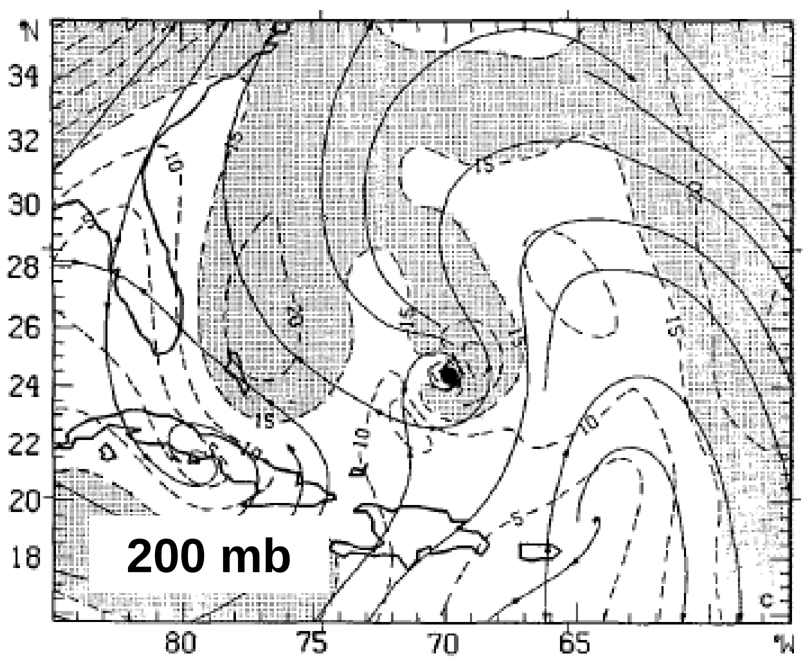




NOTE CYCLONIC CIRCULATION AT UPPER-TROPOSPHERIC LEVEL, WITHIN A FEW DEGREES RADIUS OF THE CENTER!

FIG. 4. Analysis of wind (streamlines and isotachs) on meshes 1–3 for (a) 850, (b) 500, and (c) 200 mb. Isotachs are at 5 m s^{-1} intervals. Shading indicates wind speeds greater than 60 m s^{-1}.





BEYOND A FEW DEGREES RADIUS FROM THE CENTER, THE UPPER-TROPOSPHERIC FLOW TURNS ANTICYCLONIC

FIG. 5. Analysis of wind (streamlines and isotachs) for meshes 6–7 for (a) 850, (b) 500, and (c) 200 mb. Isotachs are at 5 m s^{-1} intervals. Shading in (a) indicates area of tropical storm force winds (17.5 m s^{-1}), and in (c) areas with winds greater than 15 m s^{-1}.

UPPER-TROPOSPHERIC OUTFLOW TYPICALLY HAS SIGNIFICANT AZIMUTHAL ASYMMETRIES

TOTAL

ASYMMETRIC PART

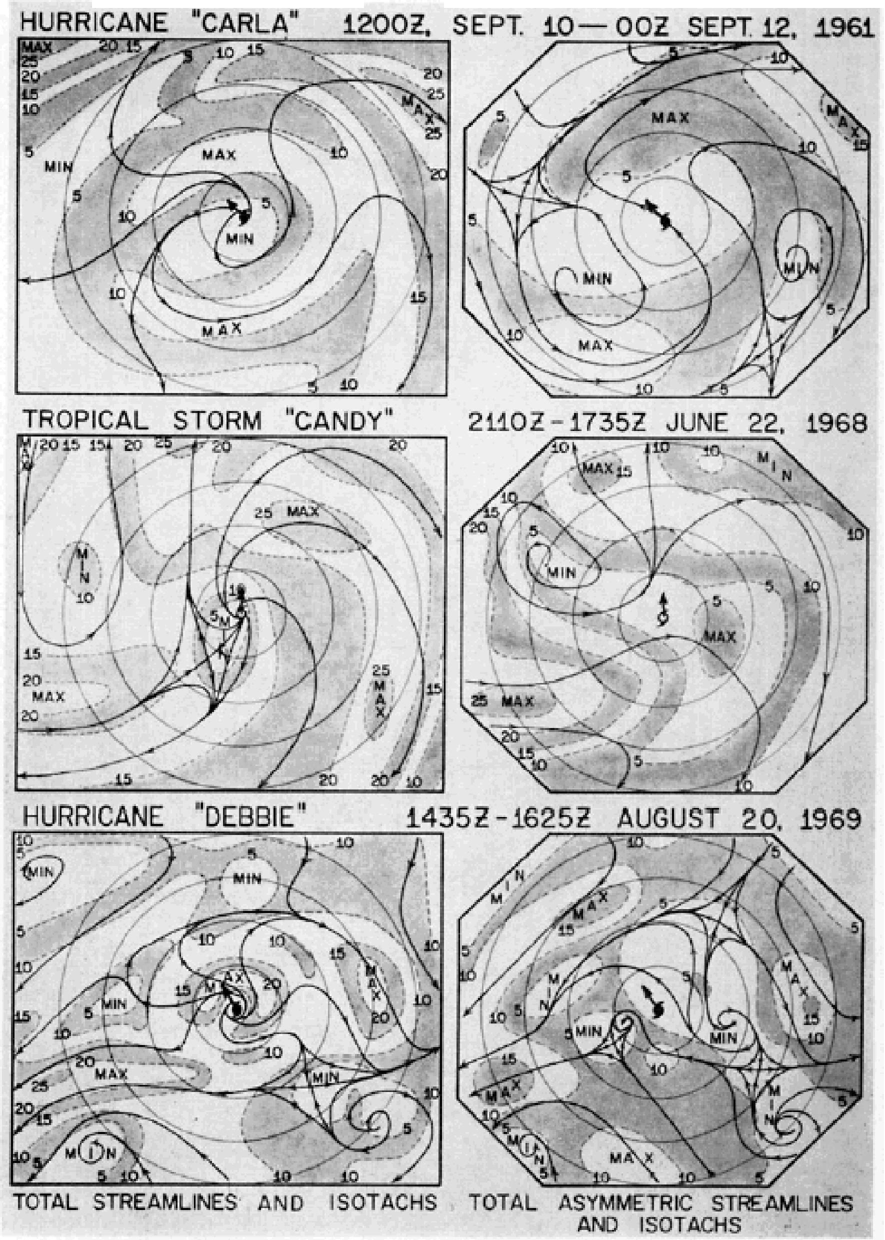


FIG. 2. Total streamlines and isotachs (m sec^{-1}), left, compared with total asymmetric streamlines and isotachs (m sec^{-1}), right, for hurricane Carla, tropical storm Candy and hurricane Debbie. The range circles are at 2° latitude radius intervals. The arrow indicates the direction of storm motion.

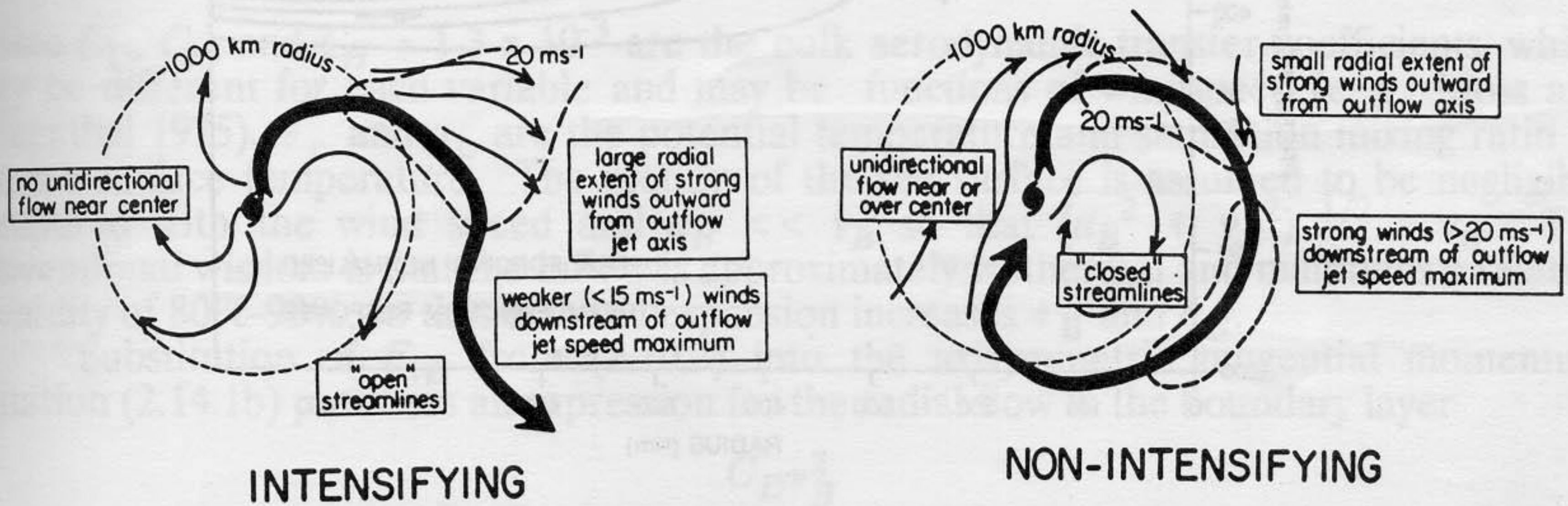
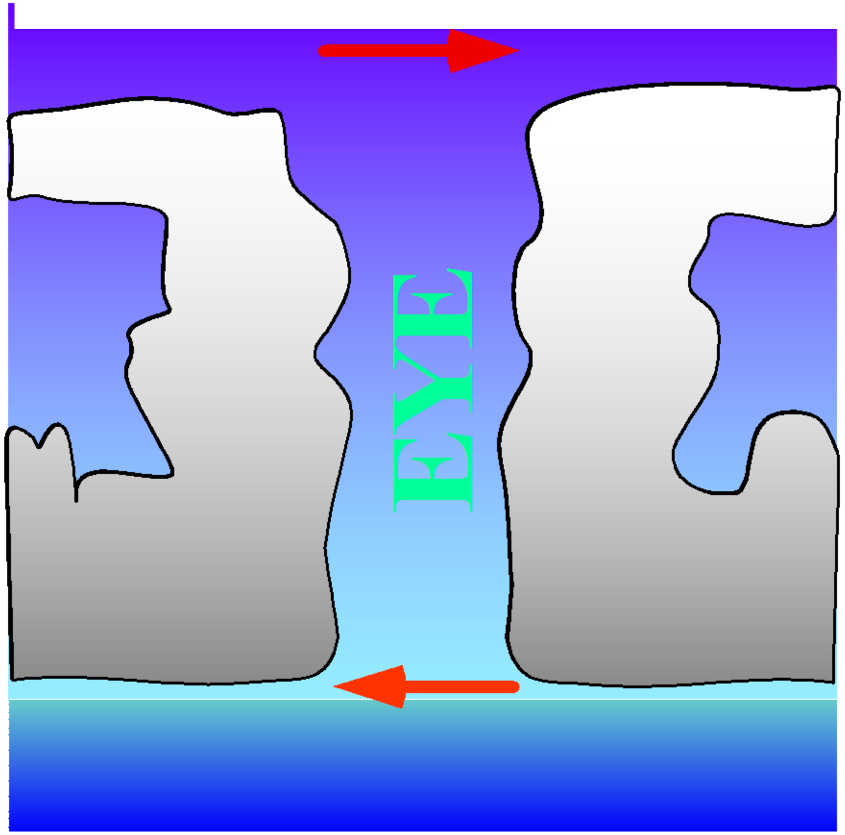
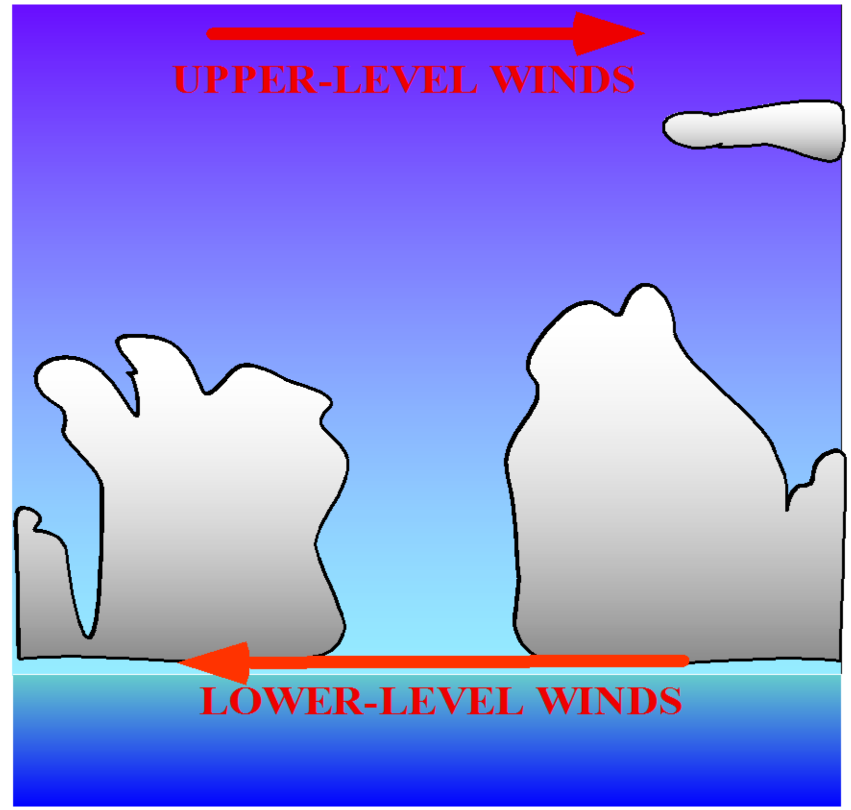


Fig. 2.17 Differences between the outflow and upper-level asymmetries of intensifying and nonintensifying hurricanes (Merrill 1988b).

Not too much "Wind Shear"

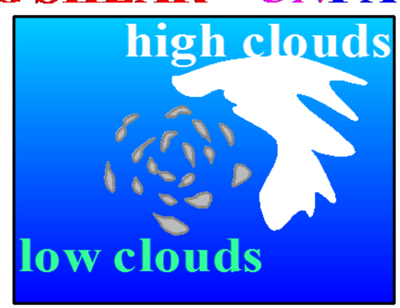
Effects of Vertical Wind Shear (V_z) on Tropical Cyclones





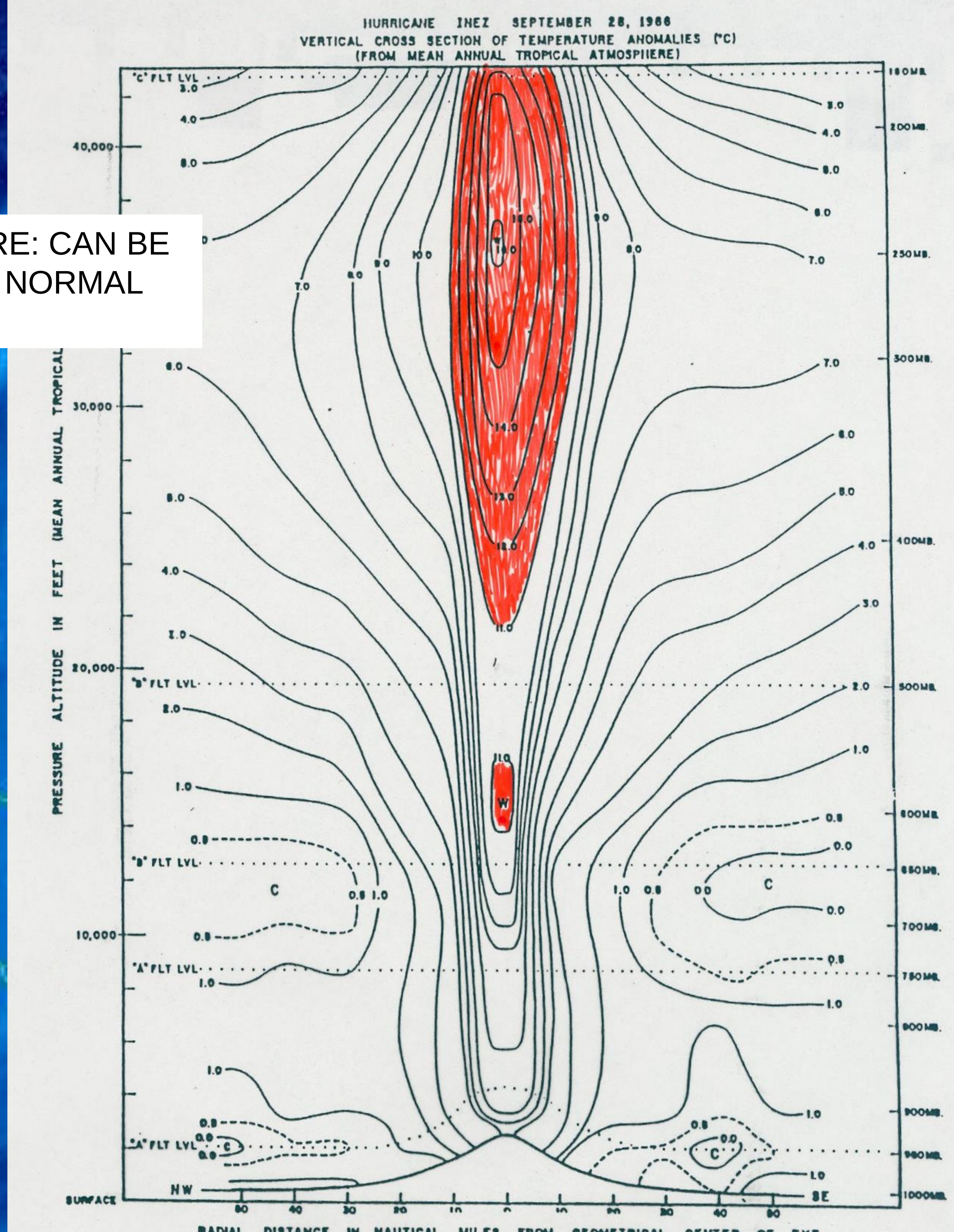
WEAK **SHEAR = FAVORABLE**

STRONG **SHEAR = *UN*FAVORABLE**

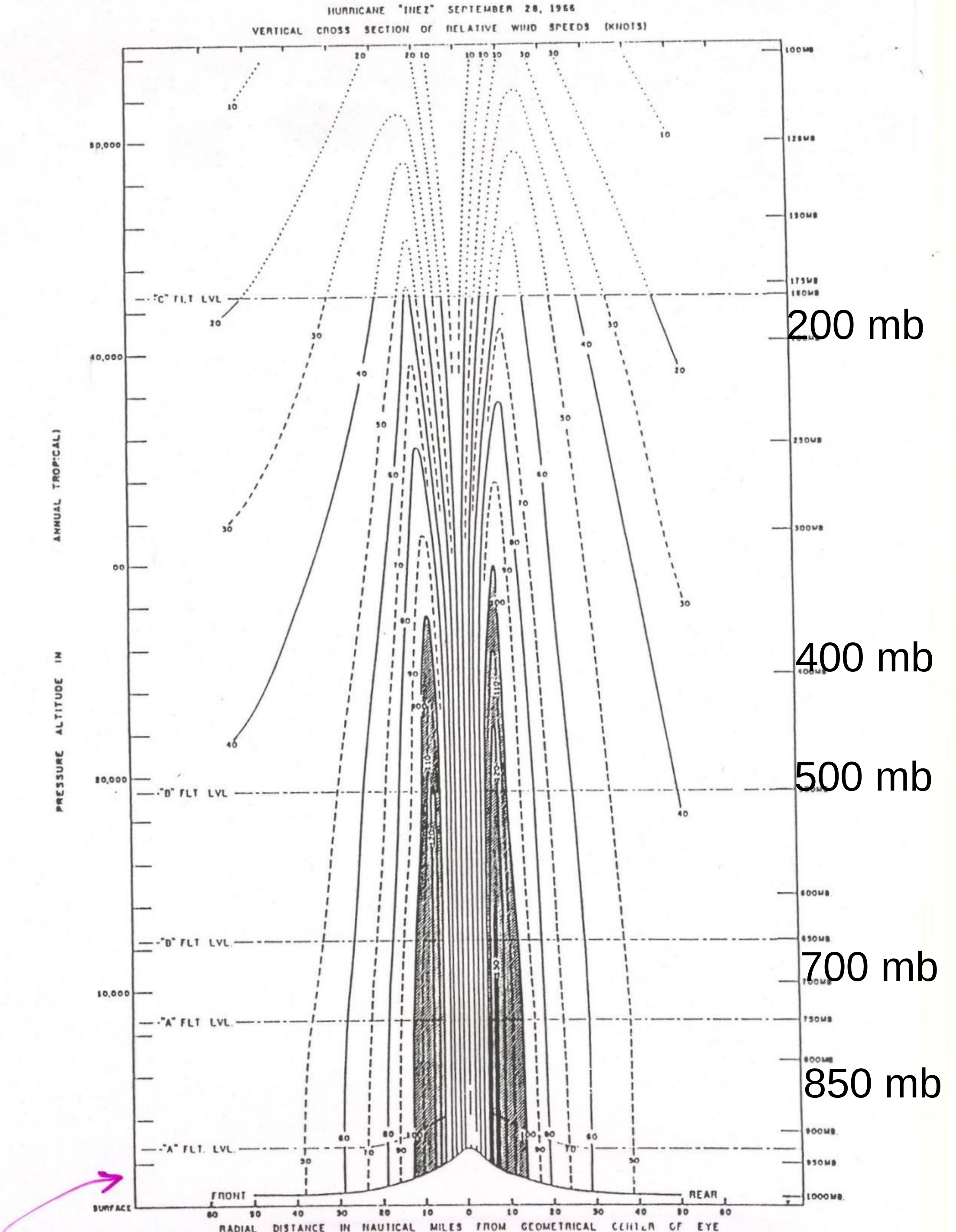


Neal Dorst/Stan Goldenberg
Hurricane Research Division
AOML/NOAA

INTENSE WARM CORE: CAN BE 16 K WARMER THAN NORMAL TROPICAL VALUES



DEEP-LAYER CYCLONIC CIRCULATION



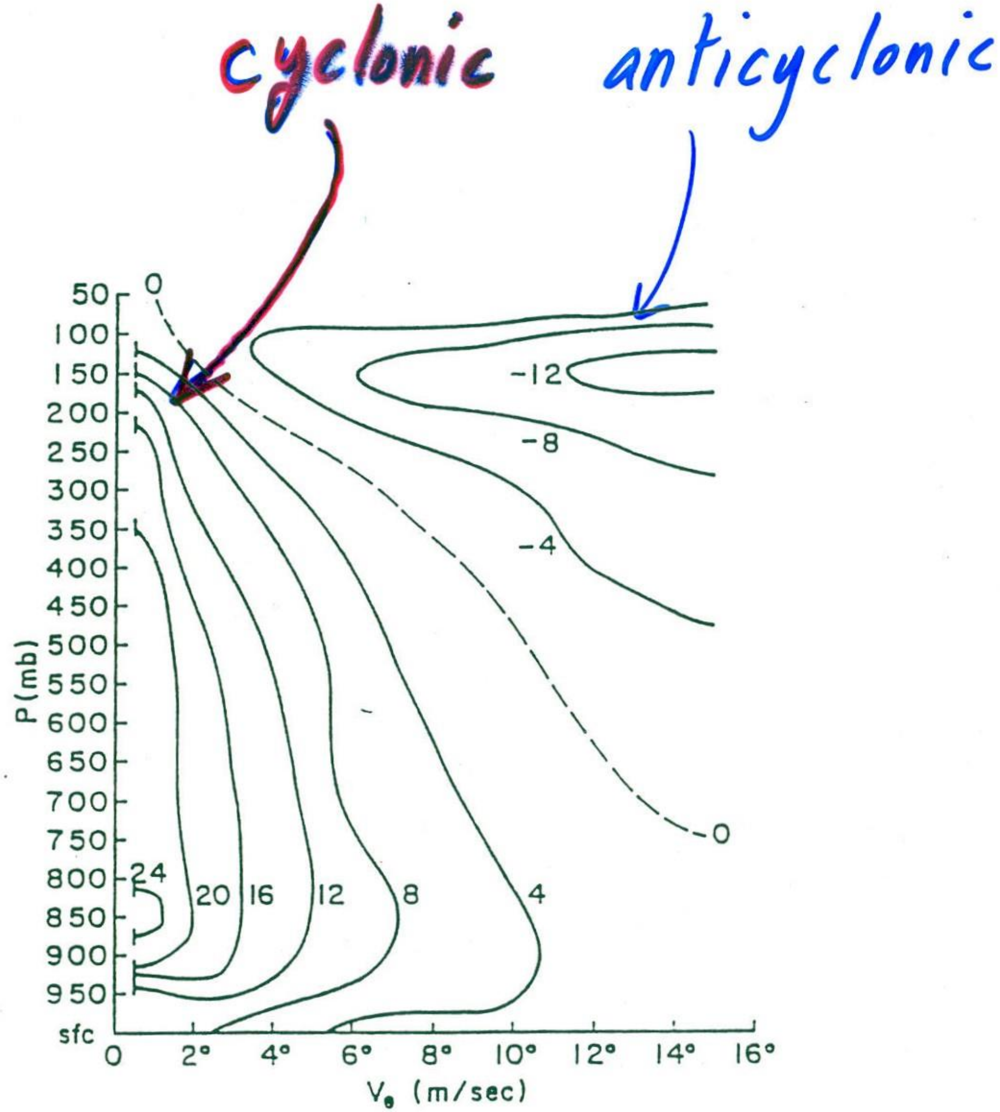


FIG. 2.6. Vertical cross section of tangential winds (m s^{-1}) for the Pacific composite typhoon (Frank, 1977a).

MEAN VERTICAL MOTION

NOTE: AT 500 mb, 100 mb/day ≈ 1.8 cm/sec

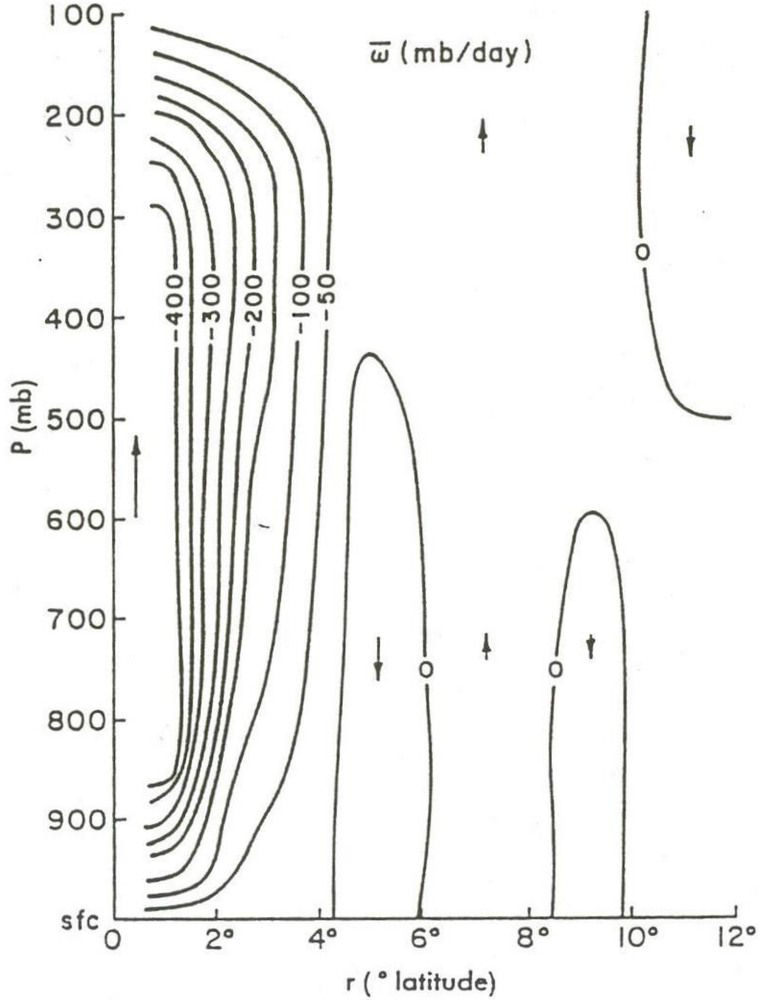


FIG. 2.14. Vertical cross section of vertical motion (mb day^{-1}) in mean typhoon (Frank, 1977a).

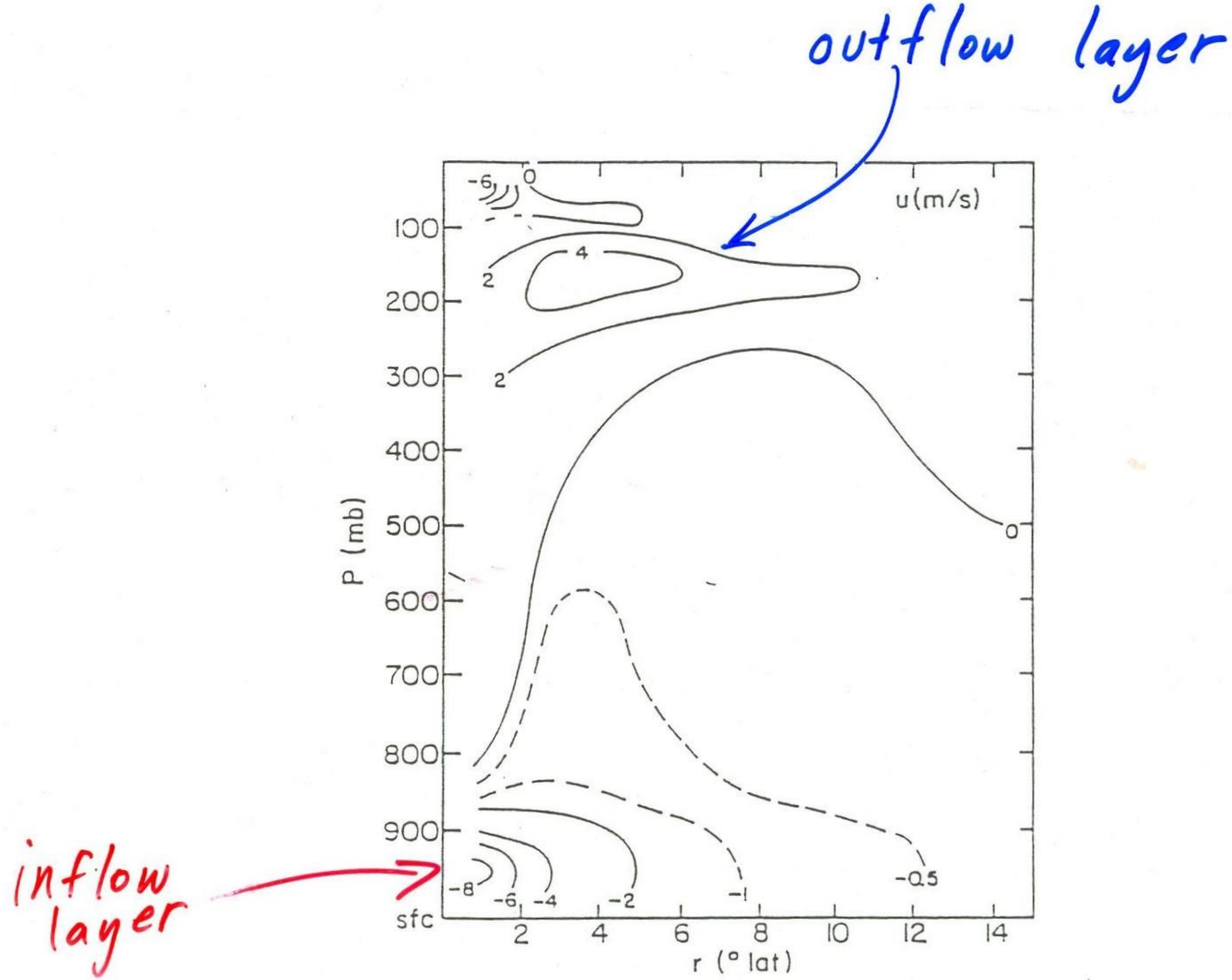


FIG. 2.5. Vertical cross section of radial winds (m s^{-1}) for the western Atlantic composite hurricane (Gray, 1979).

THE MASS (PRESSURE, HEIGHT) AND WIND FIELDS OF A TROPICAL CYCLONE ARE IN NEAR-GRADIENT OR (IN THE INNER CORE REGION) NEAR-CYCLOSTROPHIC BALANCE

RELATIONSHIP BETWEEN MINIMUM CENTRAL PRESSURE AND MAXIMUM WIND: IS THERE A UNIVERSAL ONE? MAYBE, IF ENVIRONMENTAL PRESSURE AND SIZE IS TAKEN INTO ACCOUNT

WILLOUGHBY SUGGESTED THE FOLLOWING FORMULA:

$$v_m = \sqrt{\frac{2}{3}\frac{1}{\rho_0}\left(p_\infty - p_c\right)}$$

$\rho_0 = \text{density}$

$p_\infty = \text{enviornmental pressure}$

$v_m = \text{max wind}$

$p_c = \text{central pressure}$

IF WE ASSUME AIR DENSITY TO BE ABOUT 1.17 kg/m^3, THEN WE HAVE:

$$v_m = \sqrt{0.57\left(p_\infty - p_c\right)}$$

IN THE CASE OF HURRICANE ANDREW, WHEN IT HIT NEAR MIAMI, THE CENTRAL PRESSURE WAS 922 mb. IF WE ASSUME AN ENVIRONMENTAL PRESSURE OF 1016 mb, WE HAVE:

$$v_m = \sqrt{0.57\left(101600 - 92200\right)}$$

$$= 73\,\text{m/sec}$$

$$= 141\,\text{knots}$$

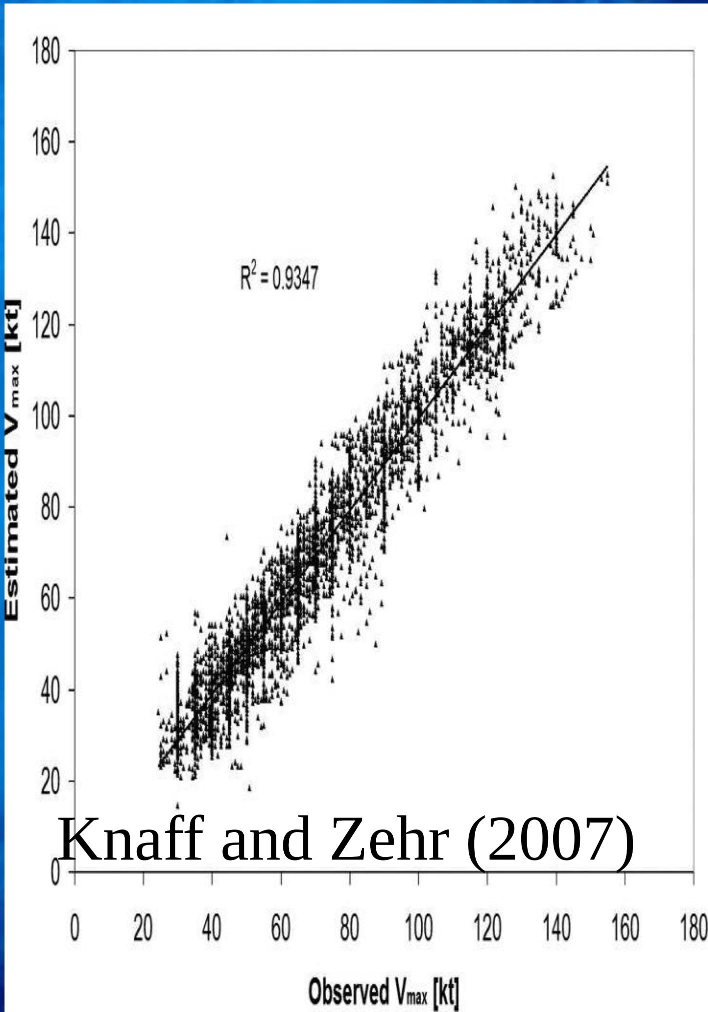
$$= 262\,\text{km/hr}$$

COMPREHENSIVE

PRESSURE-WIND RELATIONSHIP

MAXIMUM WIND = 18.633
-14.960x*SIZE*
-0.755x*LATITUDE*
-0.518x*(ENV.-CENTRAL PRESSURE)*
+9.738x*(ENV.-CENTRAL PRESSURE*)**0.5
+1.5*(SPEED)***0.63

- For example, a small RMW TC with a central pressure of 963 mb in the lower latitudes (with average environmental pressure and translational velocity) would suggest a windspeed of 100 kt, while a large RMW TC with a central pressure of 948 mb in high latitude would also suggest also a maximum wind of 100 kt.



Knaff and Zehr (2007)

THE TANGENTIAL WIND PROFILE OF A TC MAY BE APPROXIMATED BY A MODIFIED RANKINE VORTEX:

$$vr^x = \text{constant} \quad r \geq \text{RMW};$$

$$vr^{-1} = \text{constant} \quad r \leq \text{RMW}$$

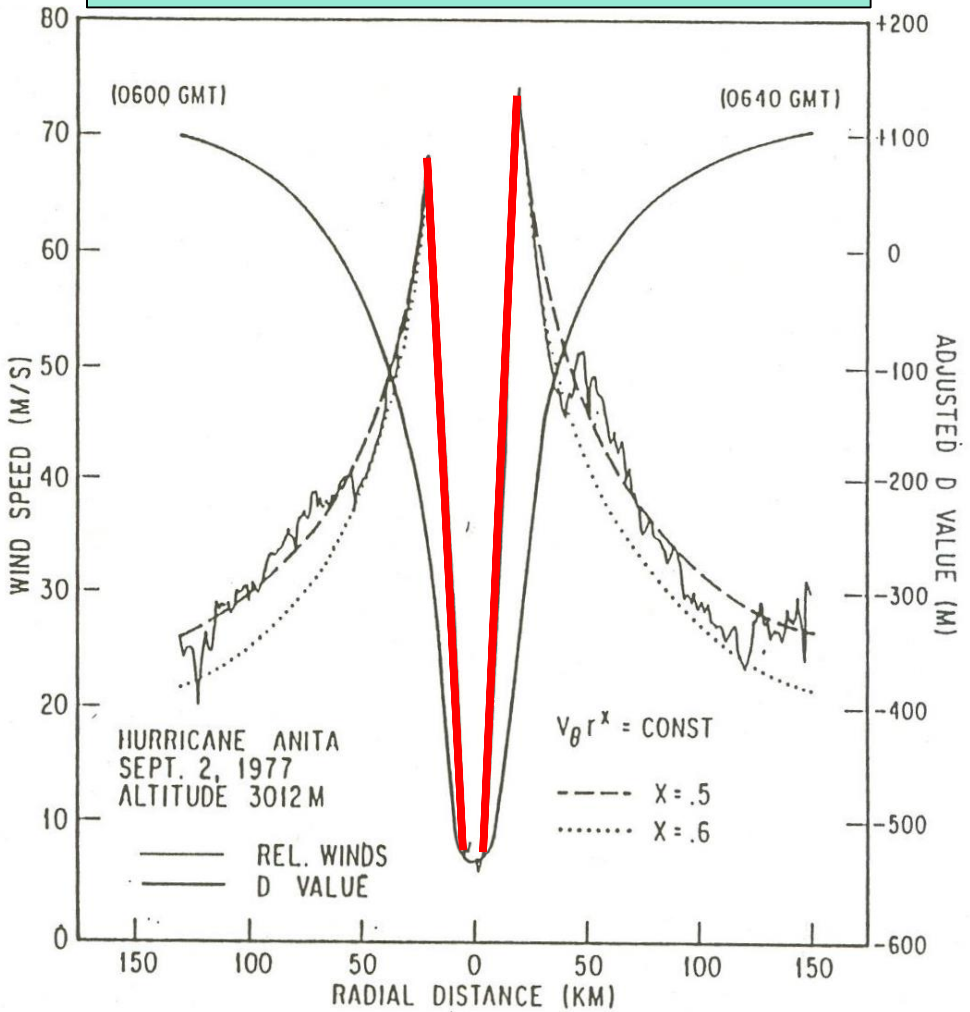


Fig. 2.8. Radial profiles of tangential wind speed (m s^{-1}) and D values (departure of isobaric height from reference value) in Hurricane Anita. Also shown are graphs $V_\theta r^x$ = constant for values of x = 0.5 and 0.6. (Sheets, 1980).

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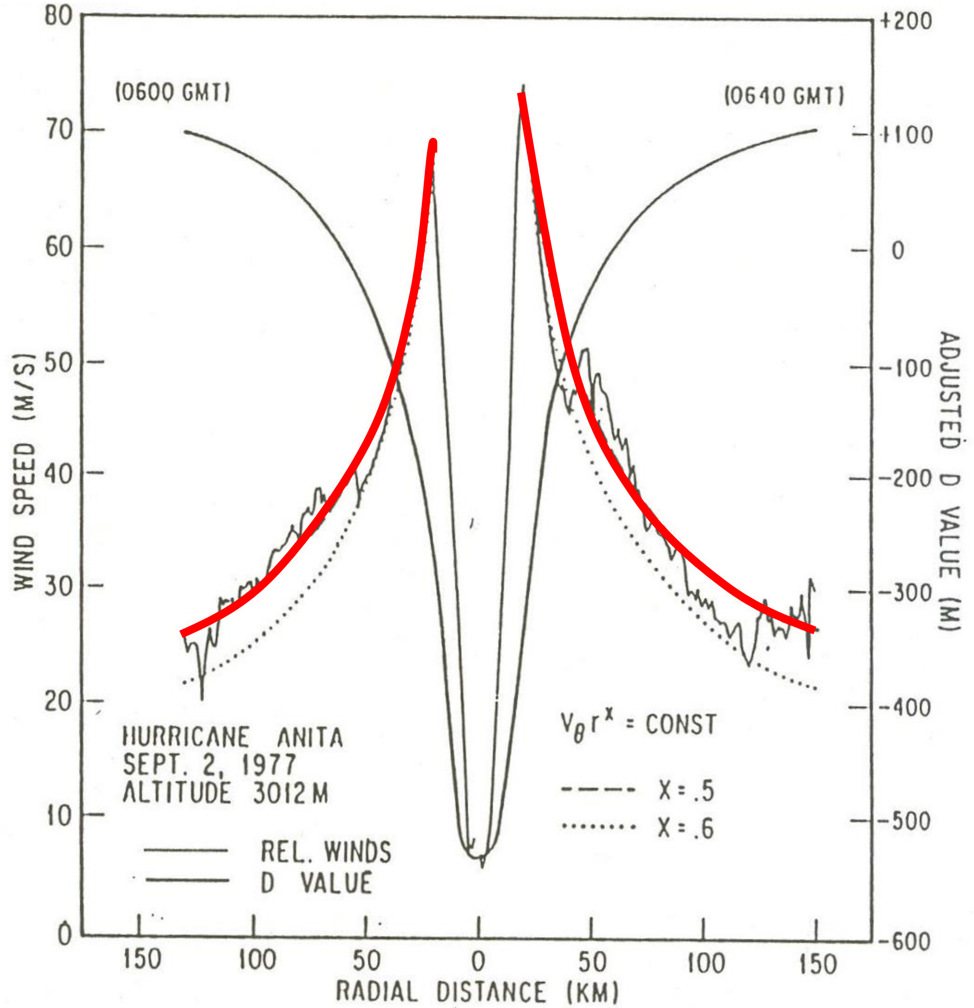

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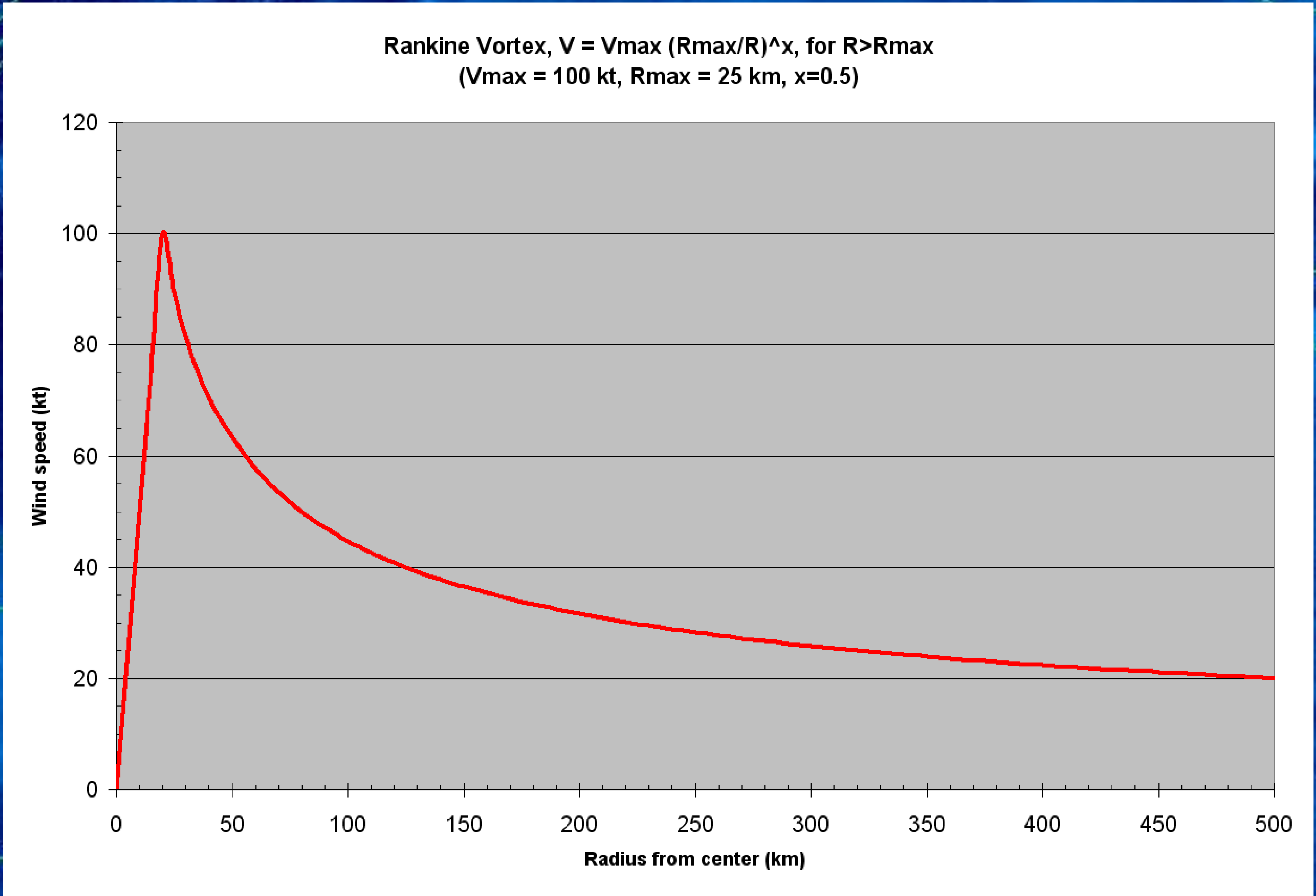
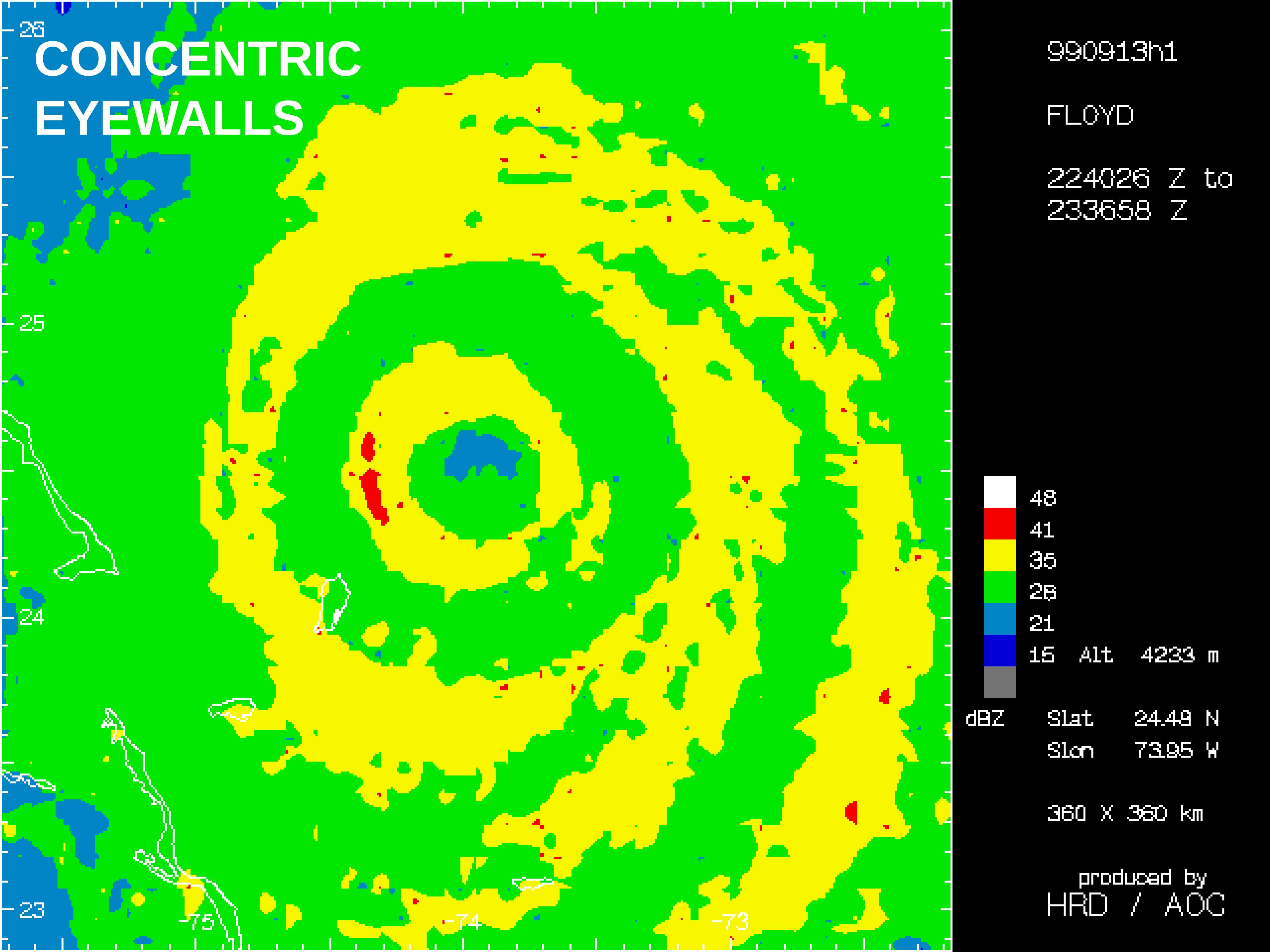
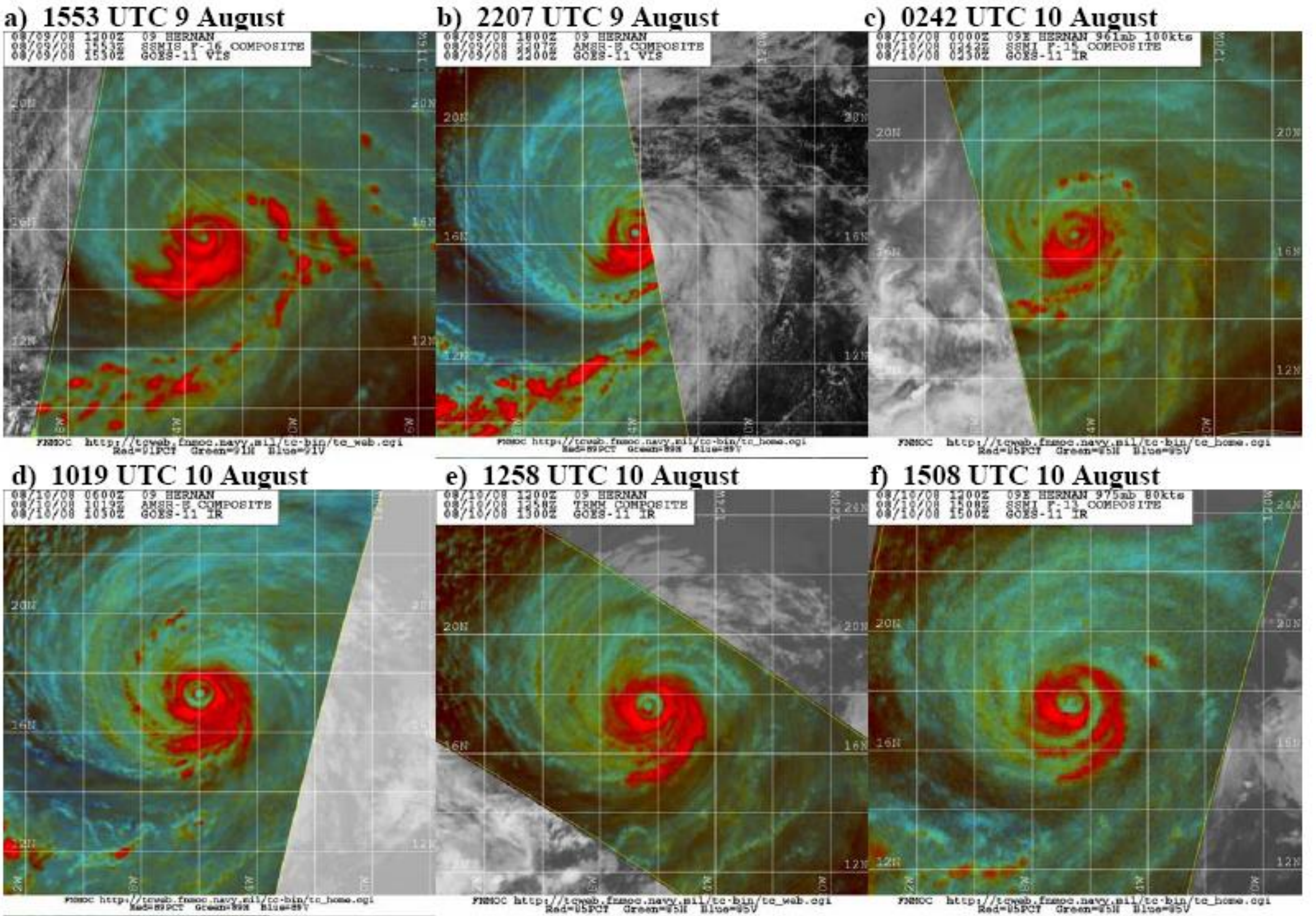
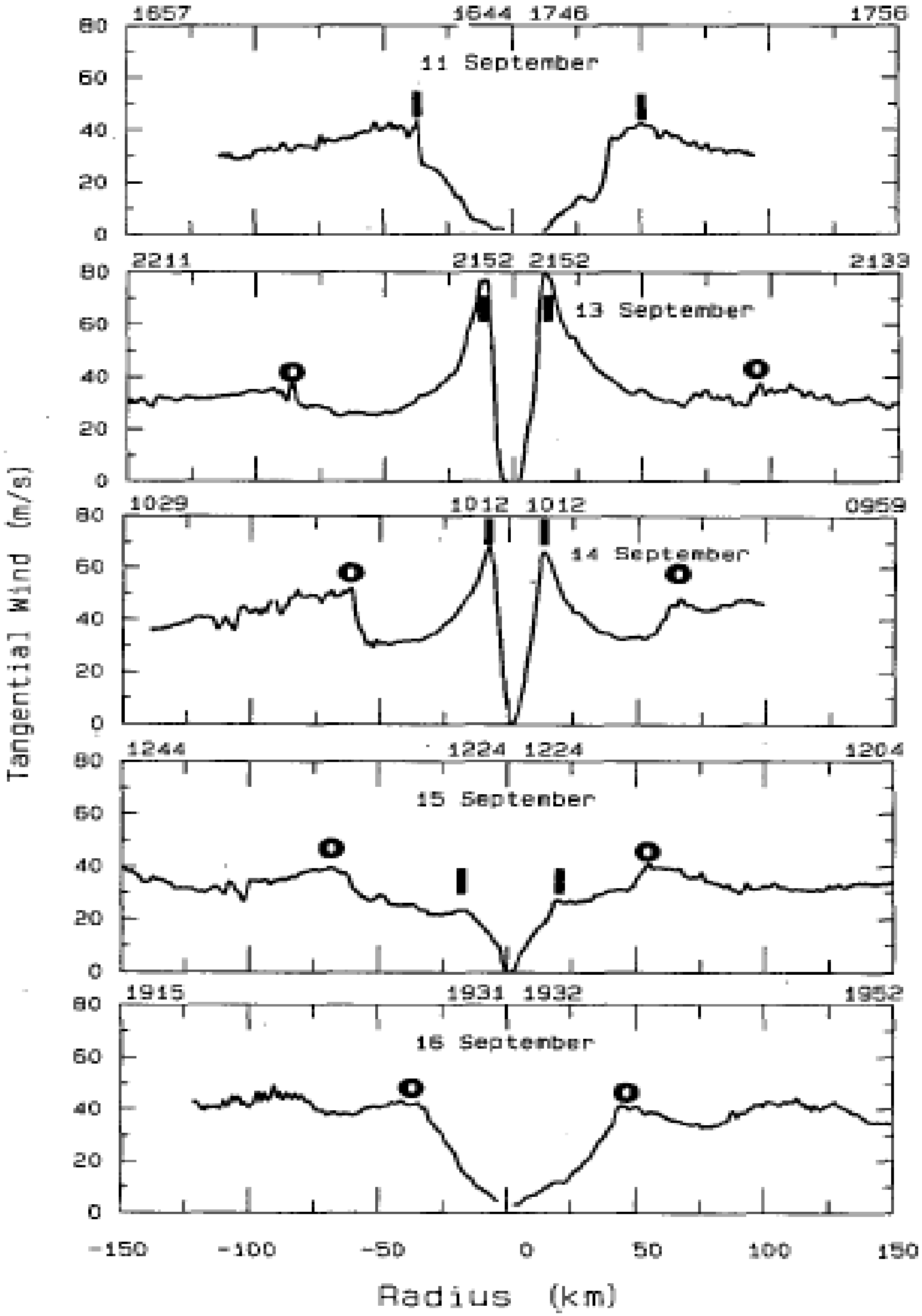

Rankine Vortex, V = Vmax (Rmax/R)^x, for R>Rmax
(Vmax = 100 kt, Rmax = 25 km, x=0.5)
Wind speed (kt)
0
20
40
60
80
100
120
0
50
100
150
200
250
300
350
400
450
500
Radius from center (km)

CONCENTRIC EYEWALLS



Concentric Eyewall Cycle – from microwave satellite imagery (Hernan)





Concentric Eyewall Cycle –

Tangential winds (Gilbert)

Black & Willoughby (1992)

CENTRAL PRESSURE VS. TIME FOR HURRICANE ALLEN, 1980: LARGE FLUCTUATIONS LARGELY DUE TO EYEWALL REPLACEMENT CYCLES

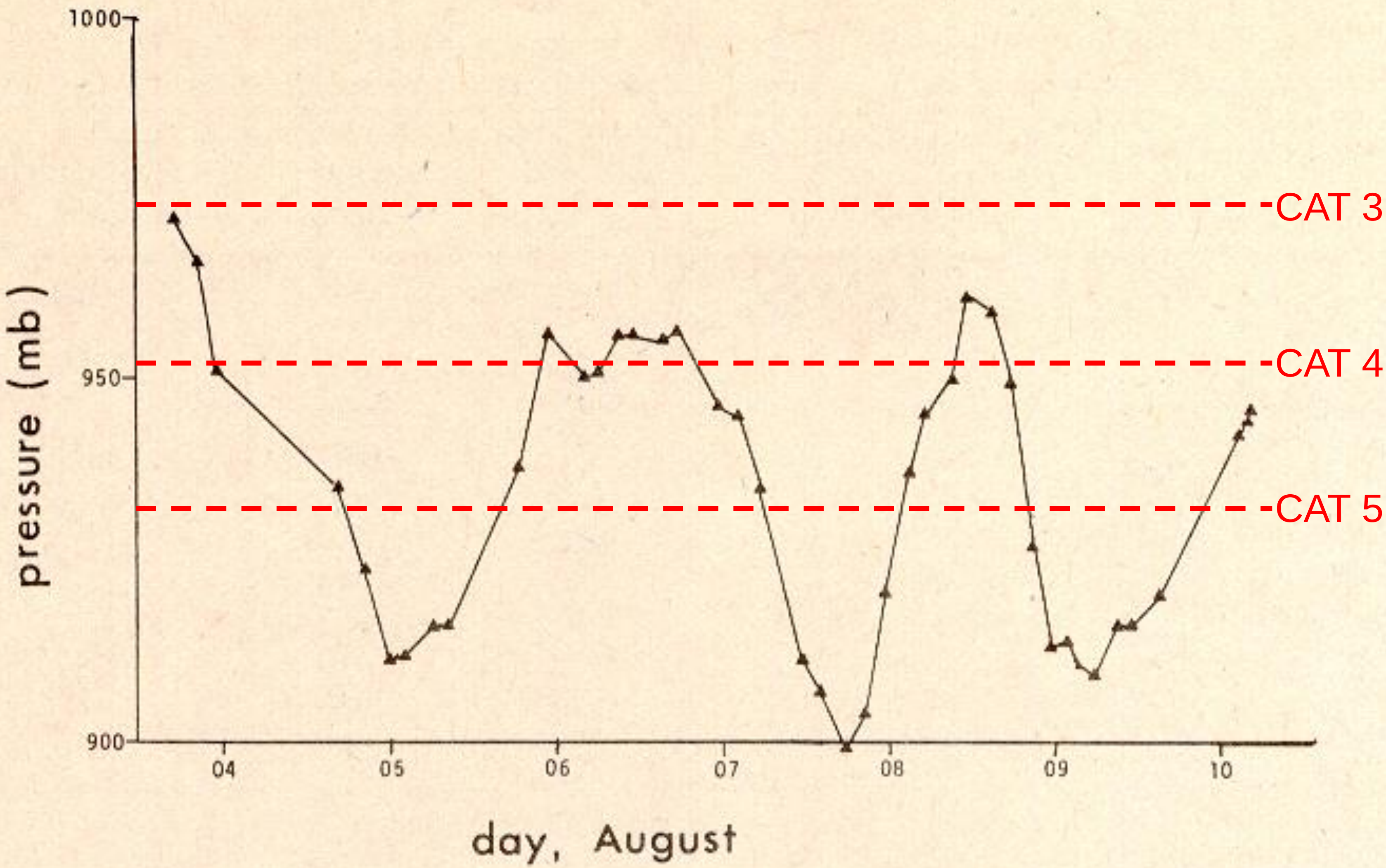
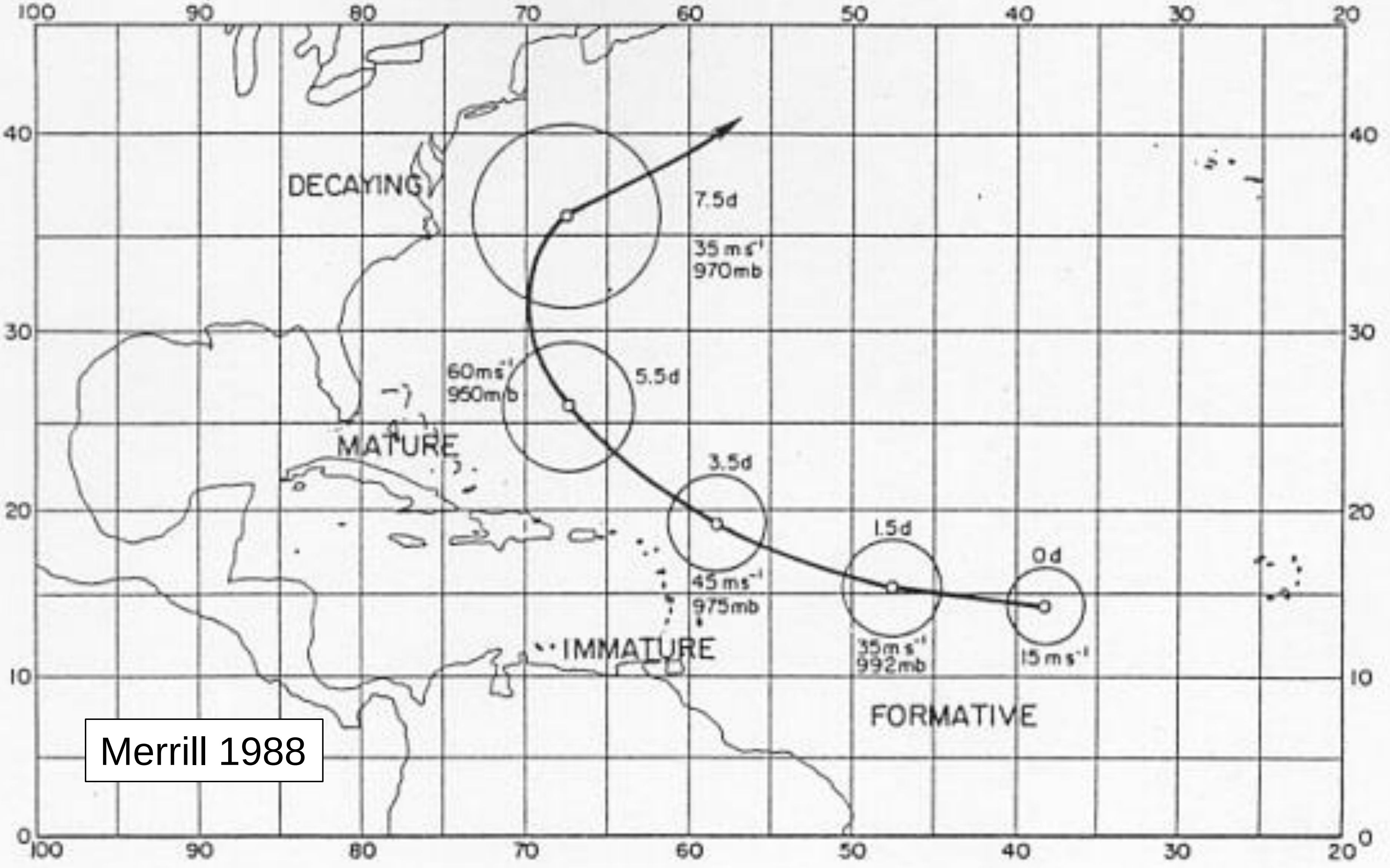


FIG. 3. Hurricane Allen: graph of minimum sea level pressure as a function of time, based on 44 aircraft observations.

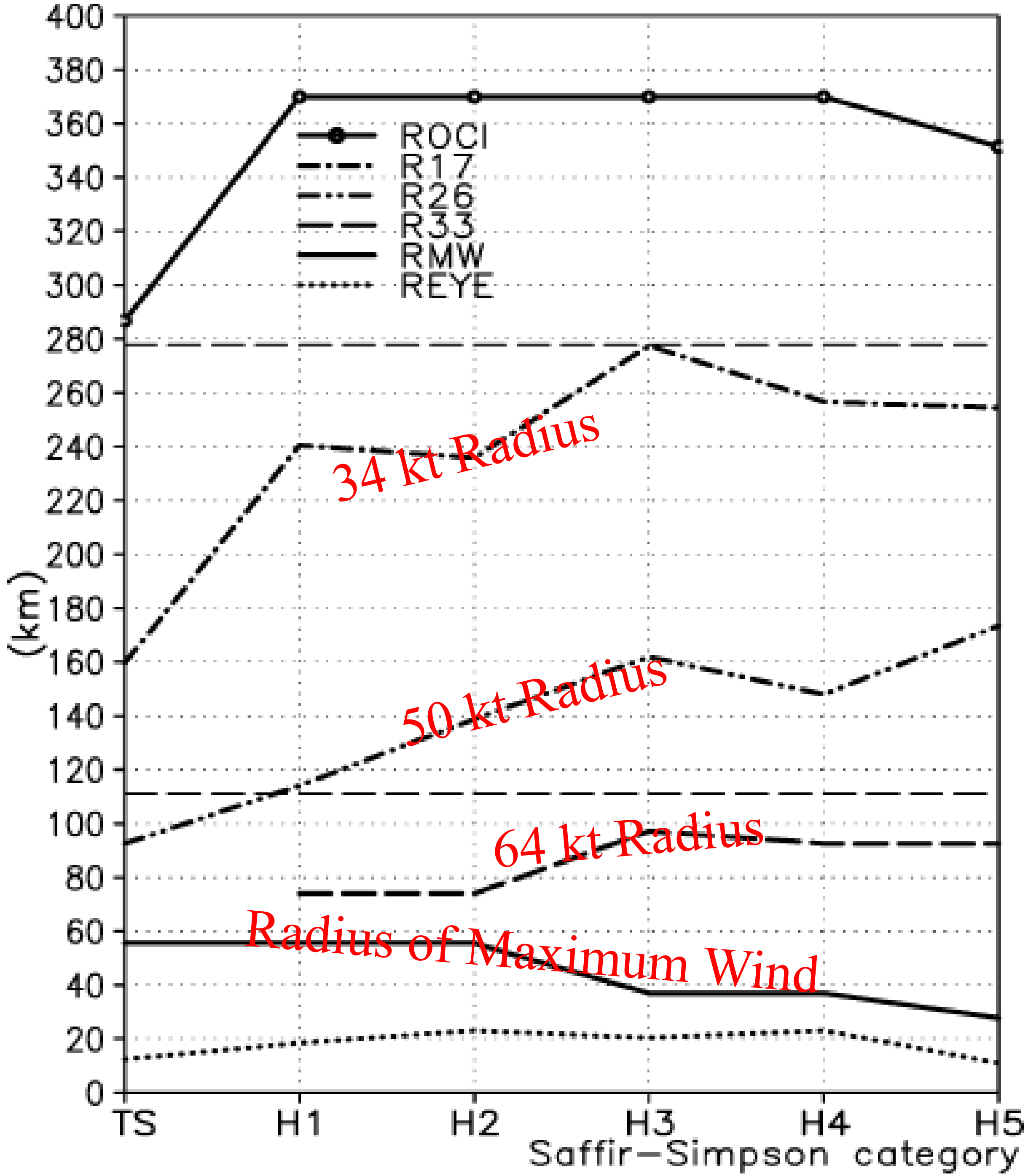
Natures Most Powerful Storm...

Size Matters!

Tropical Cyclone Size Lifecycle

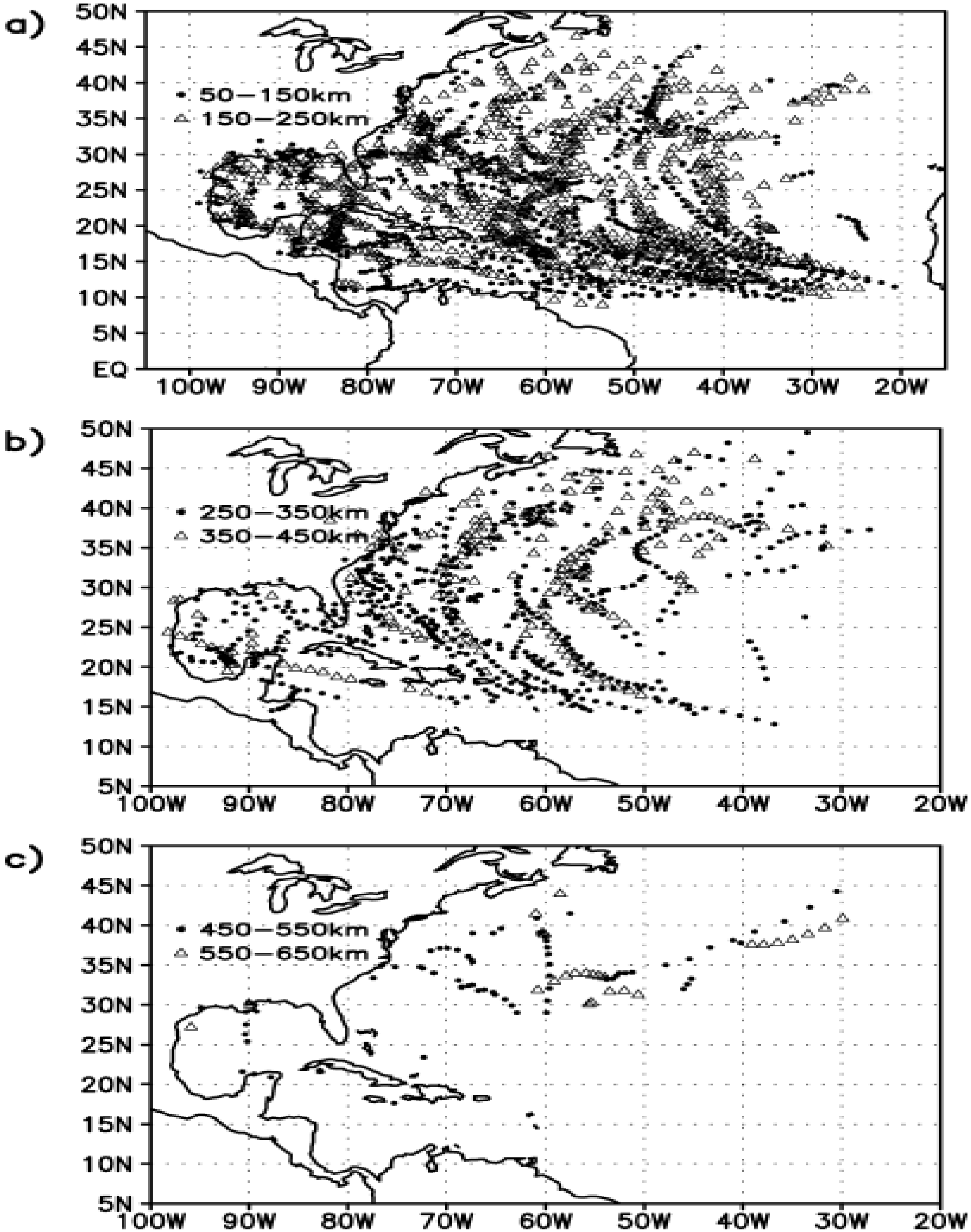


Merrill 1988



Size versus Intensity

Kimball and Mulekar (2004)



Radius of Tropical Storm Force Winds versus Location

Kimball and Mulekar (2004)

Tropical Cyclones versus Extratropical Cyclones

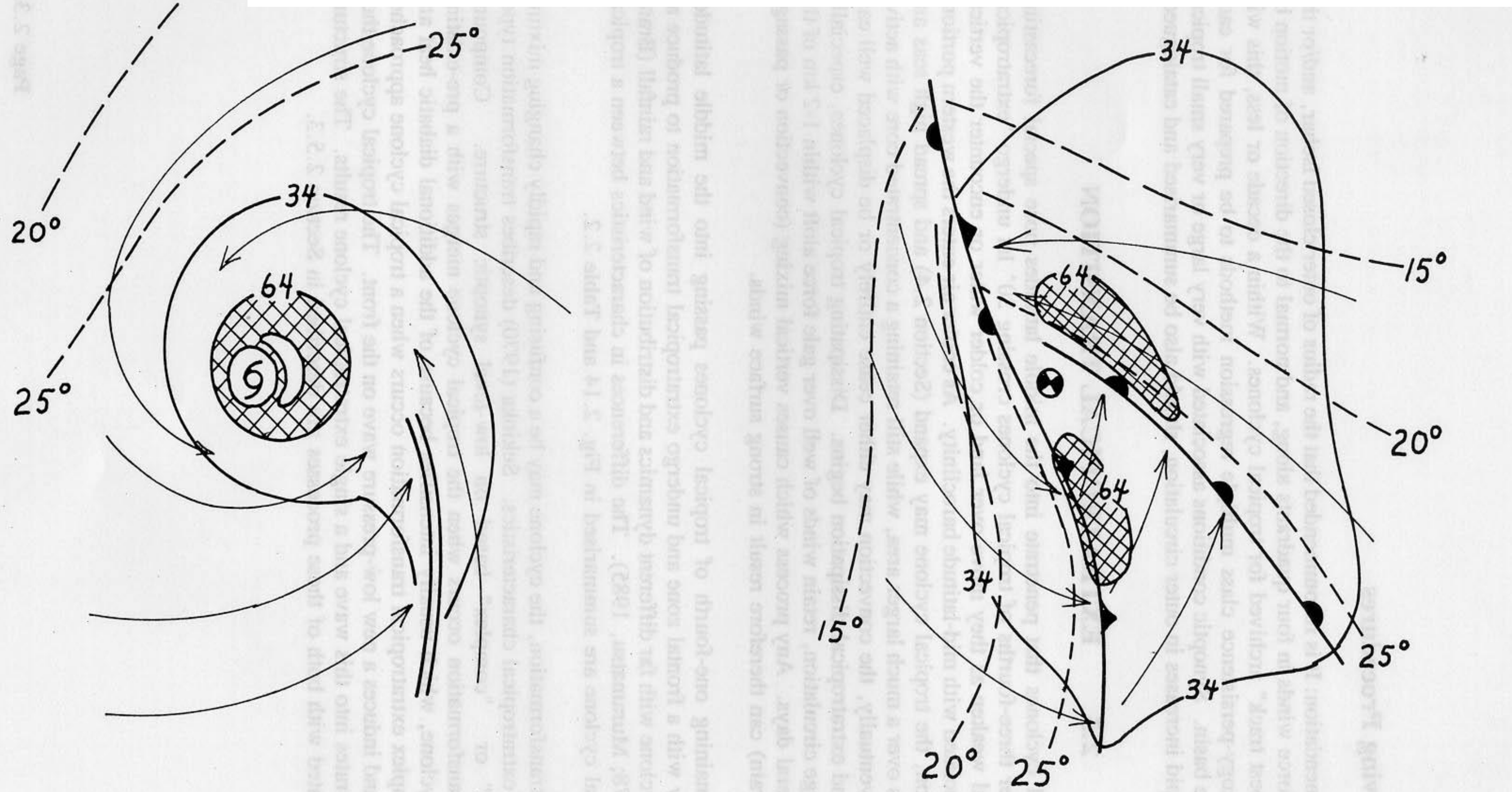
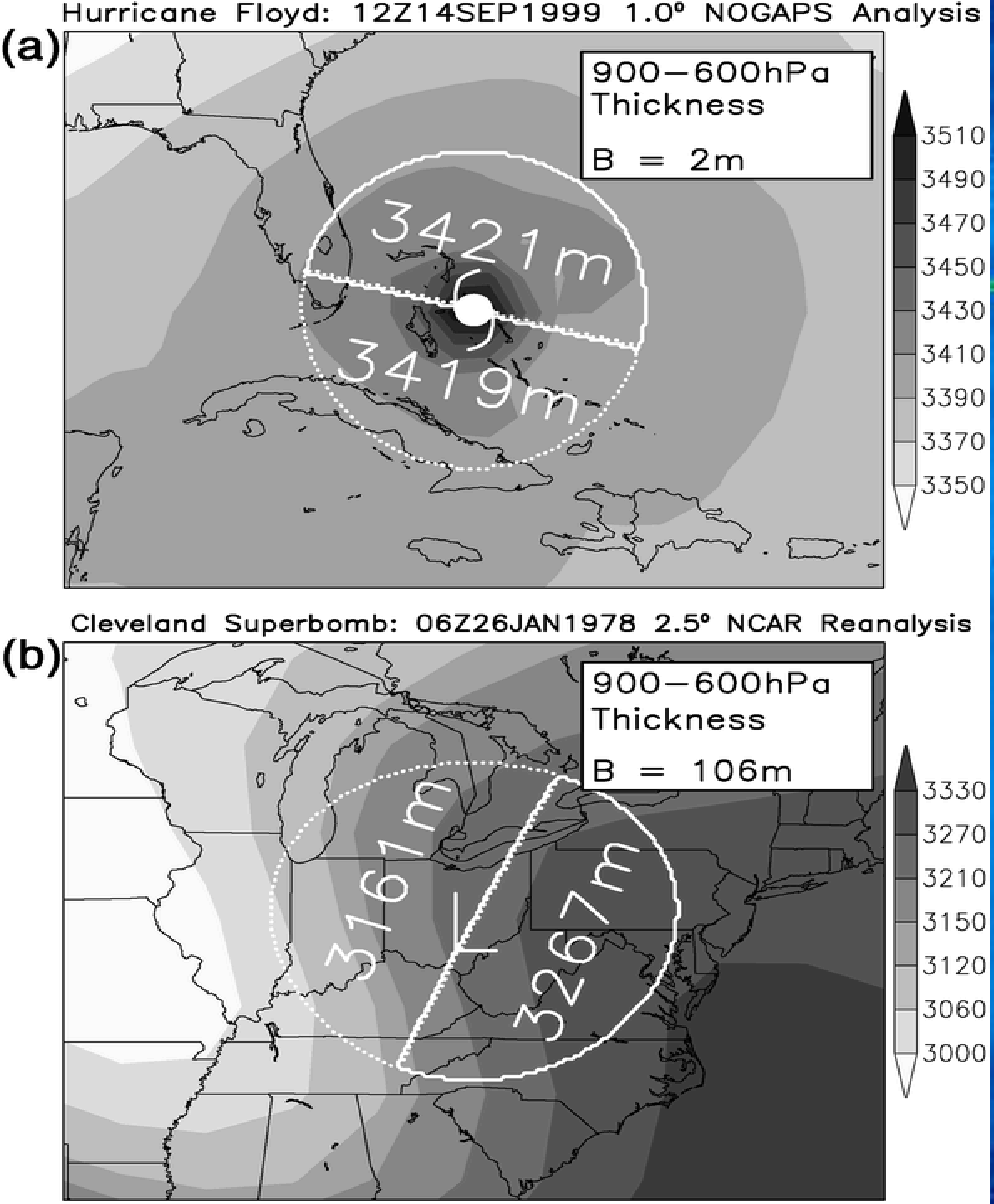


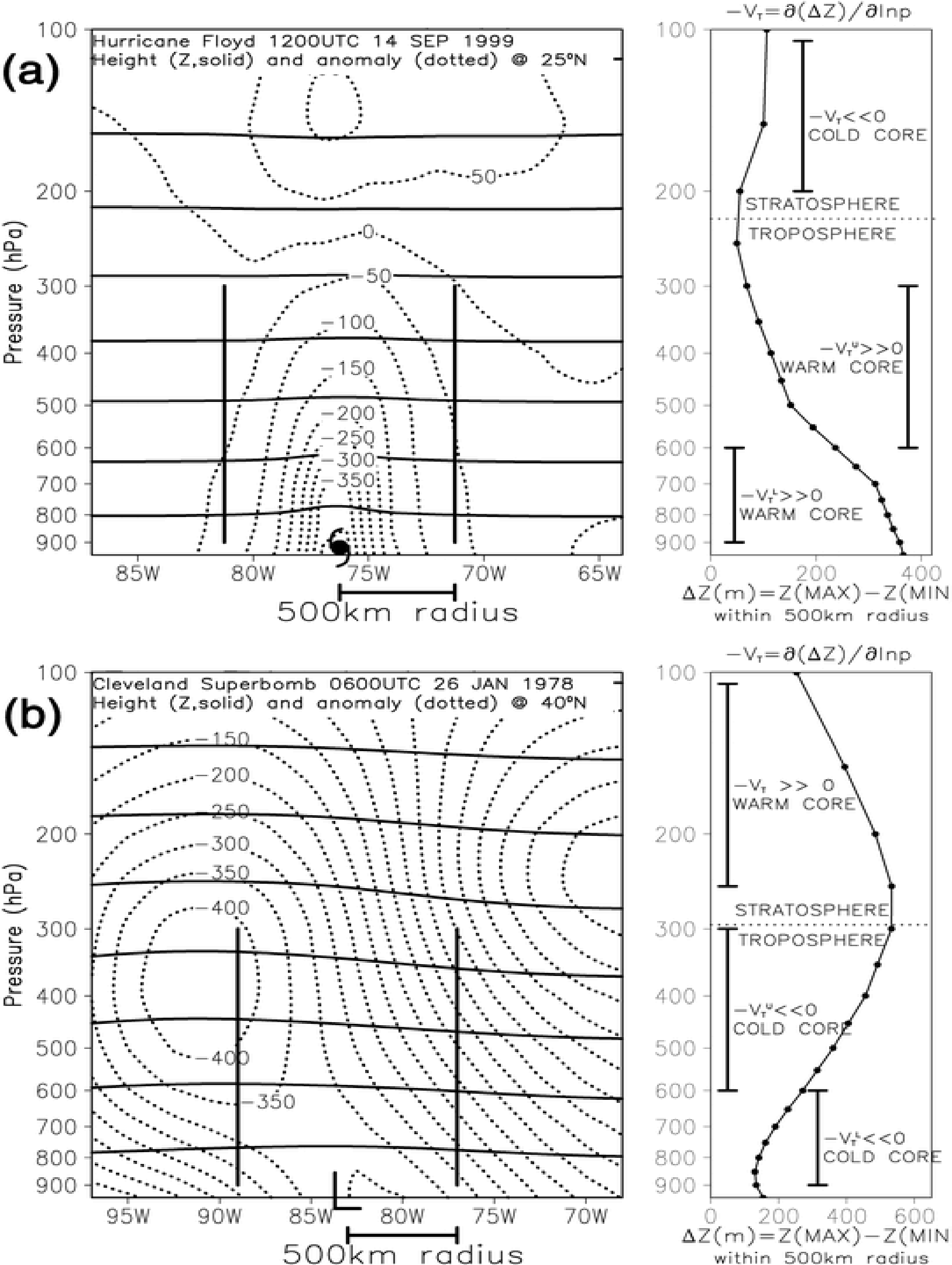
Figure 2.14: Schematic of the surface temperature and wind fields associated with a tropical cyclone (left) and an autumn marine extratropical cyclone, such as might result from an extratropical transformation of the tropical cyclone (right), adapted from Mook (1955). The structure of the extratropical cyclone and the sizes of both cyclone types can vary considerably from this example.



Tropical Cyclone versus Extratropical Cyclone:

Non-frontal versus frontal

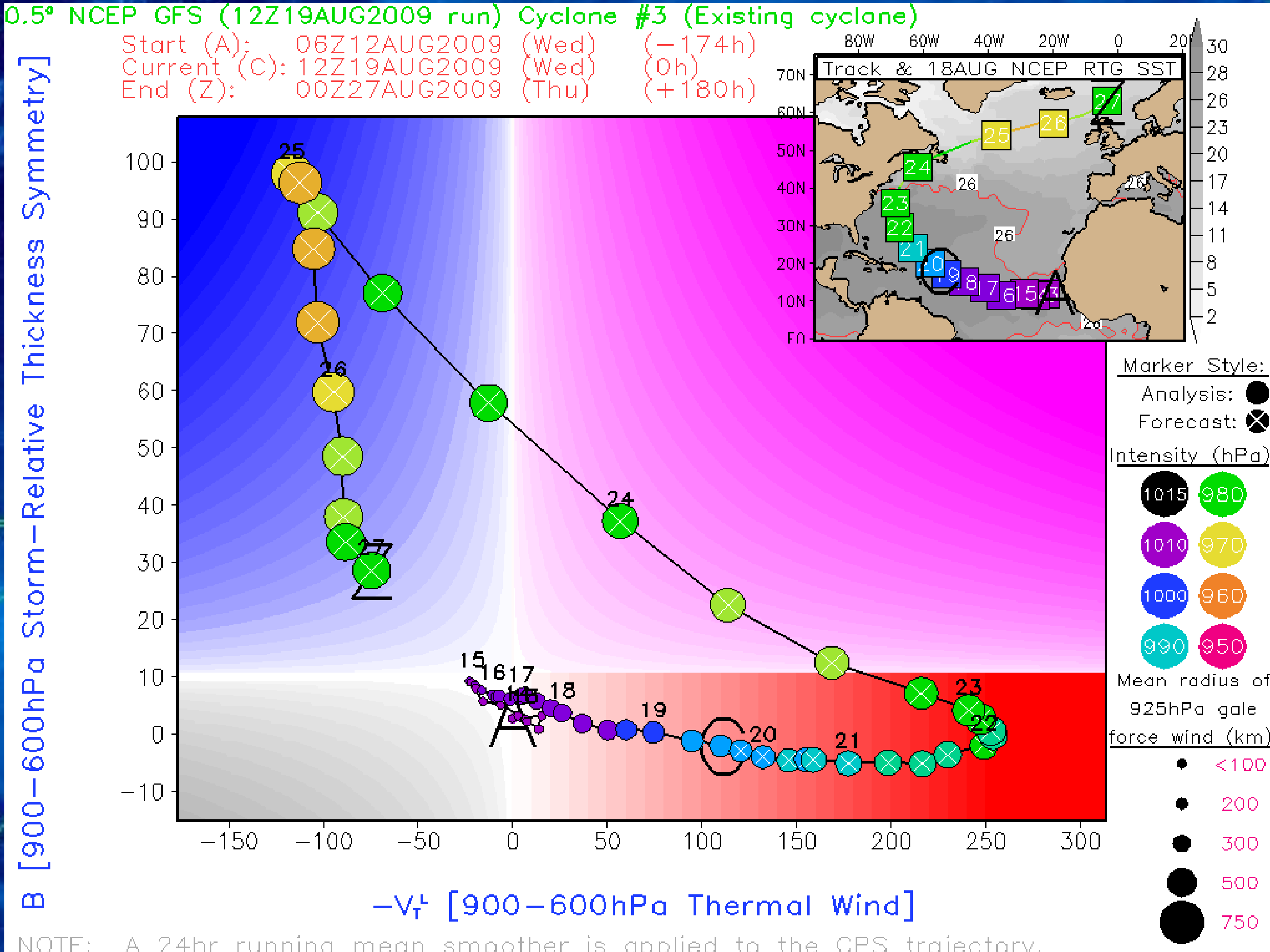
(Hart 2003)



Tropical Cyclone versus Extratropical Cyclone: "Warm" and "Cold" Cores

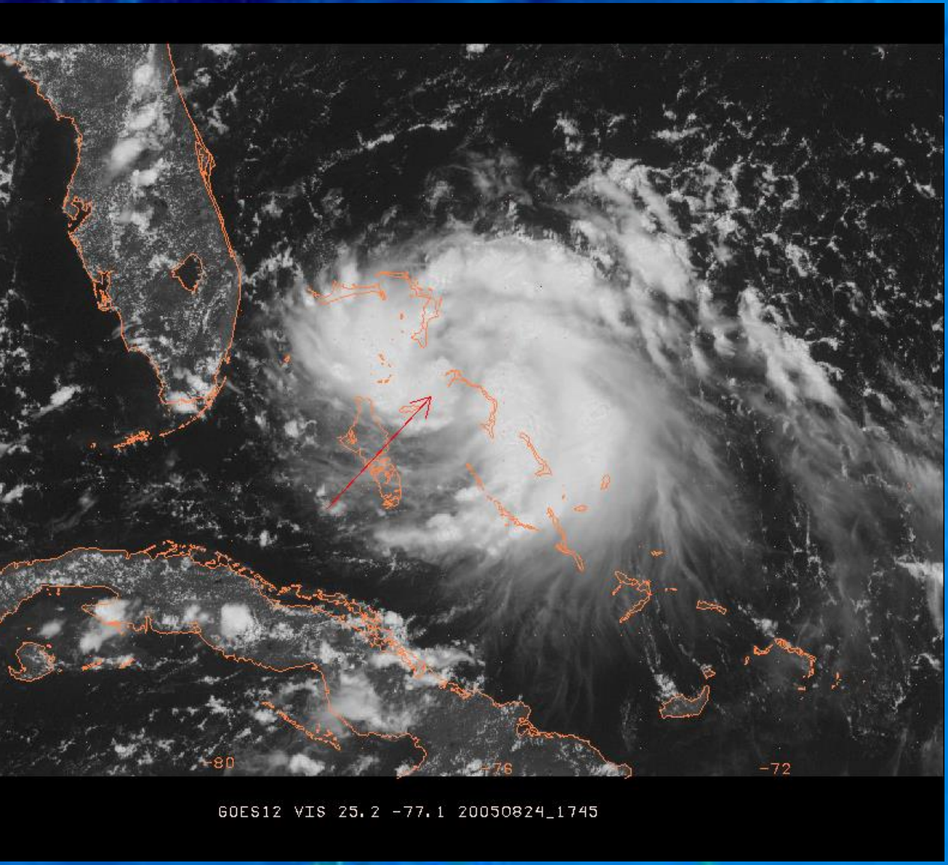
- (Hart 2003)

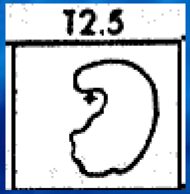
Cyclone Phase Space for Bill



Diagnosing Size…

Katrina August 24





Dvorak is very useful for position and intensity, but does NOT provide size estimates.

Tropical Cyclone Wind Radii

How big is the storm?

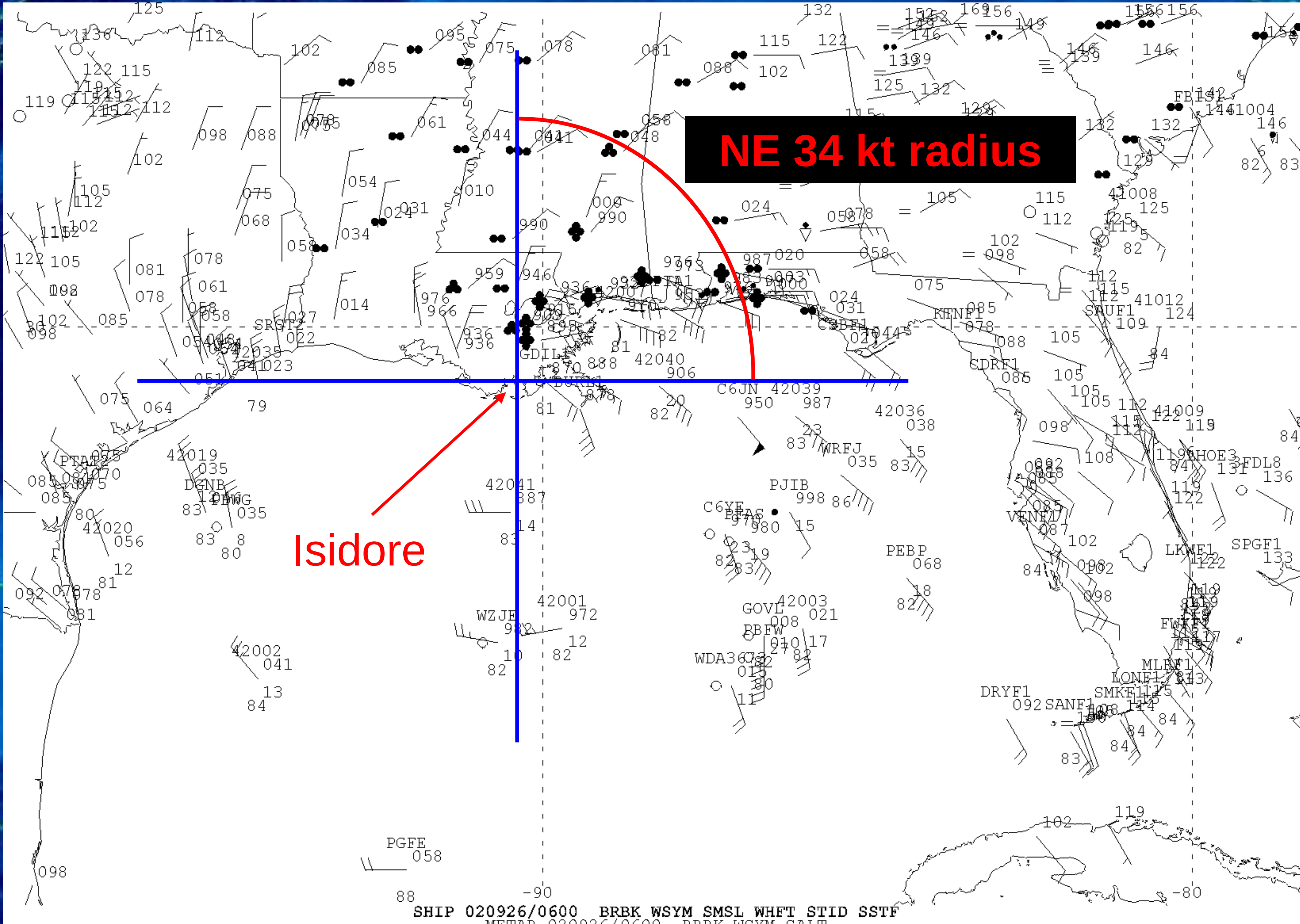
-NHC estimates cyclone "size" via wind radii in four quadrants

radii represent the largest distance from center in particular quadrant

leads to an inherent over-estimate of radii, especially near land

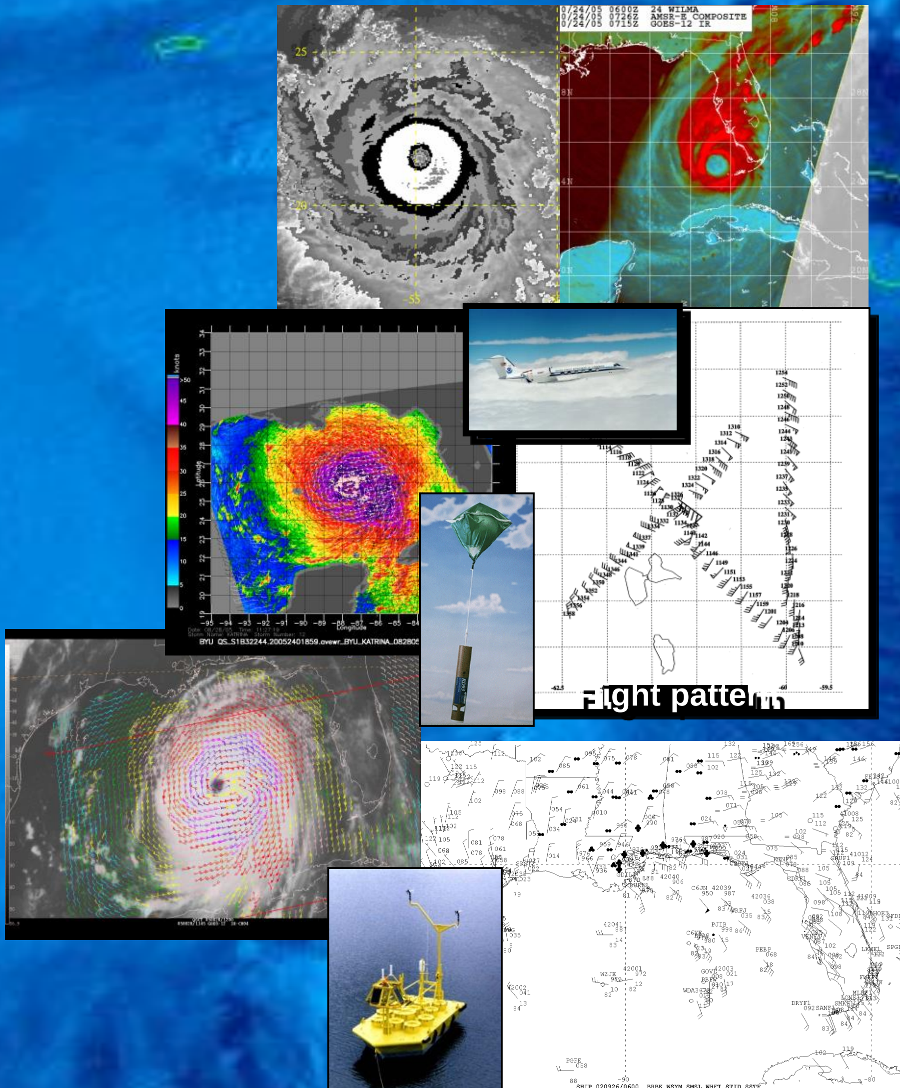
•Wind radius = Largest distance from the center of the tropical cyclone of a particular sustained surface wind speed threshold (e.g., 34, 50, 64 kt) somewhere in a particular quadrant (NE, SE, SW, NW) surrounding the center and associated with the circulation at a given point in time

Limitations of Four-Quadrant Radii

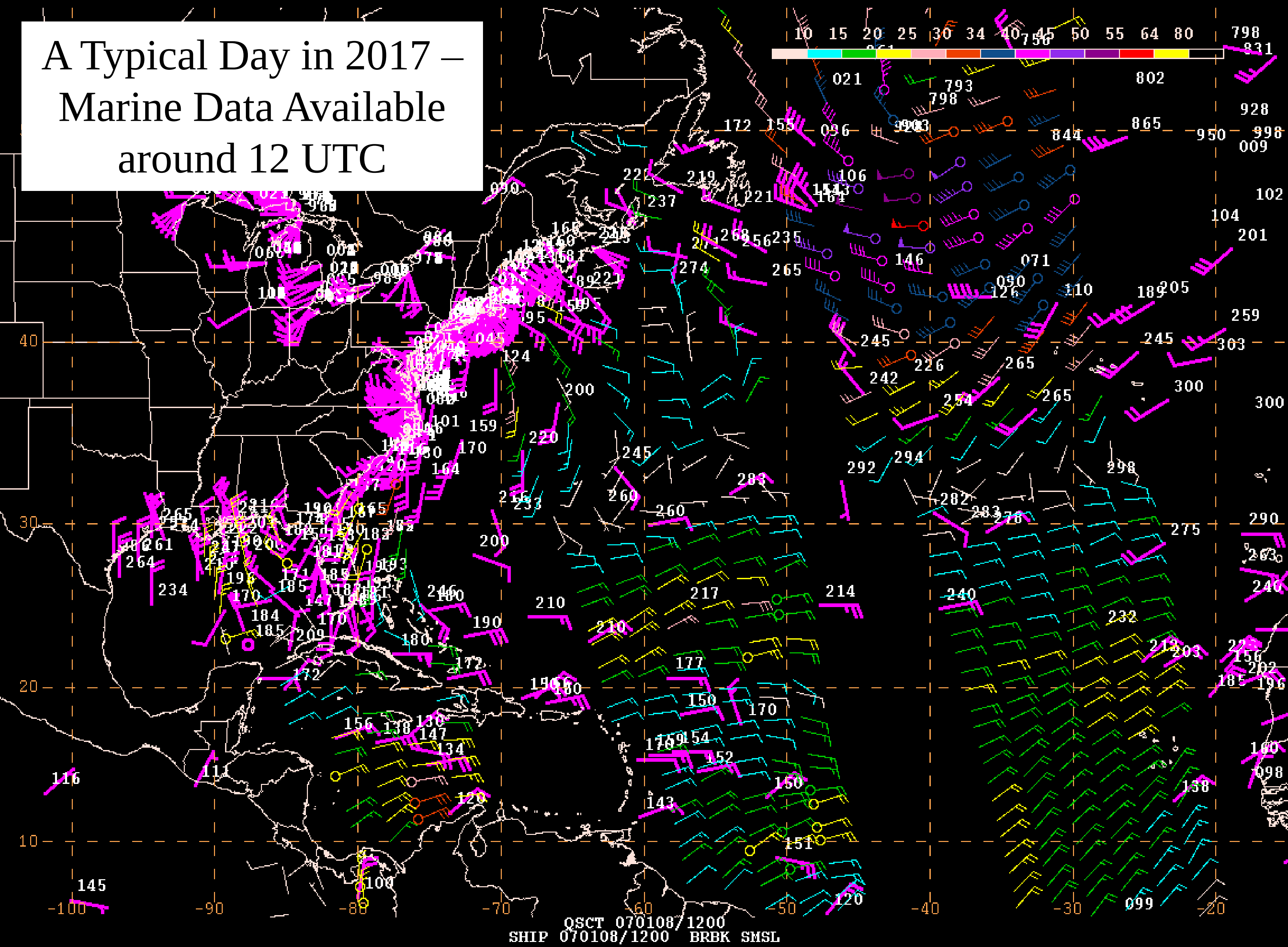


Data to Determine Tropical Cyclone Size

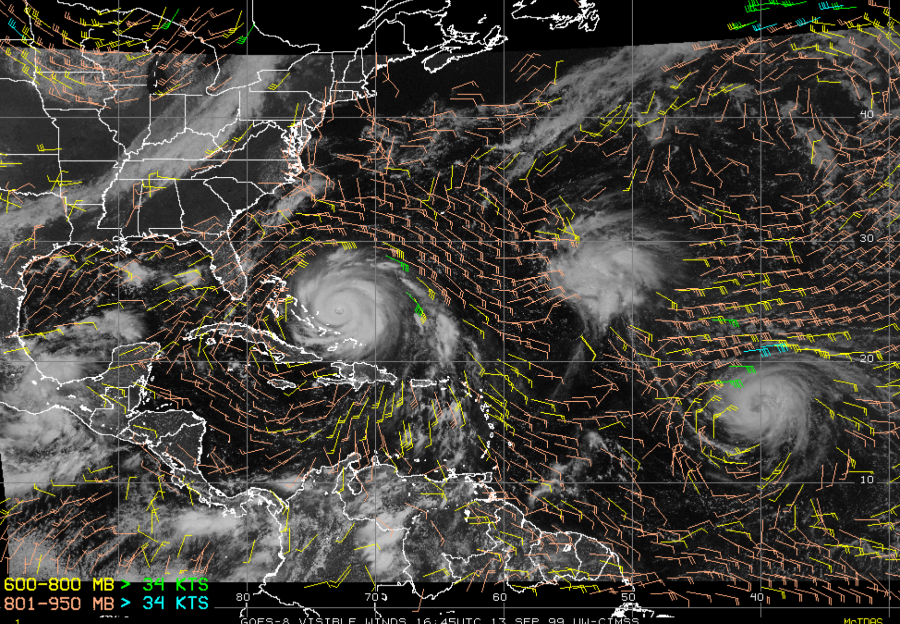
- Satellite Imagery
  - Geostationary
  - Polar-Orbiting
    - Microwave
    - Scatterometer
- Reconnaissance Data
  - Dropsondes
  - SFMR (Stepped Frequency Microwave Radiometer)
- Surface Observations



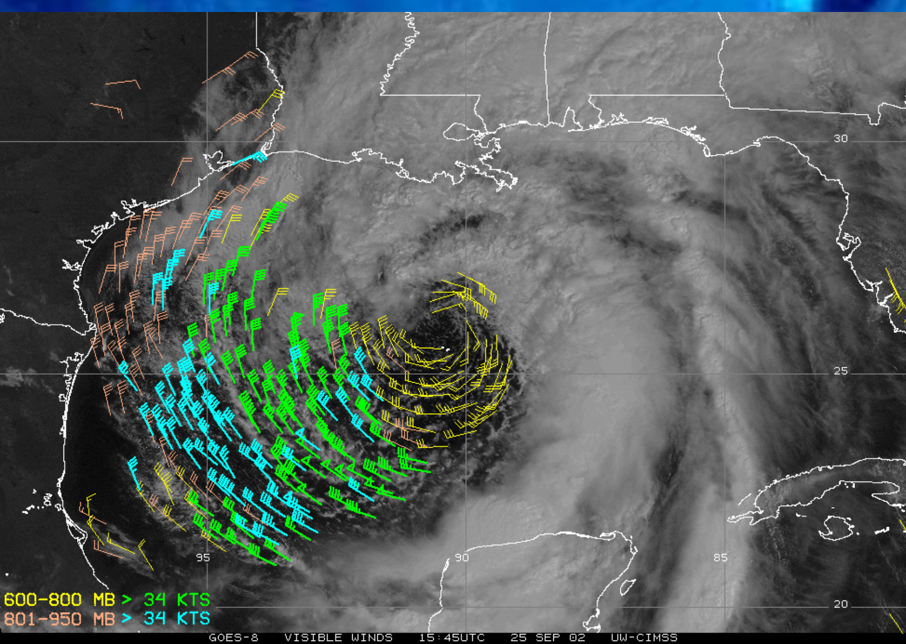
A Typical Day in 2017 – Marine Data Available around 12 UTC



Geostationary satellite – Low-level cloud drift winds

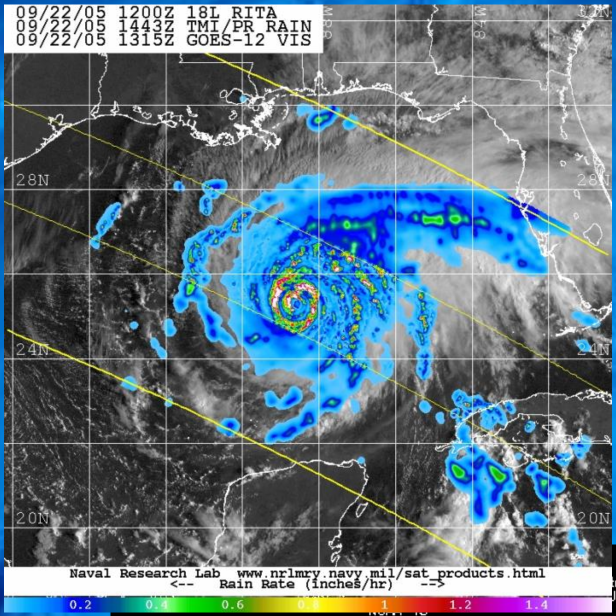


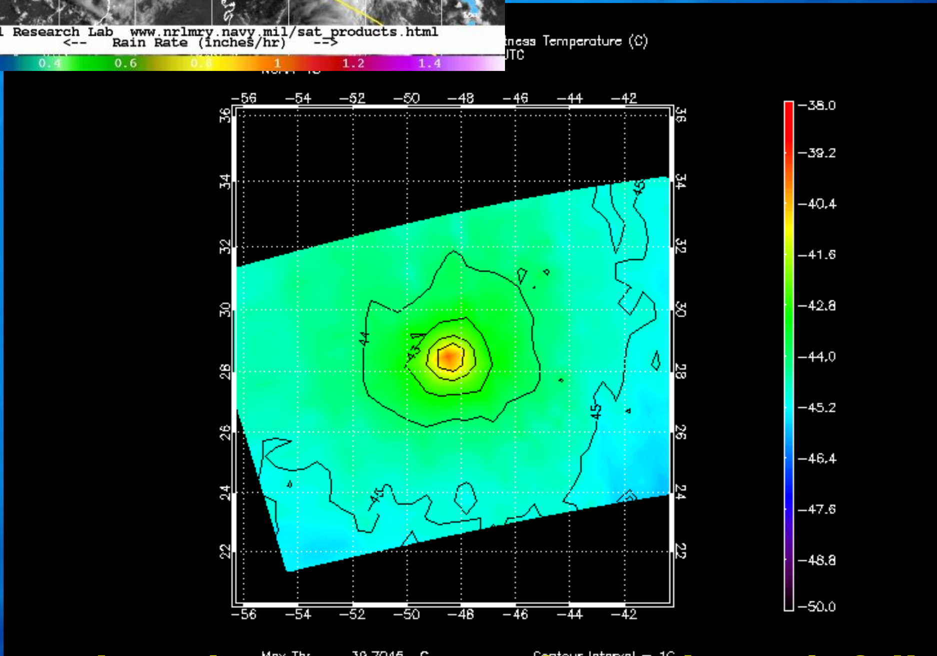
Satellite winds for nearby environment and TC size



Low-Earth-Orbit Satellites

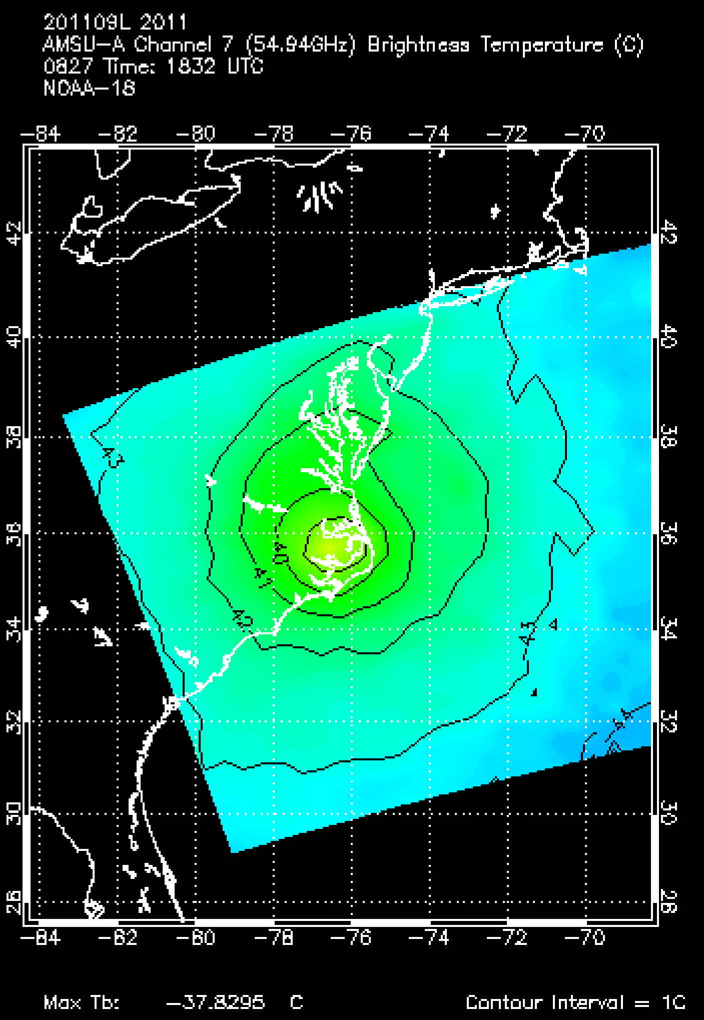
- **Carry microwave imagers and sounders that can see through cloud tops and reveal the structures underneath**
- **Gaps in instrument coverage between orbits, which causes irregular sampling of cyclones**

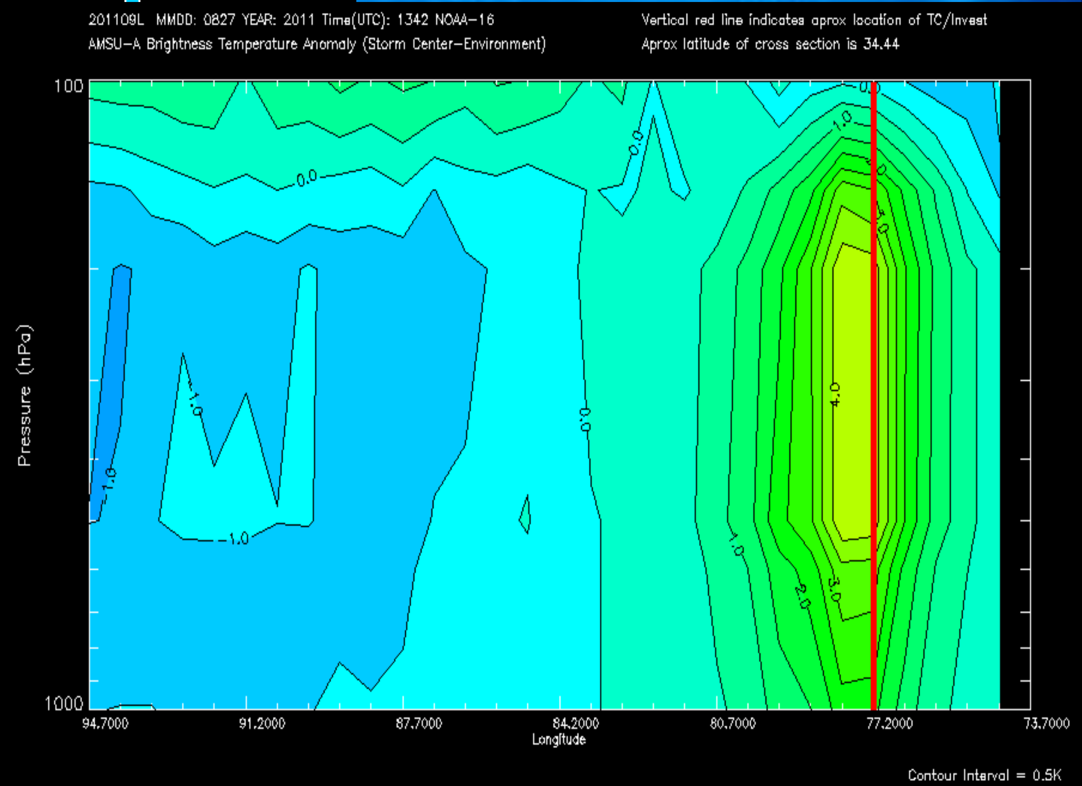




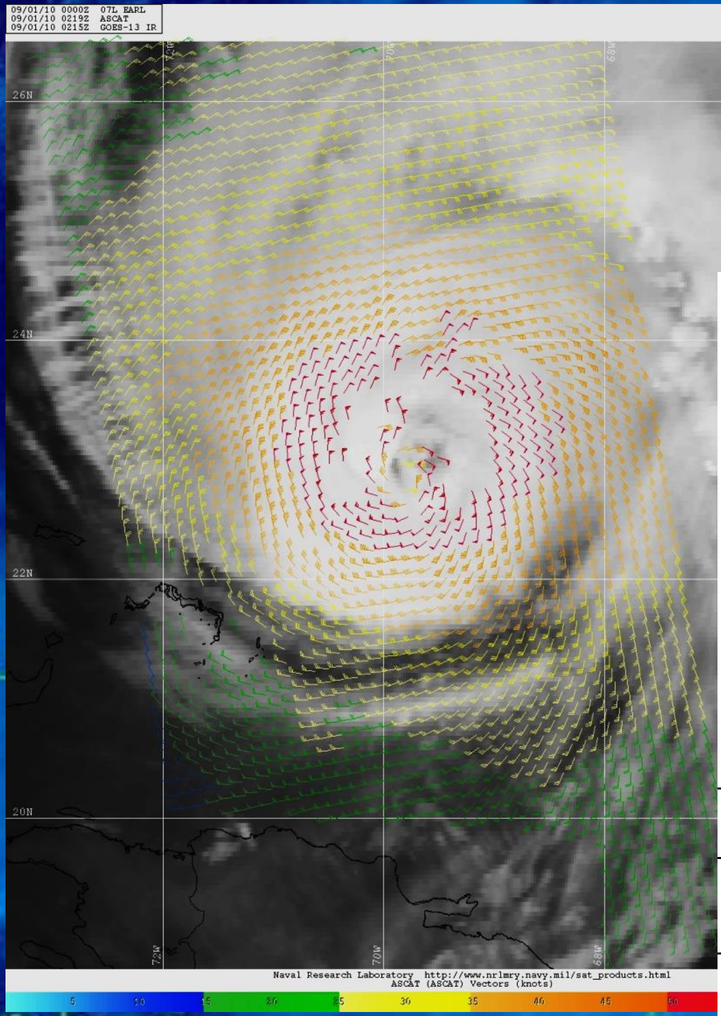
Microwave location, structure, intensity, rainfall

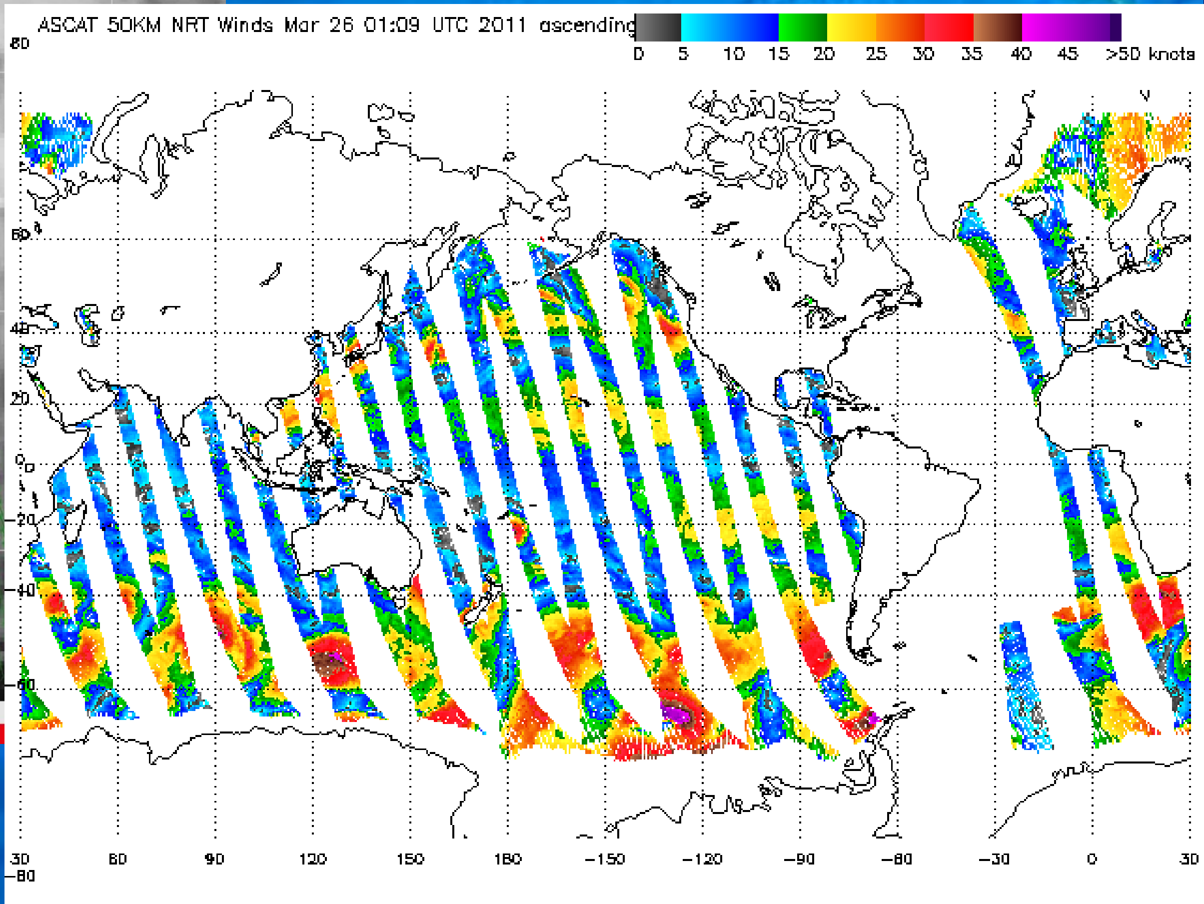
Advanced Microwave Sounding Unit



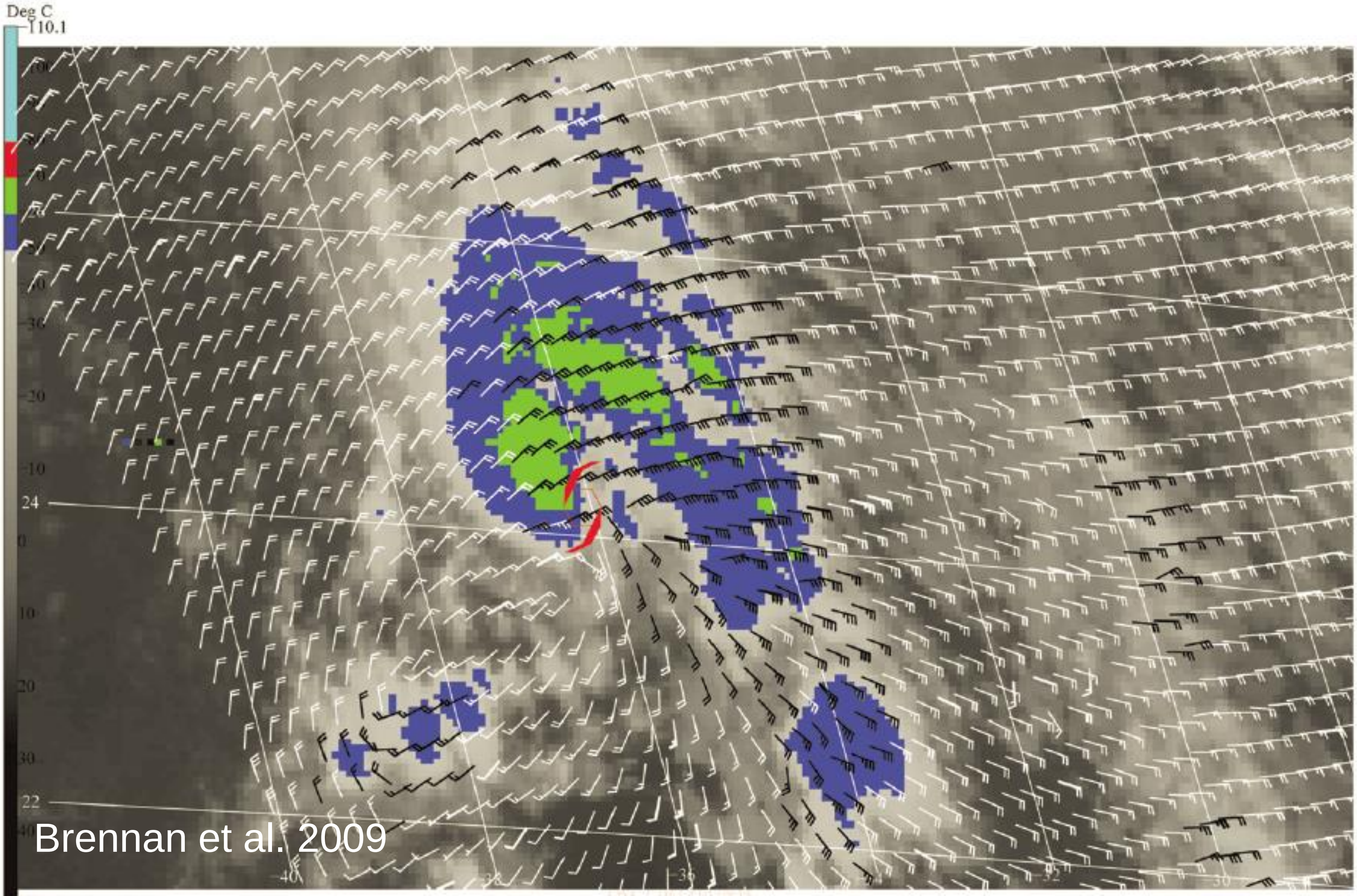


ASCAT (Advanced Scatterometer) – Surface Winds from a Polar-orbiting satellite





Rain Contamination with scatterometer data

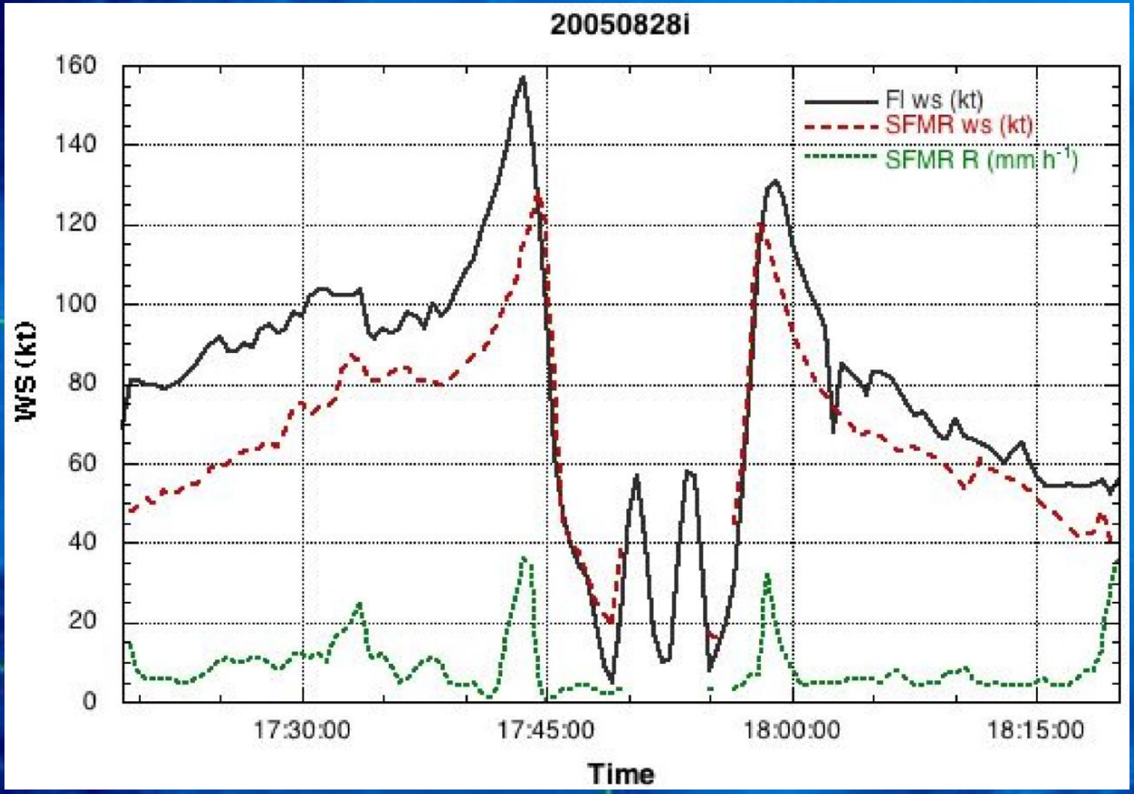


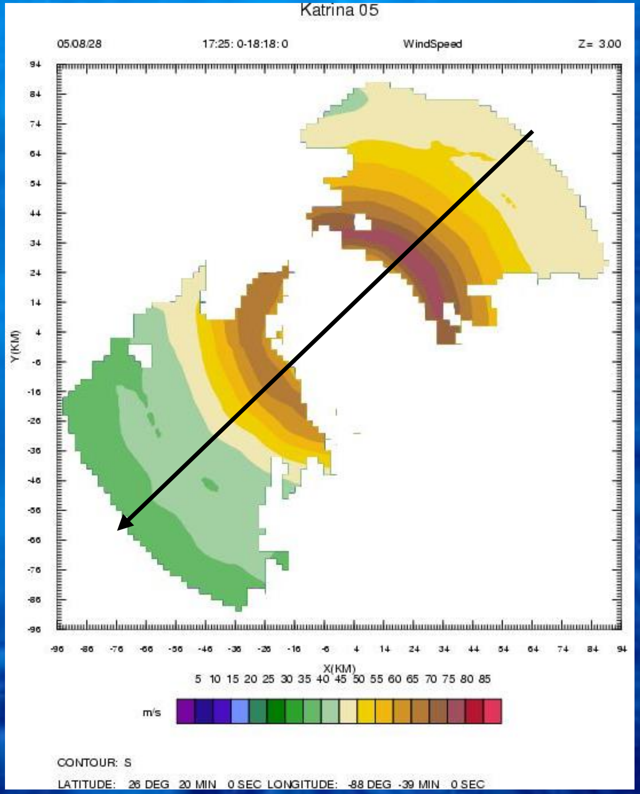
Brennan et al. 2009

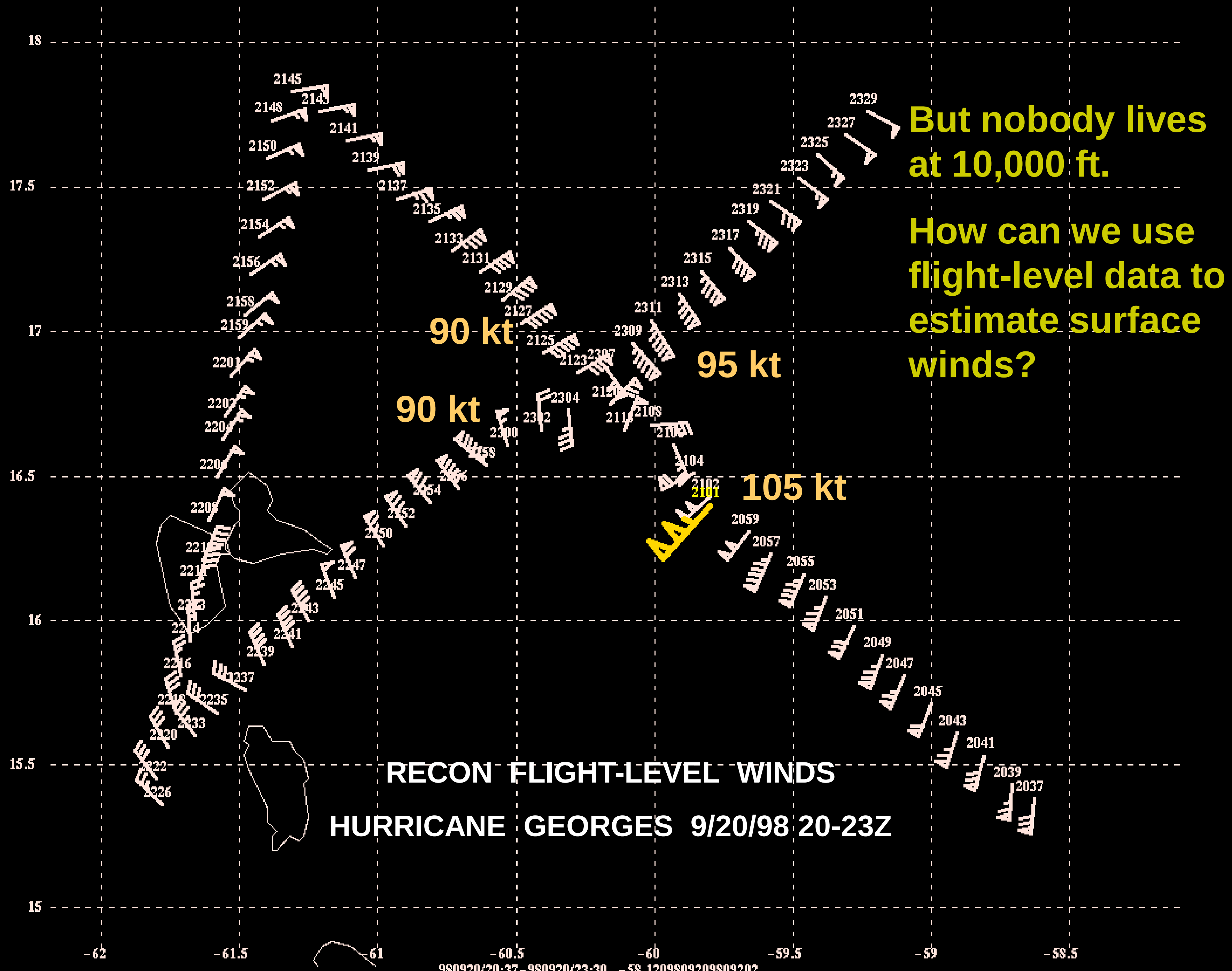
Hurricane Reconnaissance and Surveillance Aircraft (10 Air Force C-130s, 2 NOAA P3s, 1 NOAA G-IV)

Primary Aircraft Data

- Winds (along the aircraft track and dropsondes)
- Surface pressures (extrapolated and dropsonde)
- Surface winds from the Stepped Frequency Microwave Radiometer
- Aircraft Doppler Radar winds (from the P-3's)





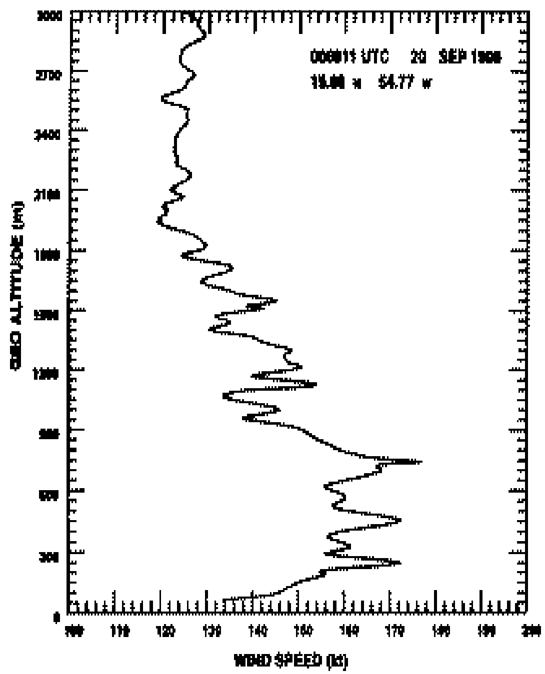


But nobody lives at 10,000 ft.
How can we use flight-level data to estimate surface winds?
90 kt
90 kt
95 kt
105 kt
RECON FLIGHT-LEVEL WINDS
HURRICANE GEORGES 9/20/98 20-23Z
18
17.5
17
16.5
16
15.5
15
-62
-61.5
-61
-60.5
-60
-59.5
-59
-58.5
980920/20:37-980920/23:30 -58.1209809209809202

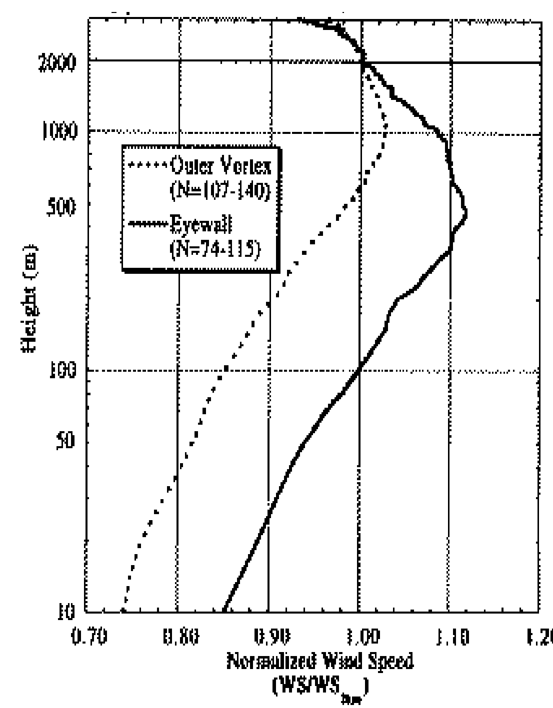
GPS Dropsondes

Measures the wind around and in hurricanes from the aircraft to the ocean's surface

Wind in Hurricane Georges



Mean Wind Profile



Franklin and Black (1999)

Surface wind analyses using flight level winds

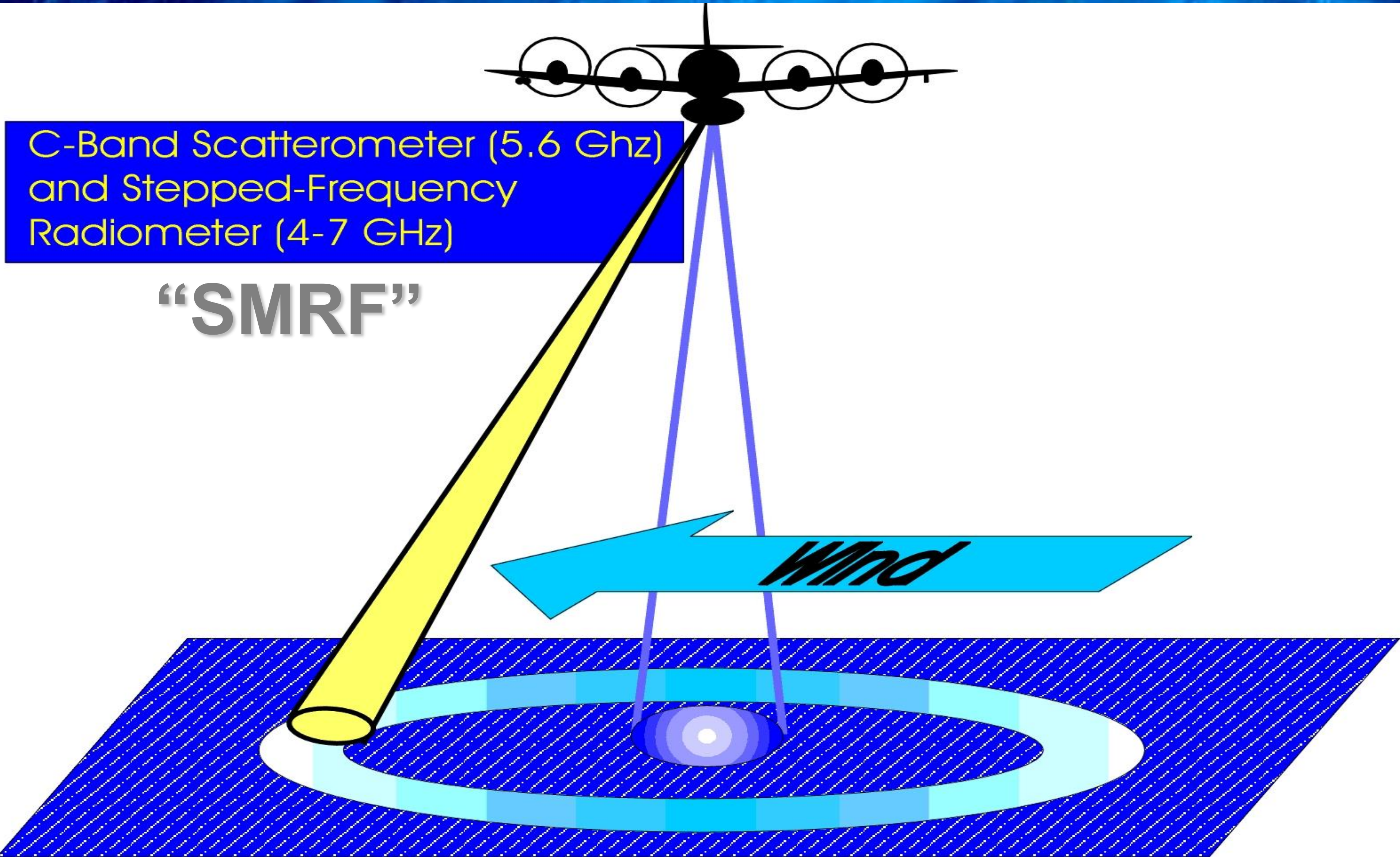
Table 2. Reduction factors and flight-level wind thresholds for determining wind radii from 700 mb data.

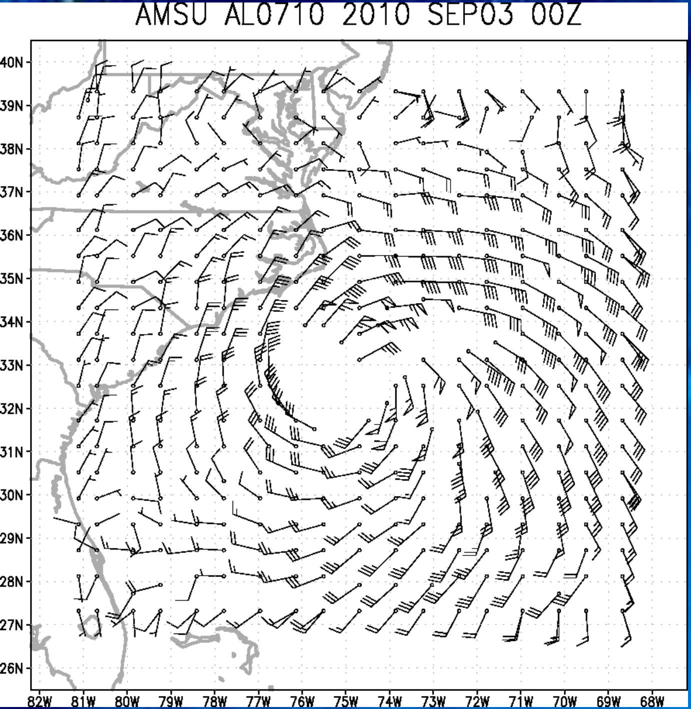
Sample	RF10m	FLW64 (kt)	FLW50 (kt)	FLW34 (kt)
Eyewall	0.90	70	55	-
Outer vortex	0.85	75	60	40
Outer vortex / Right quad	0.75	85	65	45
Outer vortex / Left quad	0.90	70	55	40

A large sample of GPS dropsondes in the inner core of TCs provides a way to determine surface wind radii from flight level winds via the mean wind profile

Franklin (2001)

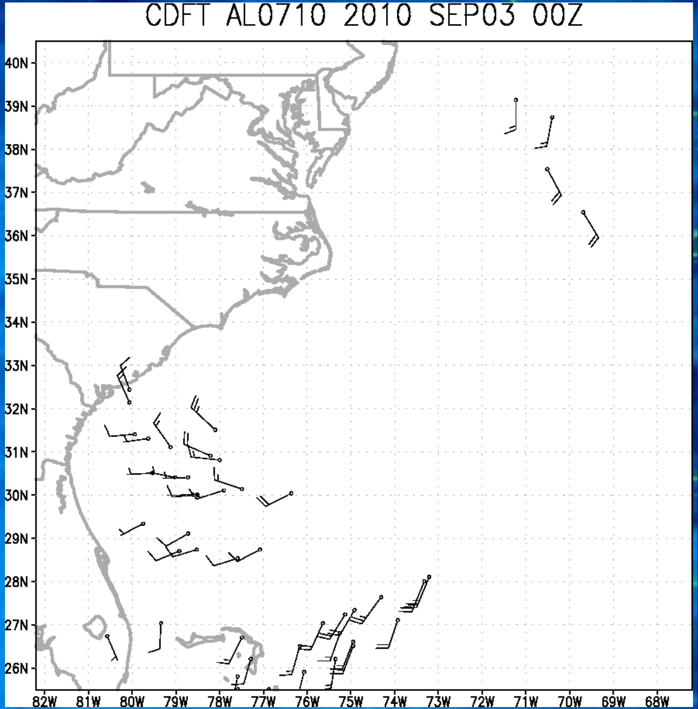
Remotely Sensed Surface Winds



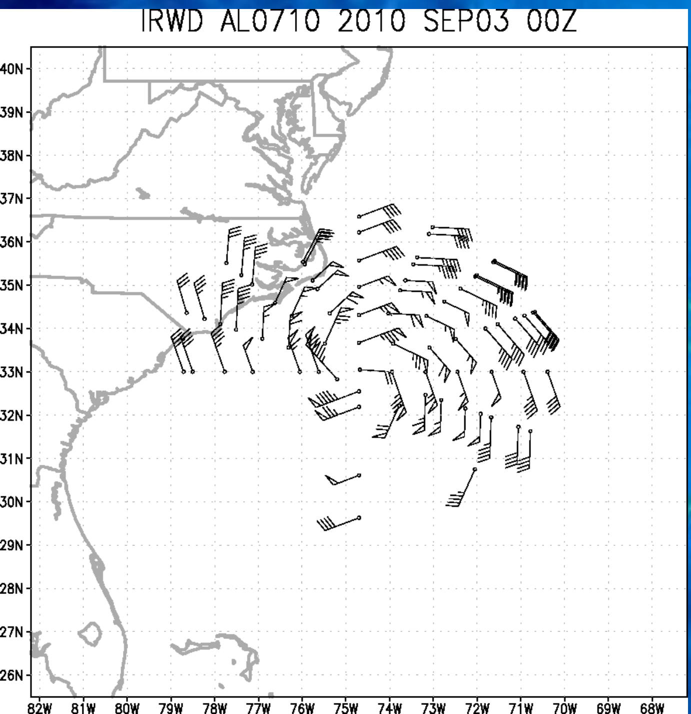


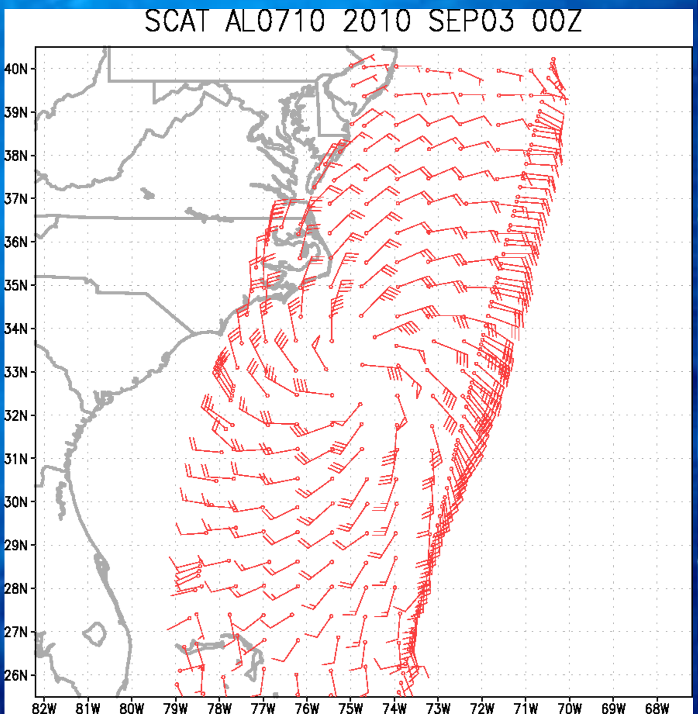
AMSU

Cloud Drift Winds



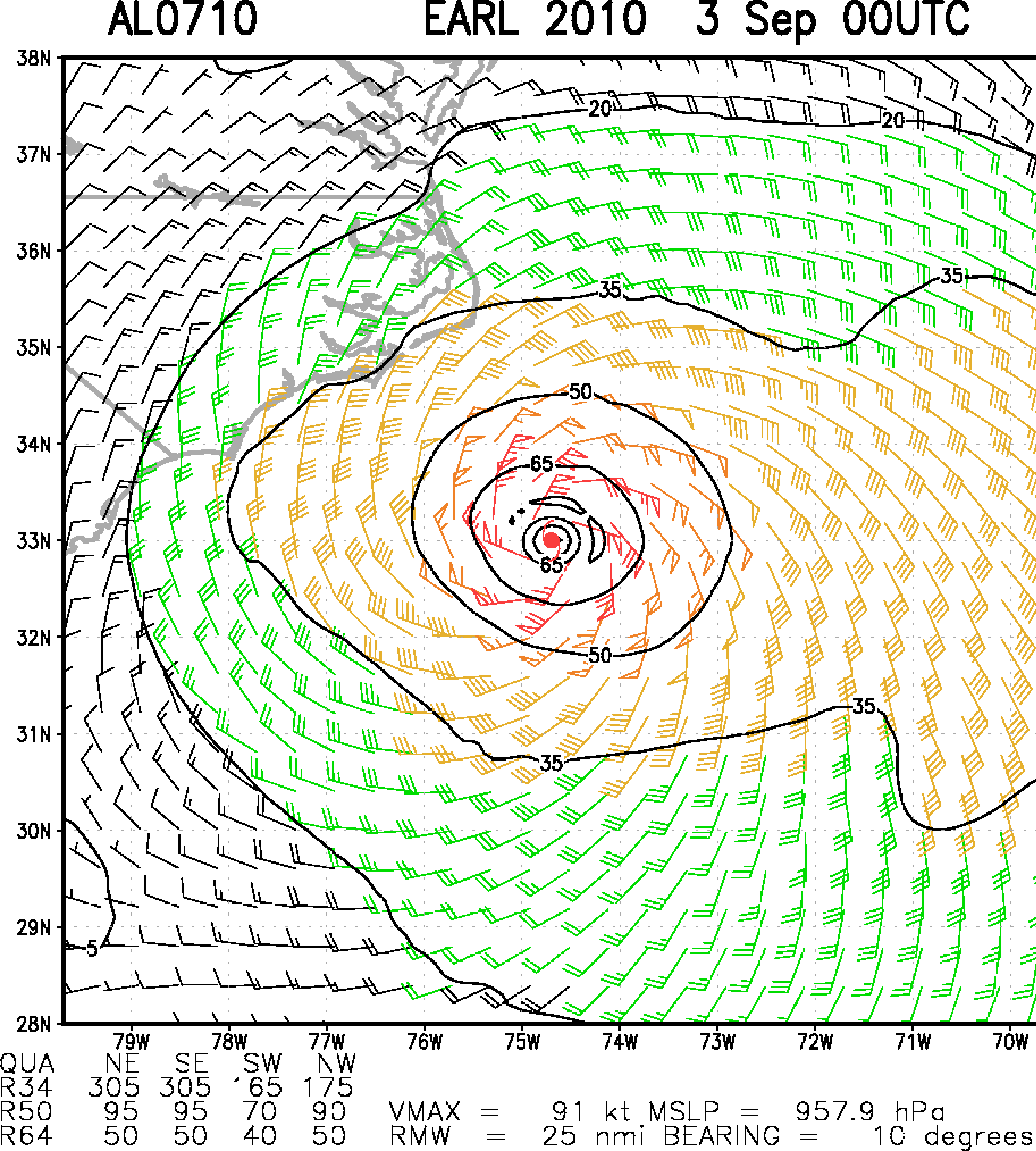
Multiplatform Satellite Surface Wind Analysis – CIRA





ASCAT

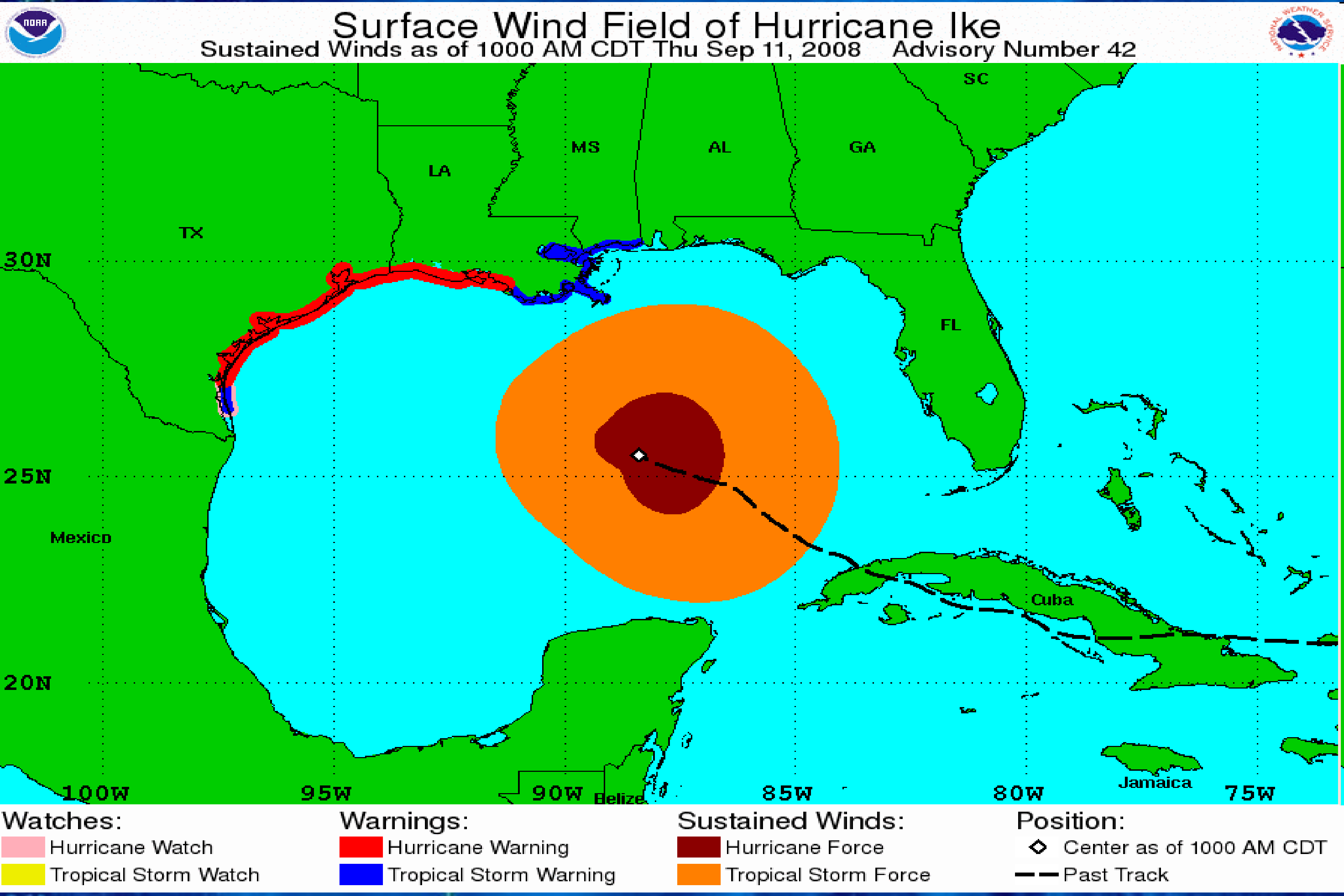
Infrared



Multiplatform Satellite Surface Wind Analysis – CIRA

Automated Surface Wind Field in Tropical Cyclones

Surface Wind Field



Wind Radii Forecast "Guidance"

- Empirical ideas
  - Is the storm strengthening or weakening?
  - Is persistence appropriate, or are conditions changing?
  - Is the storm becoming extratropical, causing wind field to expand?
  - Will all or part of the circulation be passing over land, such that radii could decrease?
  - Is the system accelerating, such that the storm could become more asymmetric?
- Guidance is essentially limited to climatology and persistence (CLIPER) models
- Occasionally can use dynamical models (not yet fully tested and verified for radii)

Hurricane Structure: Theory and Diagnosis

6 March, 2017

World Meteorological Organization Workshop

Chris Landsea

Chris.Landsea@noaa.gov

National Hurricane Center, Miami

TC Intensity Analysis Exercise

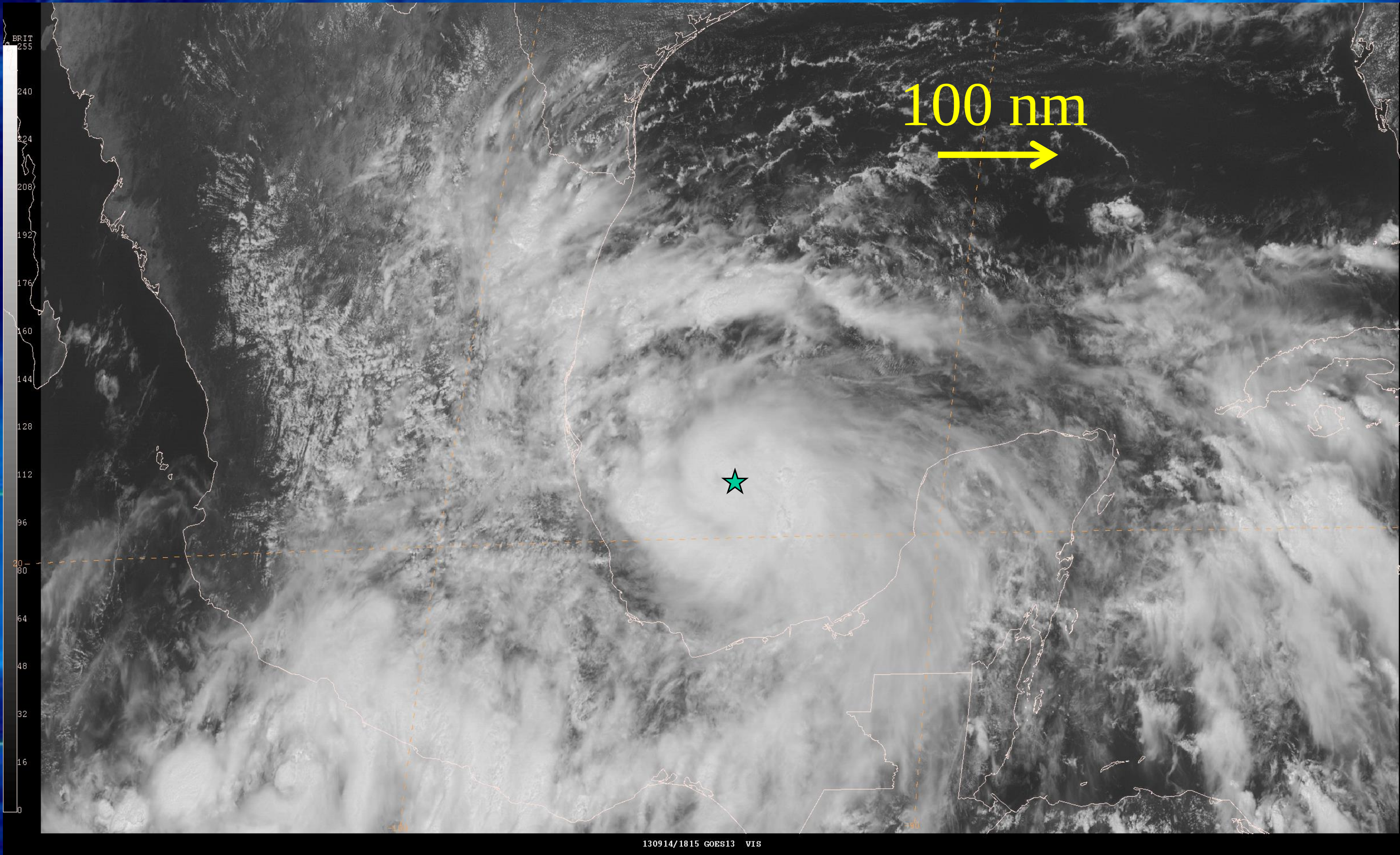
RA-IV Workshop, 7 March, 2016

What is the quadrant based (NE, SE, SW, NW) estimate of the farthest extent in nautical miles of 50 kt winds?

Answer will be in the format of:

50 kt (70 NE, 100 SE, 80 SW, 30 NW)

Ingrid – Sep. 14th, 18Z – 65 kt Intensity
How big is it?



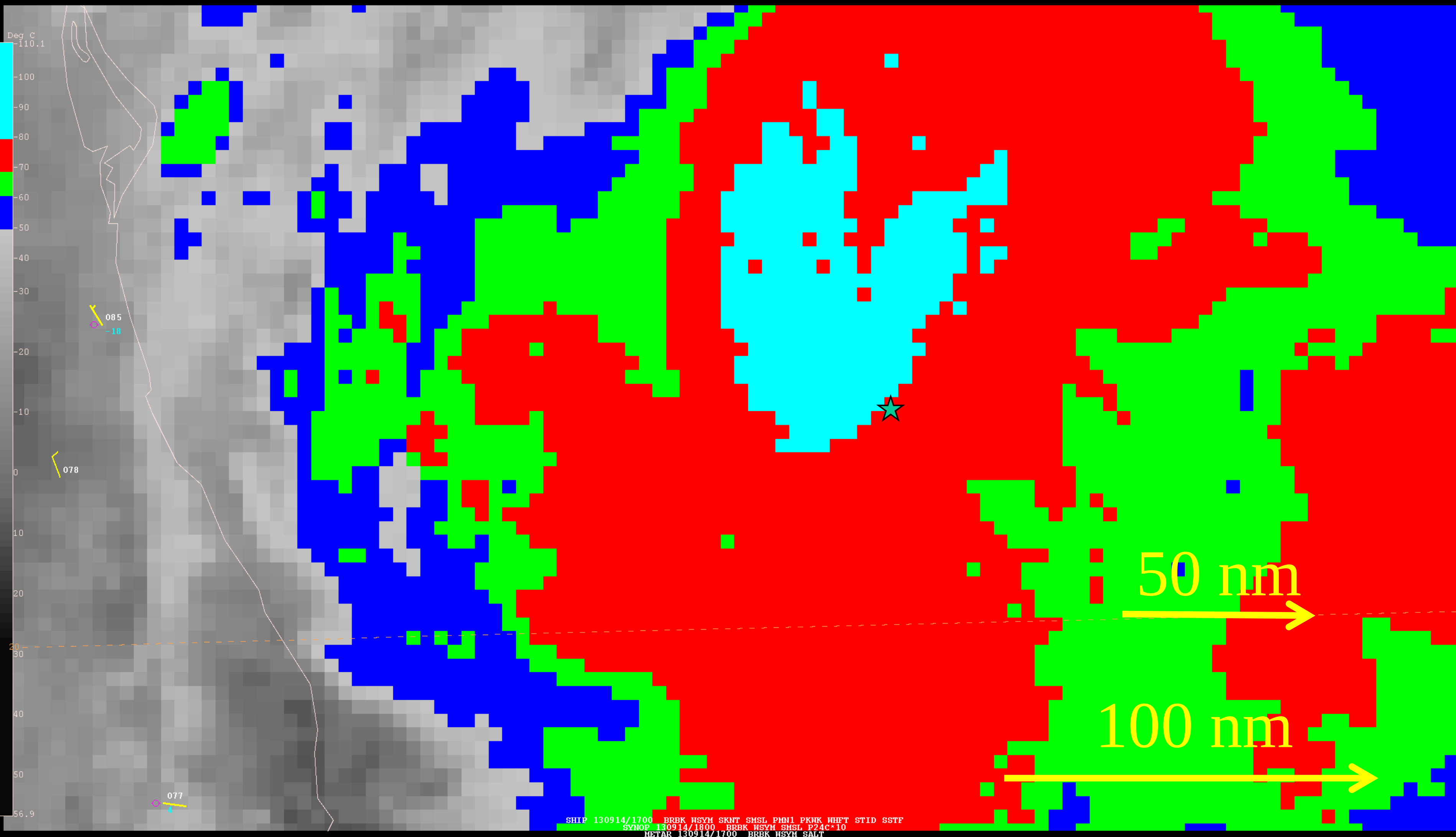
Ingrid

Sep. 14th, 18Z

65 kt intensity

CIRA AMSU:

50 kt (49 NE, 52 SE, 44 SW, 42 NW)

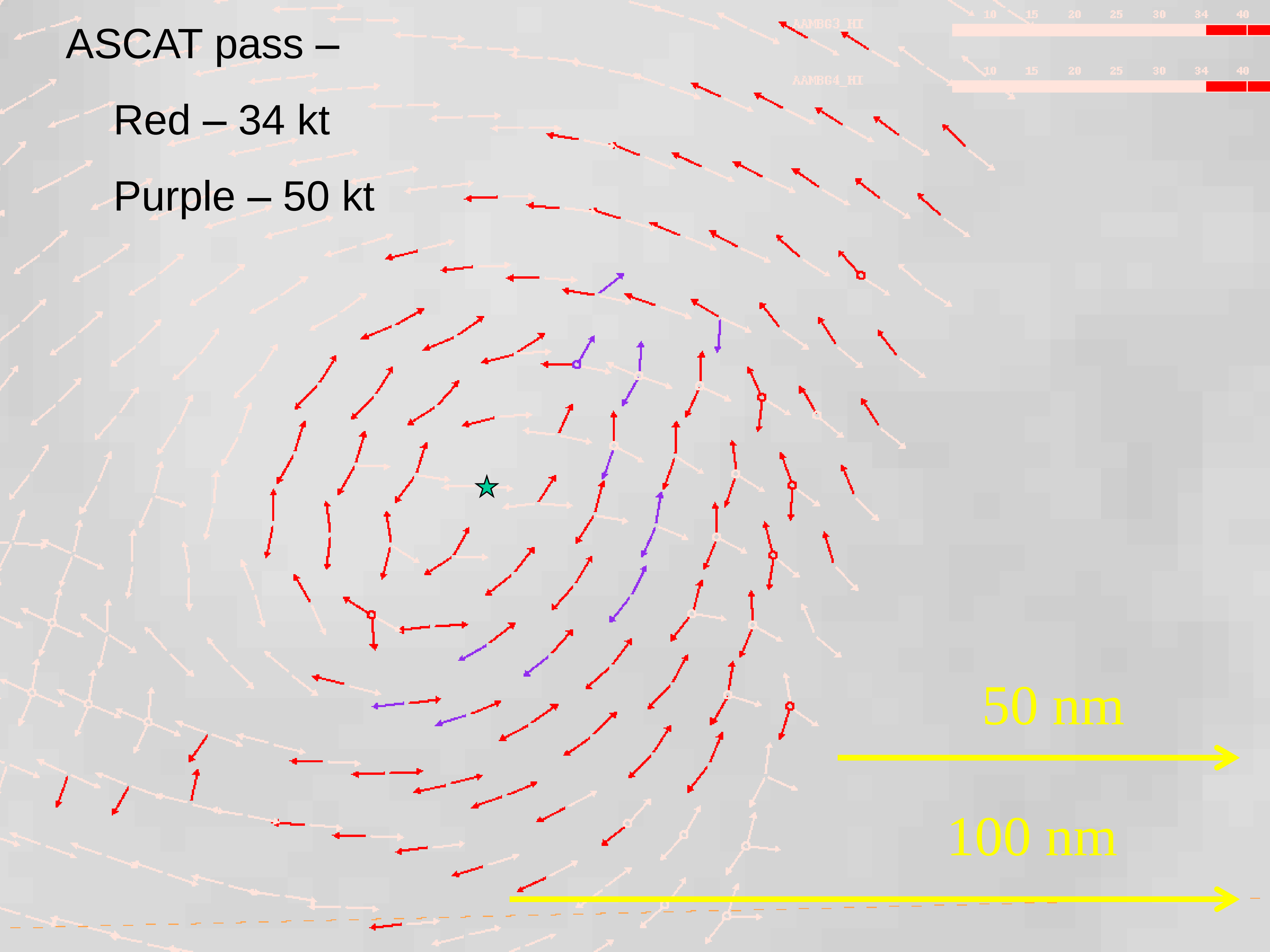


Ingrid – Sep. 14th, 18Z – 65 kt intensity

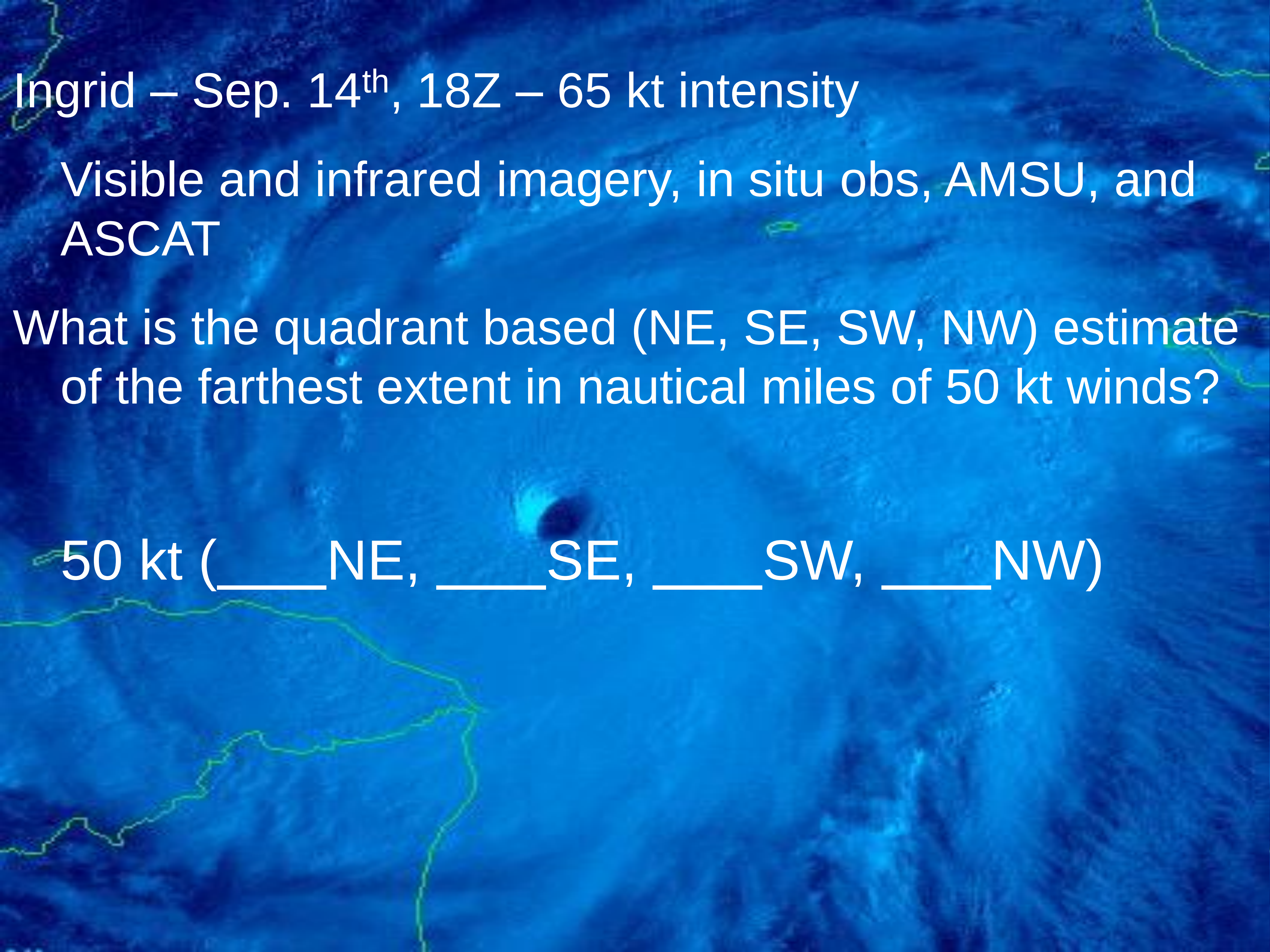
Visible and infrared imagery, in situ obs, AMSU

What is the quadrant based (NE, SE, SW, NW) estimate of the farthest extent in nautical miles of 50 kt winds?

50 kt (____NE, ____SE, ____SW, ____NW)



ASCAT pass –
Red – 34 kt
Purple – 50 kt
50 nm
100 nm



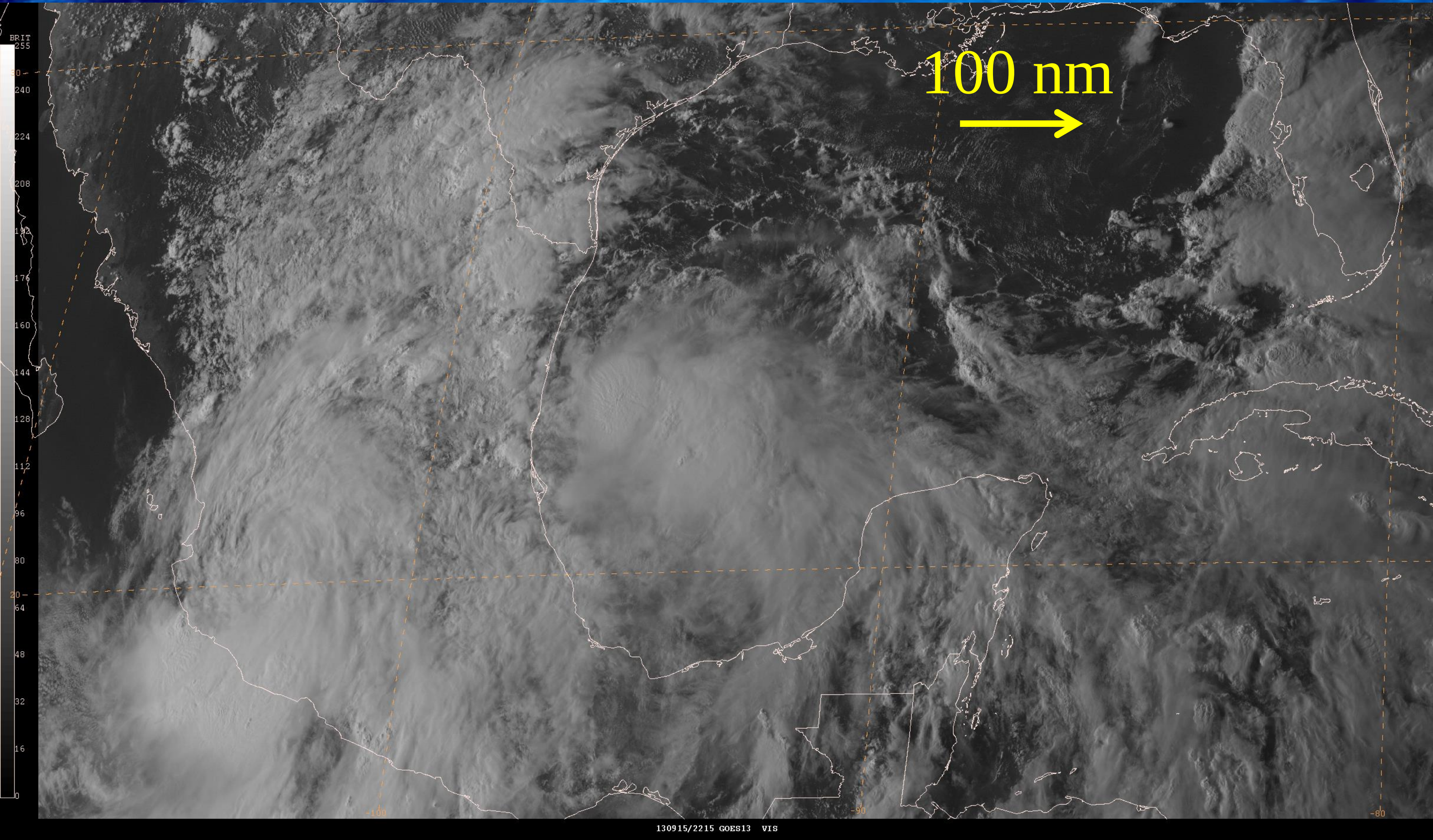
Ingrid – Sep. 14th, 18Z – 65 kt intensity

Visible and infrared imagery, in situ obs, AMSU, and ASCAT

What is the quadrant based (NE, SE, SW, NW) estimate of the farthest extent in nautical miles of 50 kt winds?

50 kt (____NE, ____SE, ____SW, ____NW)

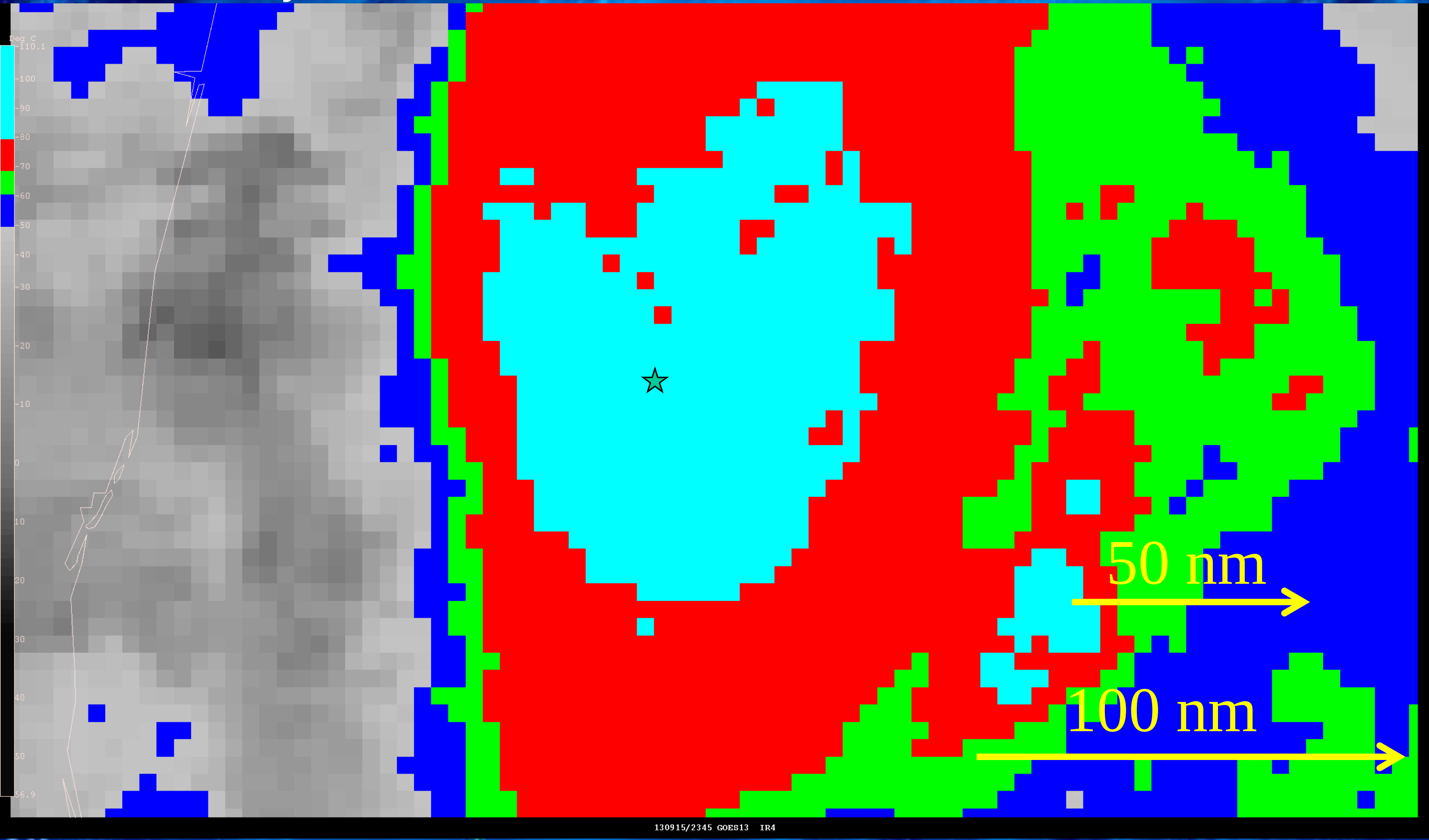
Ingrid – Sep. 16th, 00Z – 70 kt Intensity
How big is it?

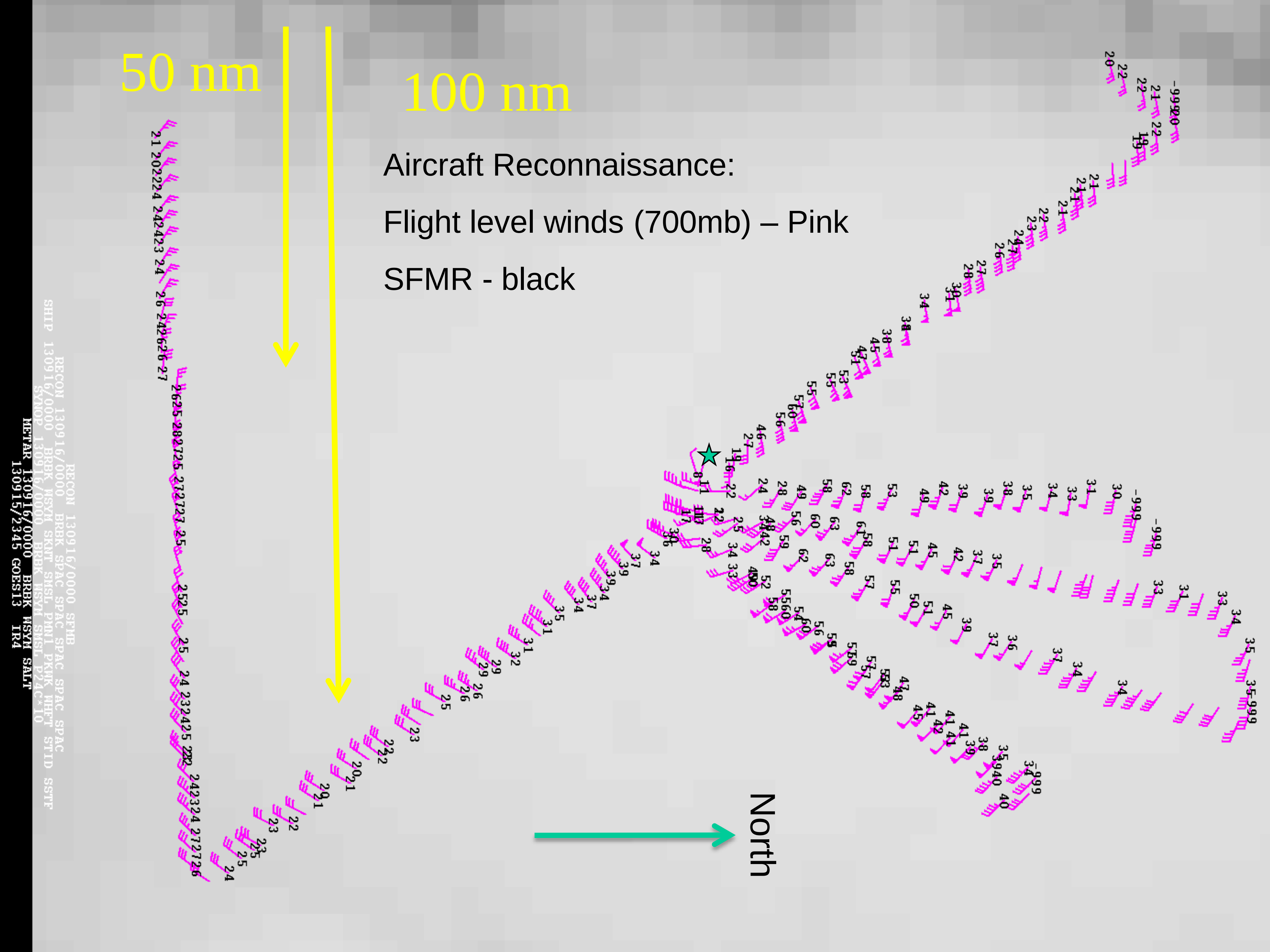


Ingrid

Sep. 16th, 00Z

70 kt intensity




50 nm
100 nm
Aircraft Reconnaissance:
Flight level winds (700mb) – Pink
SFMR - black
North

Ingrid – Sep. 16th, 00Z – 70 kt intensity

Visible and infrared imagery, in situ obs, and aircraft reconnaissance

What is the quadrant based (NE, SE, SW, NW) estimate of the farthest extent in nautical miles of 50 kt winds?

50 kt (____NE, ____SE, ____SW, ____NW)