# Hurricane Structure: Theory and Diagnosis

**7 March, 2016**

**World Meteorological Organization Workshop**

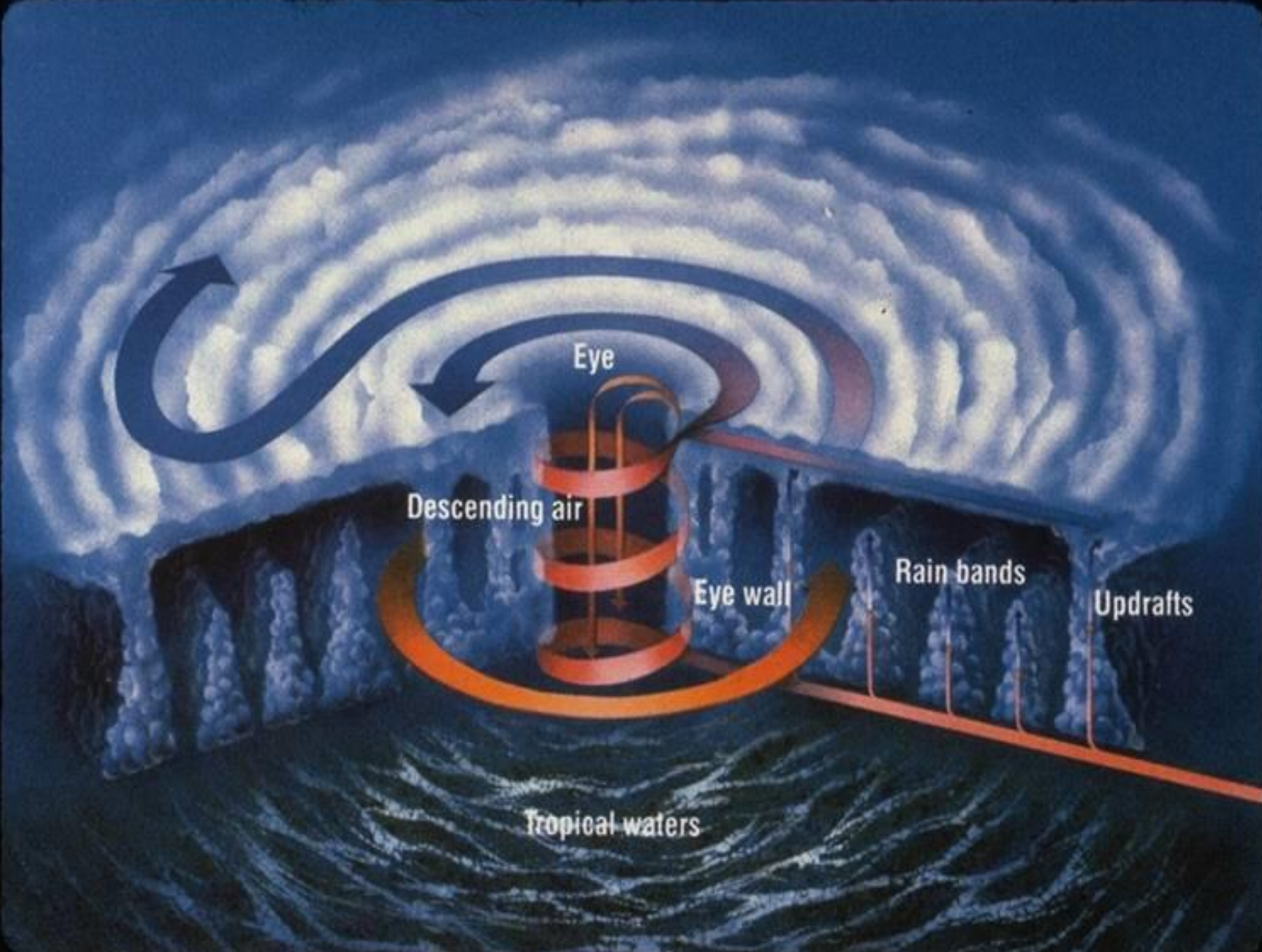

Chris Landsea

Chris.Landsea@noaa.gov

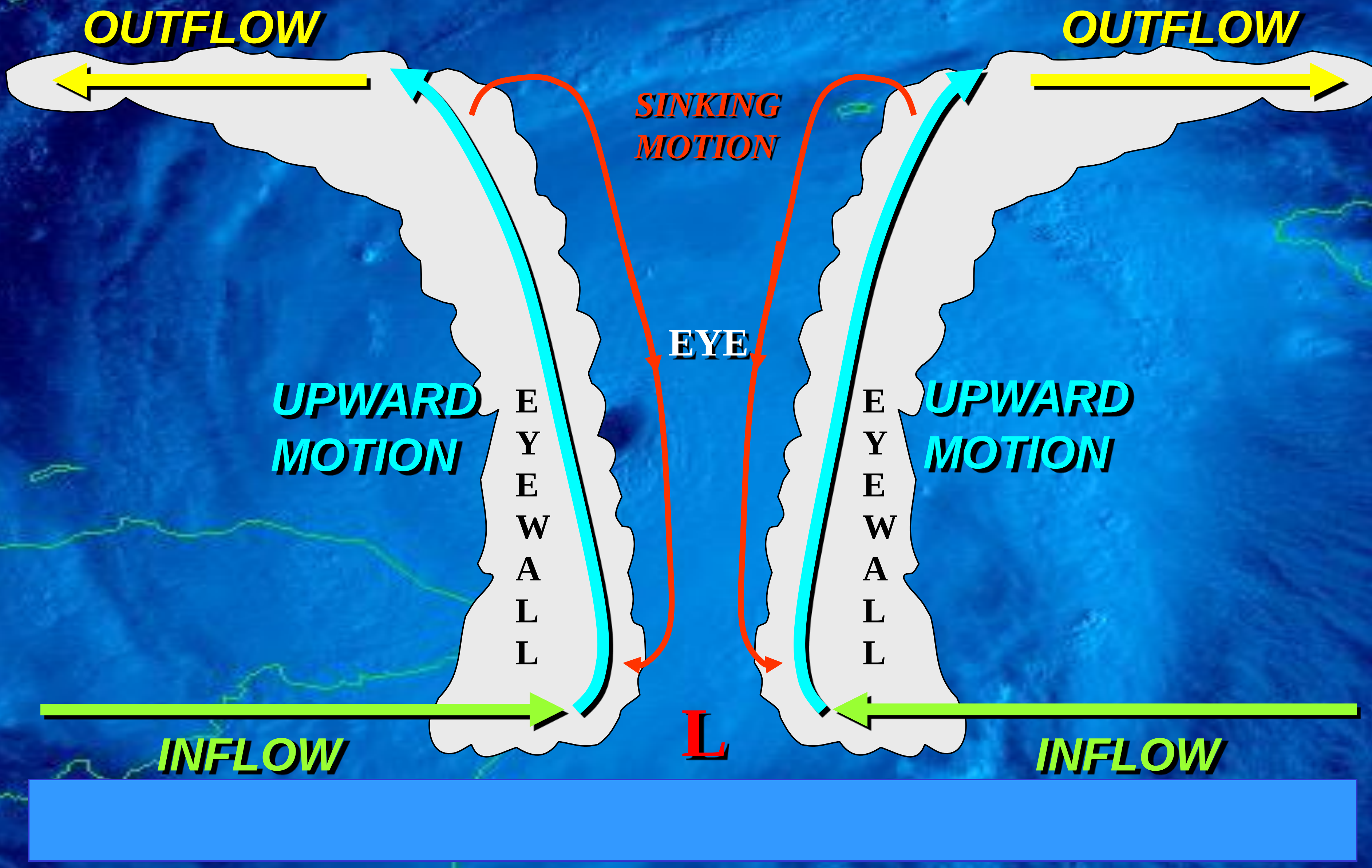
National Hurricane Center, Miami

# Outline

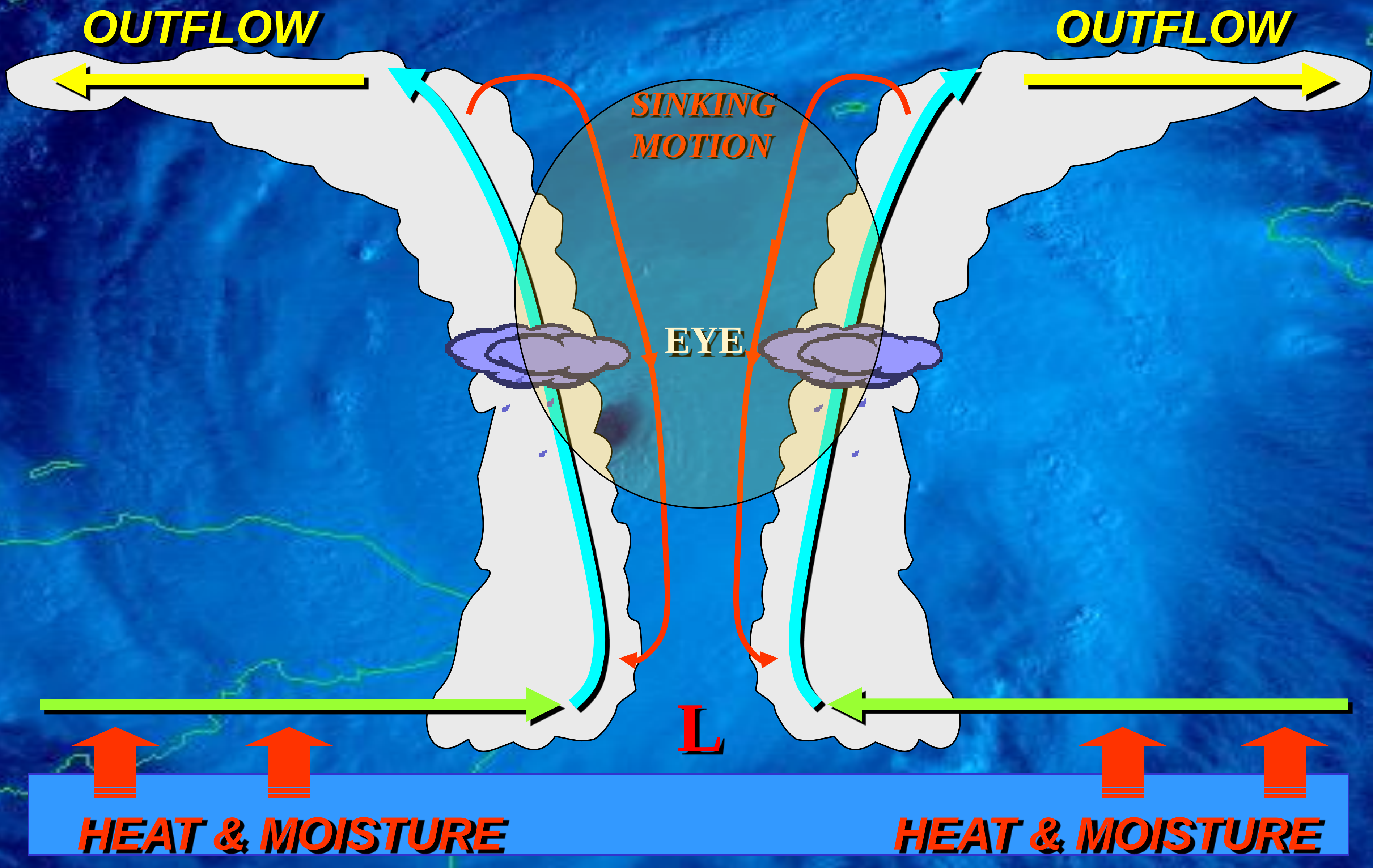
- Structure of Hurricanes – Dynamical and thermodynamical
- How is size defined and measured?
- Exercise:  Analyze size (50 kt winds)

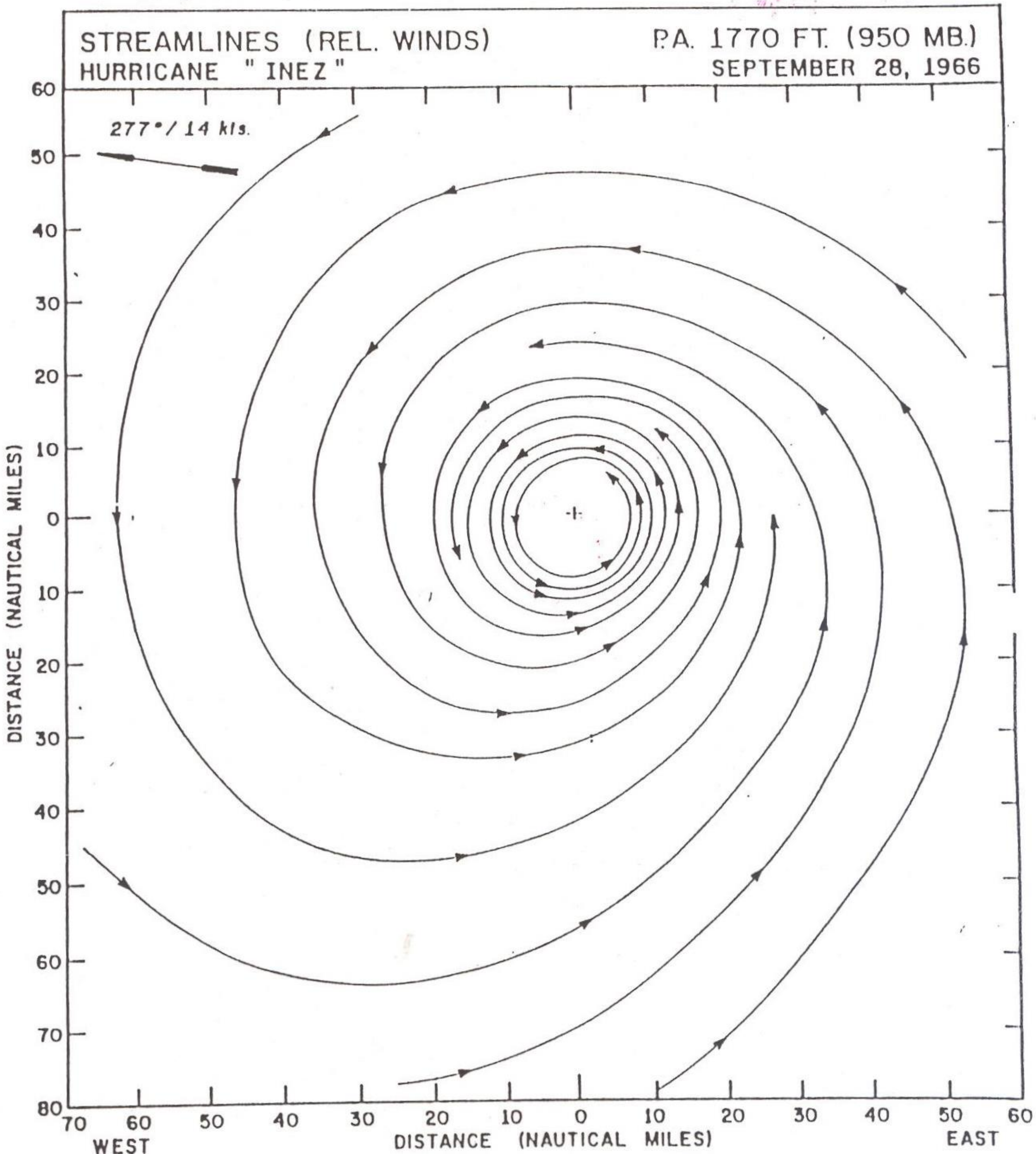

Eye
Descending air
Eye wall
Rain bands
Updrafts
Tropical waters

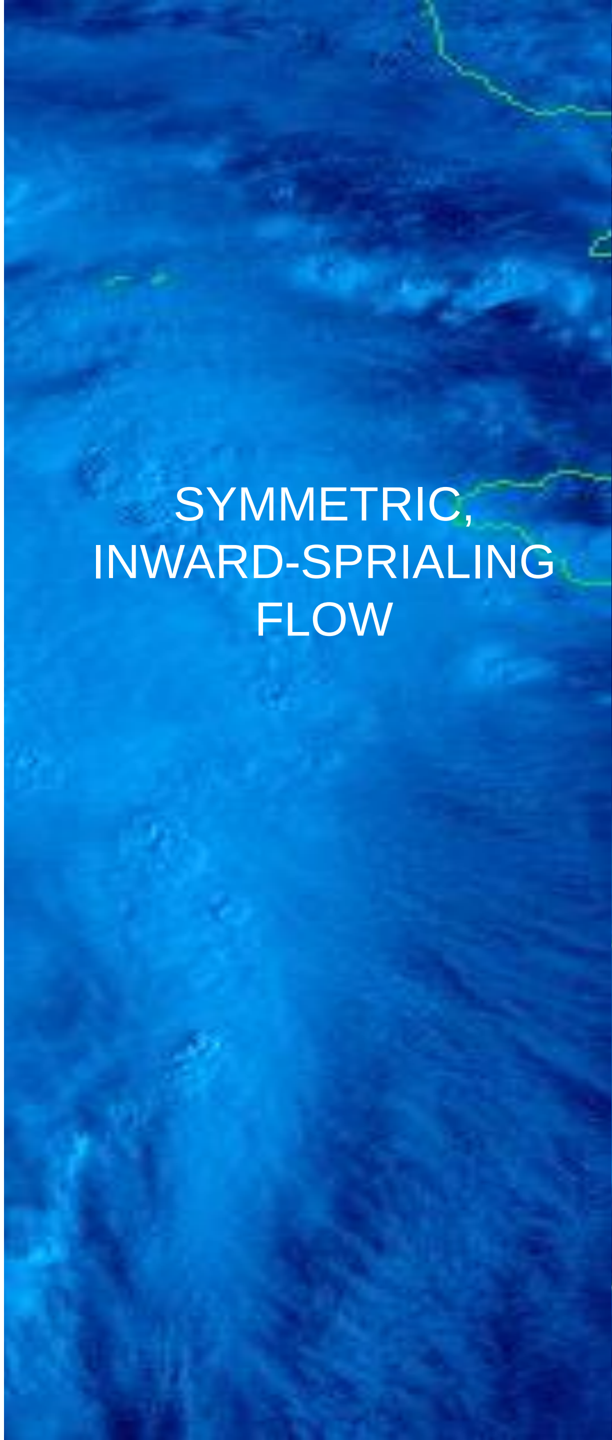
# THE WARM CORE IS A CONSEQUENCE OF BOTH LATENT HEAT RELEASE AND WARMING BY SUBSIDENCE



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




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


SYMMETRIC,
INWARD-SPRIALING
FLOW

WIND SPEEDS ARE CLOSE TO SYMMETRIC – ONLY AFTER SUBTRACTING MOTION

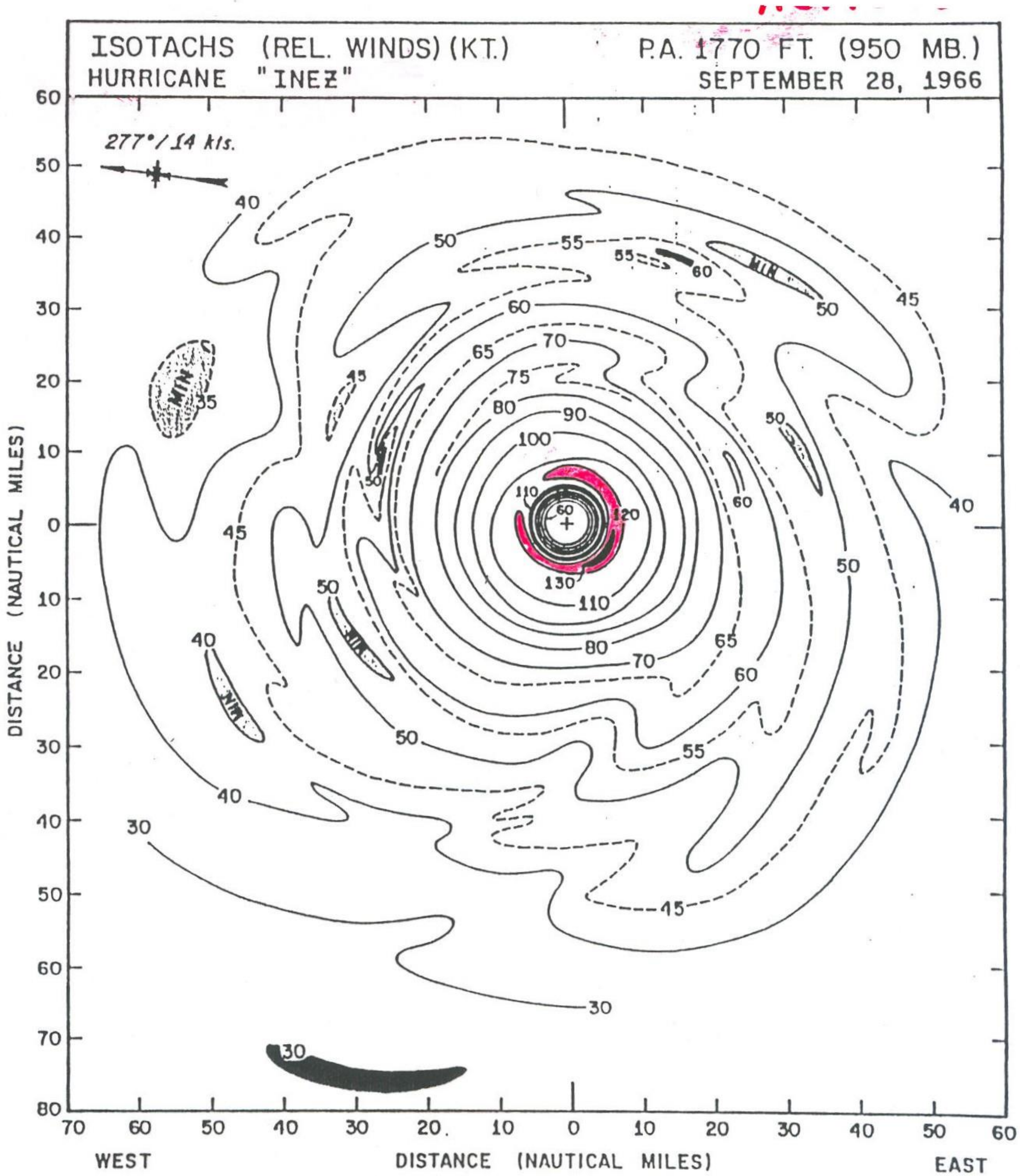
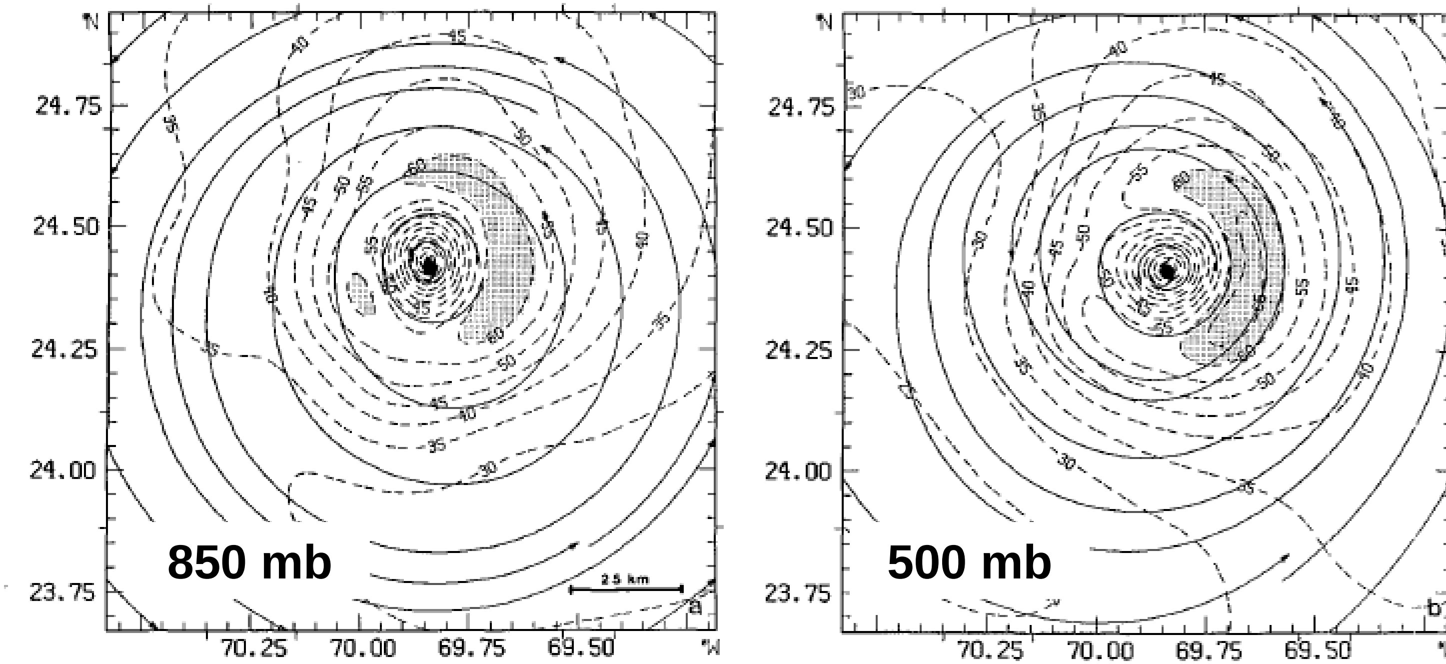
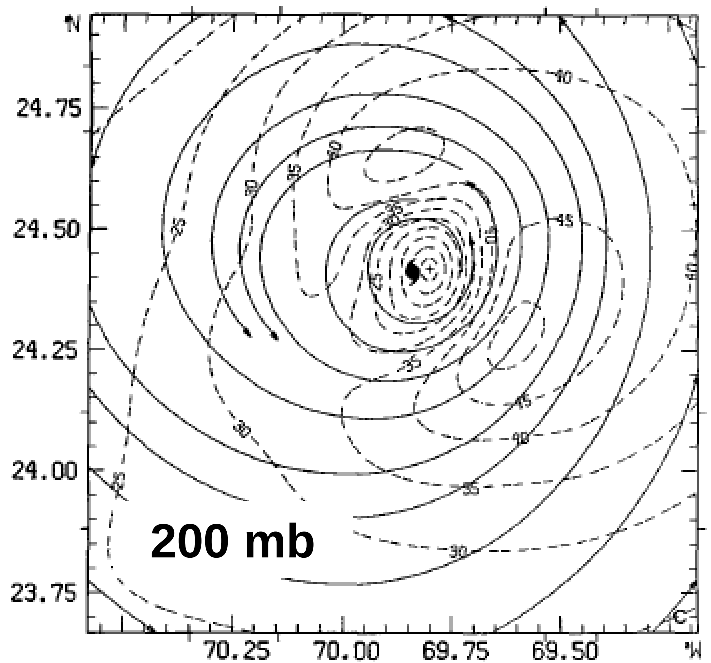


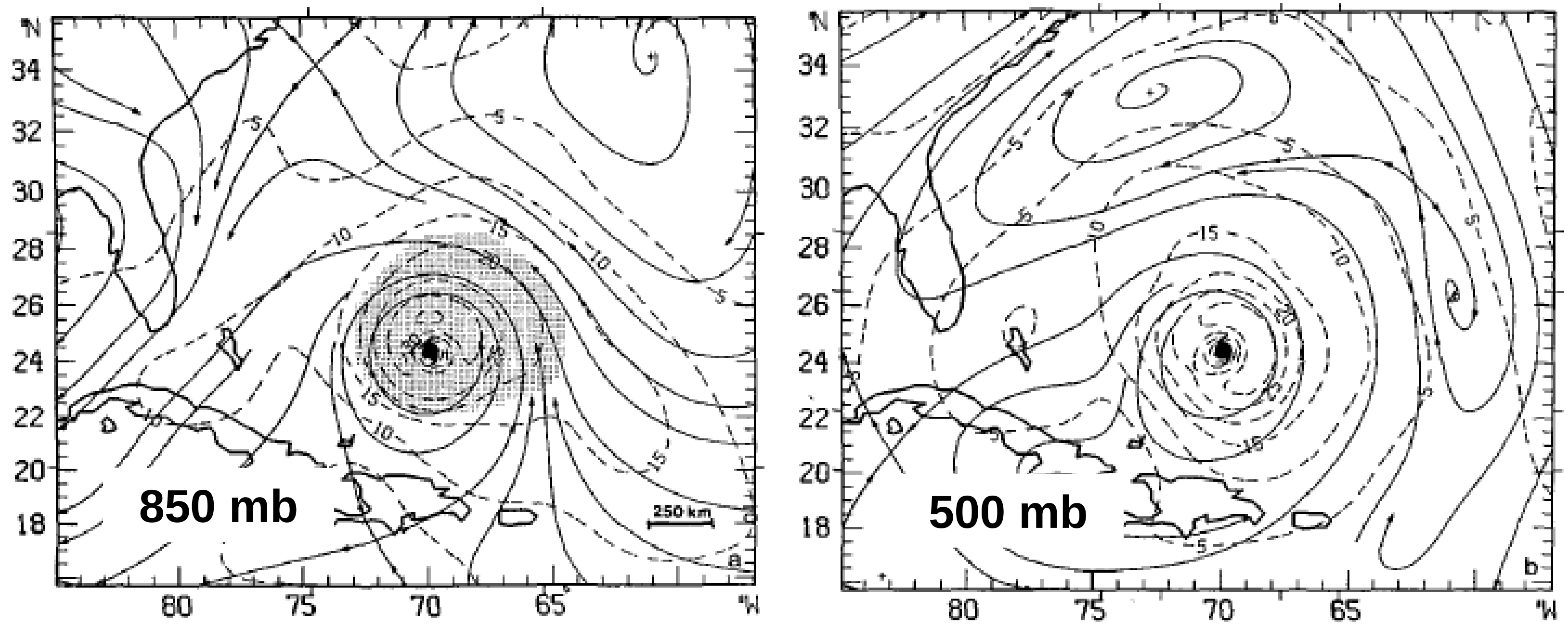

FIG. 2.4b. Low-level (950 mb) isotachs (kt) in Hurricane Inez (1966) (Hawkins and Imbembo, 1976).

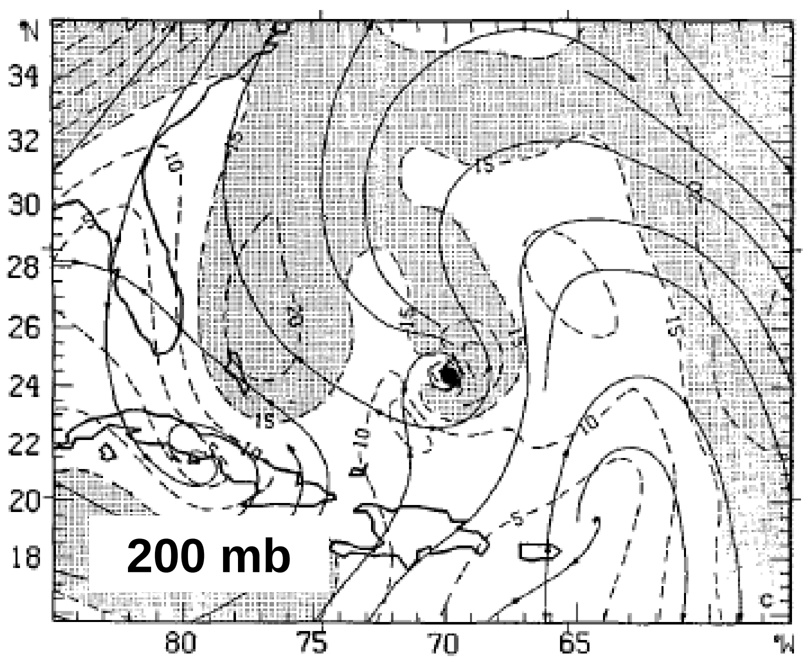



**NOTE CYCLONIC CIRCULATION AT UPPER-TROPOSPHERIC LEVEL, WITHIN A FEW DEGREES RADIUS OF THE CENTER!**

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

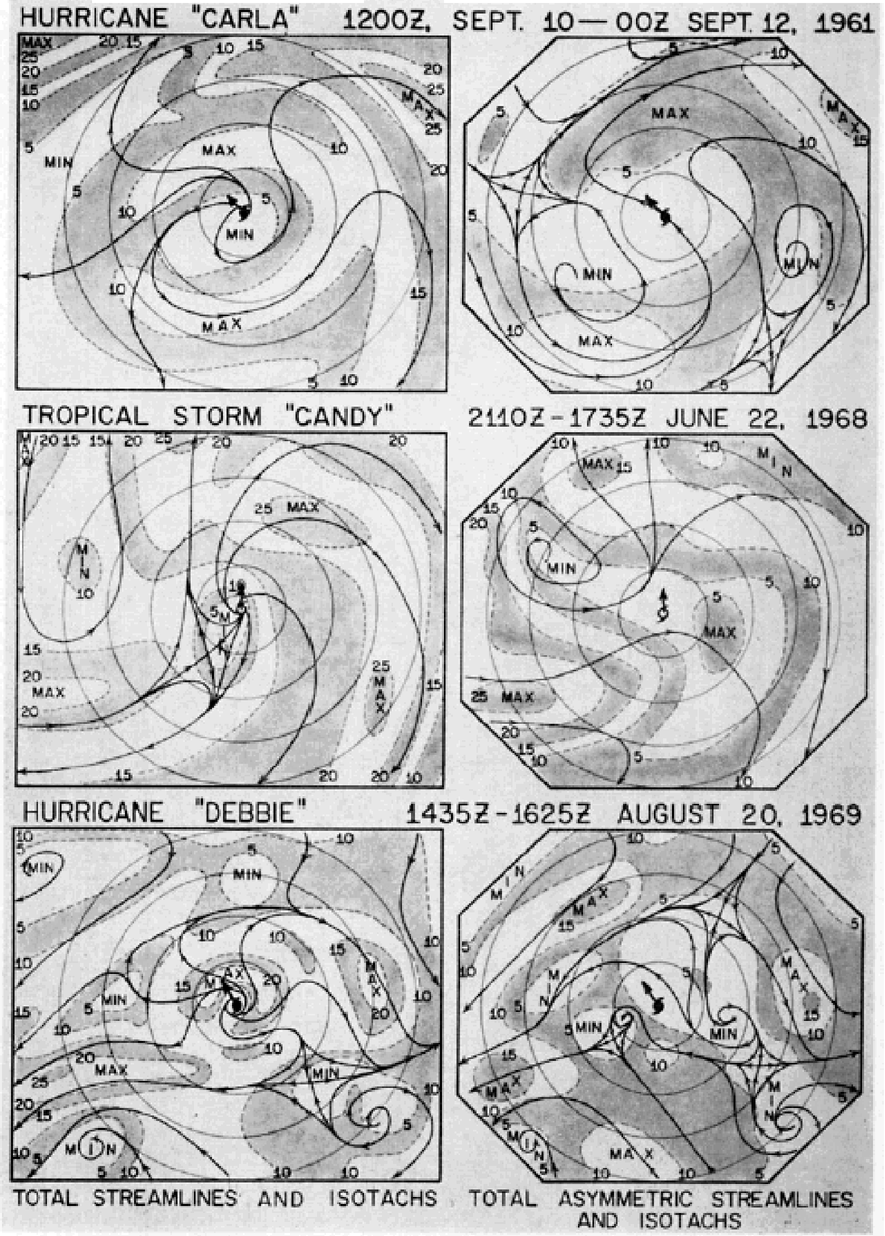



FIG. 2. Total streamlines and isotachs (m $sec^{-1}$), left, compared with total asymmetric streamlines and isotachs (m $sec^{-1}$), right, for hurricane Carla, tropical storm Candy and hurricane Debbie. The range circles are at 2° latitude radius intervals. The arrow indicates the direction of storm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

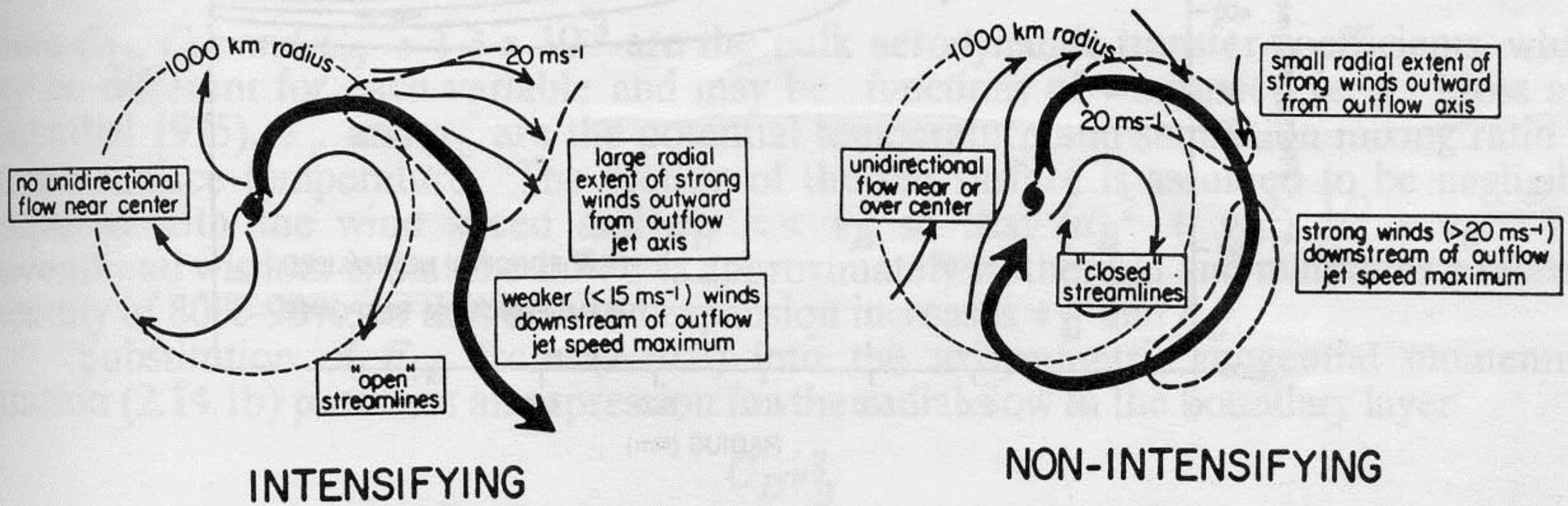
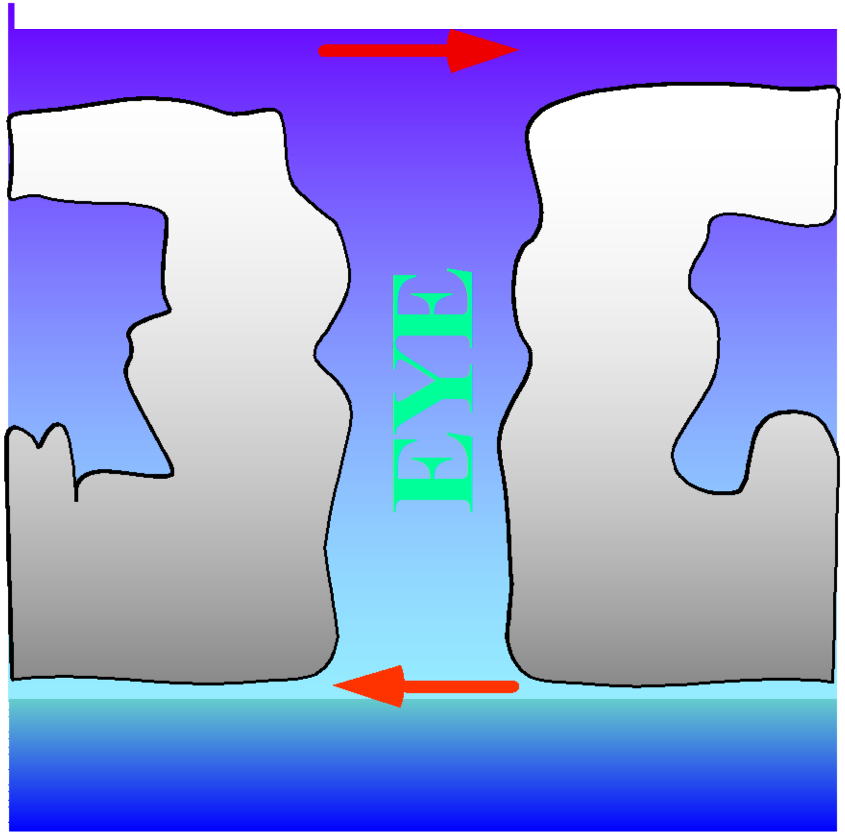
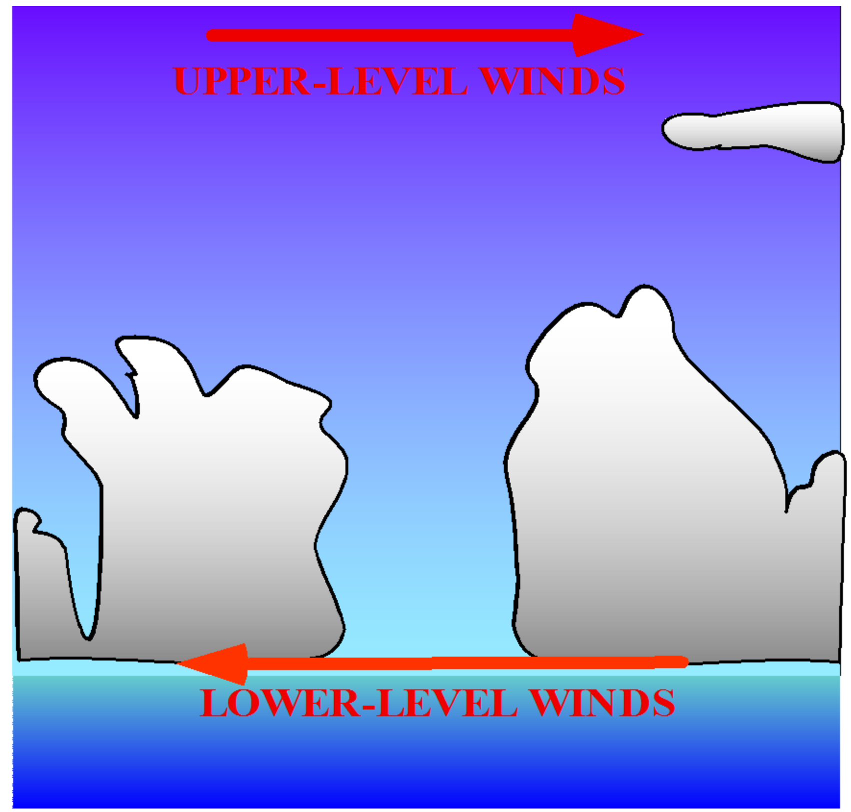



Fig. 2.17 Differences between the outflow and upper-level asymmetries of intensifying and nonintensifying hurricanes (Merrill 1988b).

# Not too much "Wind Shear"

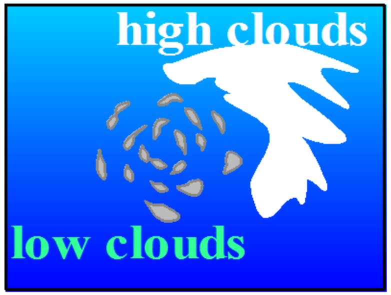
## Effects of Vertical Wind Shear ($V_z$) on Tropical Cyclones



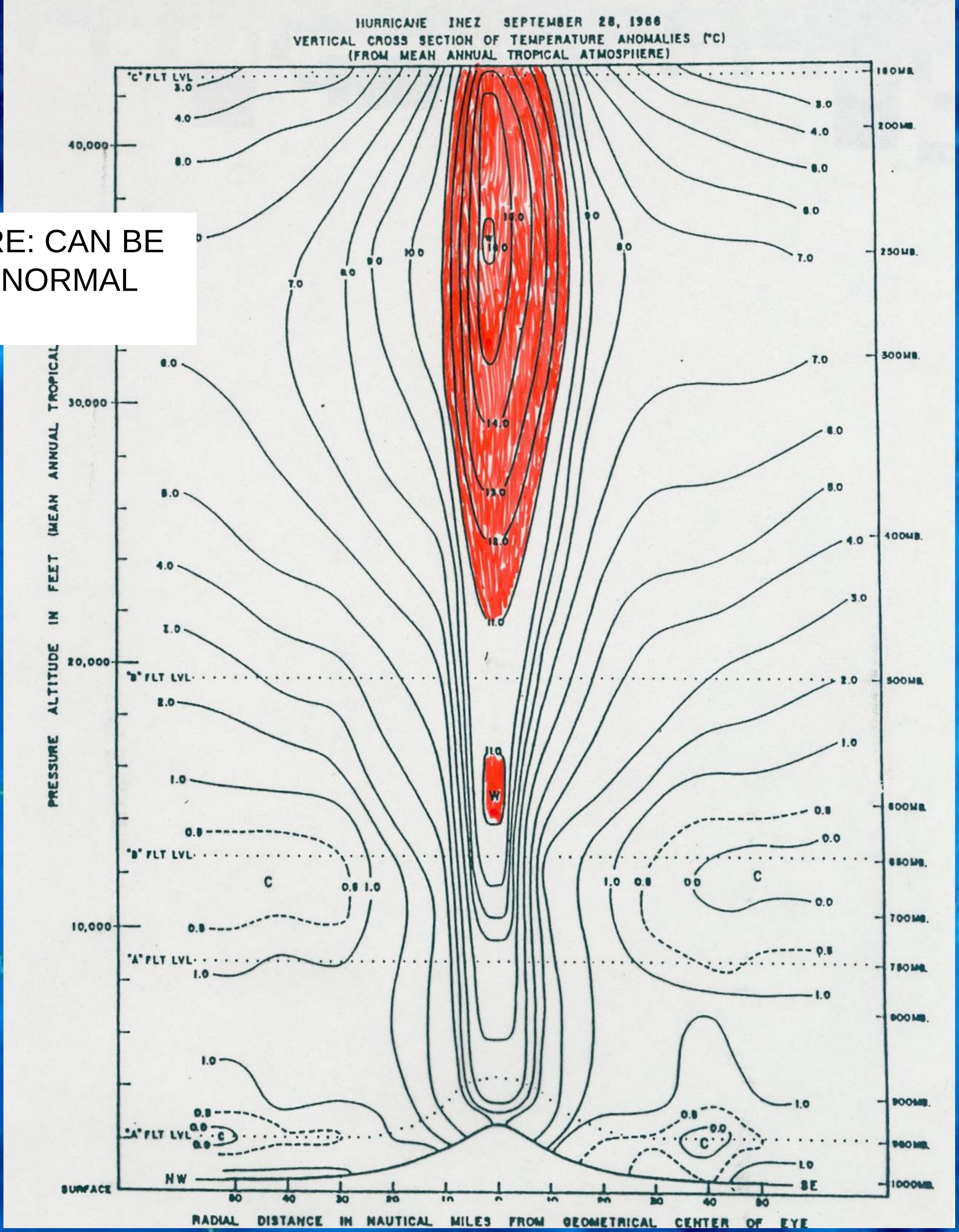

***WEAK* SHEAR = FAVORABLE**

***STRONG* SHEAR = *UN*FAVORABLE**

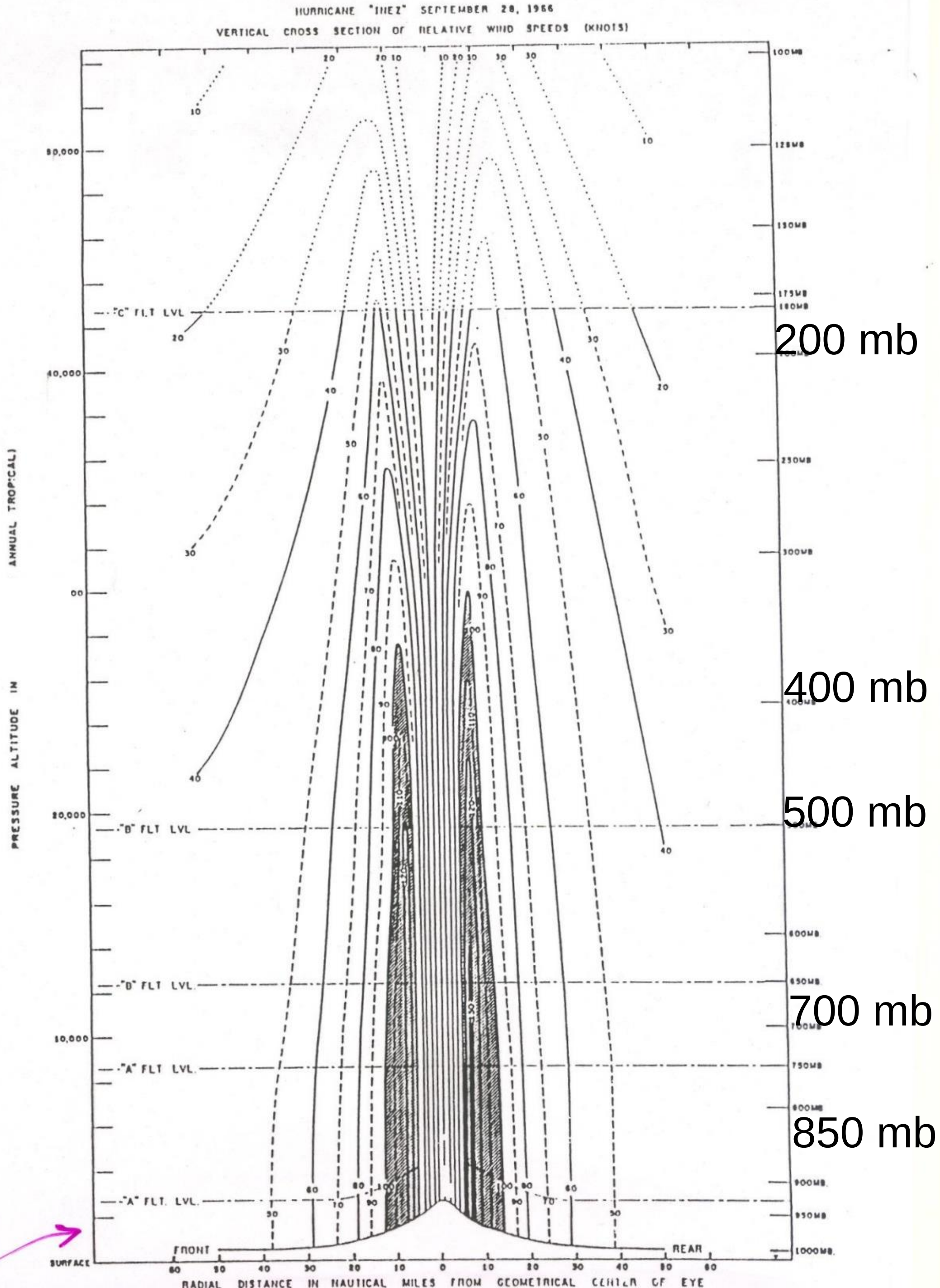



Neal Dorst/Stan Goldenberg
Hurricane Research Division
AOML/NOAA

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



DEEP-LAYER CYCLONIC CIRCULATION



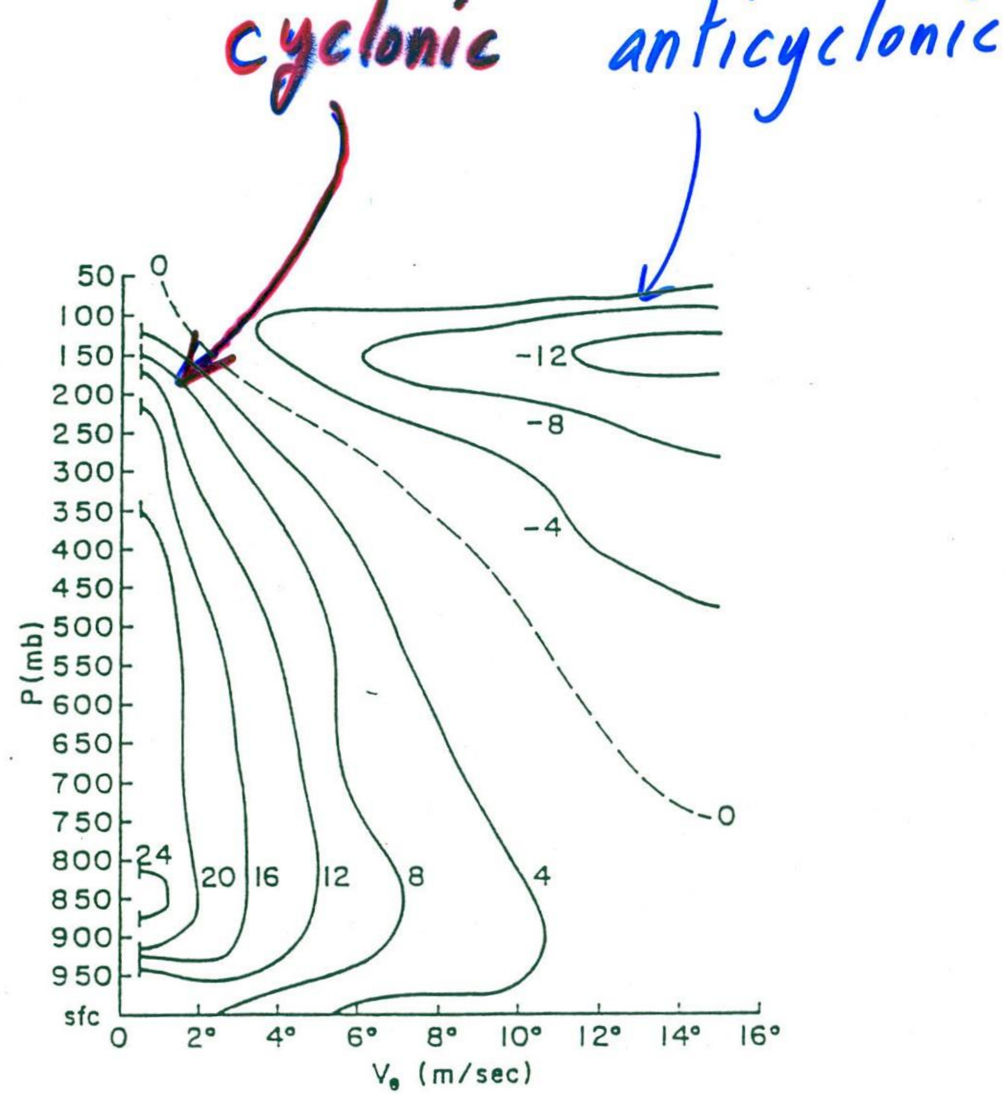



FIG. 2.6. Vertical cross section of tangential winds (m $s^{-1}$) for the Pacific composite typhoon (Frank, 1977a).

# MEAN VERTICAL MOTION

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

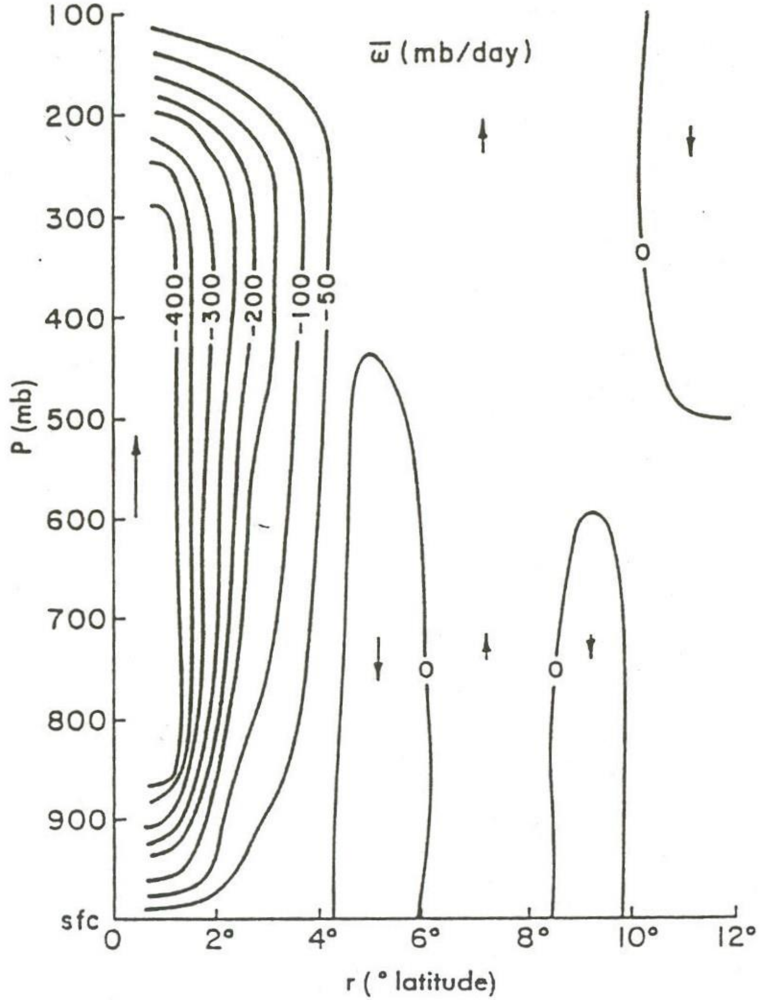



FIG. 2.14. Vertical cross section of vertical motion (mb day$^{-1}$) in mean typhoon (Frank, 1977a).

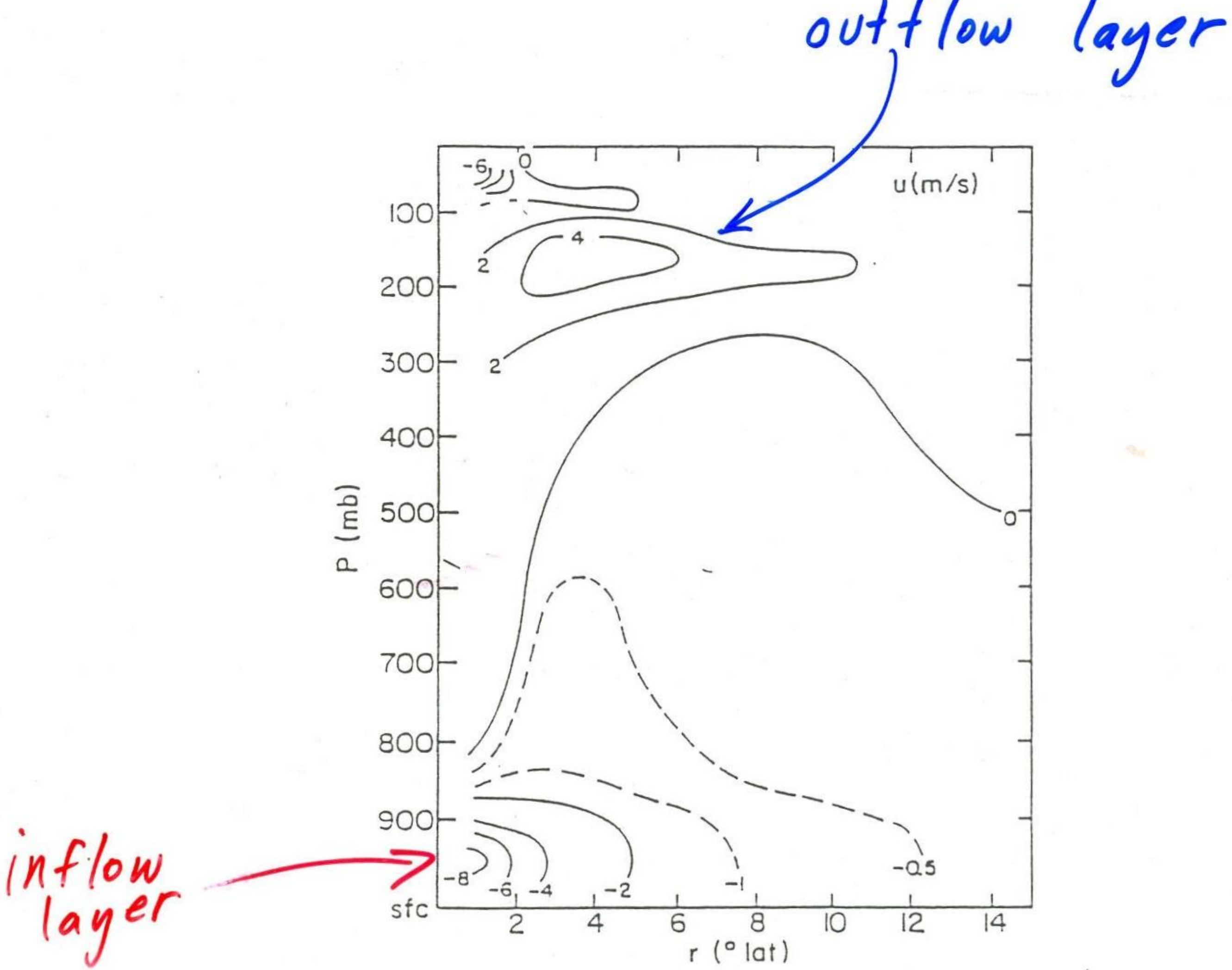



FIG. 2.5. Vertical cross section of radial winds (m $s^{-1}$) for the western Atlantic composite hurricane (Gray, 1979).

**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:

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

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

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

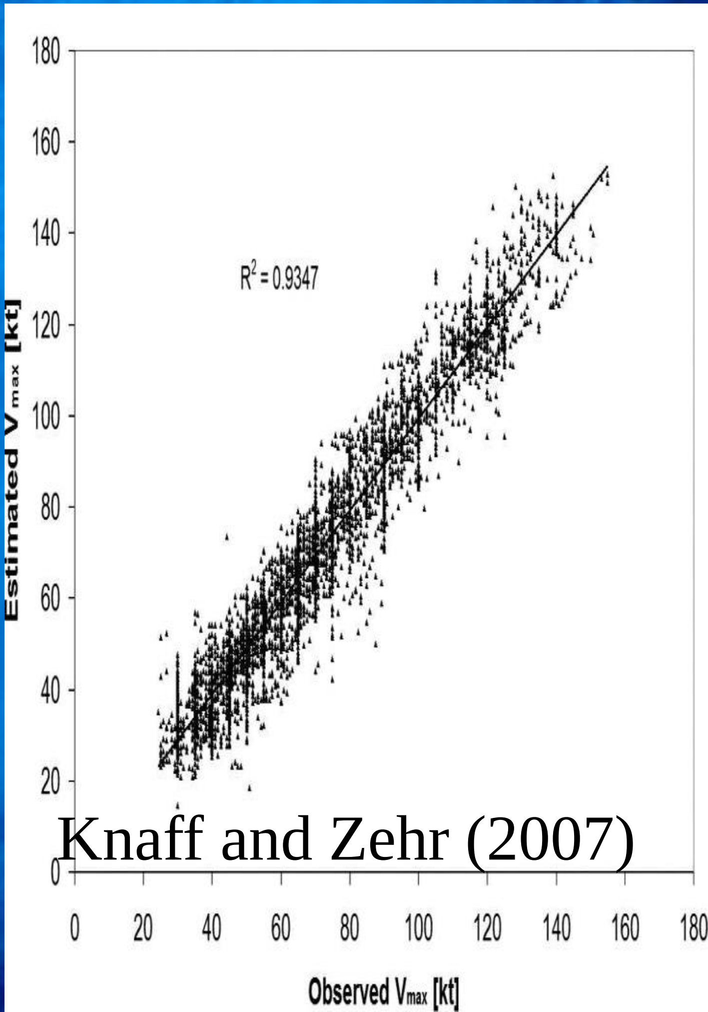
$$= 262\,\mathrm{km/hr}$$

# 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:**

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

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

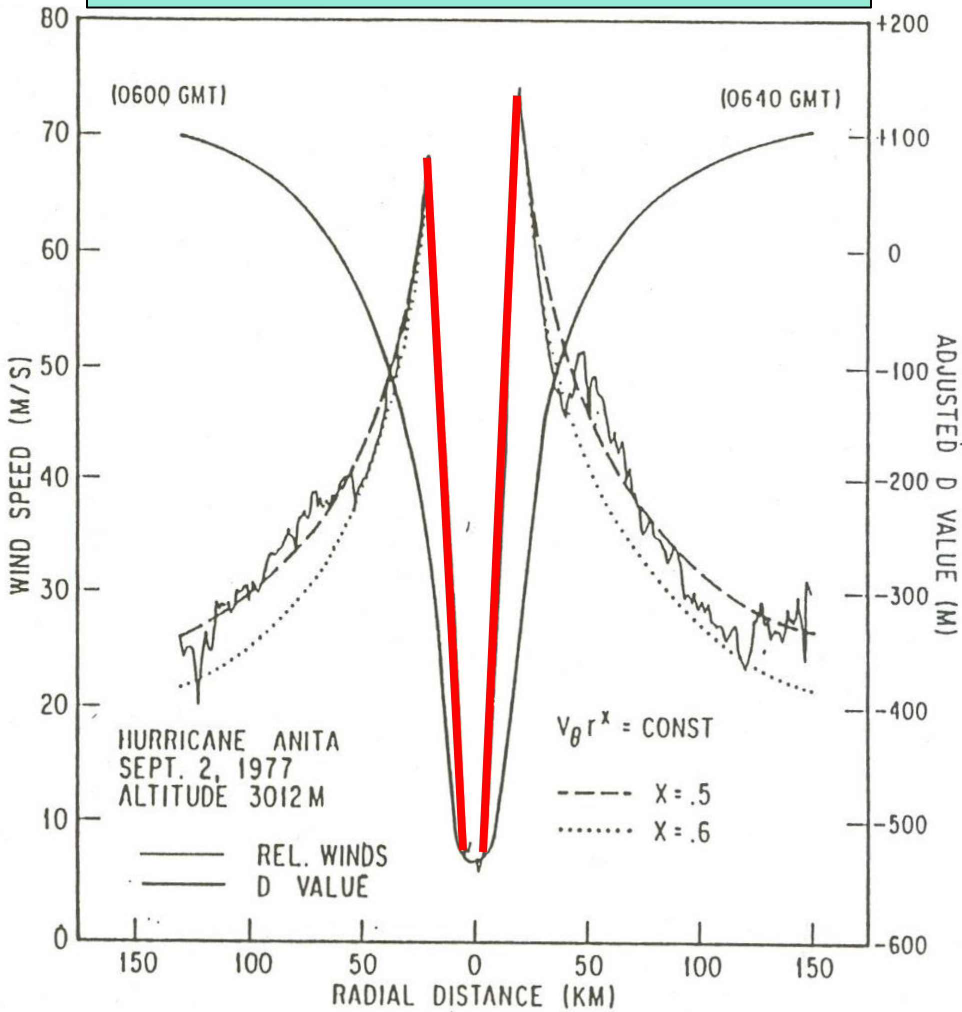



FIG. 2.8. Radial profiles of tangential wind speed (m s$^{-1}$) and $D$ values (departure of isobaric height from reference value) in Hurricane Anita. Also shown are graphs $V_\theta r^x$ = constant for values of $x$ = 0.5 and 0.6. (Sheets, 1980).

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

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

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

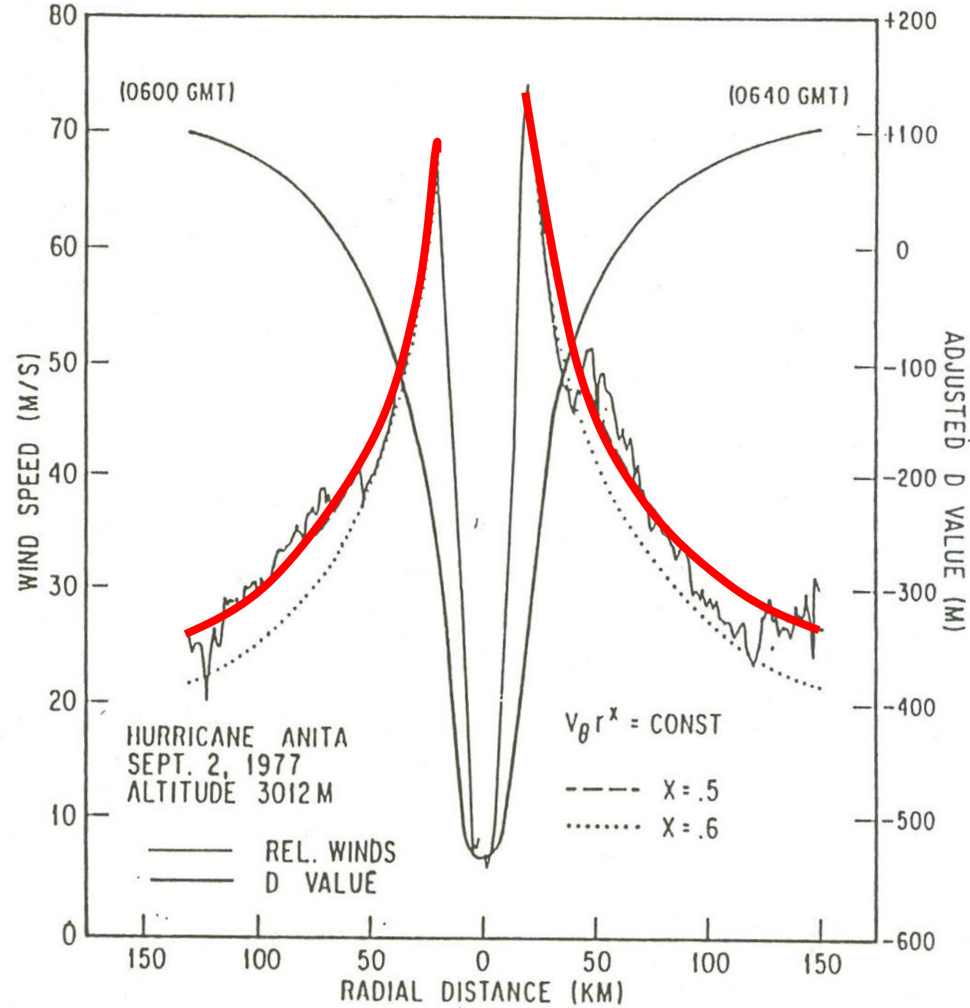
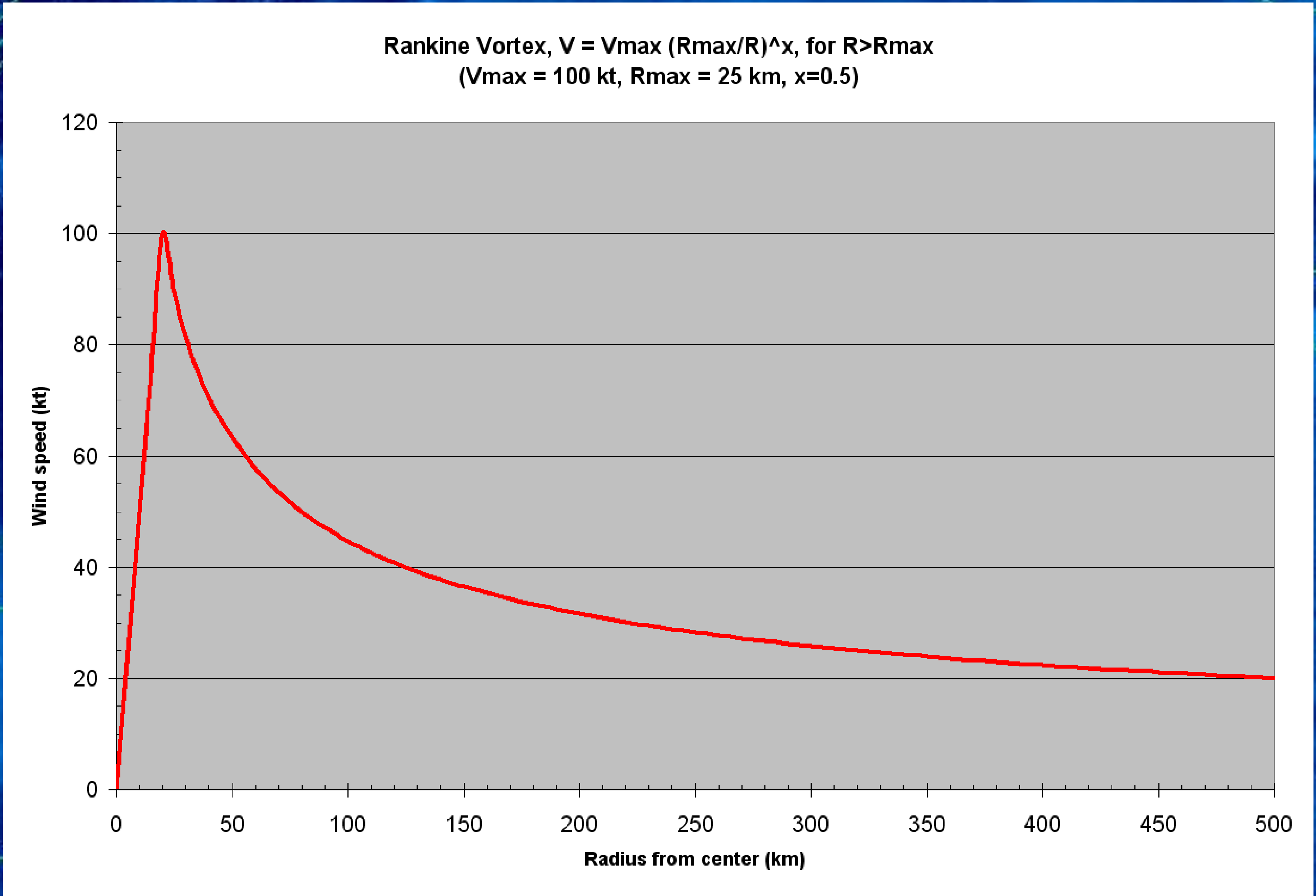
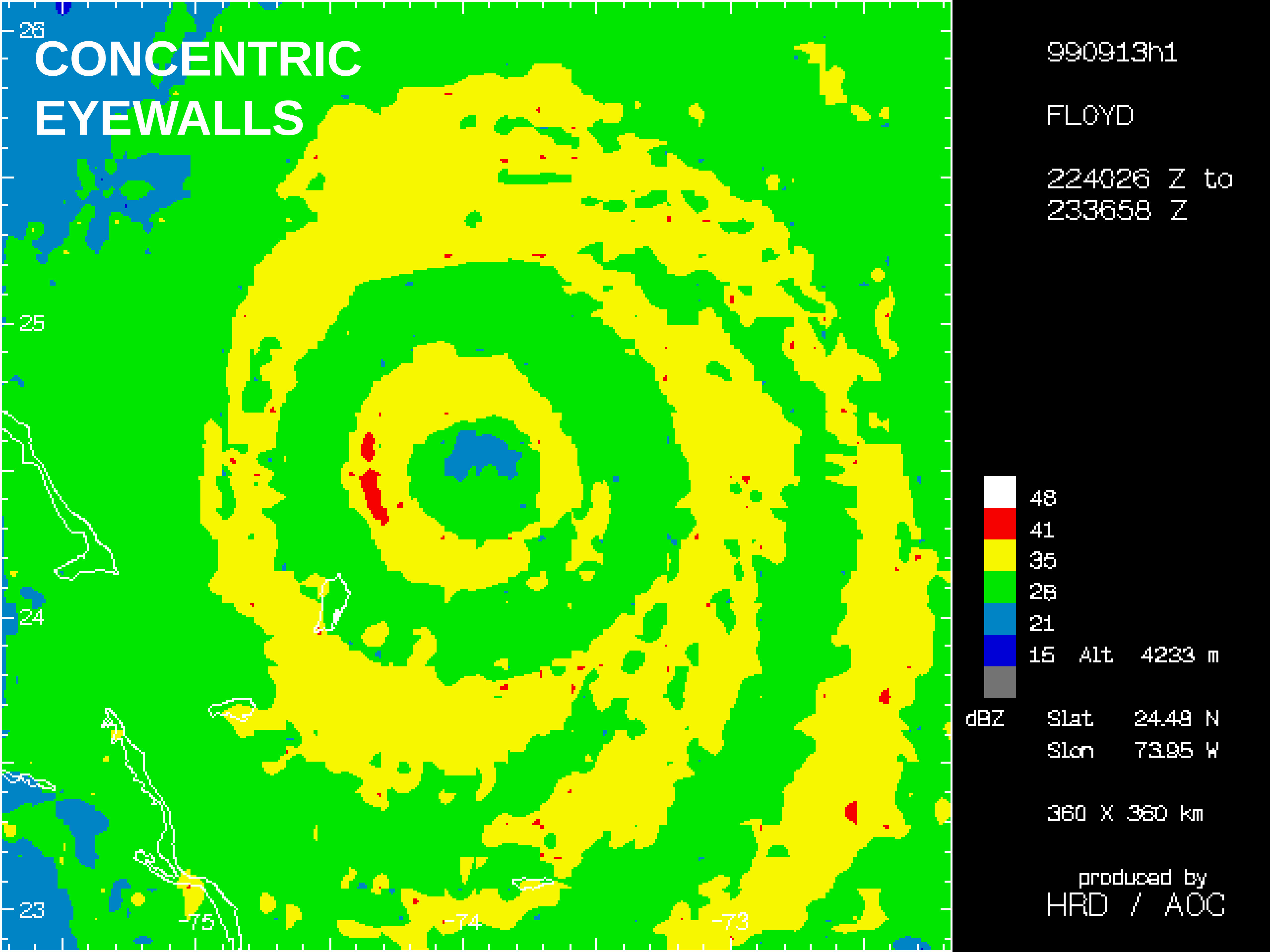


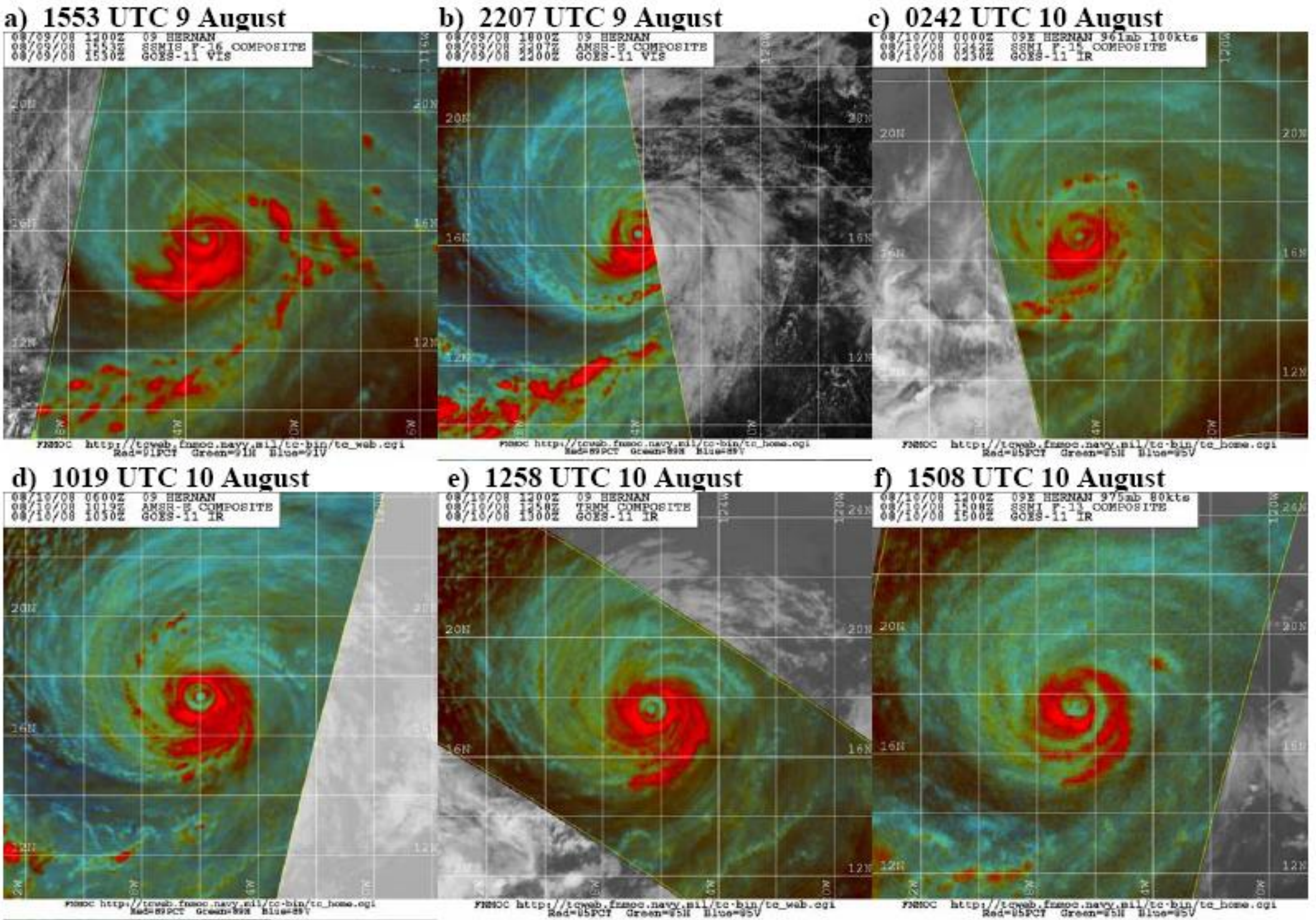

FIG. 2.8. Radial profiles of tangential wind speed (m s$^{-1}$) and $D$ values (departure of isobaric height from reference value) in Hurricane Anita. Also shown are graphs $V_\theta r^x$ = constant for values of $x$ = 0.5 and 0.6. (Sheets, 1980).

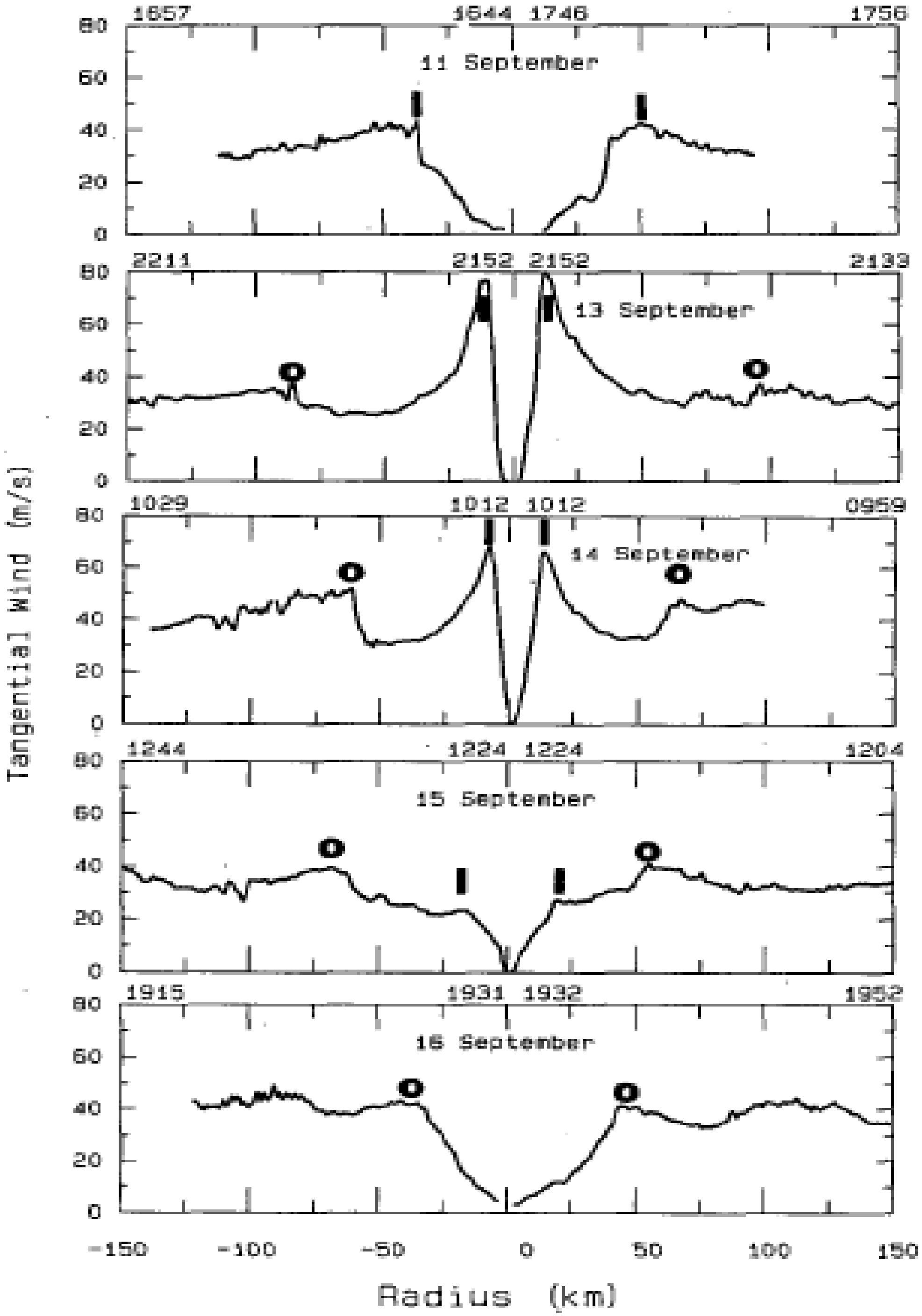

Rankine Vortex, V = Vmax (Rmax/R)^x, for R>Rmax
(Vmax = 100 kt, Rmax = 25 km, x=0.5)
Wind speed (kt)
0
20
40
60
80
100
120
Radius from center (km)
0
50
100
150
200
250
300
350
400
450
500



CONCENTRIC
EYEWALLS
990913h1
FLOYD
224026 Z to
233658 Z
48
41
35
28
21
15 Alt 4233 m
dBZ
Slat 24.49 N
Slon 73.95 W
360 X 360 km
produced by
HRD / AOC
26
25
24
23
-75
-74
-73

# 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

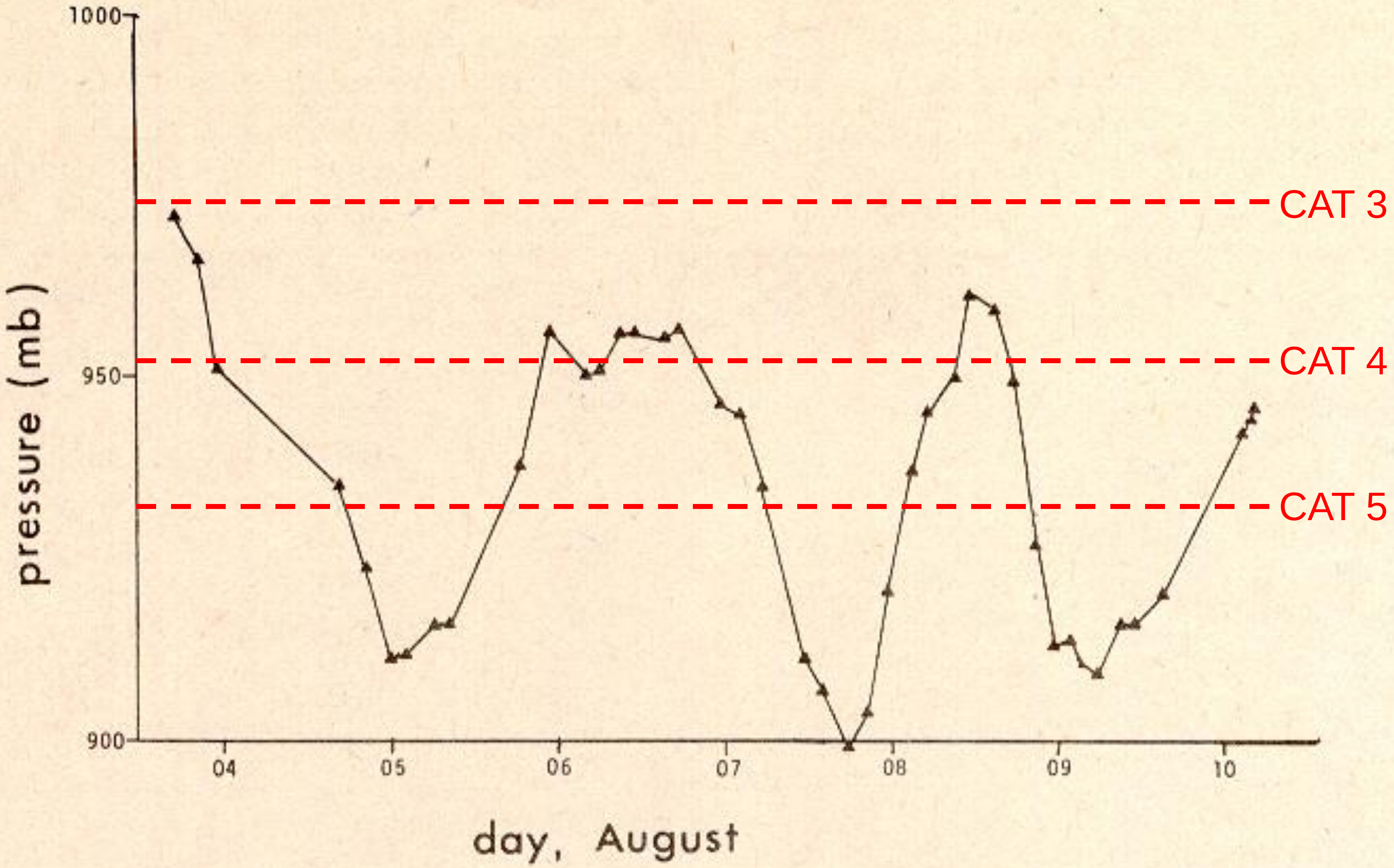


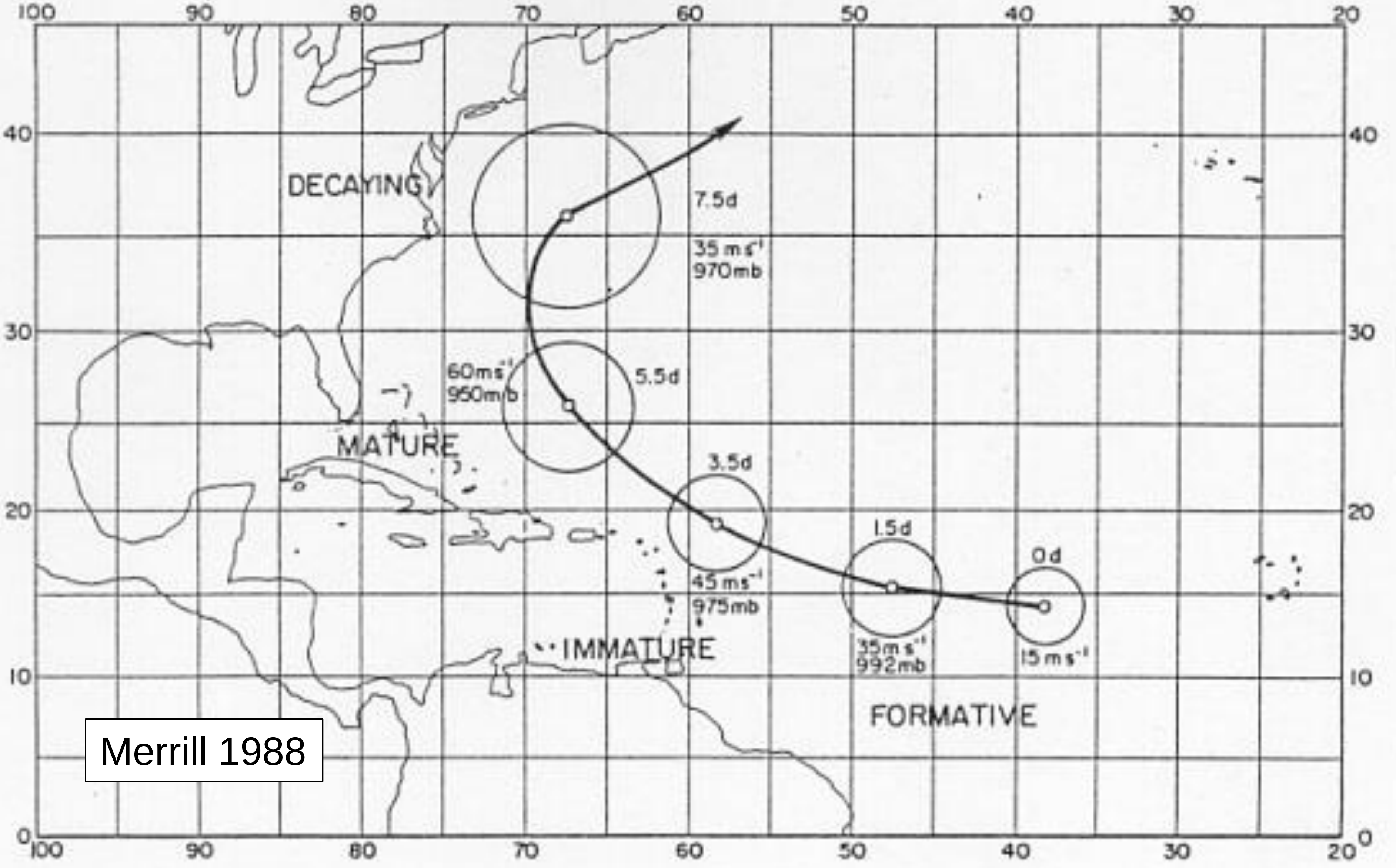

FIG. 3. Hurricane Allen: graph of minimum sea level pressure as a function of time, based on 44 aircraft observations.

# Natures Most Powerful Storm...



# Size Matters!

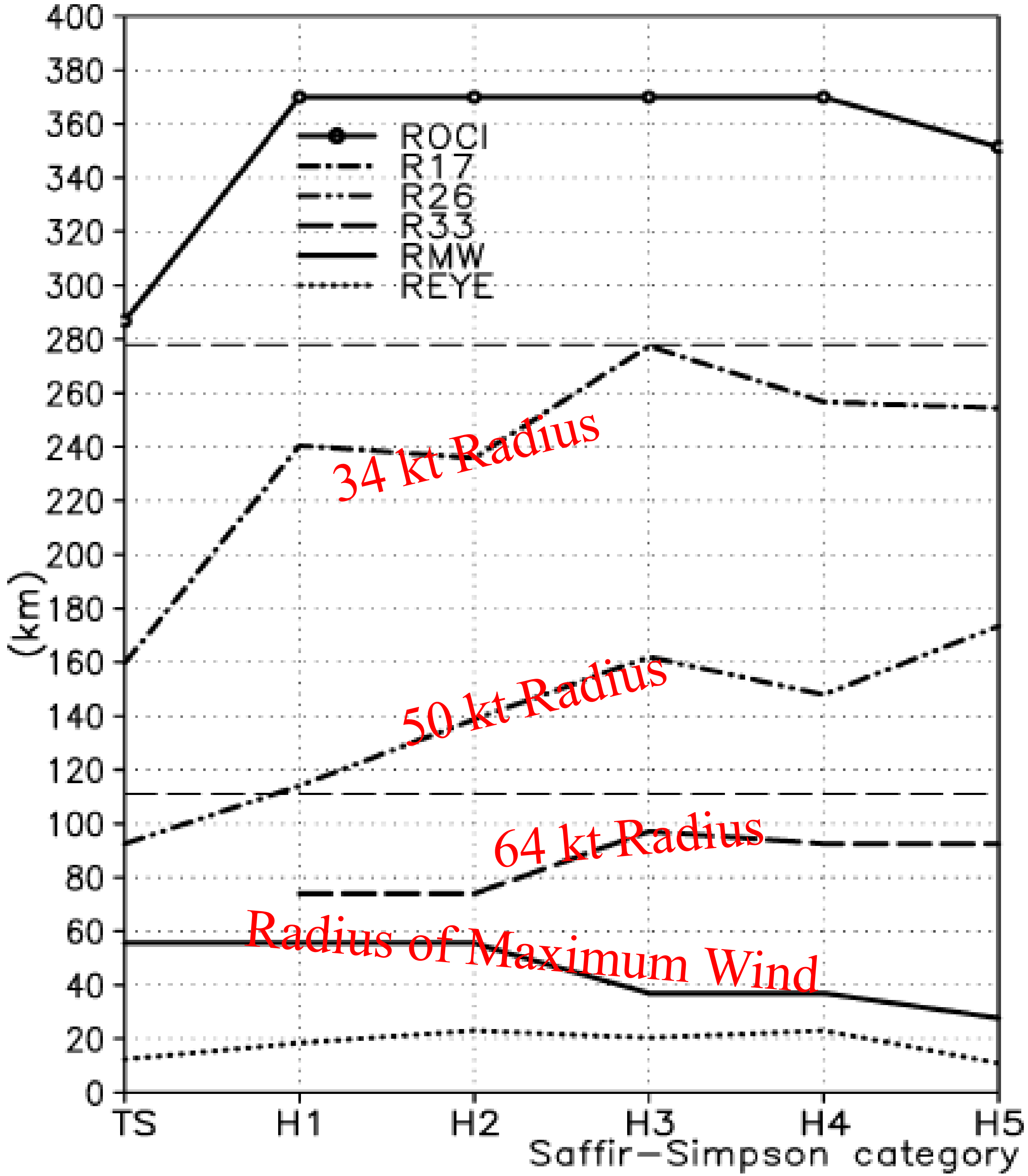
# Tropical Cyclone Size Lifecycle

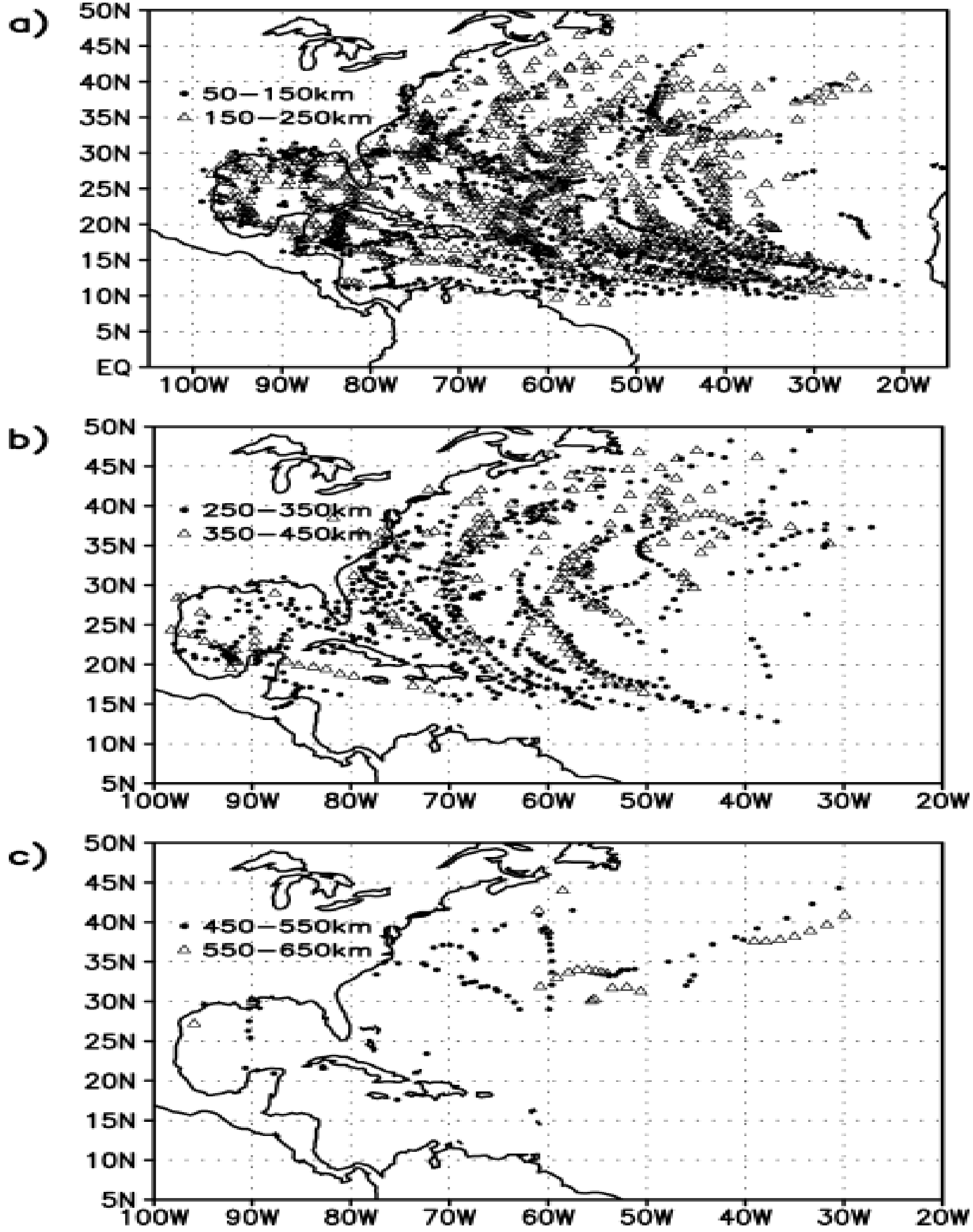



Merrill 1988

# Size versus Intensity

Kimball and Mulekar (2004)






# Radius of Tropical Storm Force Winds versus Location

Kimball and Mulekar (2004)

# Tropical Cyclones versus Extratropical Cyclones



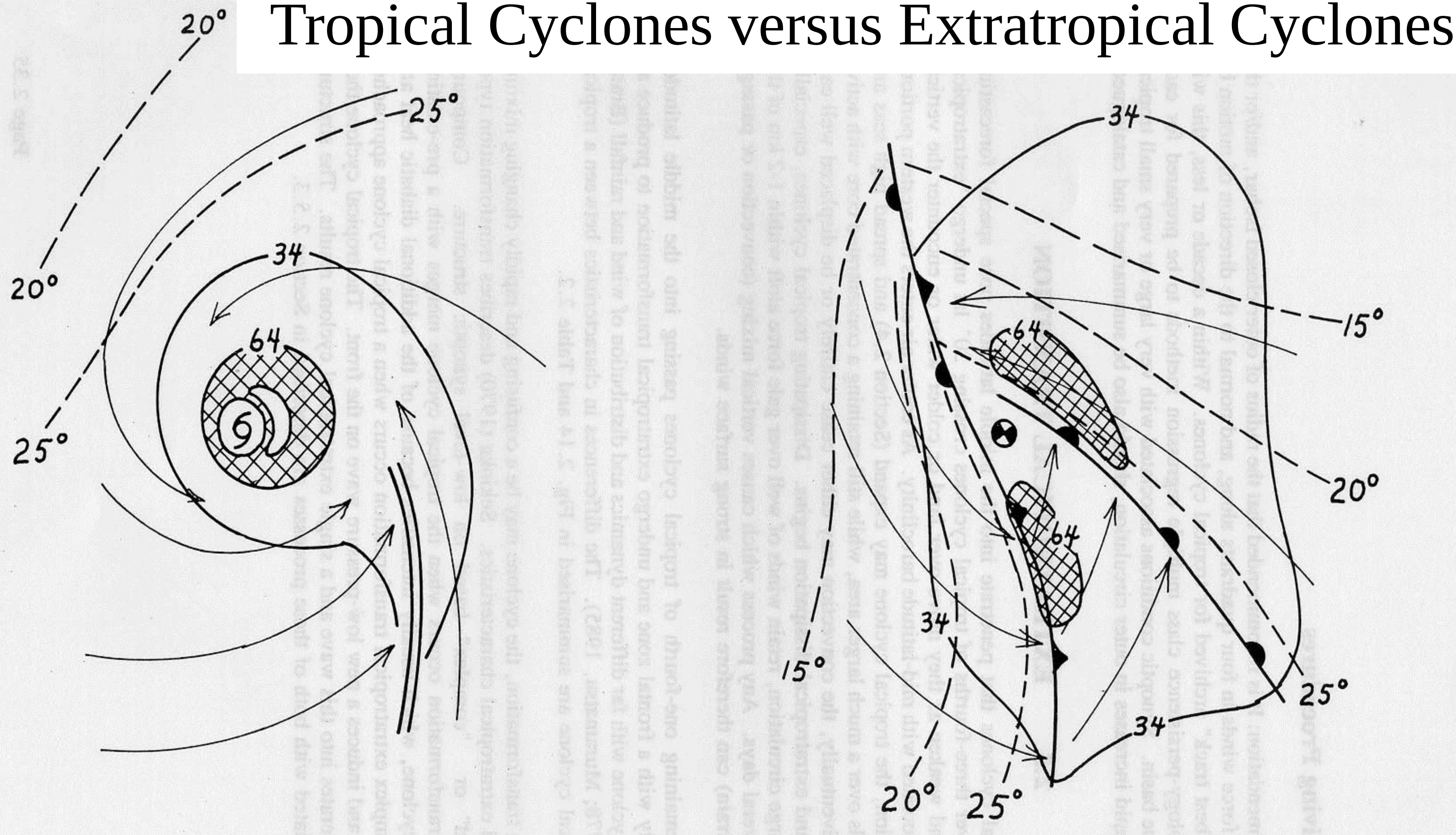
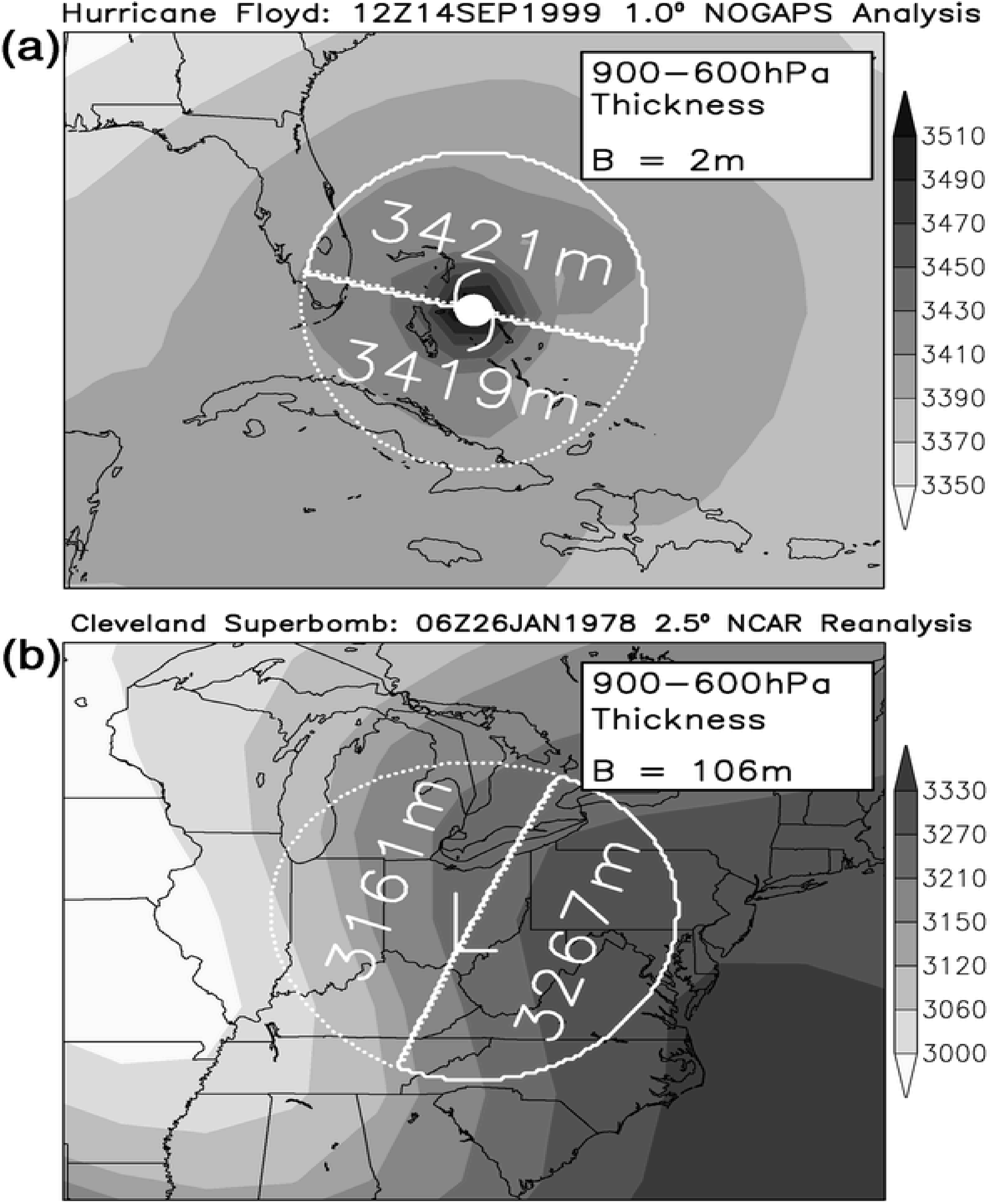


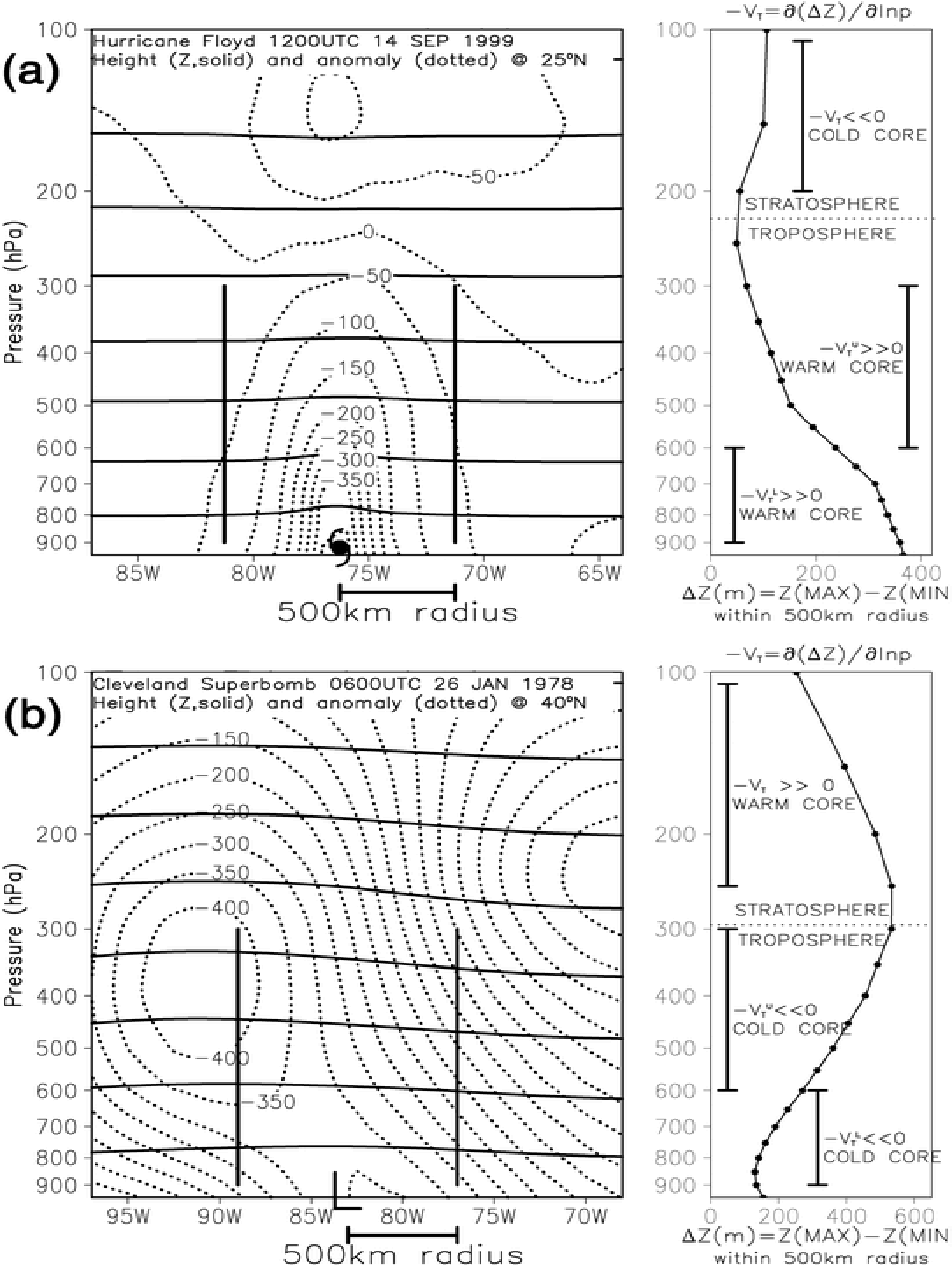

**Figure 2.14:** Schematic of the surface temperature and wind fields associated with a tropical cyclone (left) and an autumn marine extratropical cyclone, such as might result from an extratropical transformation of the tropical cyclone (right), adapted from Mook (1955). The structure of the extratropical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




Tropical Cyclone versus Extratropical Cyclone:

Non-frontal versus frontal

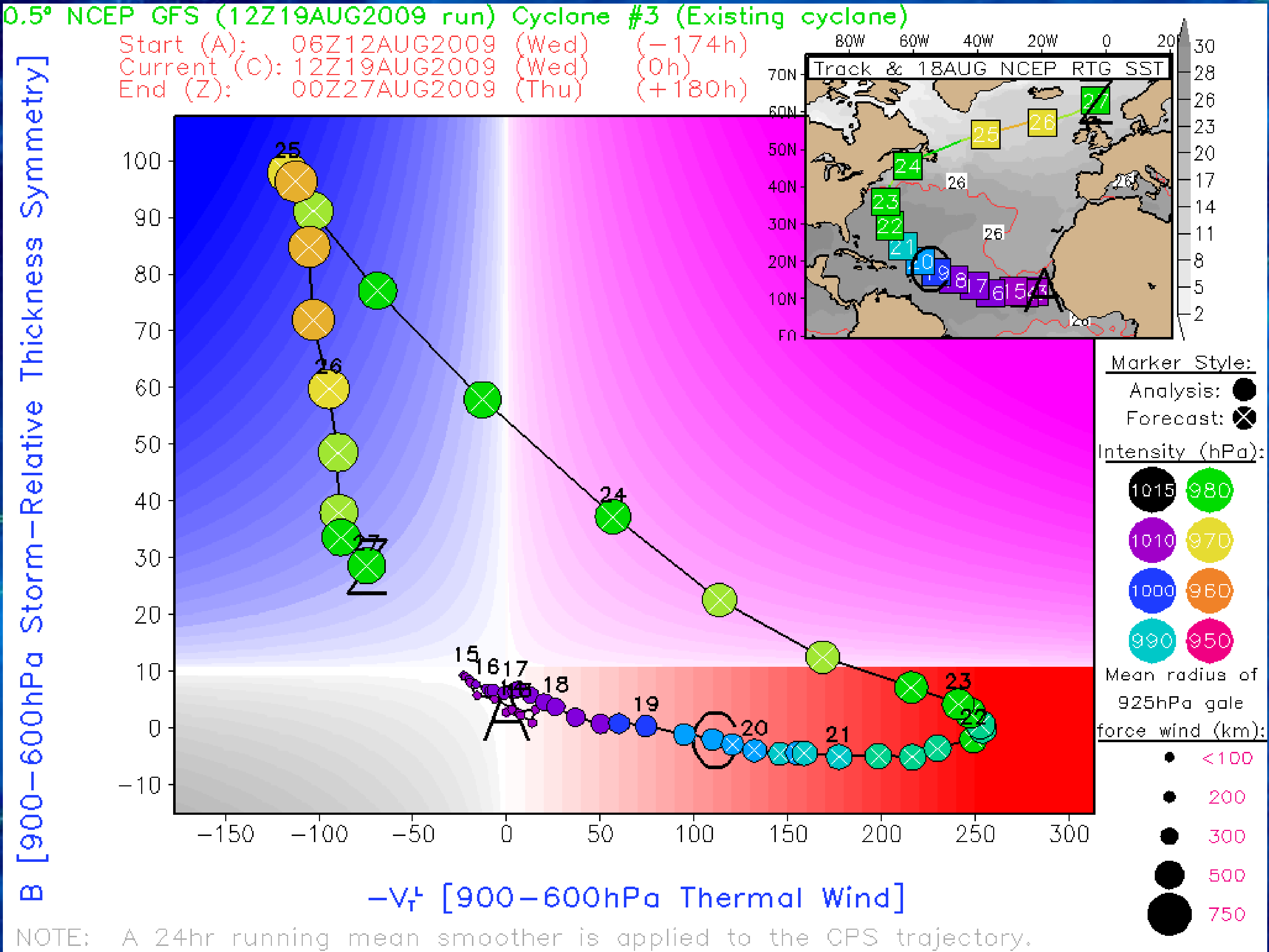
(Hart 2003)




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

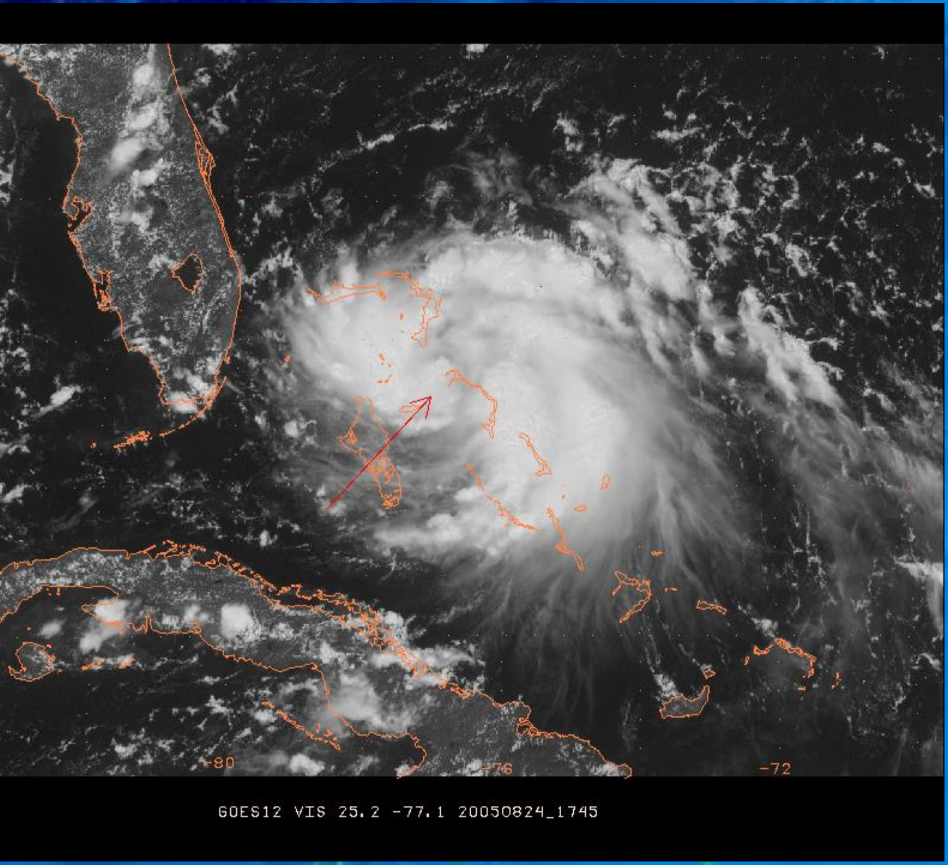
- (Hart 2003)

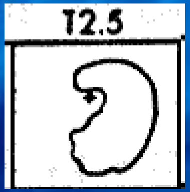
# Cyclone Phase Space for Bill



# 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?**

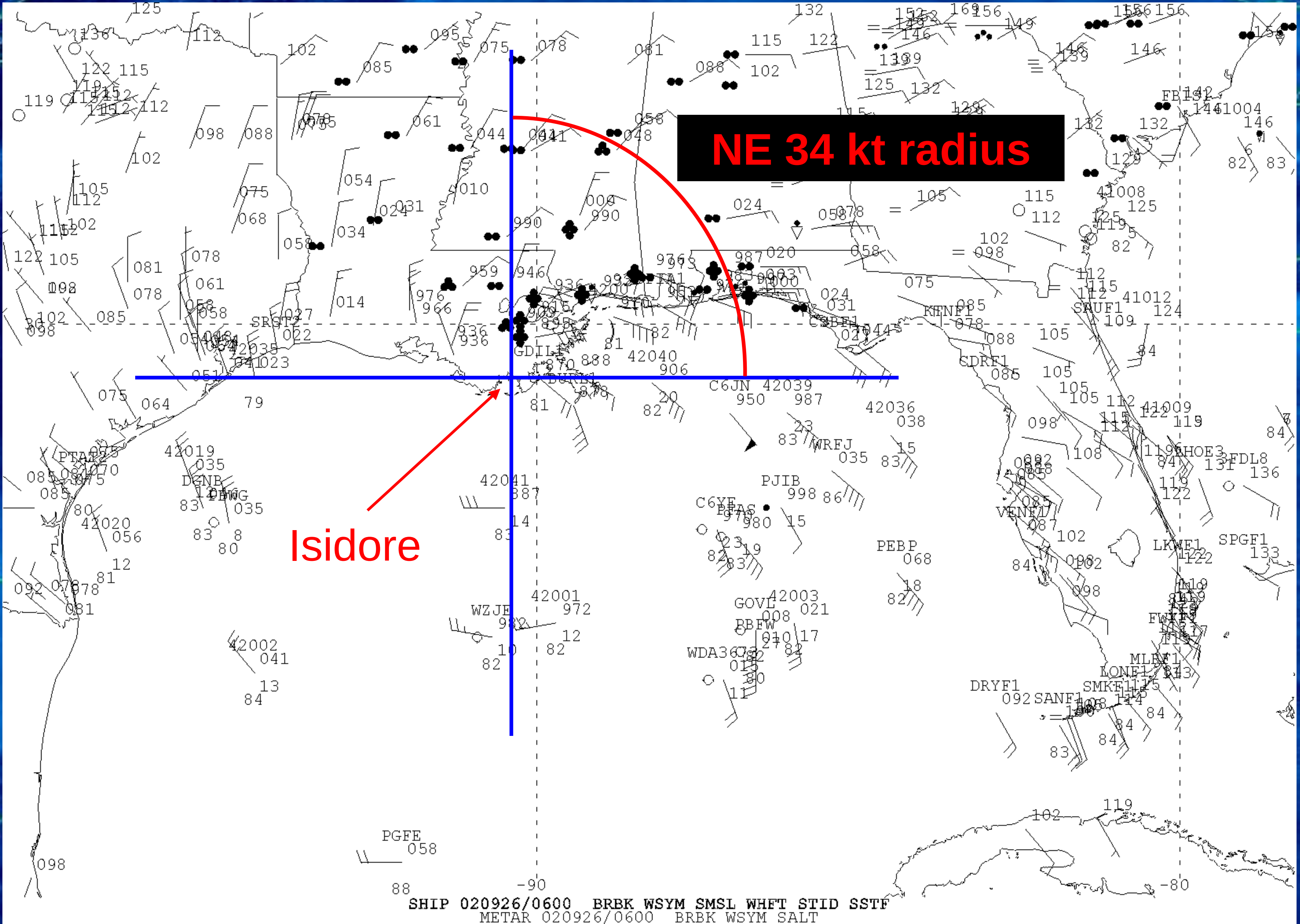
-NHC estimates cyclone "size" via wind radii in four quadrants

radii represent the largest distance from center in particular quadrant


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

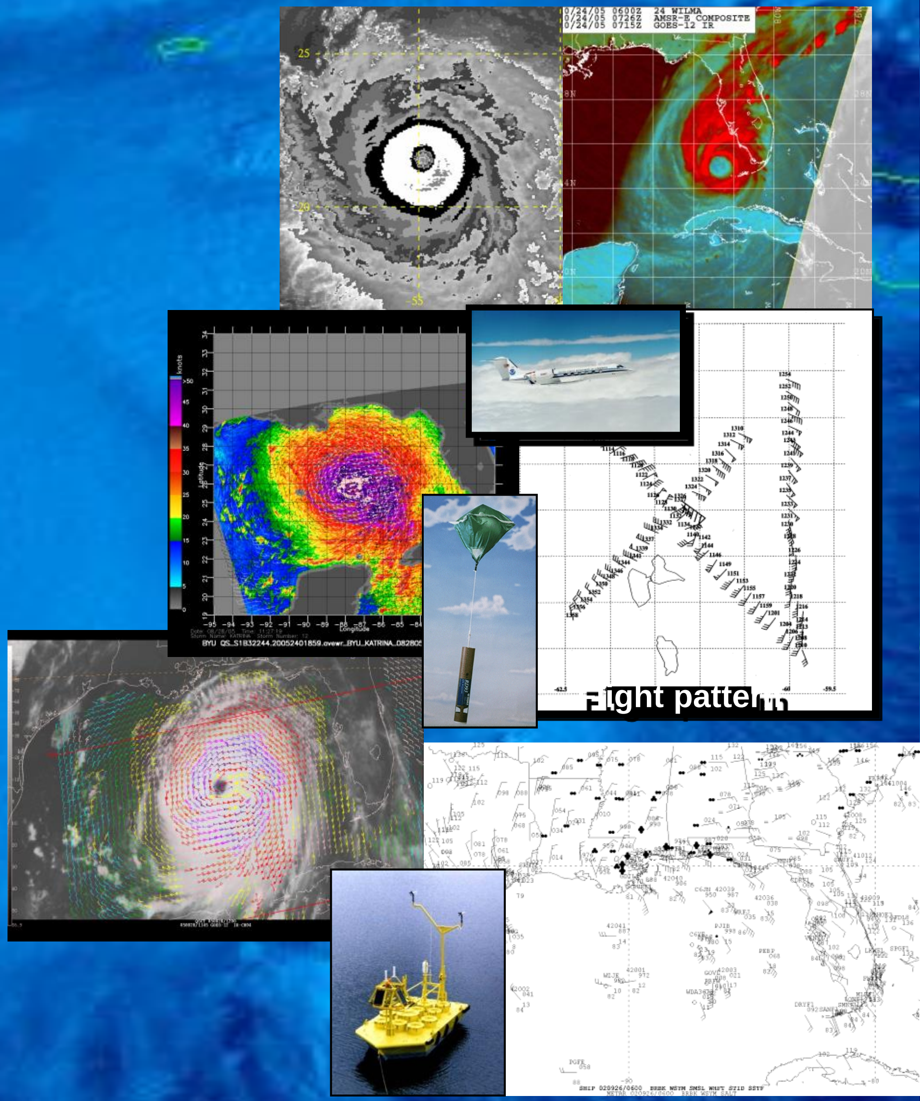
•Wind radius = Largest distance from the center of the tropical cyclone of a particular sustained surface wind speed threshold (e.g., 34, 50, 64 kt) somewhere in a particular quadrant (NE, SE, SW, NW) surrounding the center and associated with the circulation at a given point in time

# Limitations of Four-Quadrant Radii

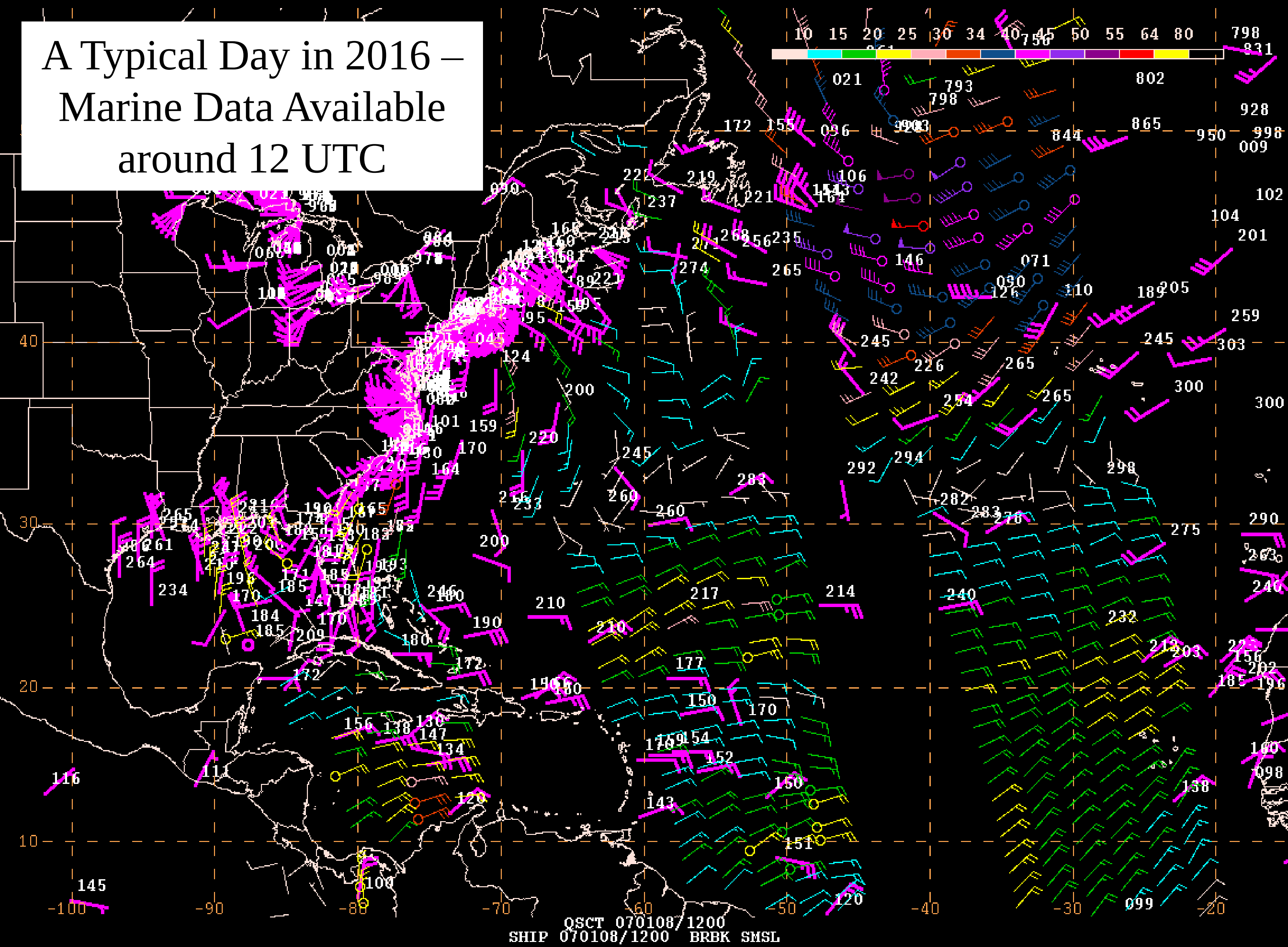


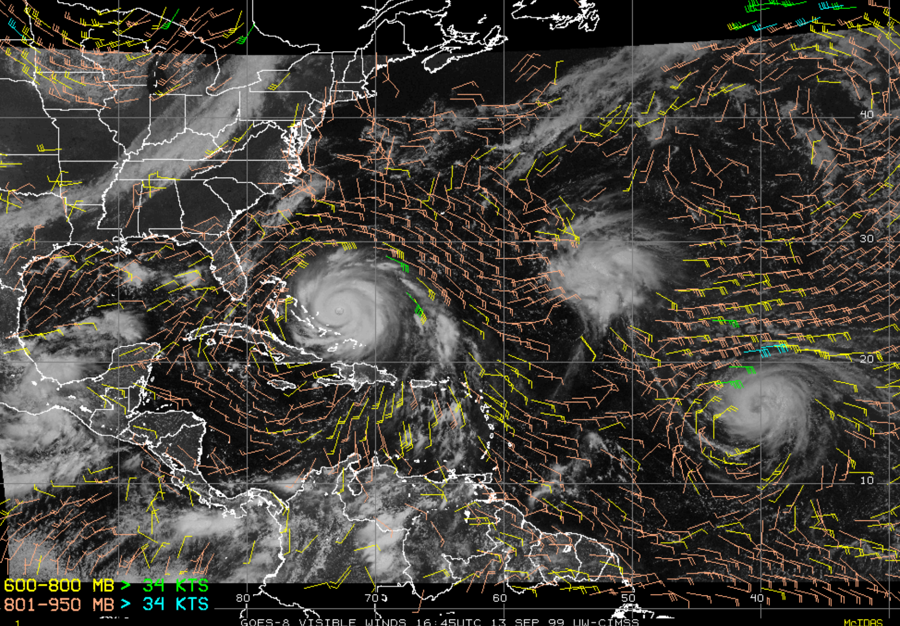
# Data to Determine Tropical Cyclone Size

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

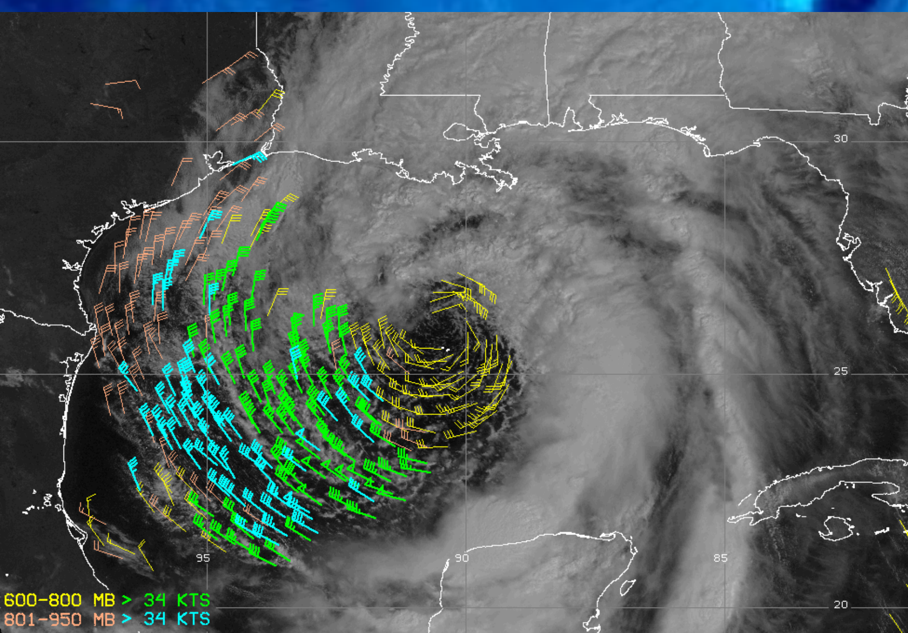


# A Typical Day in 2016 – Marine Data Available around 12 UTC





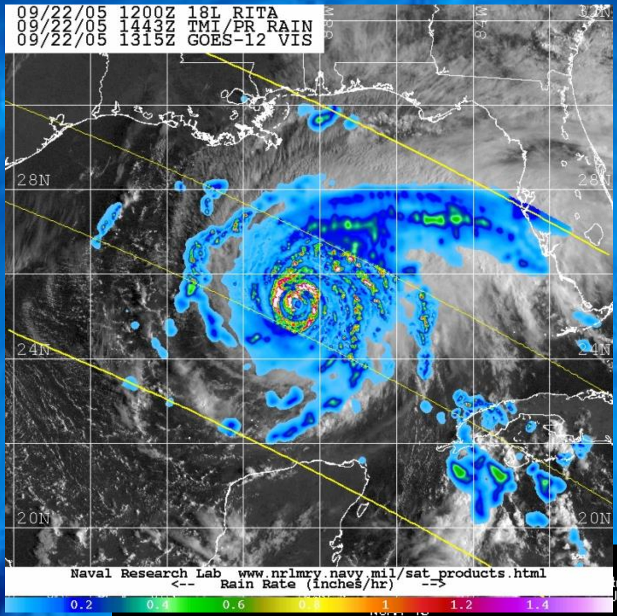

Satellite winds for nearby environment and TC size

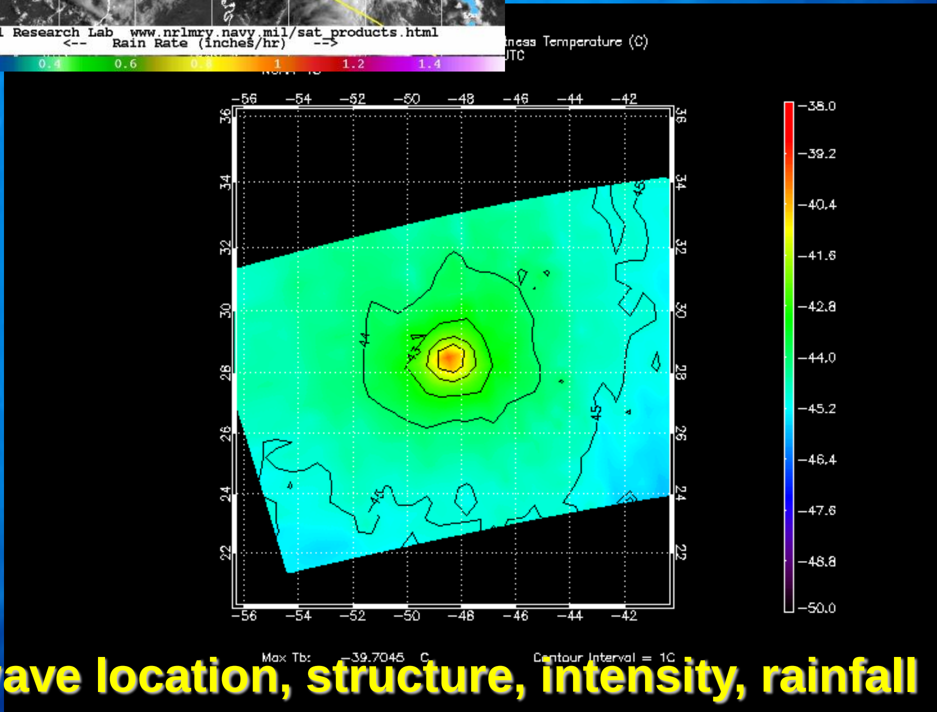



# Geostationary satellite – Low-level cloud drift winds

# Low-Earth-Orbit Satellites

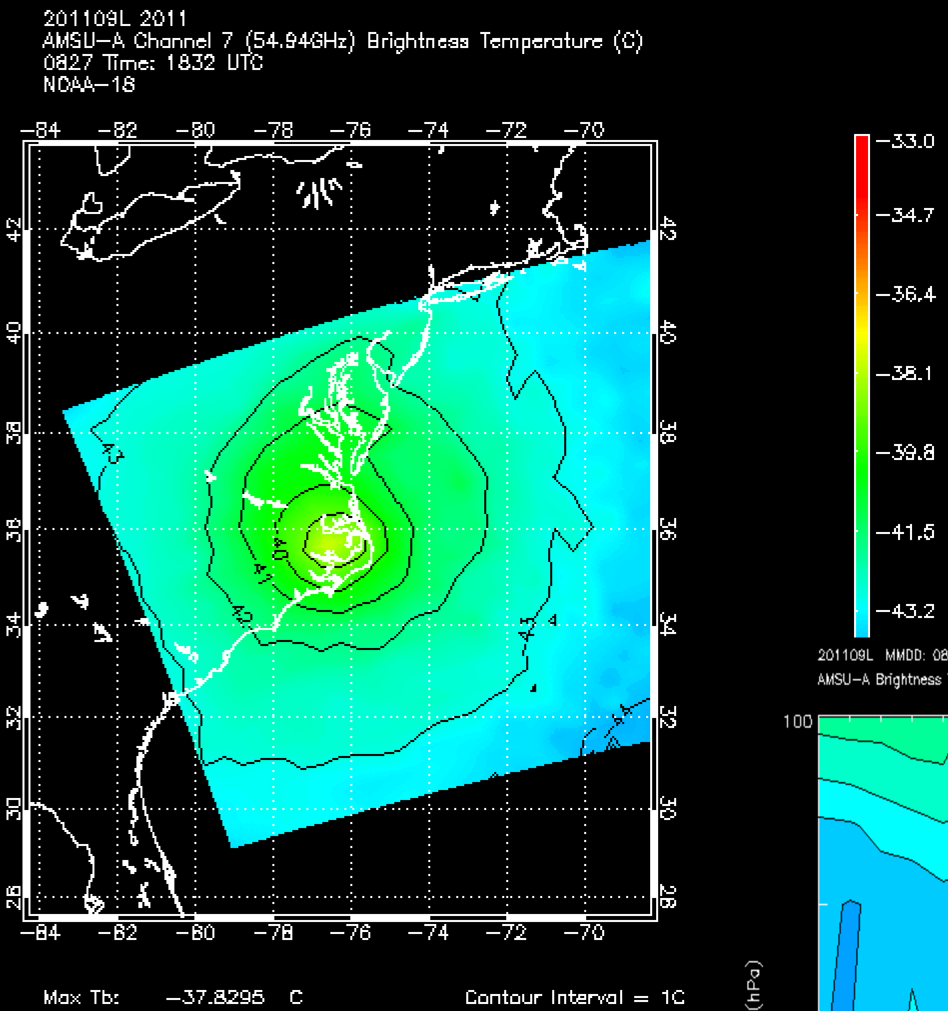
- Carry microwave imagers and sounders that can see through cloud tops and reveal the structures underneath
- Gaps in instrument coverage between orbits, which causes irregular sampling of cyclones

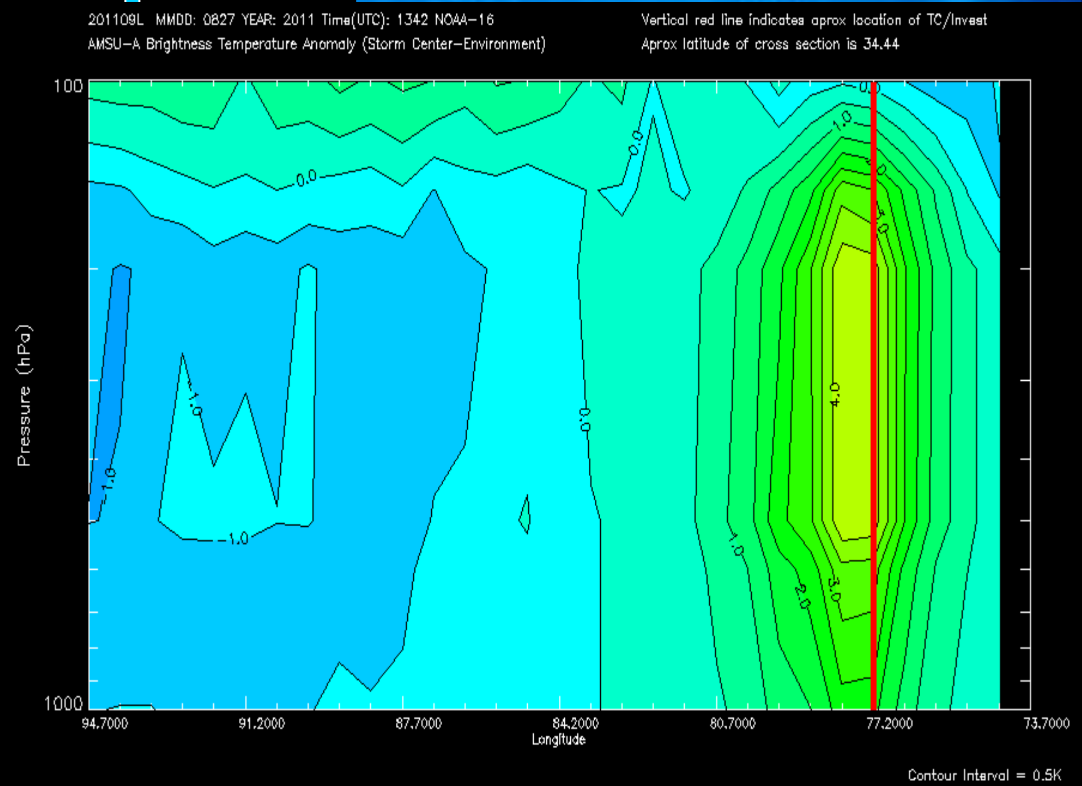



Microwave location, structure, intensity, rainfall

# Advanced Microwave Sounding Unit

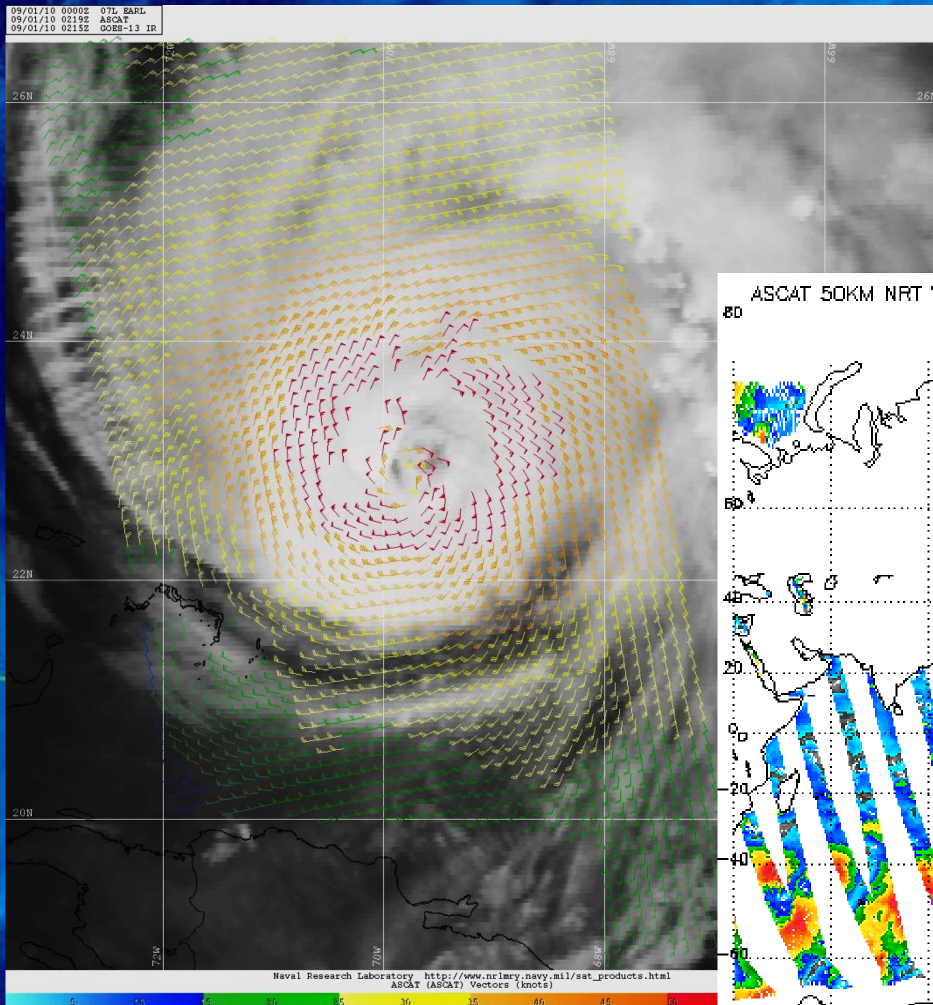


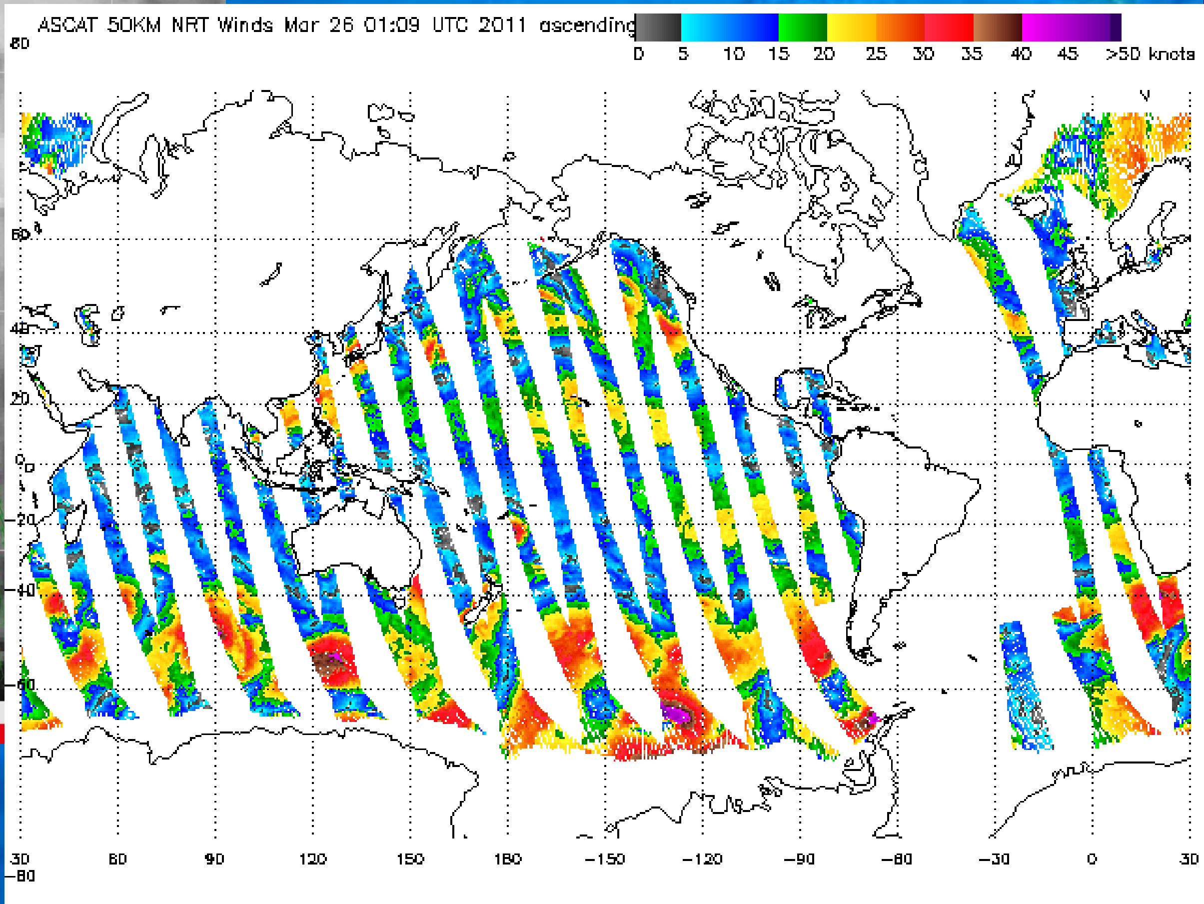




# AMSU Size Recommendations

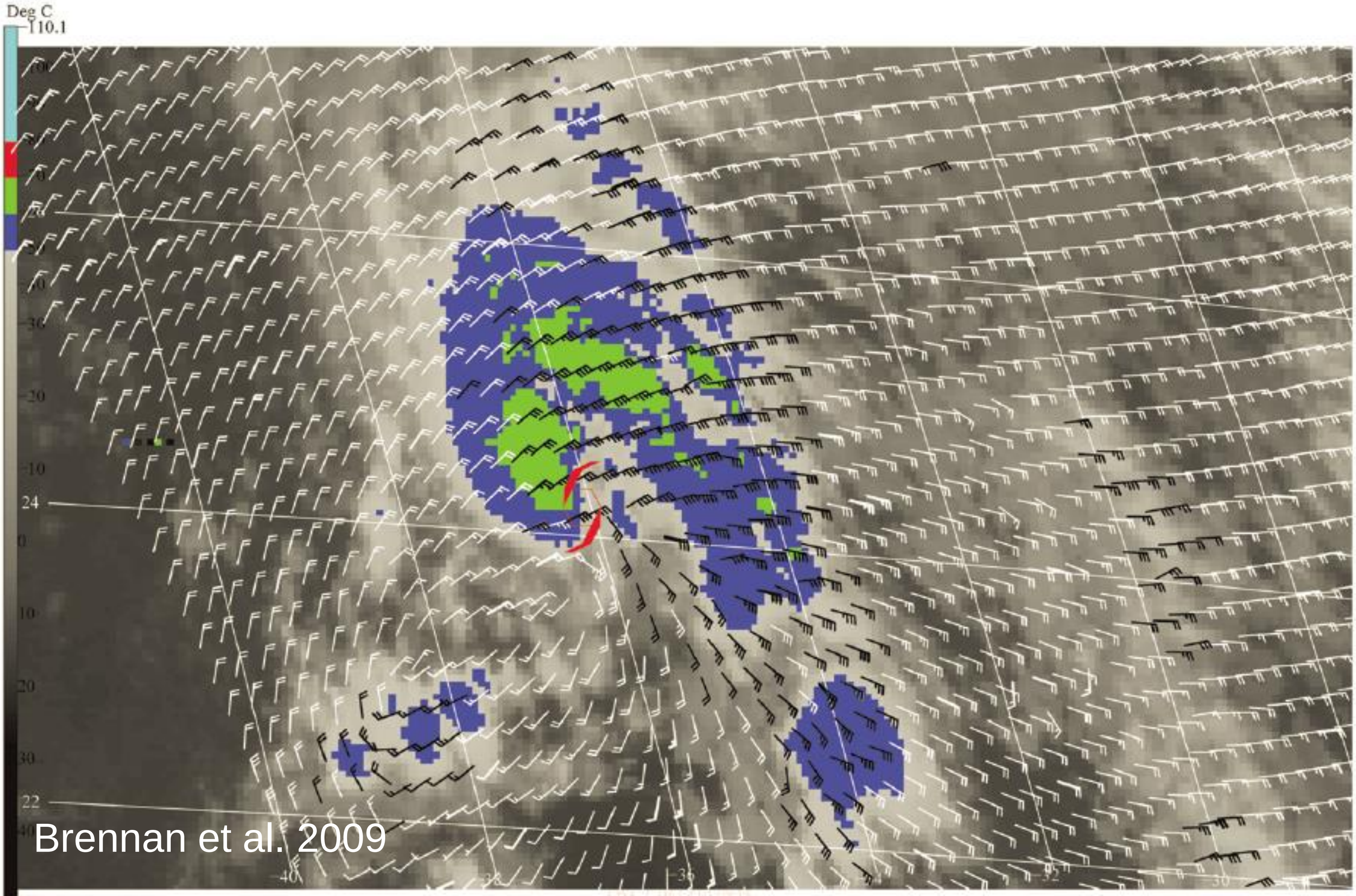
- Given the skill (substantial improvement over stratified climatology) in the AMSU size estimates and the frequent lack of other tools, its use is recommended in the absence of aircraft reconnaissance
- Considerations in its use:
  - 34 kt radii too small, 64 kt too large – can adjust by ~20%
  - AMSU is too round – make right front quad larger by ~20%, make left rear quad smaller by ~20%
  - AMSU method does not have enough sensitivity – smallest TCs aren't small enough, largest TCs aren't big enough
  - Can weight the AMSU 34 kt and 50 kt radii more for hurricanes than tropical storms
  - Can weight the AMSU 64 kt radii more for major hurricanes than Category 1 and 2 hurricanes

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



# Rain Contamination with scatterometer data

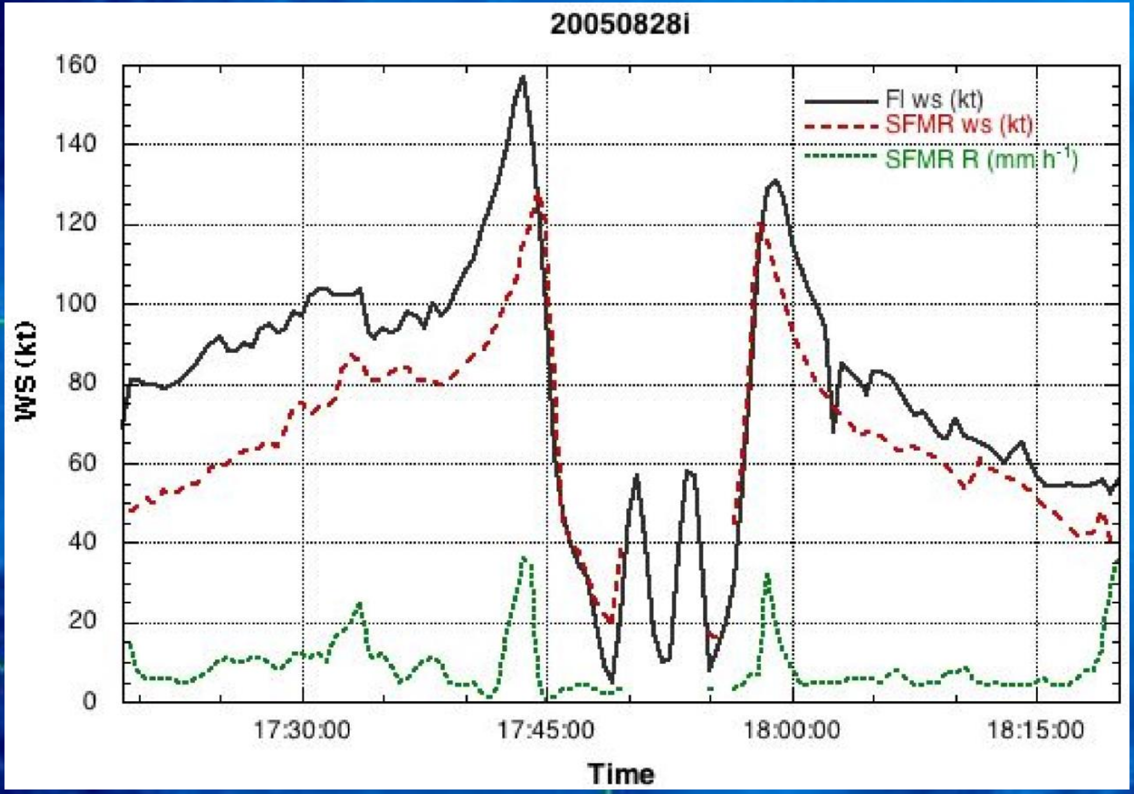


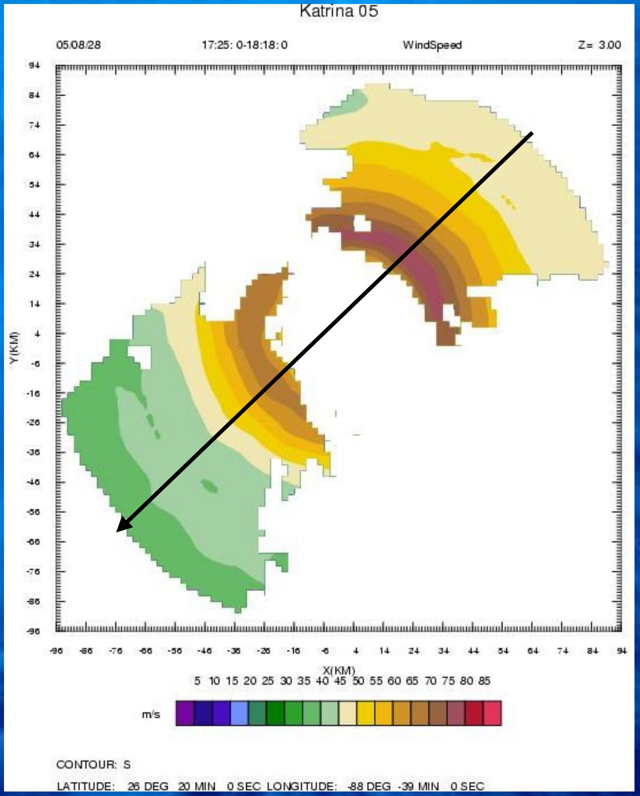

Brennan et al. 2009

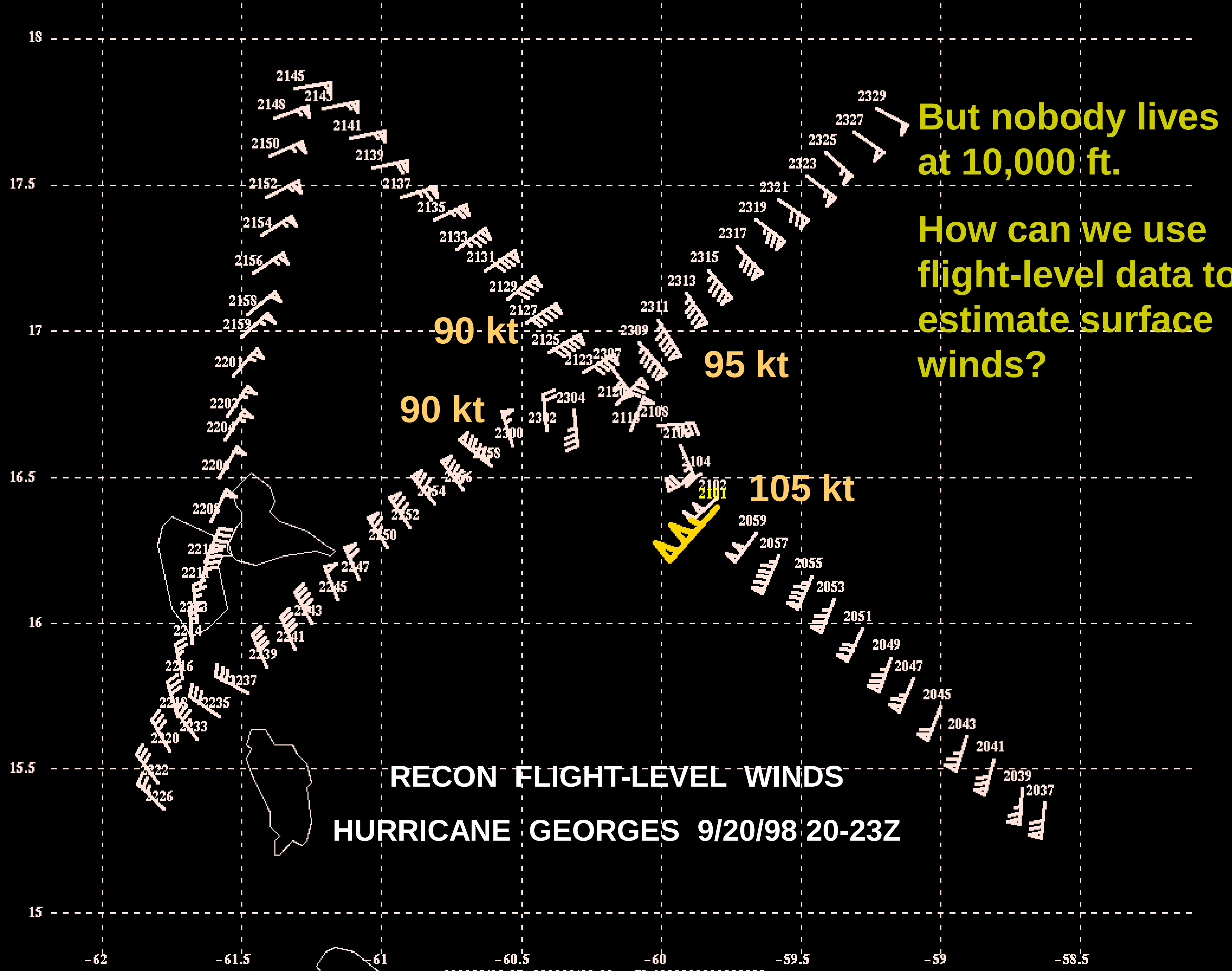
Hurricane Reconnaissance and Surveillance Aircraft (10 Air Force C-130s, 2 NOAA P3s, 1 NOAA G-IV)


# 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)



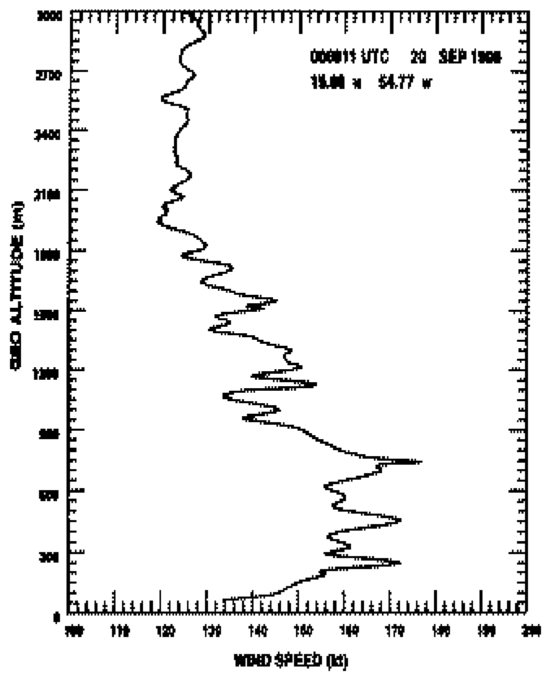




But nobody lives at 10,000 ft.
How can we use flight-level data to estimate surface winds?
90 kt
90 kt
95 kt
105 kt
RECON FLIGHT-LEVEL WINDS
HURRICANE GEORGES 9/20/98 20-23Z
18
17.5
17
16.5
16
15.5
15
-62
-61.5
-61
-60.5
-60
-59.5
-59
-58.5
980920/20:37-980920/23:30 -58.1209809209809202

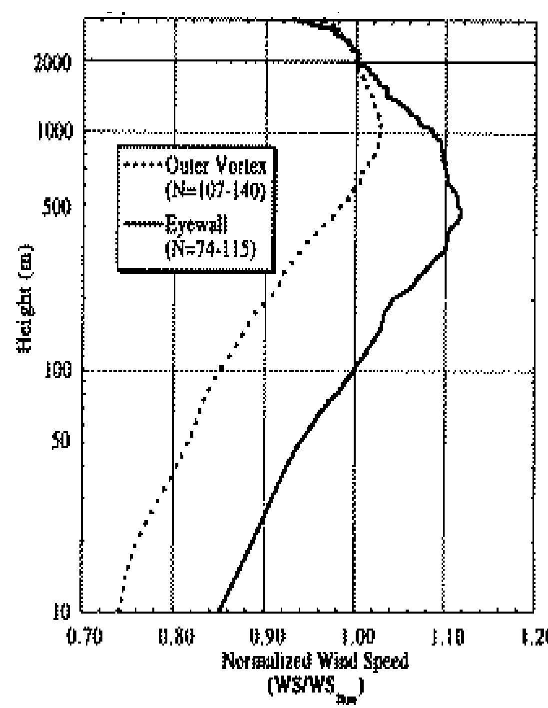
# GPS Dropsondes

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

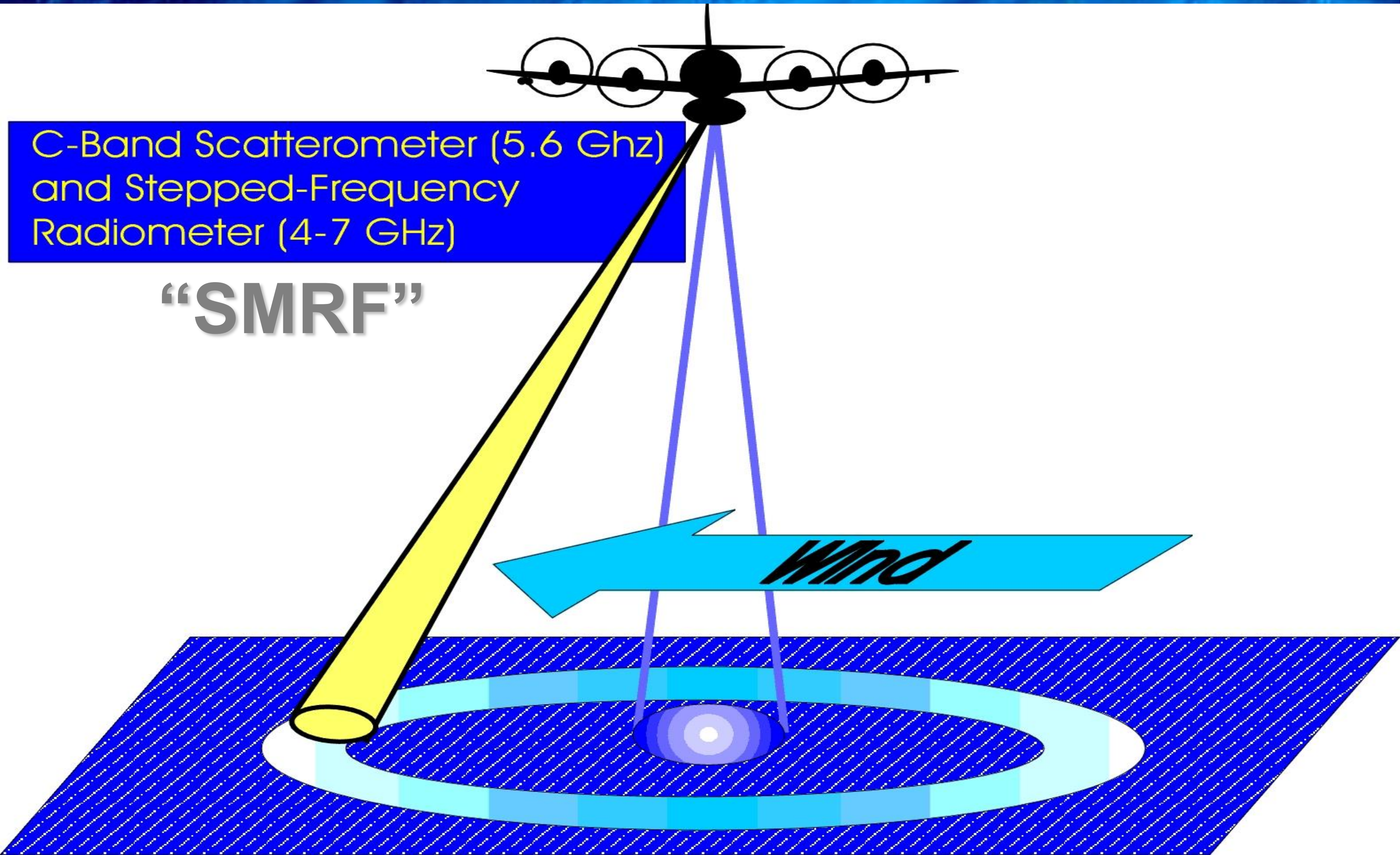
Table 2. Reduction factors and flight-level wind thresholds for determining wind radii from 700 mb data.

| 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**

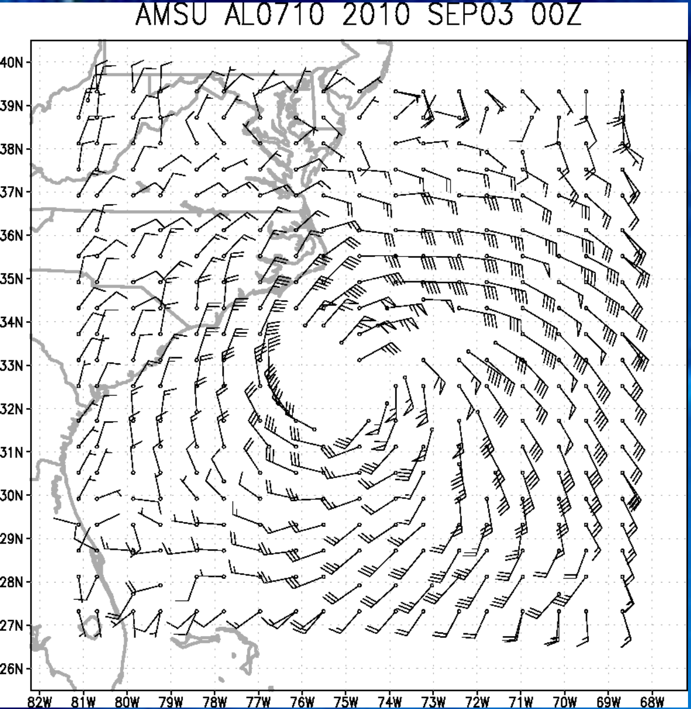
Franklin (2001)

# Remotely Sensed Surface Winds

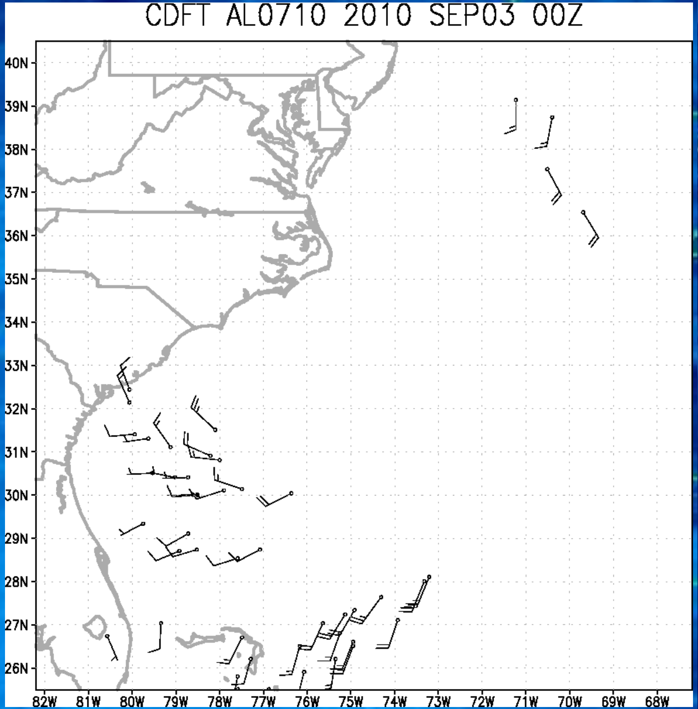


# Multiplatform Satellite Surface Wind Analysis – CIRA

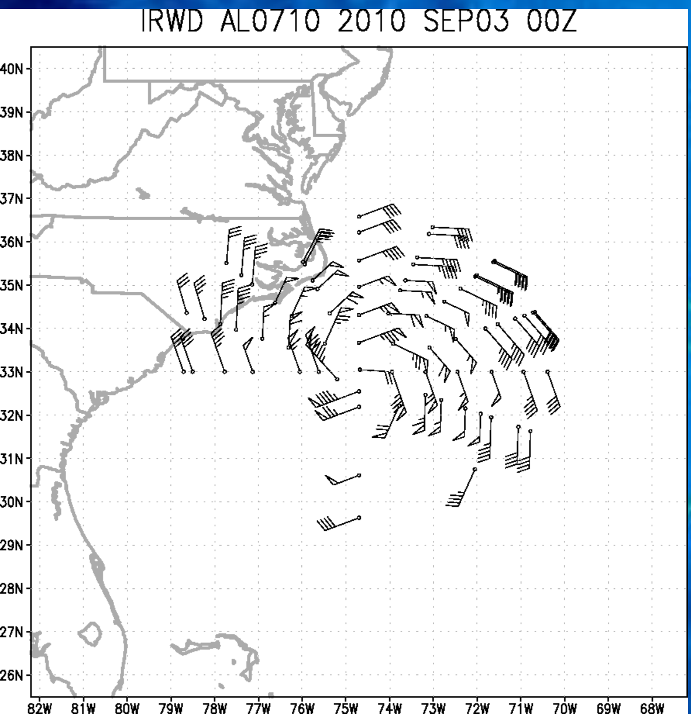
**AMSU**



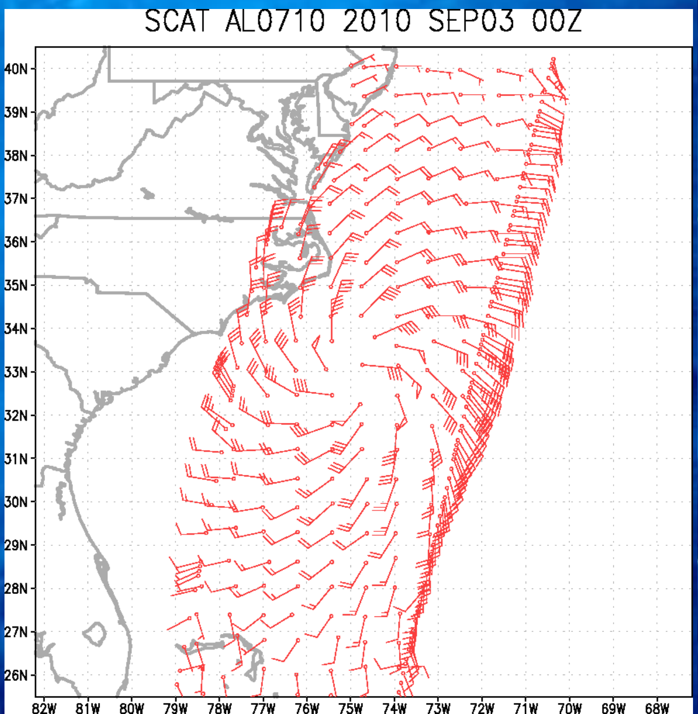

**Cloud Drift Winds**

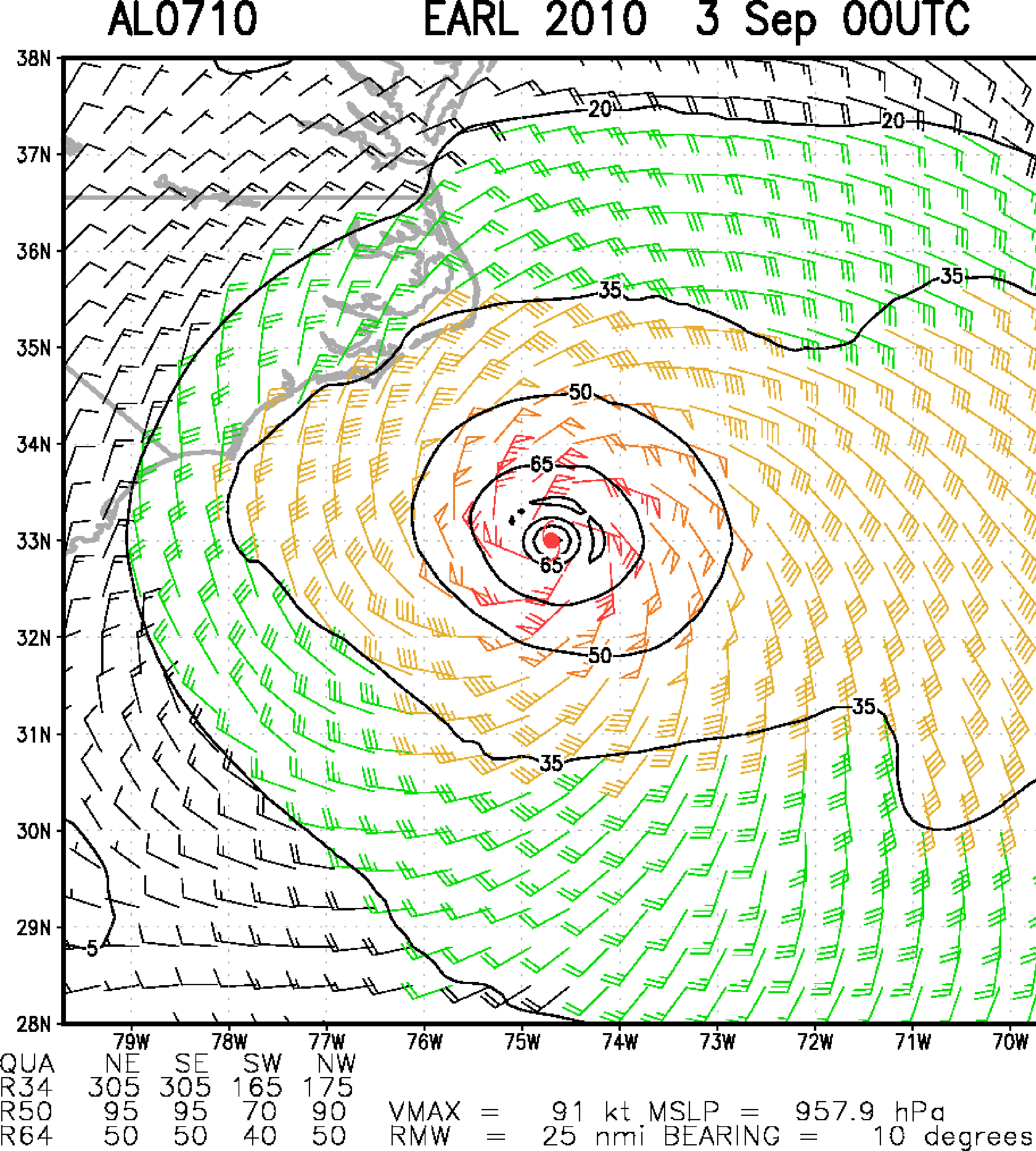



**Infrared**




**ASCAT**

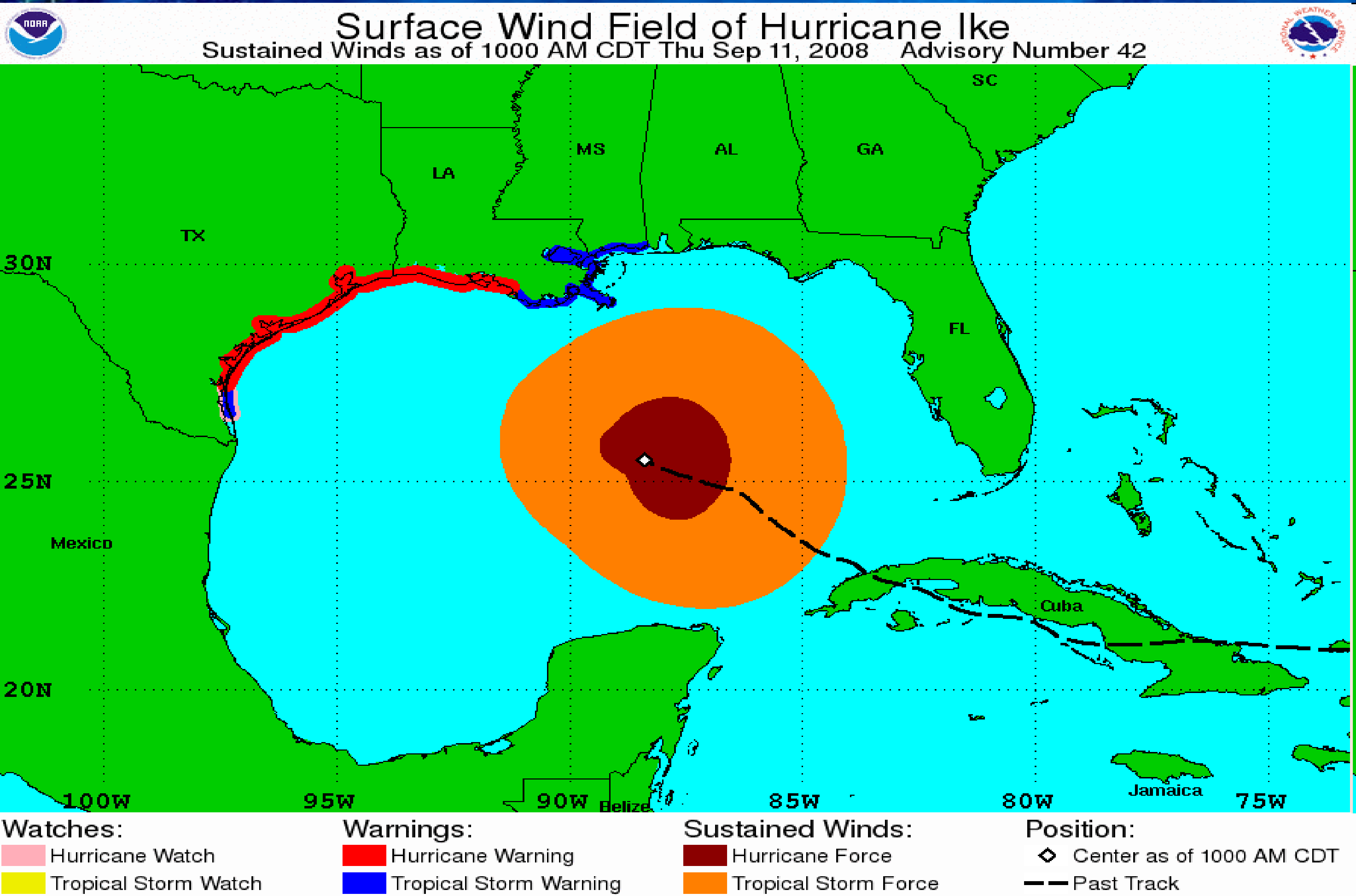





**Multiplatform Satellite Surface Wind Analysis – CIRA**

# 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

**7 March, 2016**

**World Meteorological Organization Workshop**

Chris Landsea

Chris.Landsea@noaa.gov

National Hurricane Center, Miami

NATIONAL WEATHER SERVICE

NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION
NCEP
TROPICAL PREDICTION CENTER
NATIONAL HURRICANE CENTER

NOAA

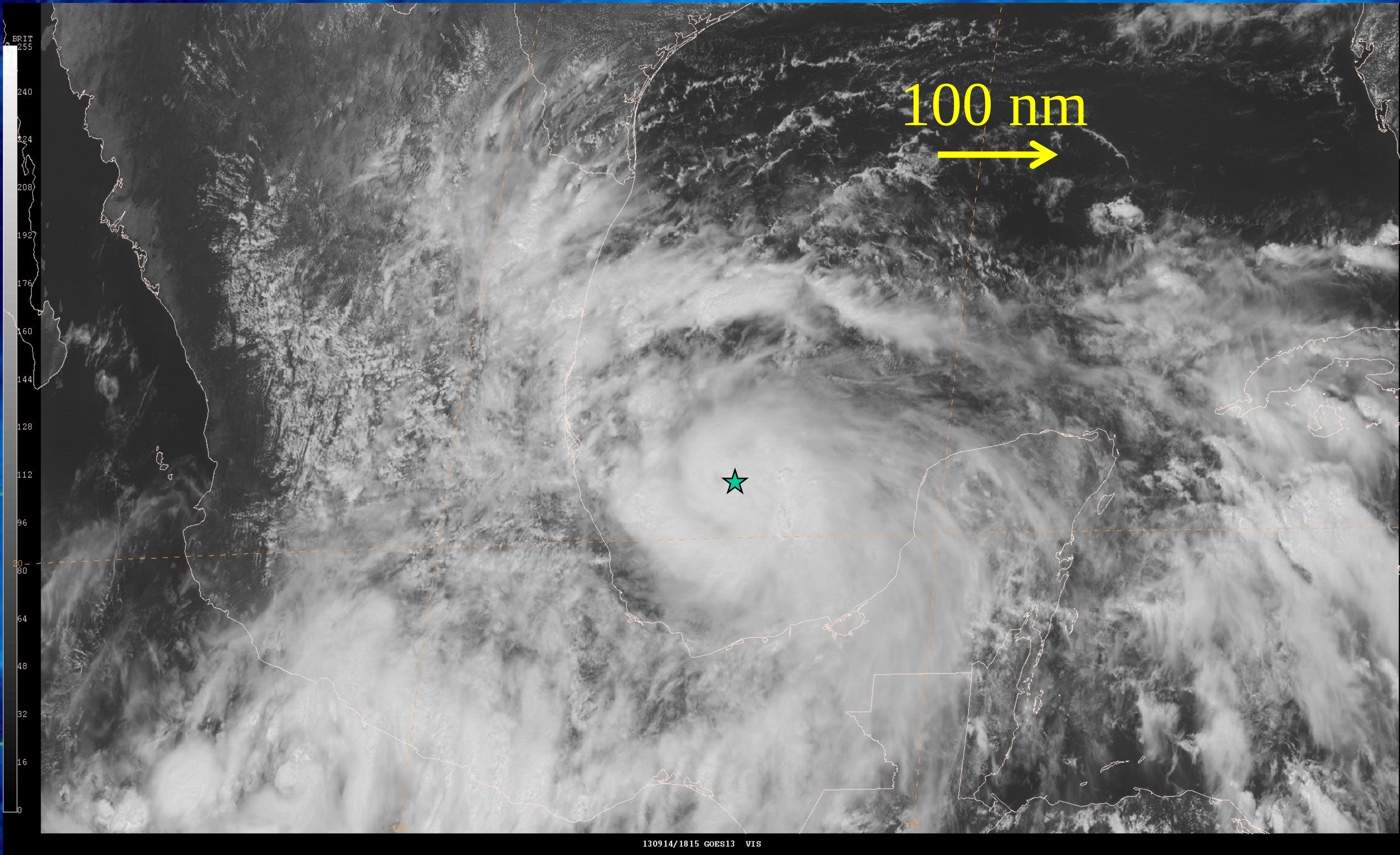
# TC Intensity Analysis Exercise
# RA-IV Workshop, 7 March, 2016

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?



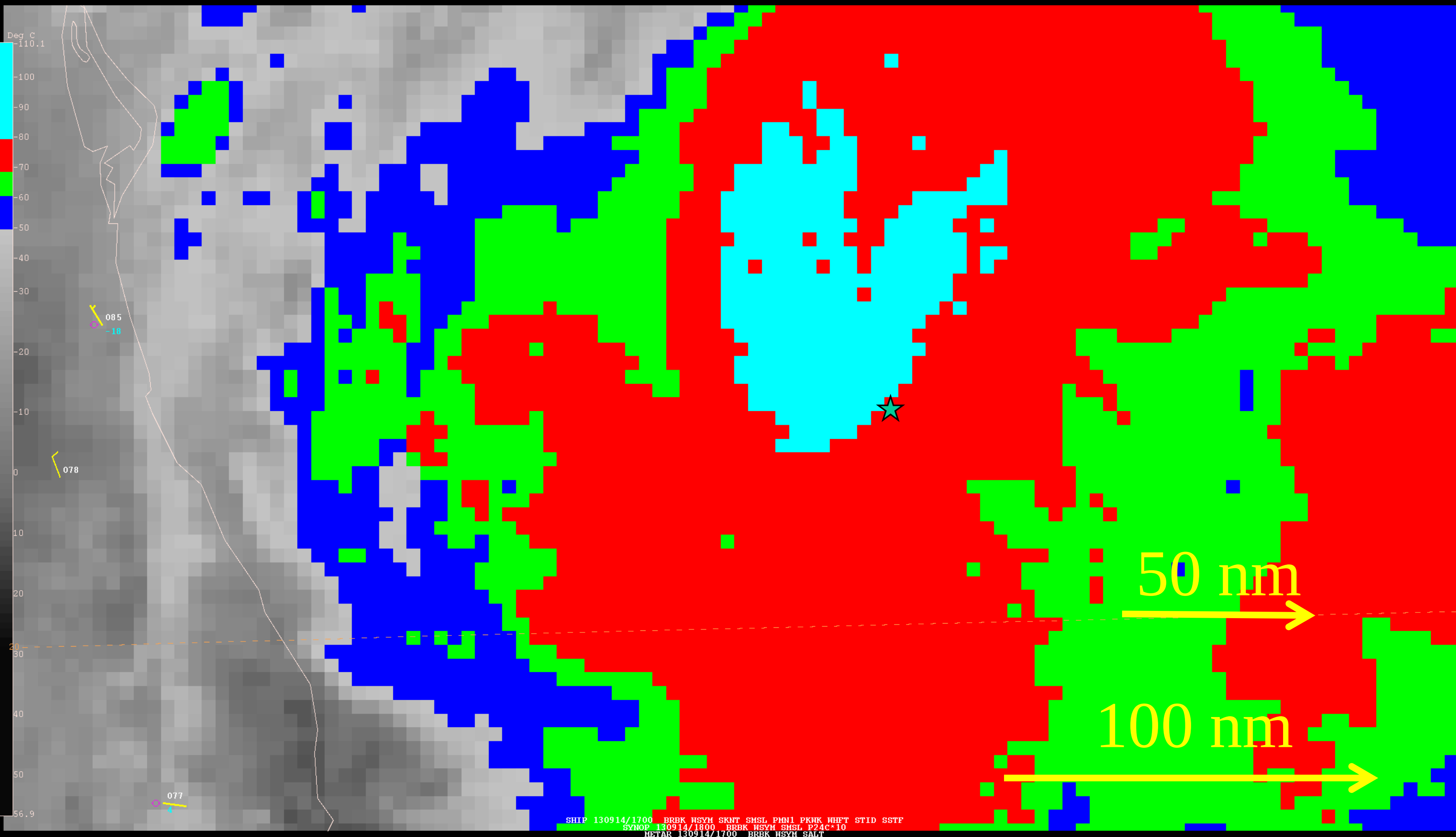
**Ingrid**

**Sep. 14th, 18Z**

**65 kt intensity**

CIRA AMSU:

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

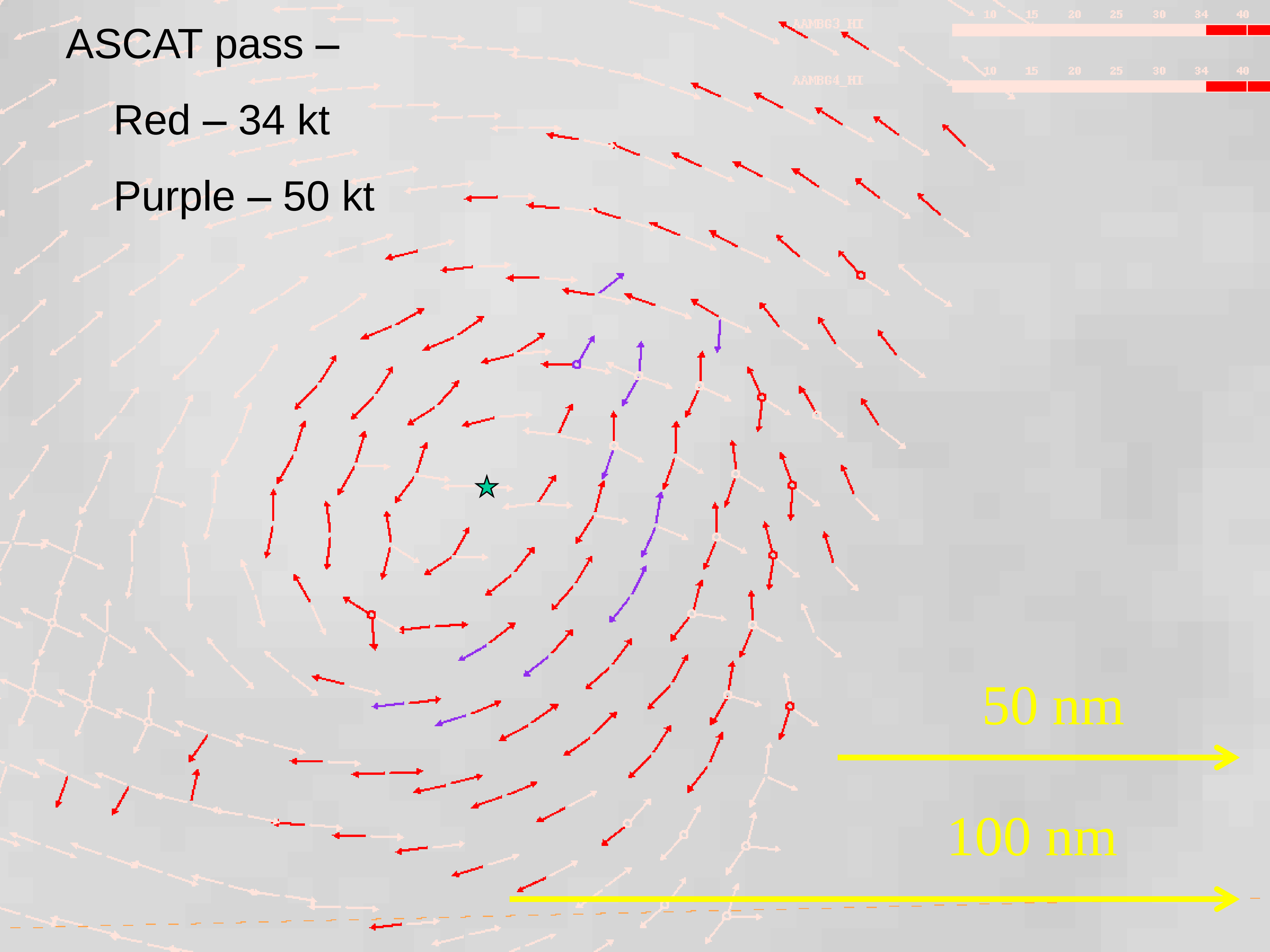


Ingrid – Sep. $14^{th}$, 18Z – 65 kt intensity

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
AAMBG3_HI
AAMBG4_HI
10 15 20 25 30 34 40
10 15 20 25 30 34 40
50 nm
100 nm

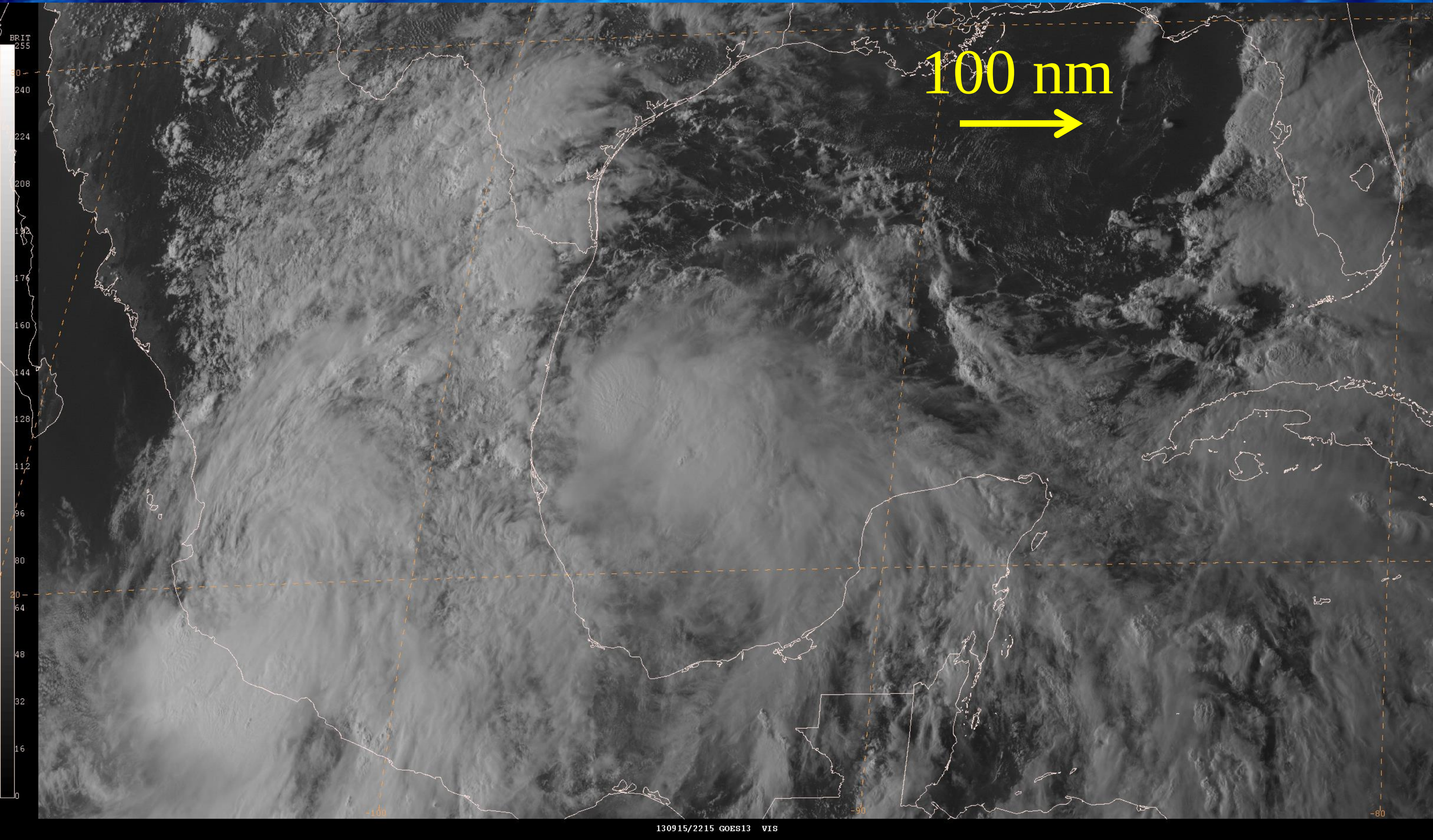
Ingrid – Sep. 14th, 18Z – 65 kt intensity

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)

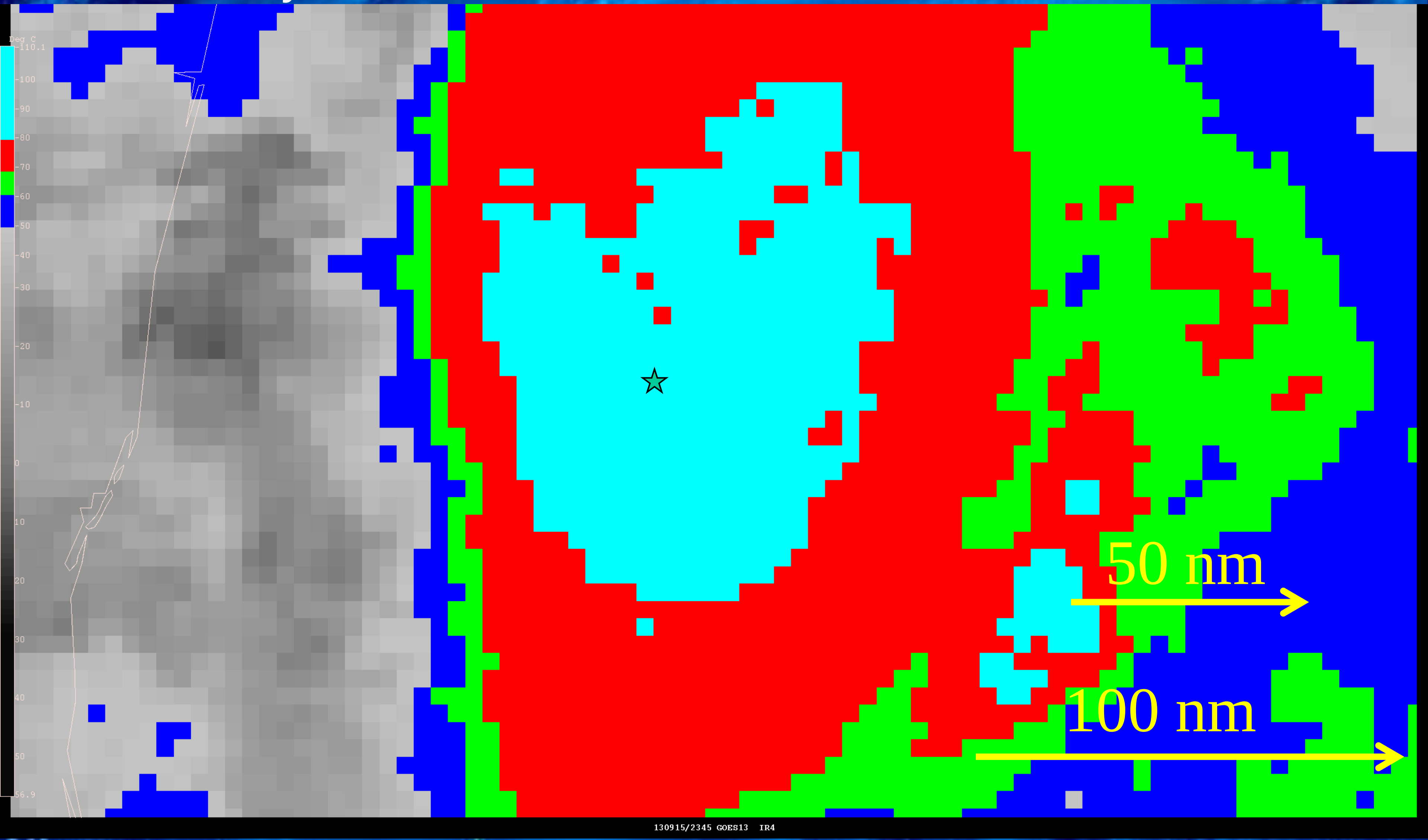
# Ingrid – Sep. 16th, 00Z – 70 kt Intensity
# How big is it?

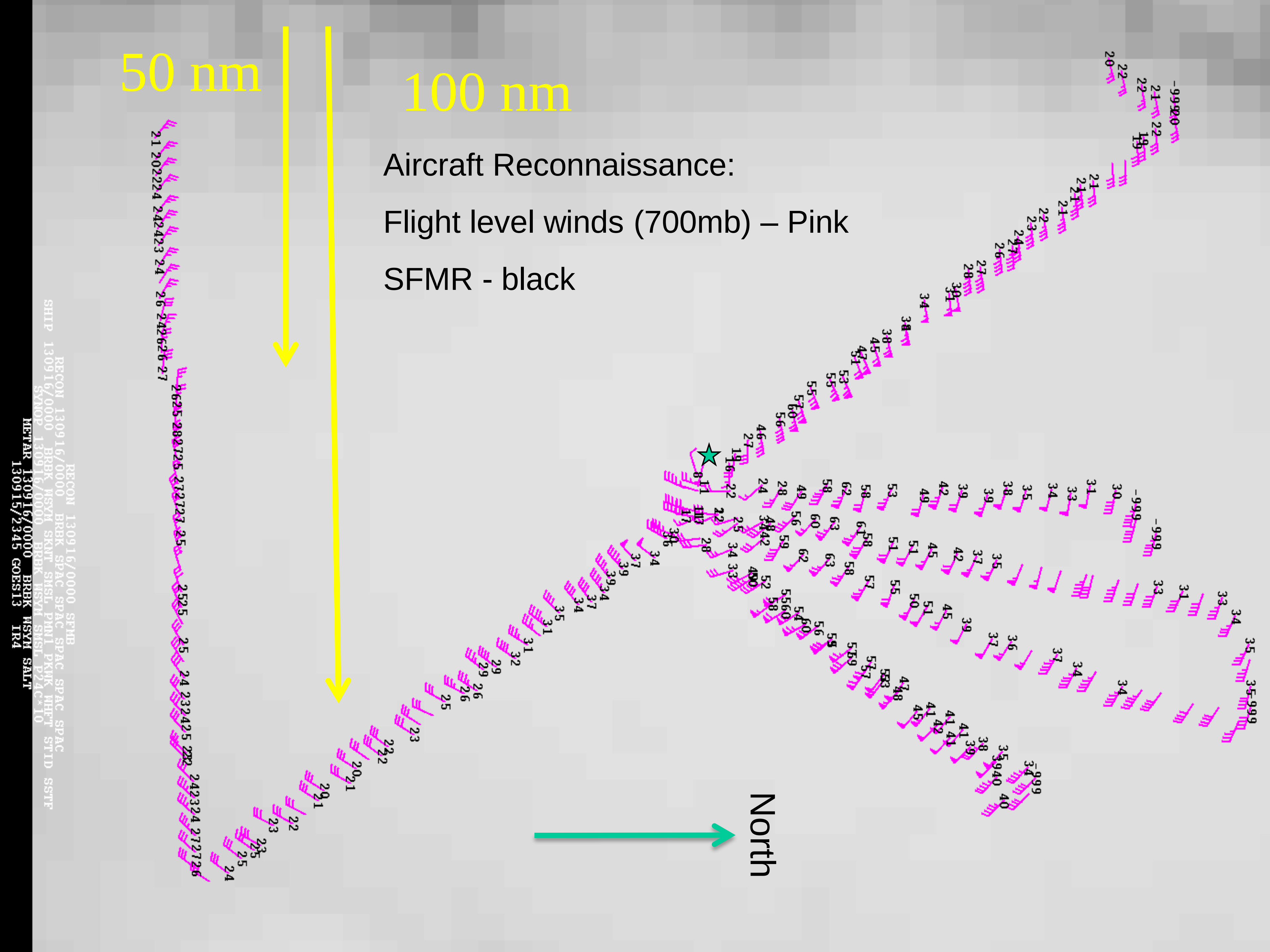


Ingrid

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)