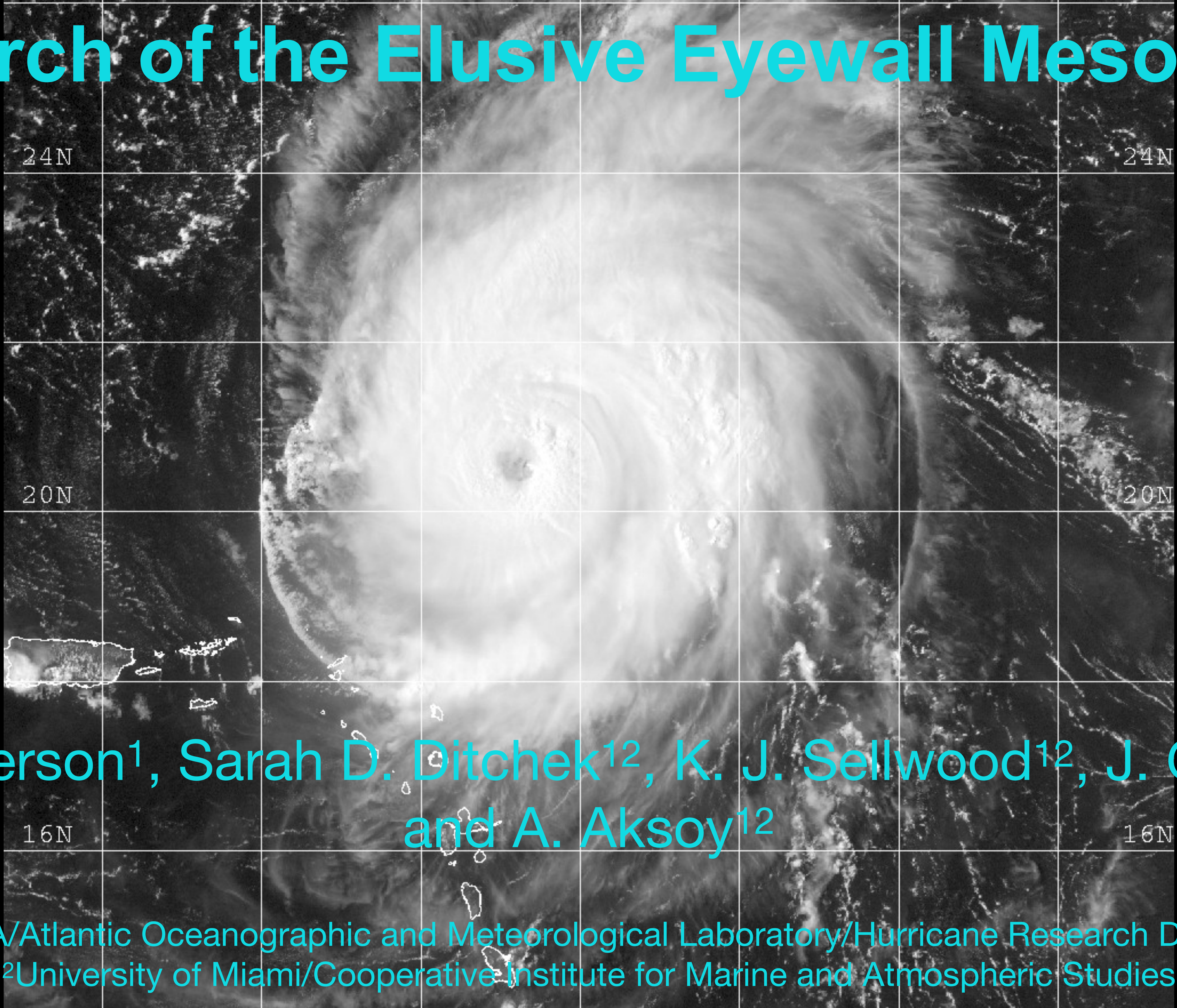
In Search of the Elusive Eyewall Mesovortex



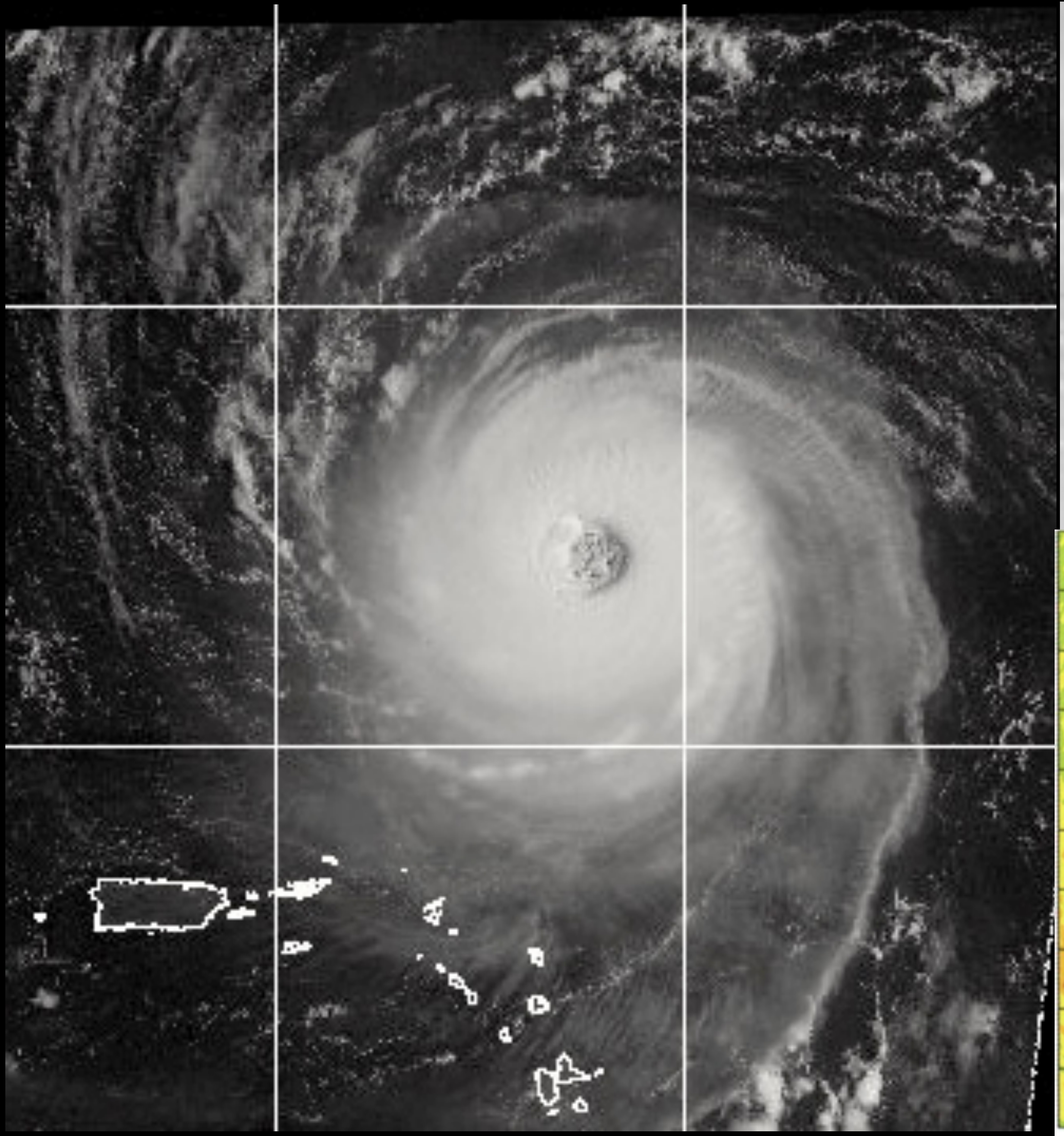
Sim D. Aberson[1], Sarah D. Ditchek[12], K. J. Sellwood[12], J. Gamache[1], and A. Aksoy[12]

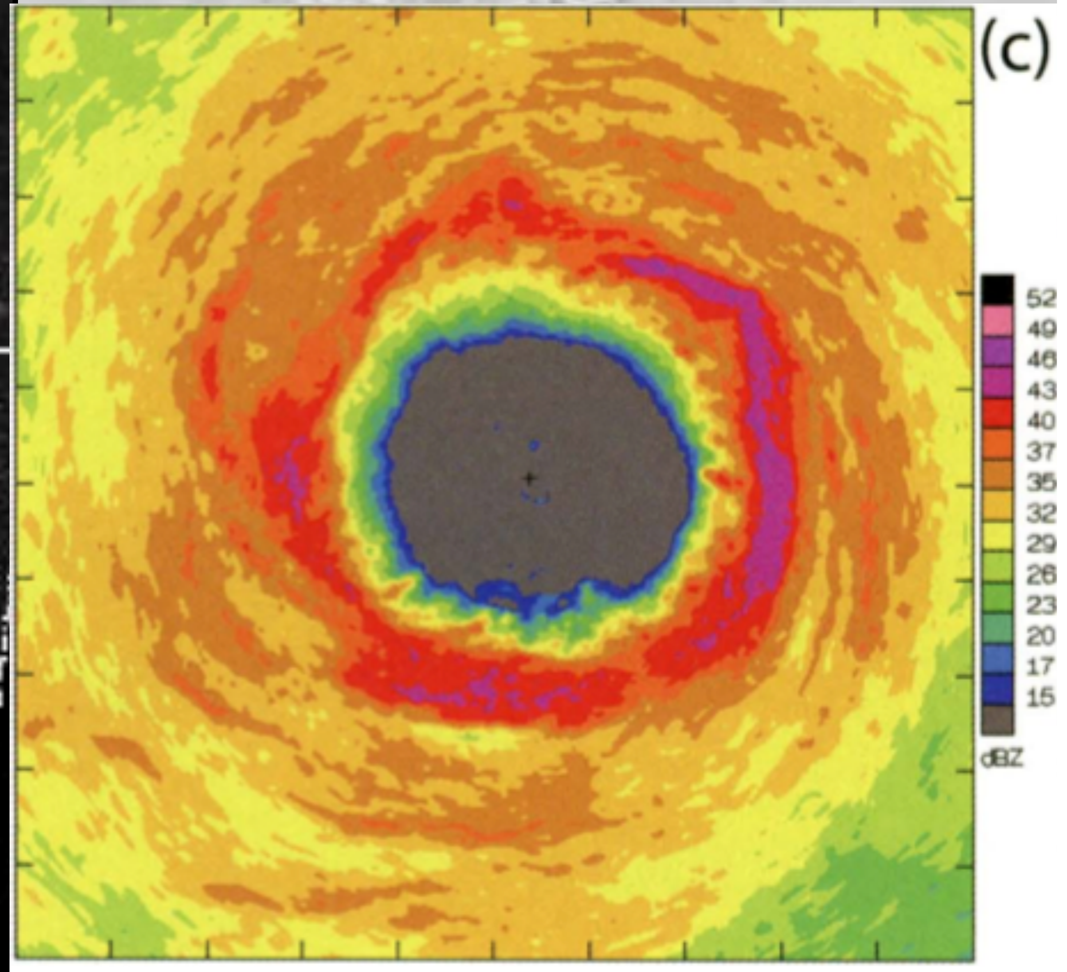
[1]NOAA/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division
[2]University of Miami/Cooperative Institute for Marine and Atmospheric Studies

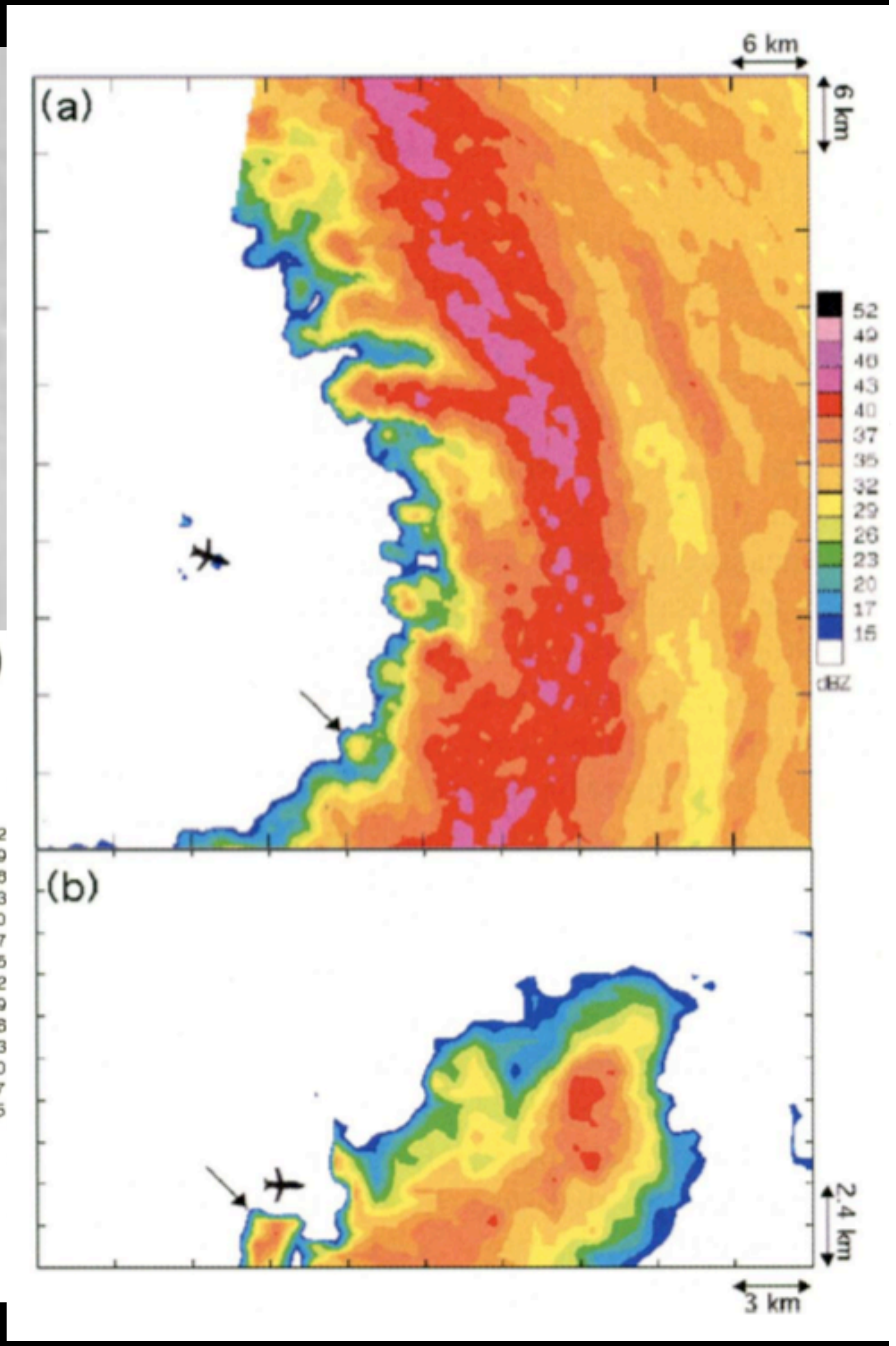
Hurricane Isabel

Meso-scale - having a horizontal scale of a few to several hundred km.
Miso-scale - having a horizontal scale of 40 m to 4 km.

Vortex: a flow with closed streamlines.
Cyclone: a cyclonic circulation, a closed circulation.







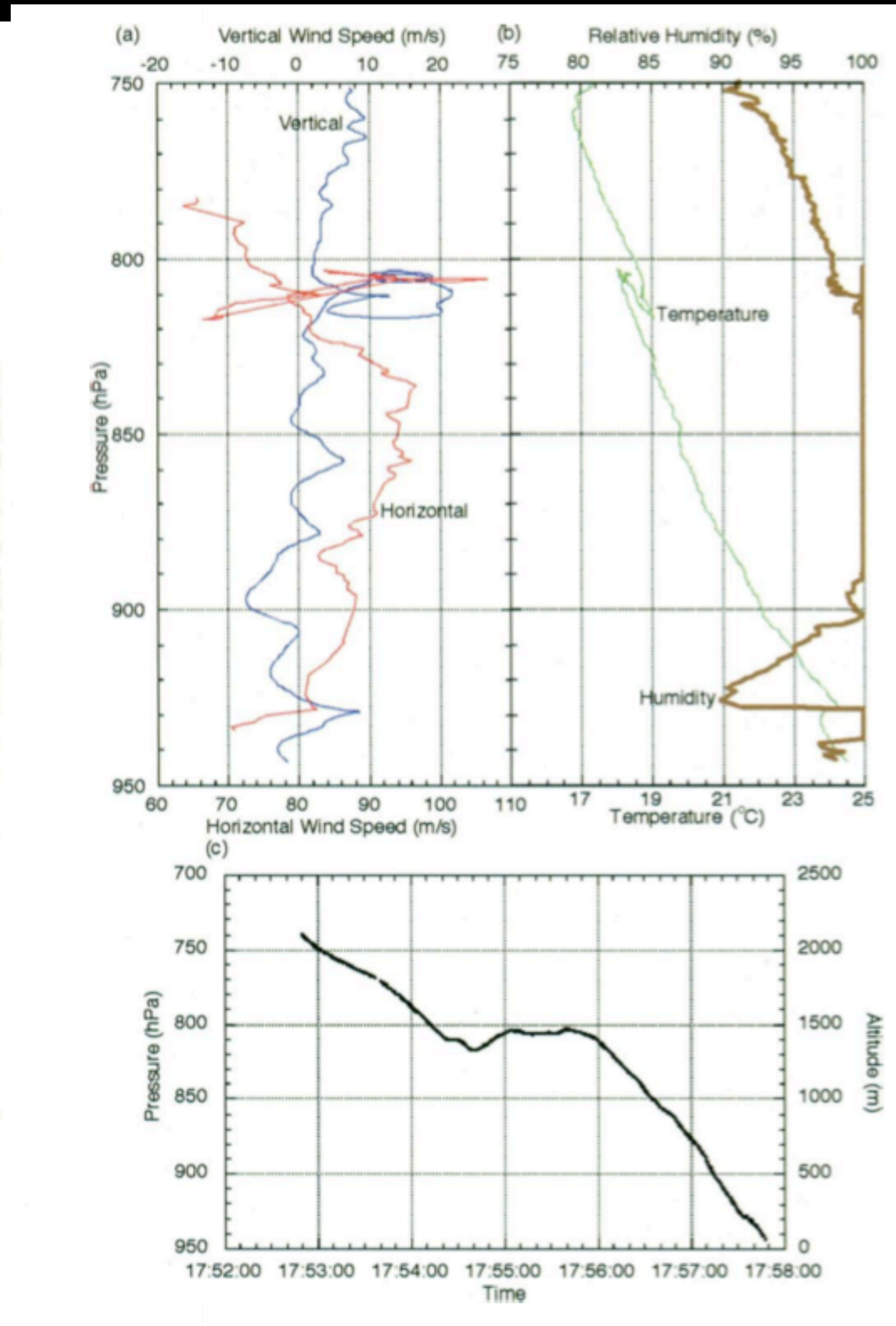


FIG. 1. Data obtained by the dropwindsonde released inside the inner edge of the eyewall of Hurricane Isabel at 1752 UTC 13 Sep 2003: (a) horizontal and vertical wind speeds as a function of pressure, (b) temperature and relative humidity as a function of pressure, and (c) altitude and pressure as a function of time.

http://glossary.ametsoc.org/

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes". *Bull. Amer. Met. Soc.*. 56, 527–530.
Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, 38, 1511–1534.

Model experiments show breakdown of the vortex on the inner edge of the eyewall, and closed wind centers (zero tangential wind). Wind and pressure centers are not in the same locations.

Rapid Filamentation Zones in Intense Tropical Cyclones

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Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

James P. Kossin
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

(Manuscript received 11 November 2003, in final form 12 August 2004)

Polygonal Eyewalls, Asymmetric Eye Contraction, and Potential Vorticity Mixing in Hurricanes

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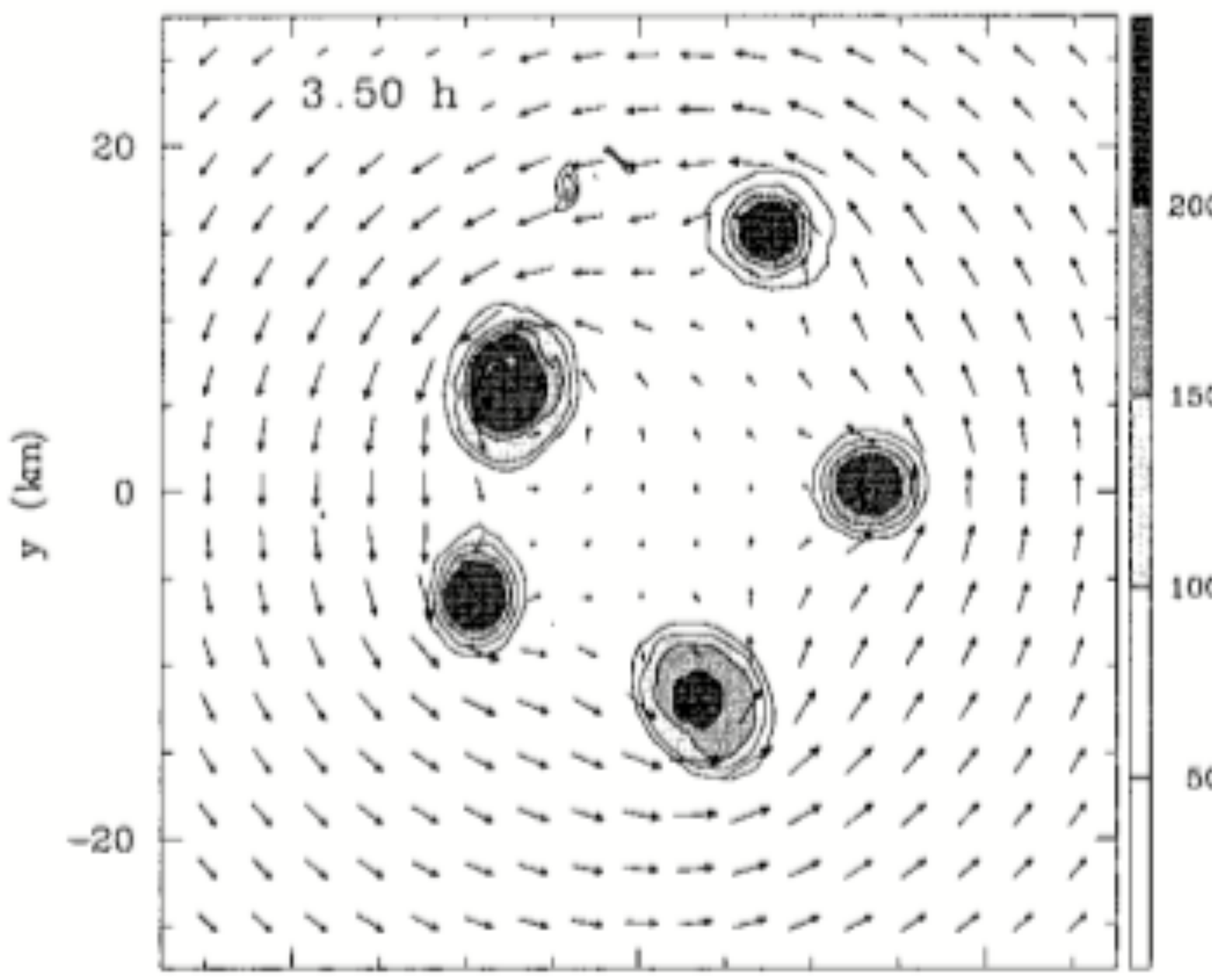
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

Vortical Swirls in Hurricane Eye Clouds

James P. Kossin
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

Brian D. McNoldy and Wayne H. Schubert
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

11 April 2002 and 14 June 2002



High-Resolution Simulation of Hurricane Bonnie (1998). Part I: The Organization of Eyewall Vertical Motion

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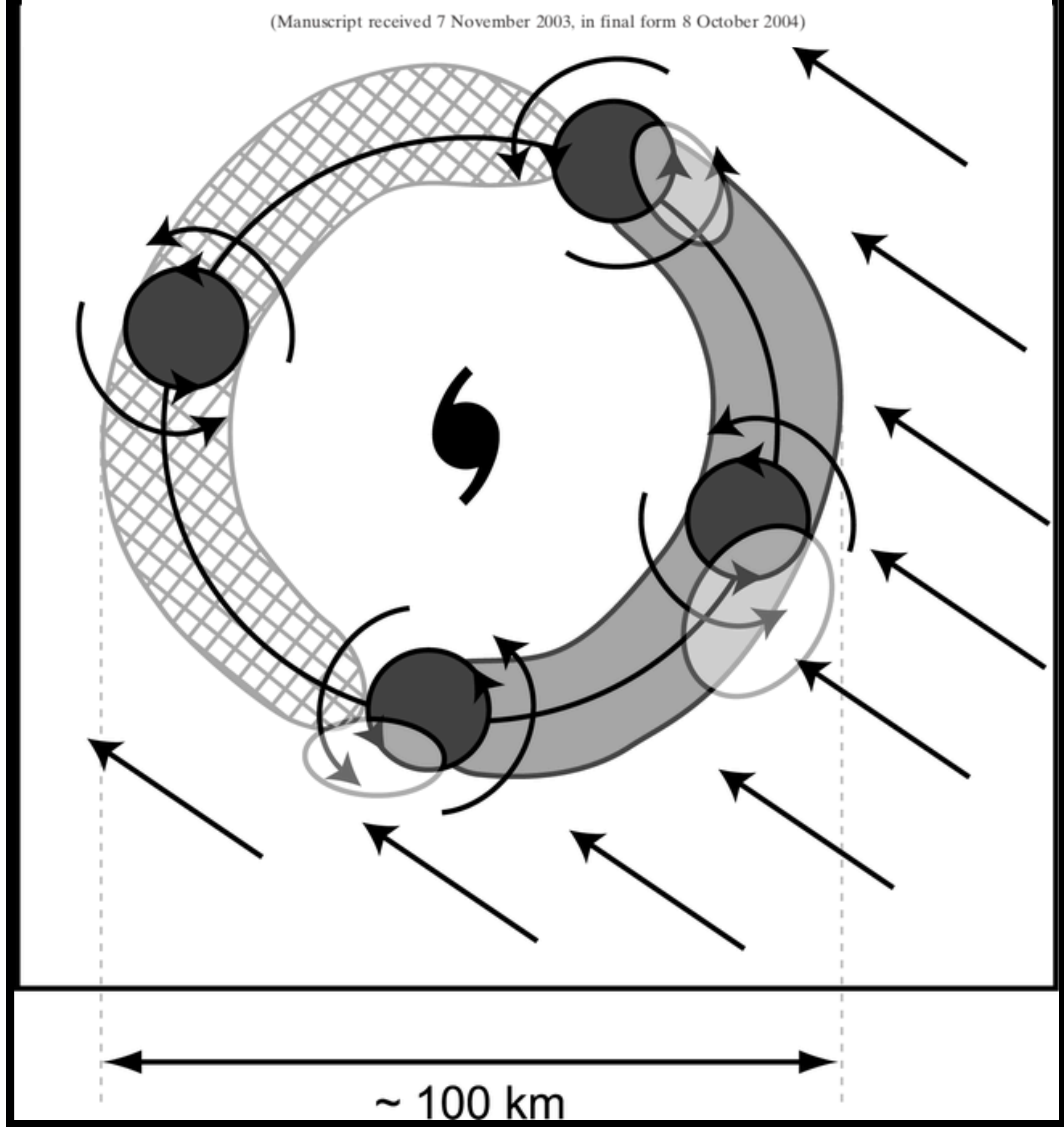
Michael T. Montgomery
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

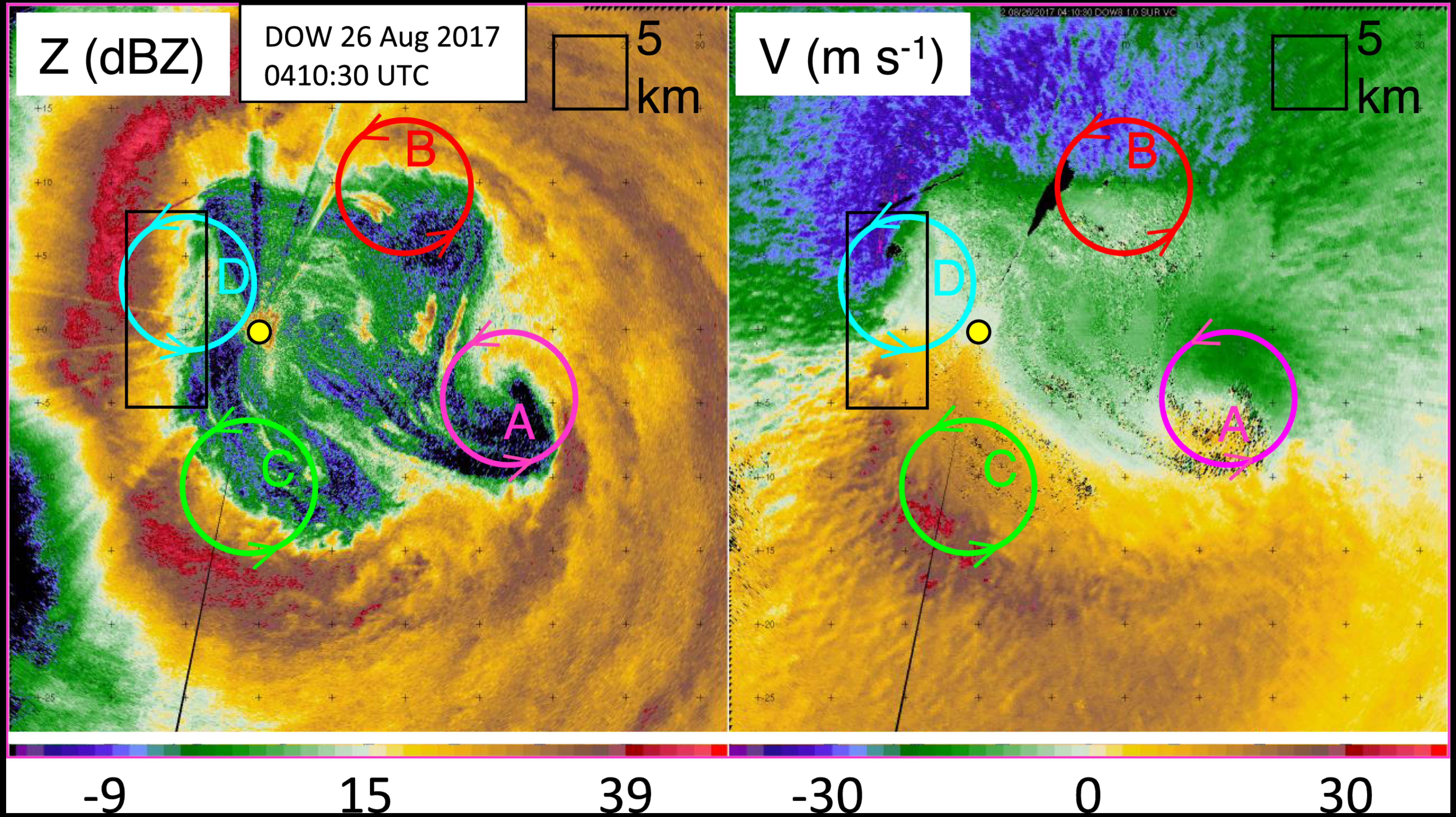
Zhaoxia Pu
Department of Meteorology, University of Utah, Salt Lake City, Utah

(Manuscript received 7 November 2003, in final form 8 October 2004)



Schematic diagram summarizing the interaction between eyewall mesovortices and the low-level inflow associated with the environmental wind shear. The elongated semicircular areas indicate where shear effects favor upward (light shading) and downward (cross hatching) motion. The relative flow associated with the environmental shear is indicated by the straight arrows, while the mesovortices and their local cyclonic circulations are indicated by darkly shaded circles and curved arrows. The semitransparent, lightly shaded ovals represent areas of enhanced low-level convergence and upward motion.

“first direct evidence of MVs” and their role in enhancing surface winds



Finescale DOW radar imagery of hurricane eye and eyewall, including four MVs. (left) Radar reflectivity and (right) Doppler velocity measured from inside eye (DOW location indicated with yellow dot) at 0410:30 UTC 26 Aug 2017. Four MVs revolving about the eye are highlighted schematically with colored circles. Black rectangle is zoomed-in area shown in Fig. 6.

Wurman, J., and K. Kosiba, 2018: The Role of Small-Scale Vortices in Enhancing Surface Winds and Damage in Hurricane Harvey (2017). *Mon. Wea. Rev.*, 146, 713–722, https://doi.org/10.1175/MWR-D-17-0327.1.

So:

Polygonal eyewalls are very common in intense tropical cyclones.

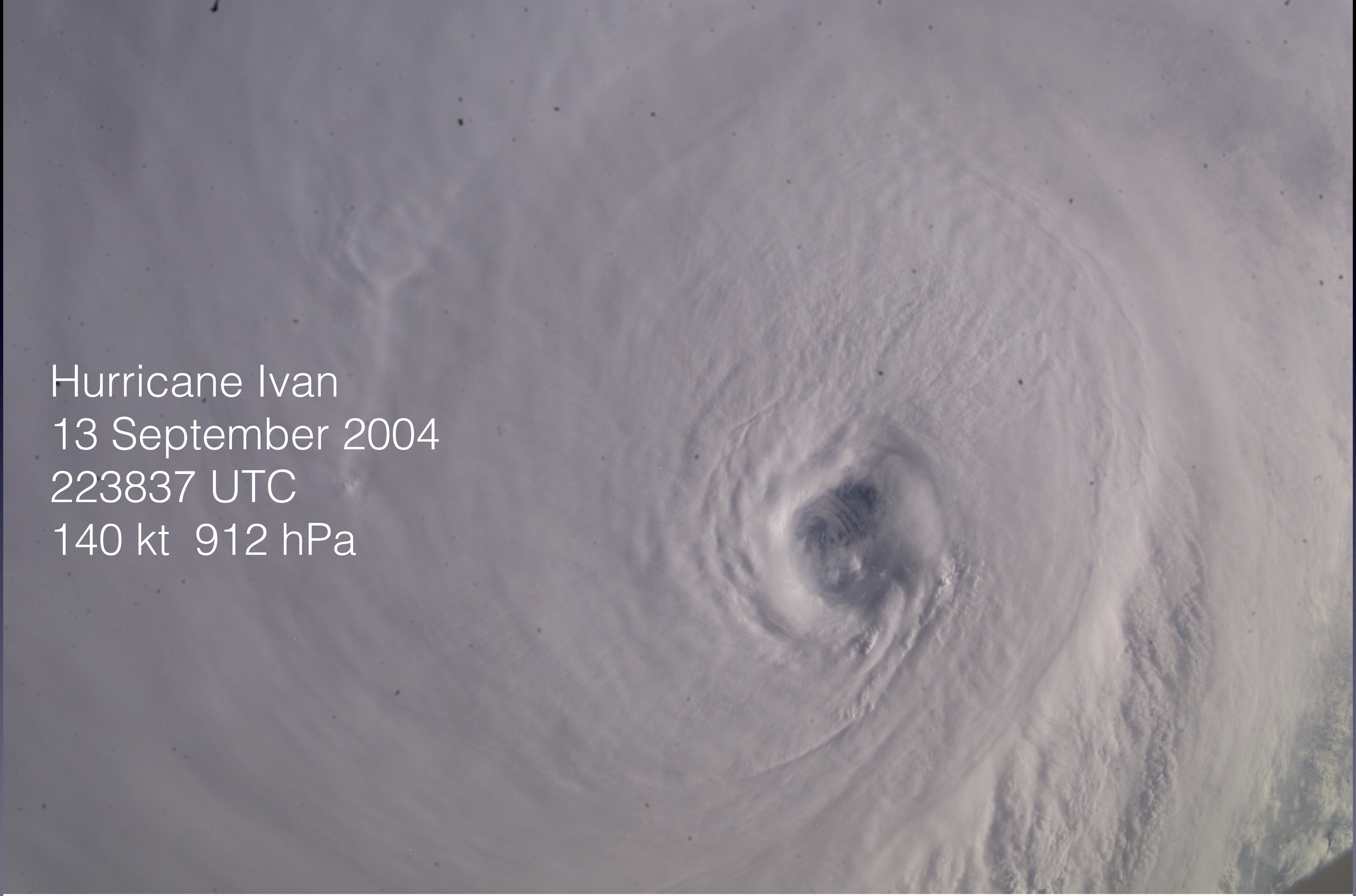
Low-level cloud lines and other patterns are common in intense tropical cyclones.

It has been hypothesized that:

Polygonal eyewalls and low-level cloud liners are signatures of eyewall mesovortices.

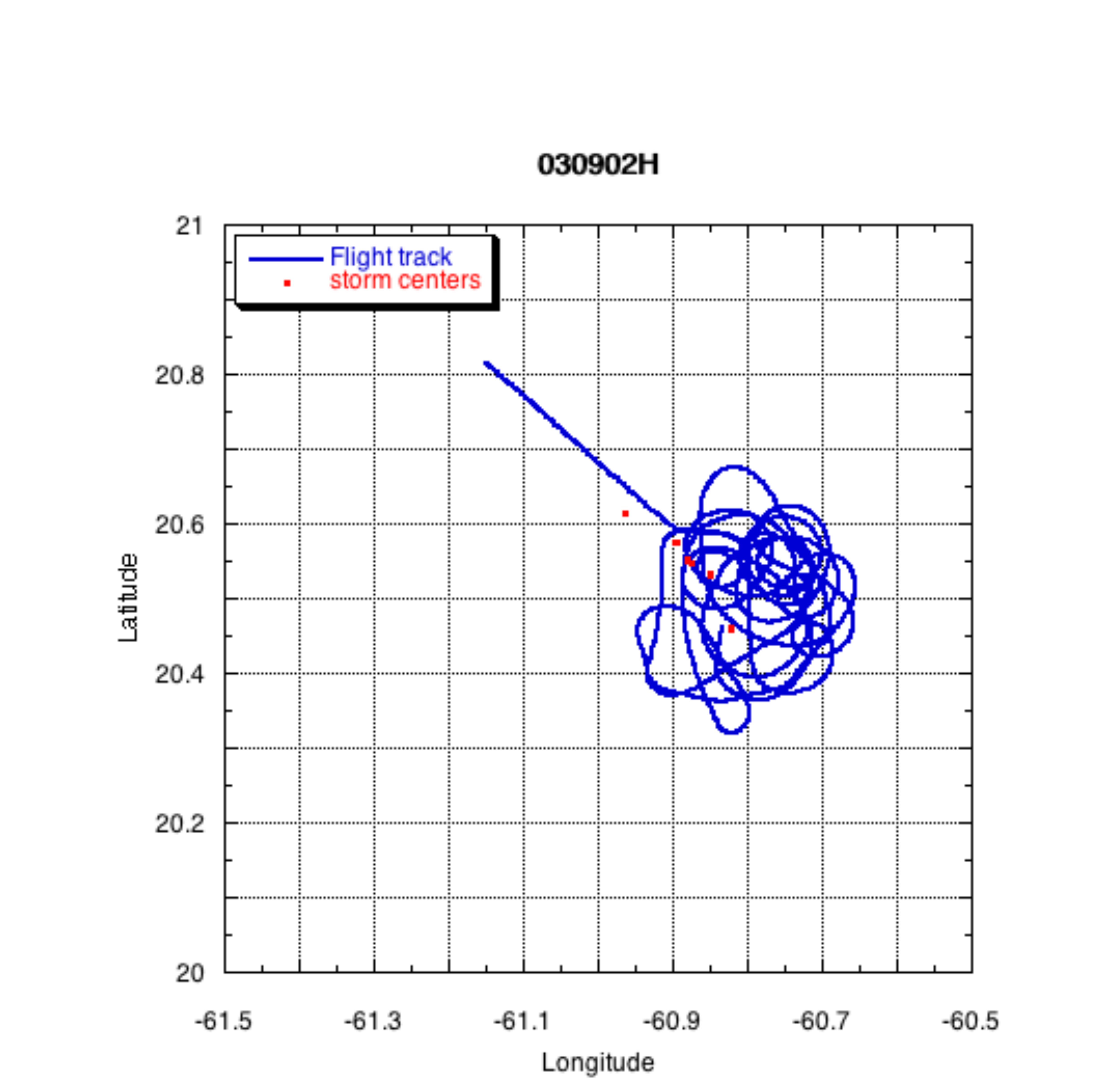
Eyewall mesovortices play a role in bringing high-entropy air from the eye into the eyewall increasing buoyancy.   Thus, they play a role in intensity change.

Why don’t we see eyewall mesovortices when we cross the eyes of intense tropical cyclones in the P-3 (nor do the C-130s)? Are these solely low-level features?

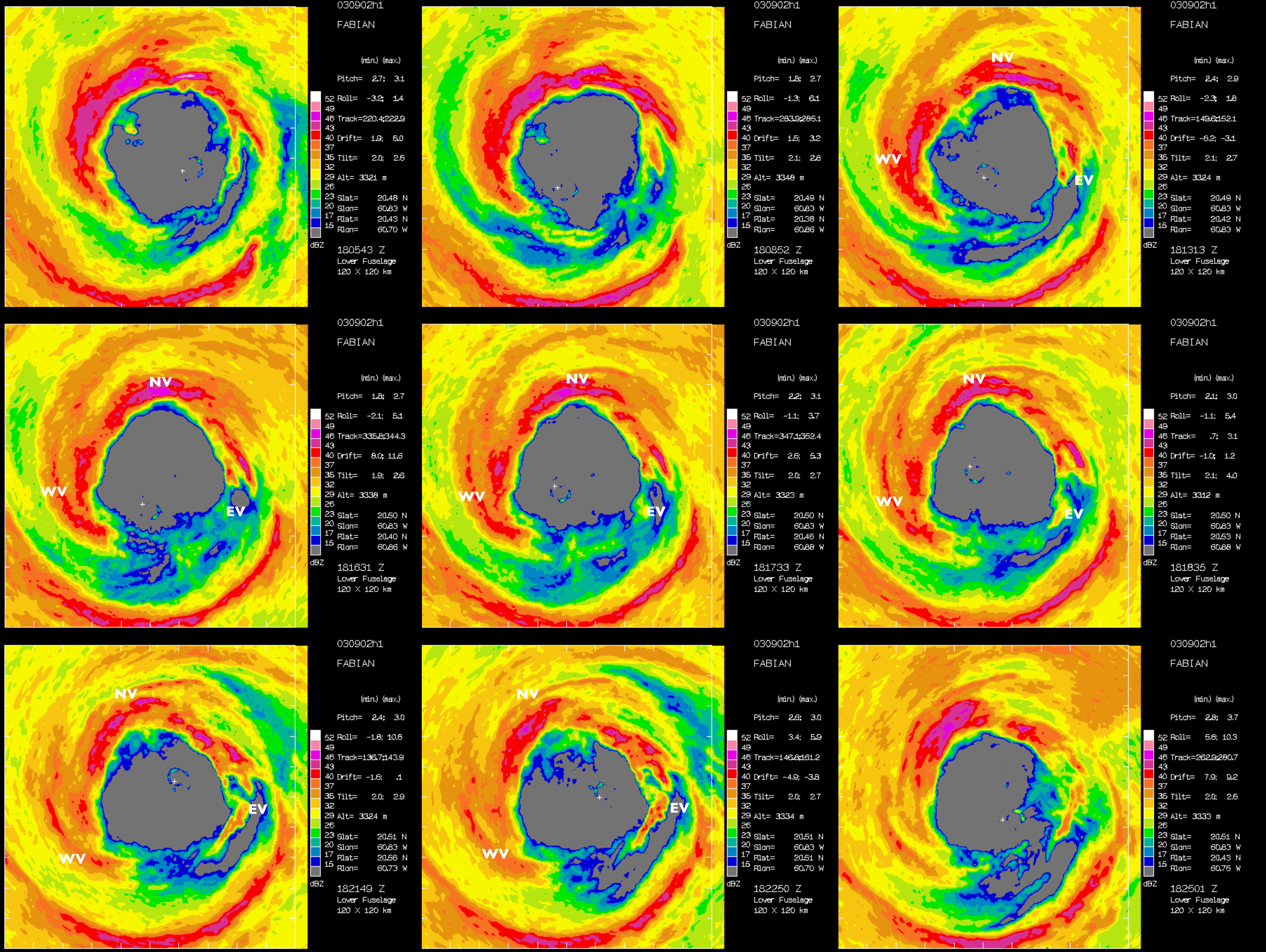


ISS009E22488

Hurricane Fabian (02 September 2003) 120 kt
Both NOAA P-3 aircraft circled in the eye for up to two hours



During this time, the eyewall shape changed from circular to triangular (1813 UTC) and back (1823 UTC). The P-3s made three circles in the eye during that time, allowing for unprecedented coverage of the eyewall on short timescales with Doppler radar.



The vertices rotated along the eyewall at ~4.5 degrees per minute, or a rotation period of about **80 minutes**.

The theoretical speed of waves c is given by

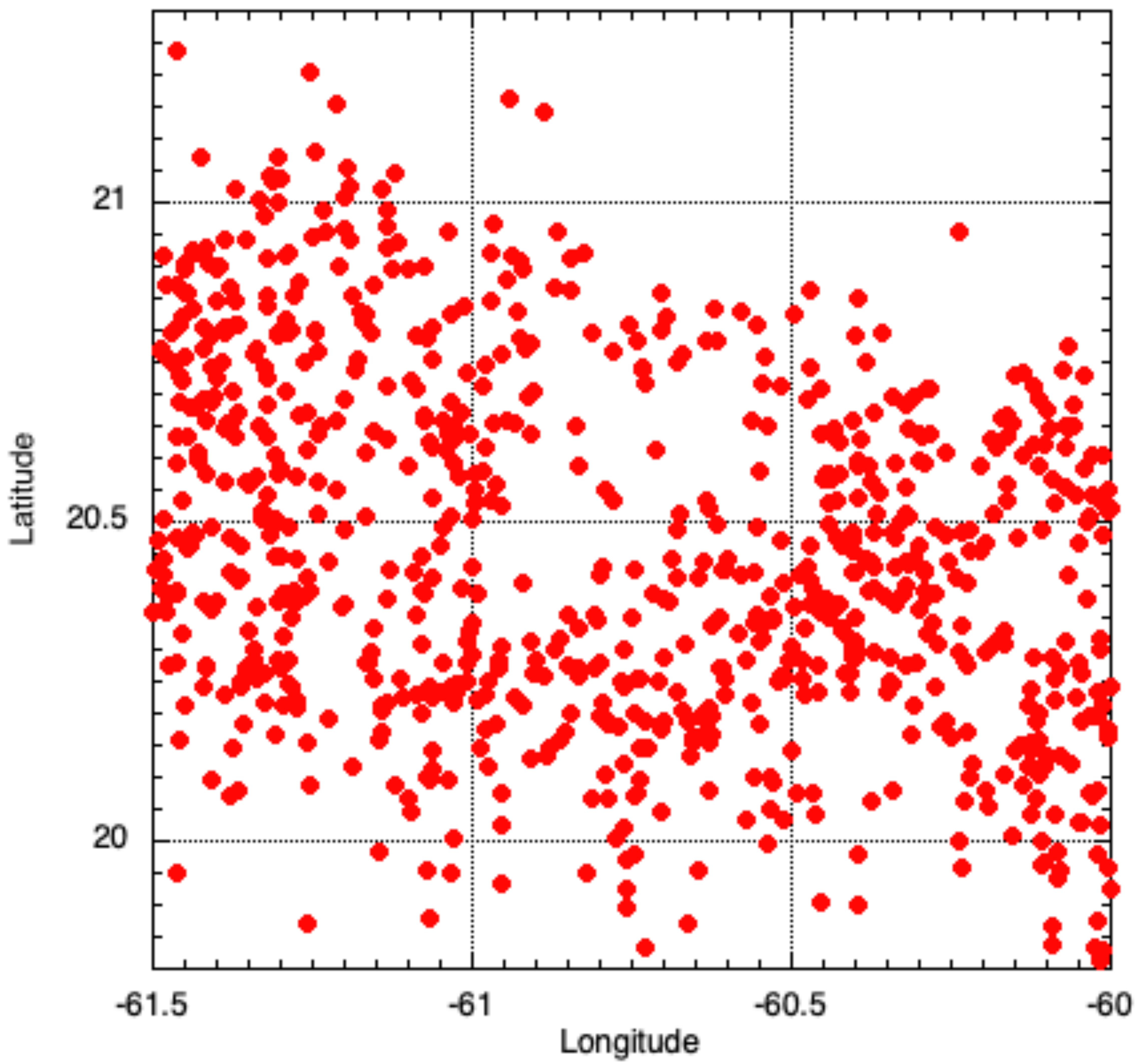
$$c=v_{max}(1-1/m)$$

where v_{max} is the tangential speed of the mean flow, and m is the wavenumber (Thomson 1880, Lamb 1932 and by Guinn and Schubert 1993).

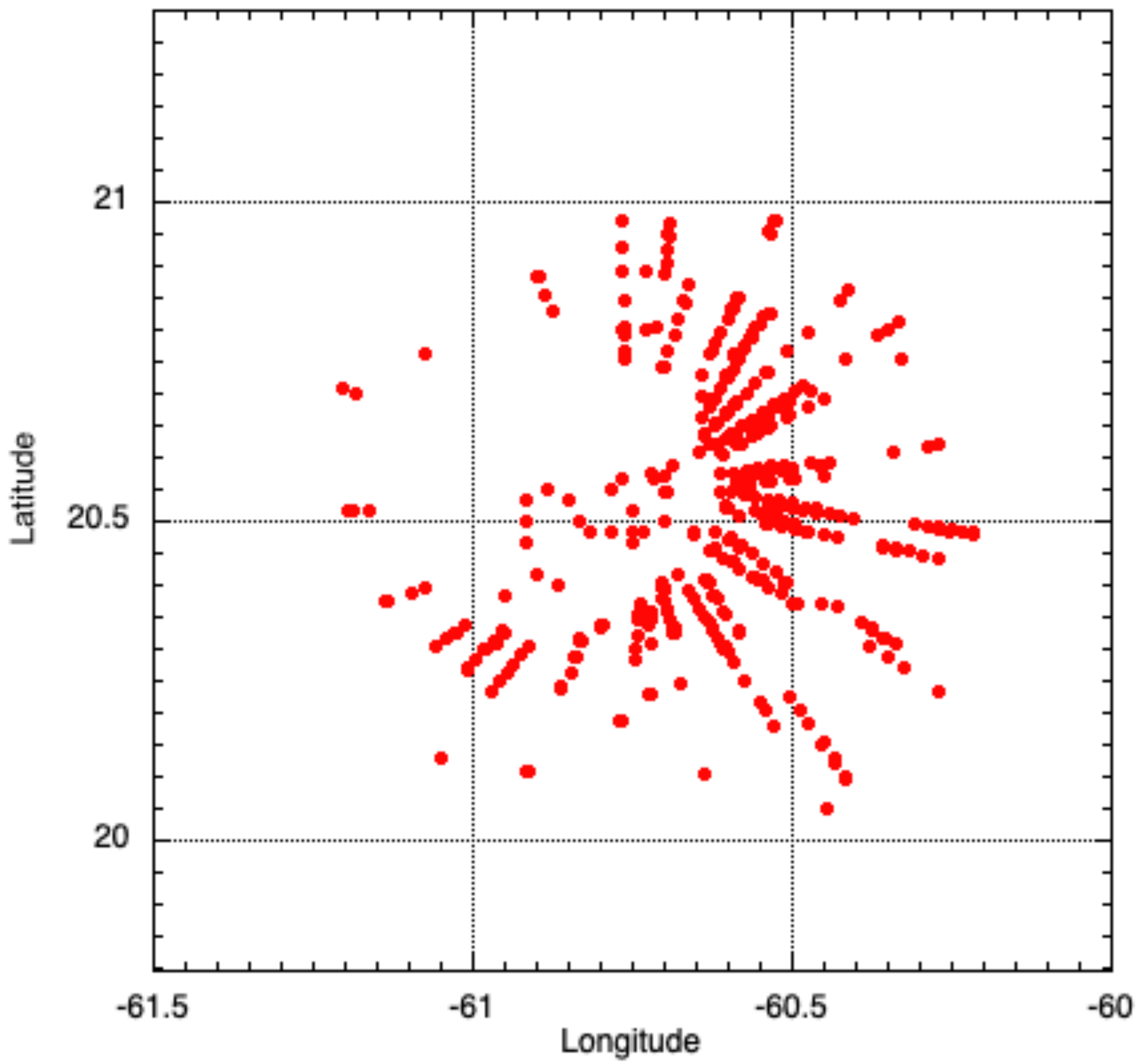
At the approximate altitude of the radar observations (~ 3 km), the mean flow was about 57 ms^{-1}, giving a theoretical speed of 37 ms^{-1}, corresponding to a rotation period of **76 minutes**.


29 August 2019
0600 UTC
Ensemble spin up
0900 UTC
0930 UTC
1000 UTC
1030 UTC
1100 UTC
1130 UTC
1200 UTC
1230 UTC
1300 UTC
1330 UTC
1400 UTC
1430 UTC
1500 UTC
1
2
3
30
Flight track + SFMR Winds: DORIAN (NOAA 20190829H1)
Fix Time MSLP
130257Z 987mb
140454Z 988mb
145143Z 987mb
153430Z 987mb
Flight Track
SFMR Wind Speed
Dropsonde
GOES16 VIS 2019-08-29 15:05:05Z
23°N
22°N
21°N
20°N
19°N
69°W
68°W
67°W
66°W
65°W
0 10 20 30 34 40 45 50 55 60 64 74 83 90 96 105 113 125 137 >150
Wind Speed (kt)
Storm-relative data
Ensemble mean analyses
Latitude
Longitude

Storm-relative



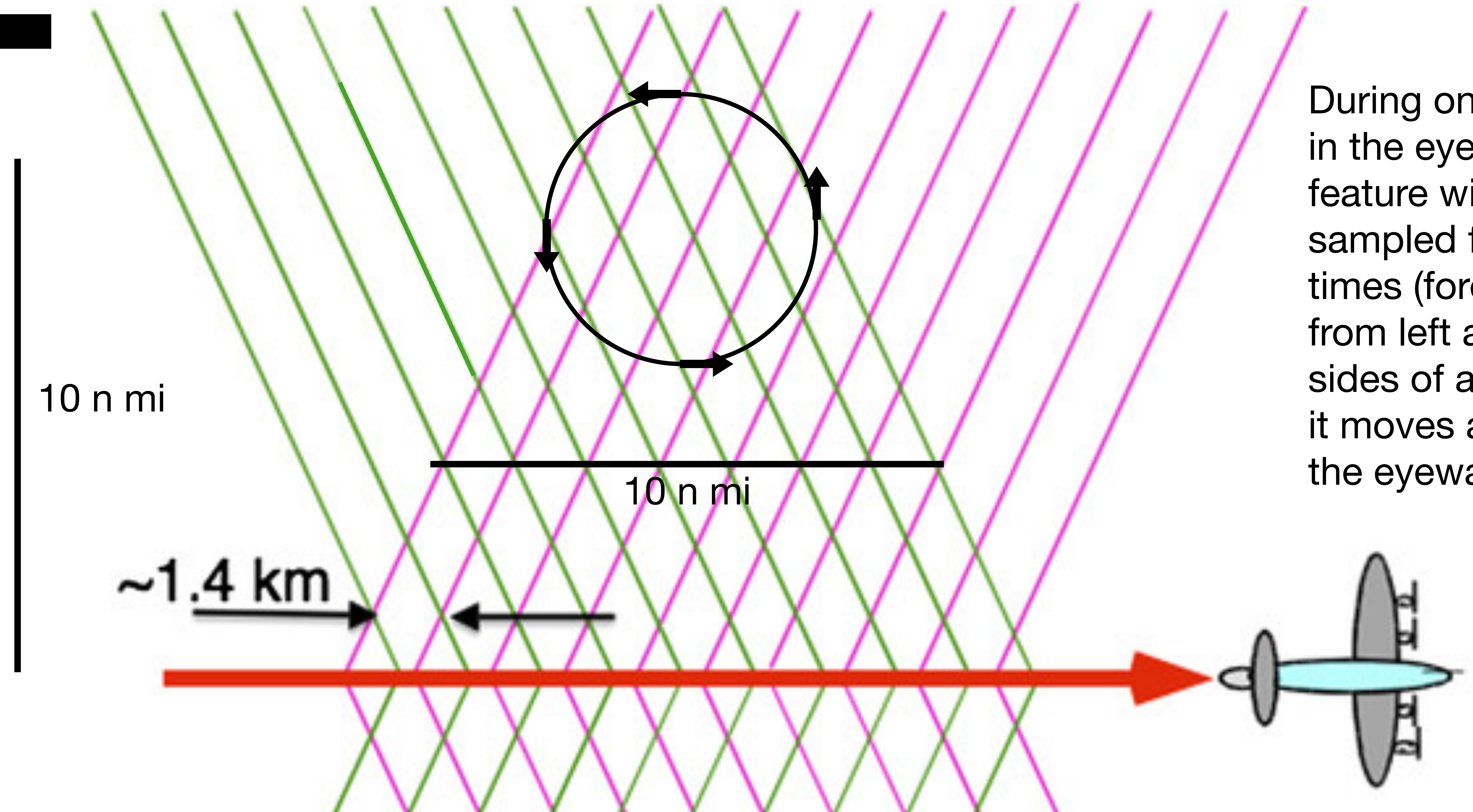
Earth-relative



Can we see these small-scale features with airborne Doppler radar?

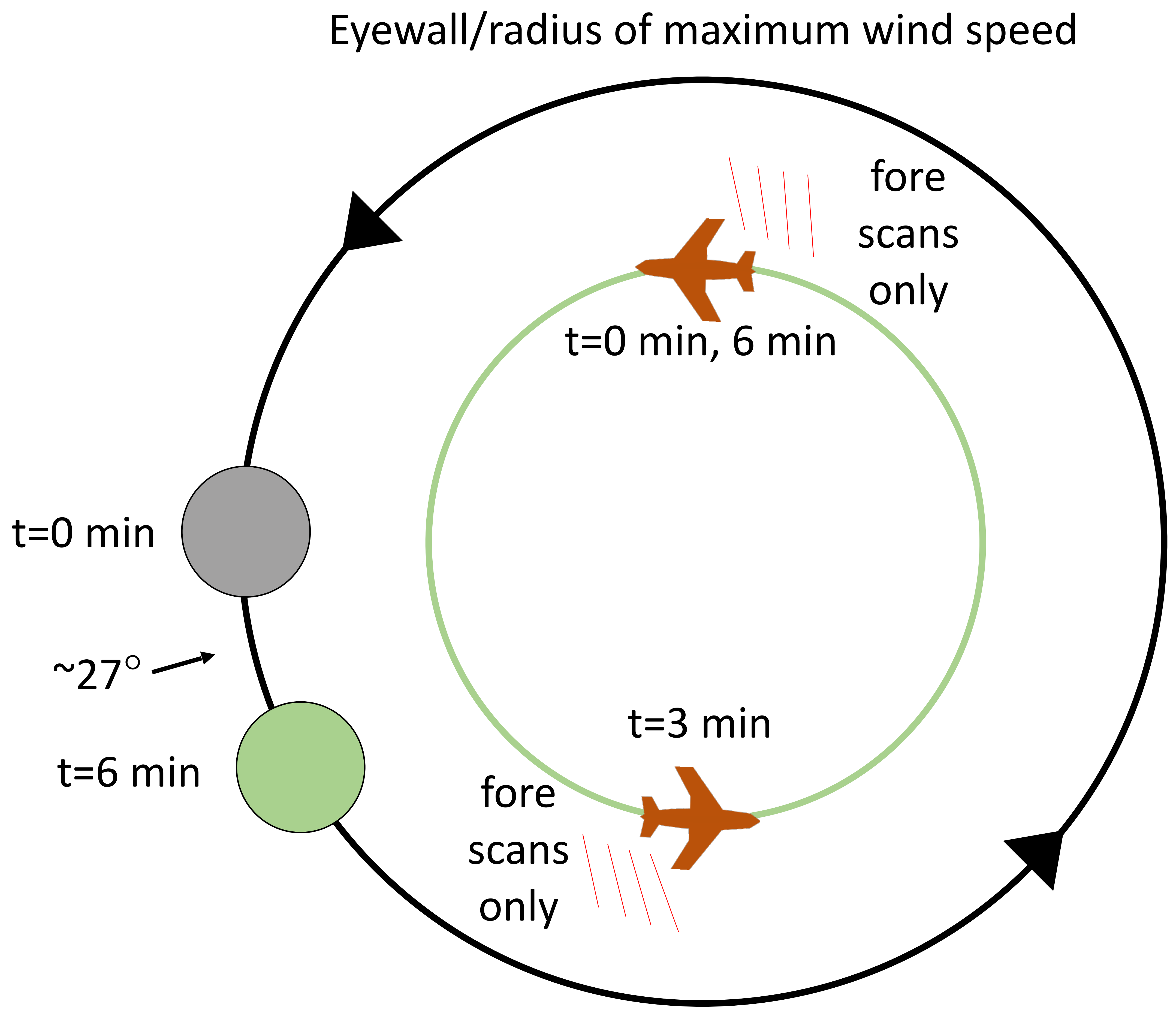
moving 75 kt

For every 10 n mi distance the P3 flies from a vortical feature, radar pulses will cross the same location about 1 min apart, and the feature moves 1.25 n mi.

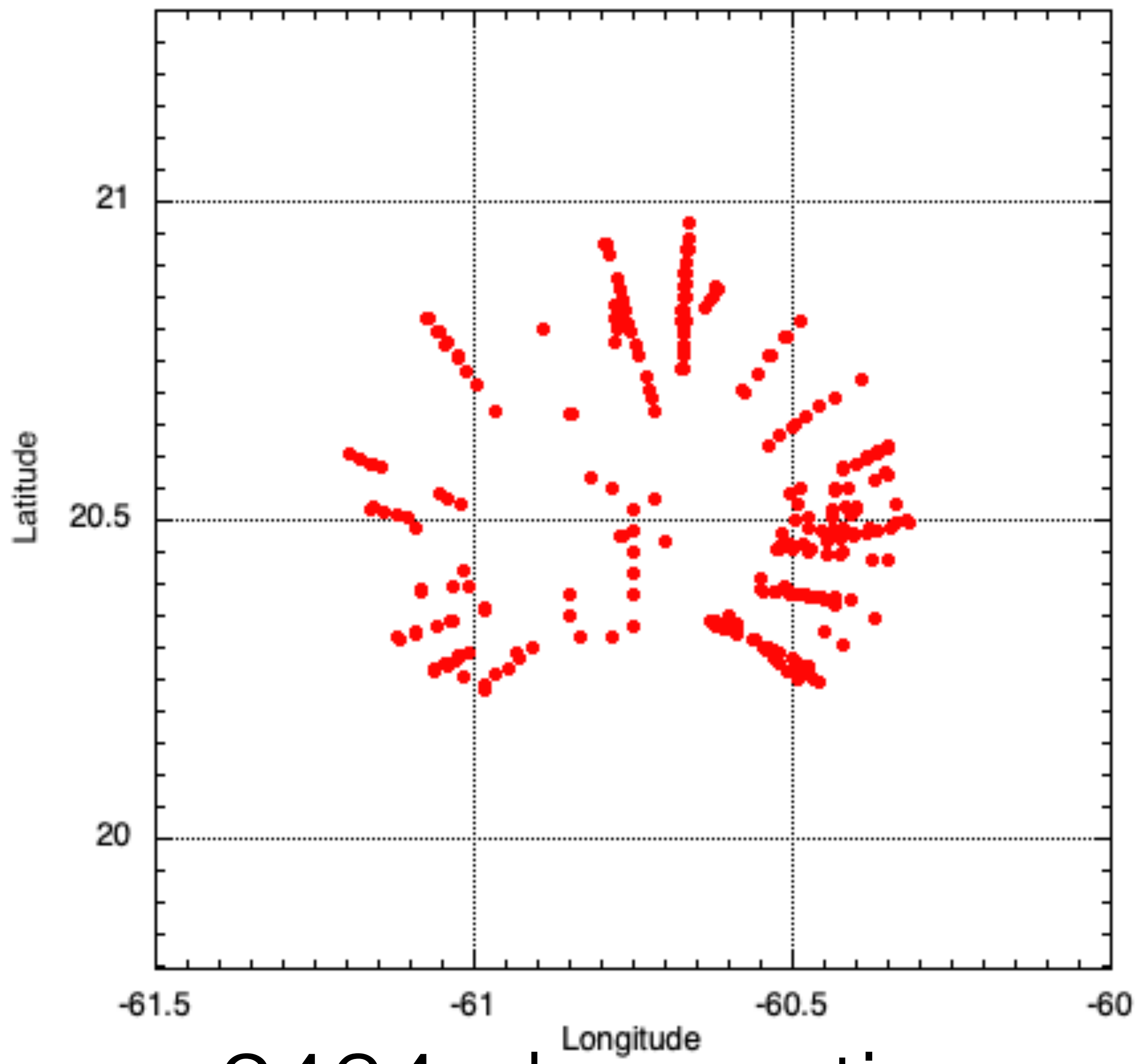


During one circle in the eye, each feature will be sampled four times (fore and aft from left and right sides of aircraft) as it moves around the eyewall.

In an attempt to alleviate this problem, we limit the eyewall to be sampled once every time the aircraft circles the eye (every ~5 min) and using data only to the side of the aircraft closest to the eyewall, and only either fore or aft scans.



Data assimilated for 1830 UTC analysis (1827-1833 UTC)



2464 observations

Features of HEDAS analyses:

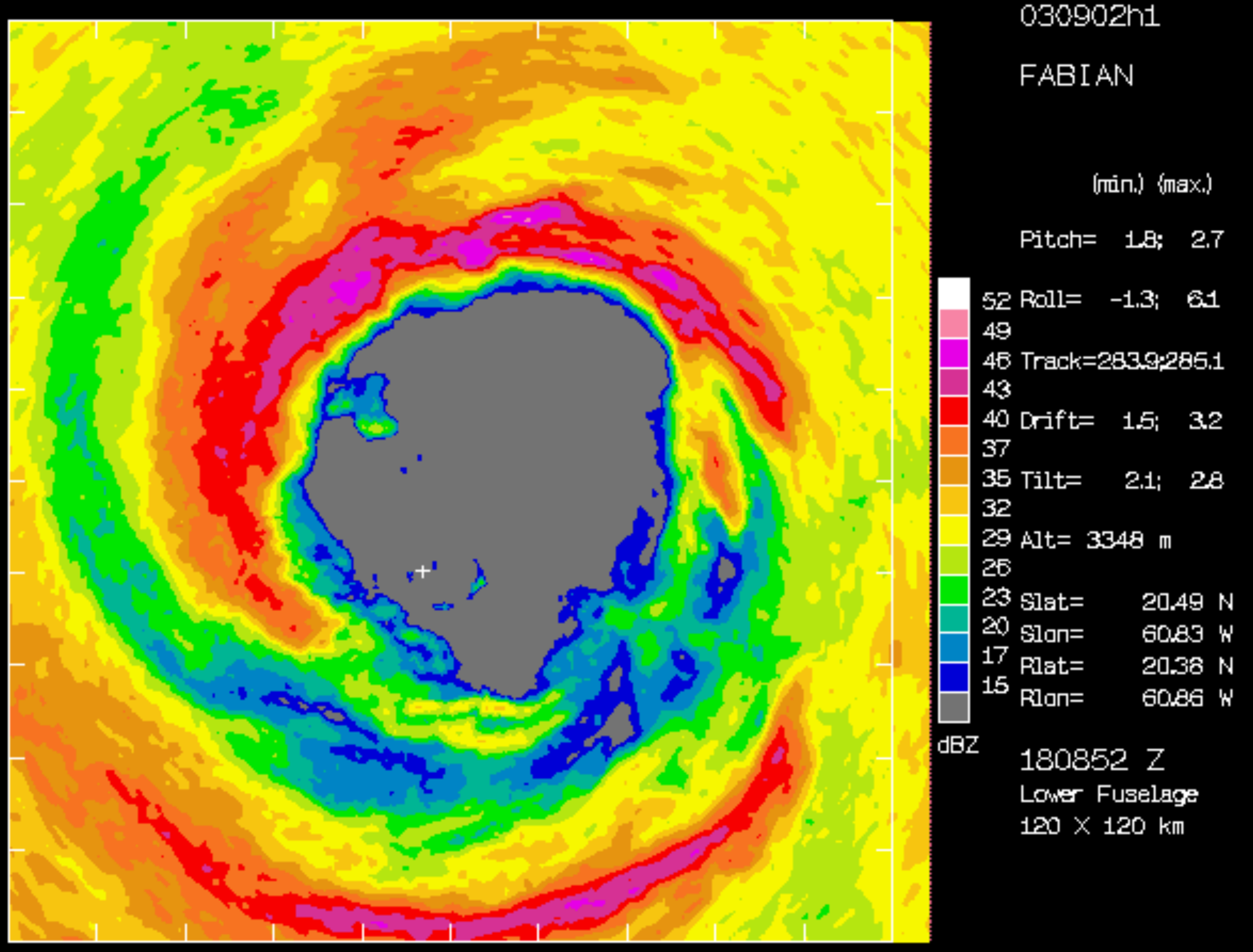
Analyses center location, maximum wind speed, radius of maximum wind speed, etc., largely match best track and center fixes.

Maximum reflectivity just outside location of maximum low-level radial convergence.

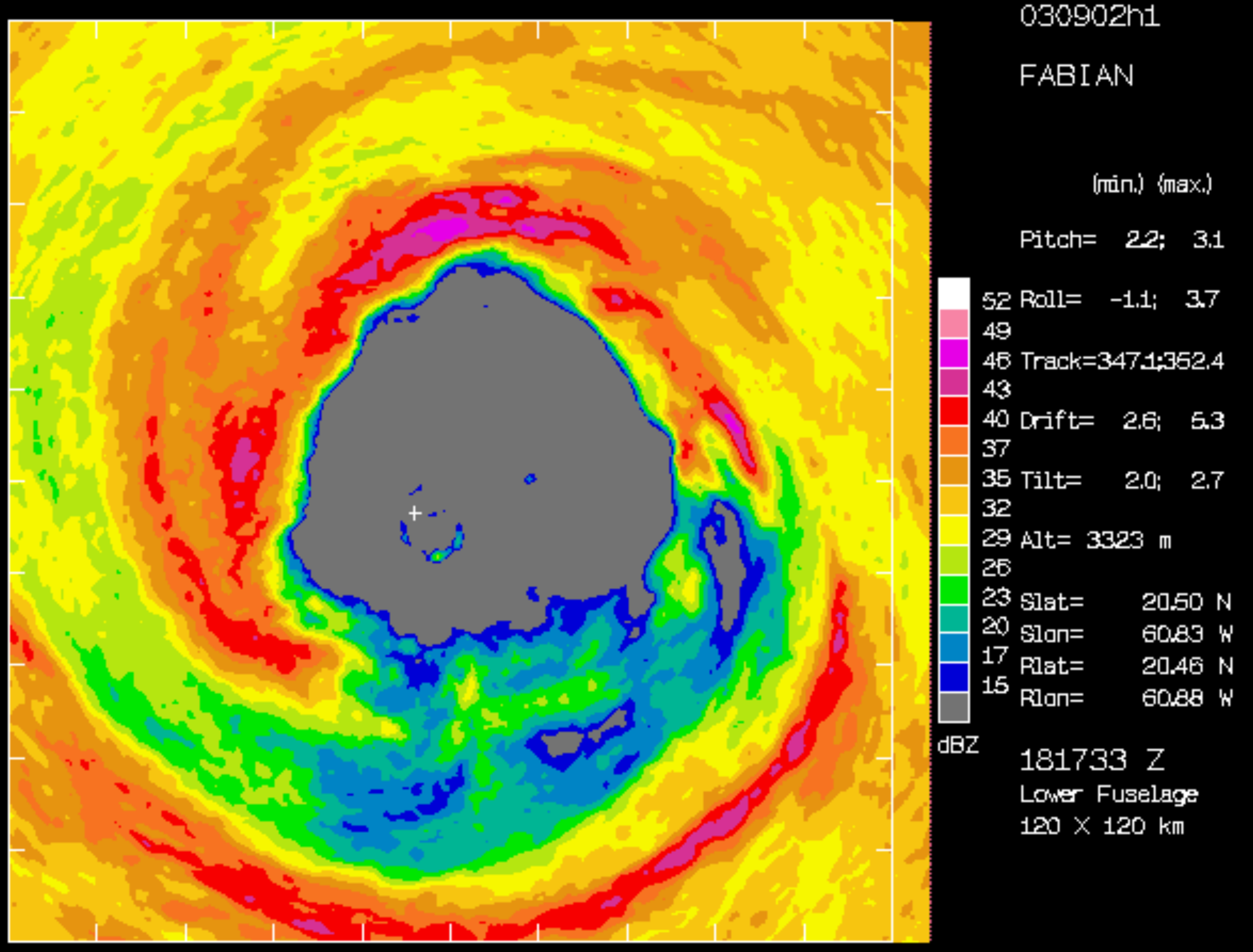
Leading edge of convection of west/southwest side of eyewall forms and retreats with location of maximum low-level inflow.

All O-A and O-F statistics are available.

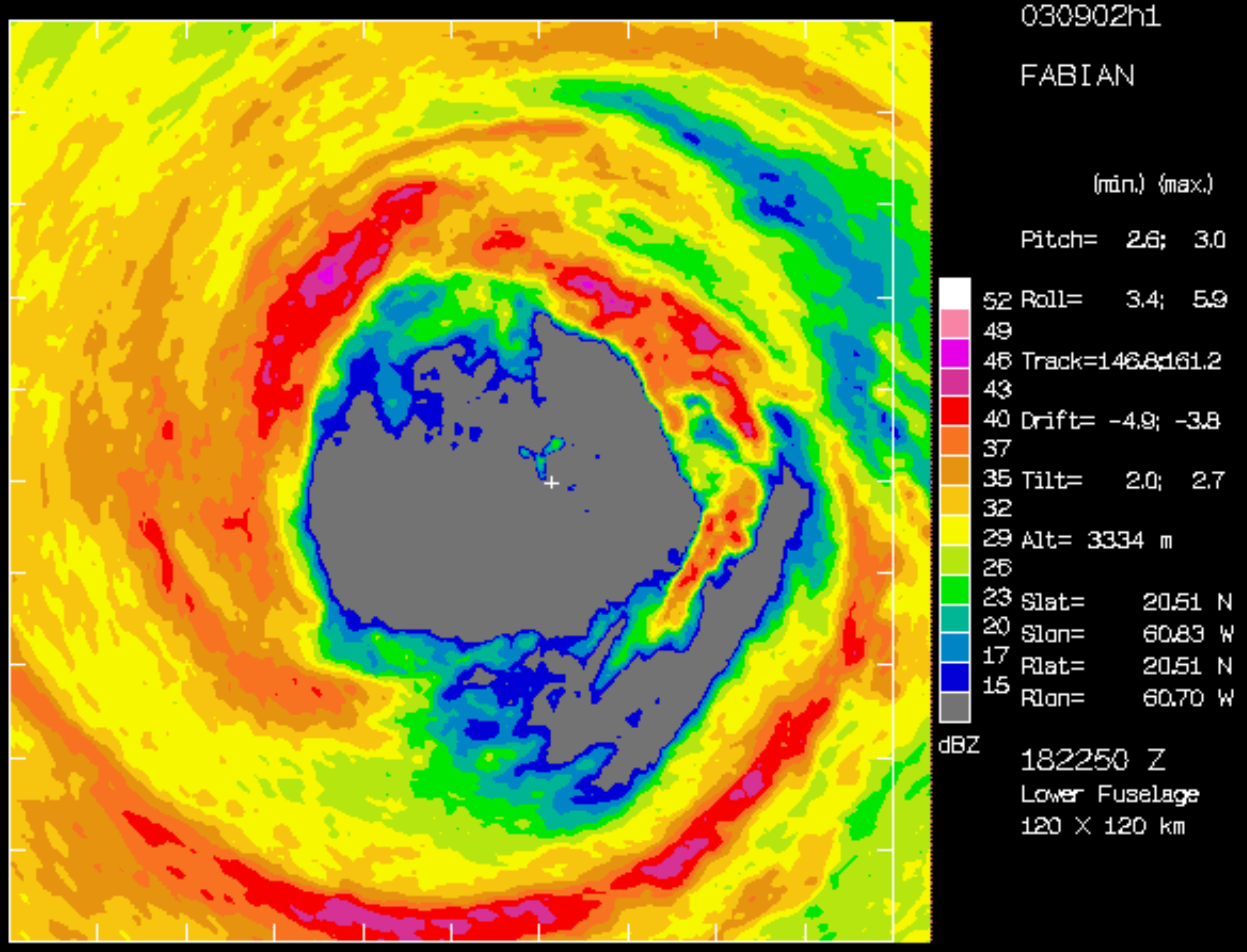
1812 UTC



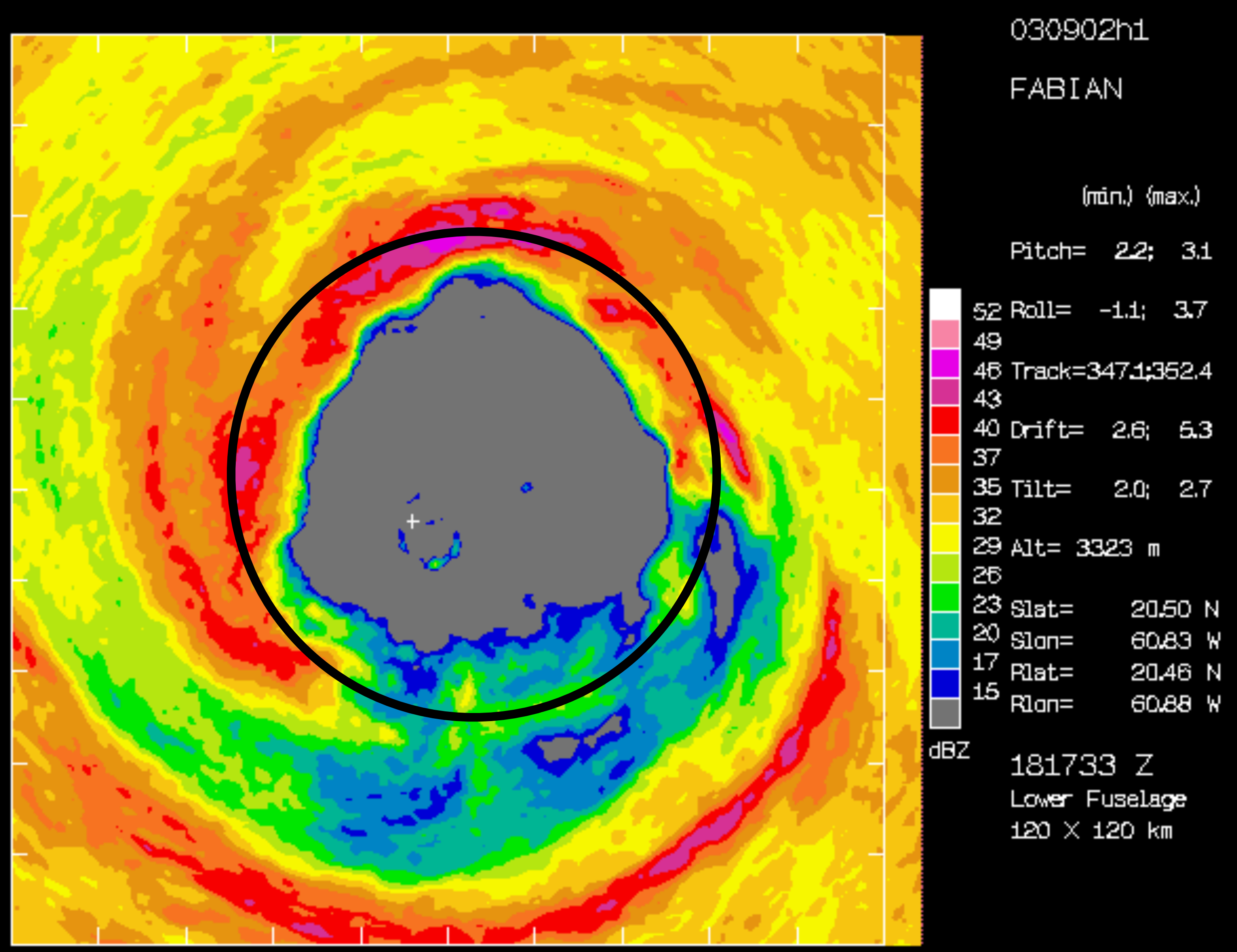
1818 UTC



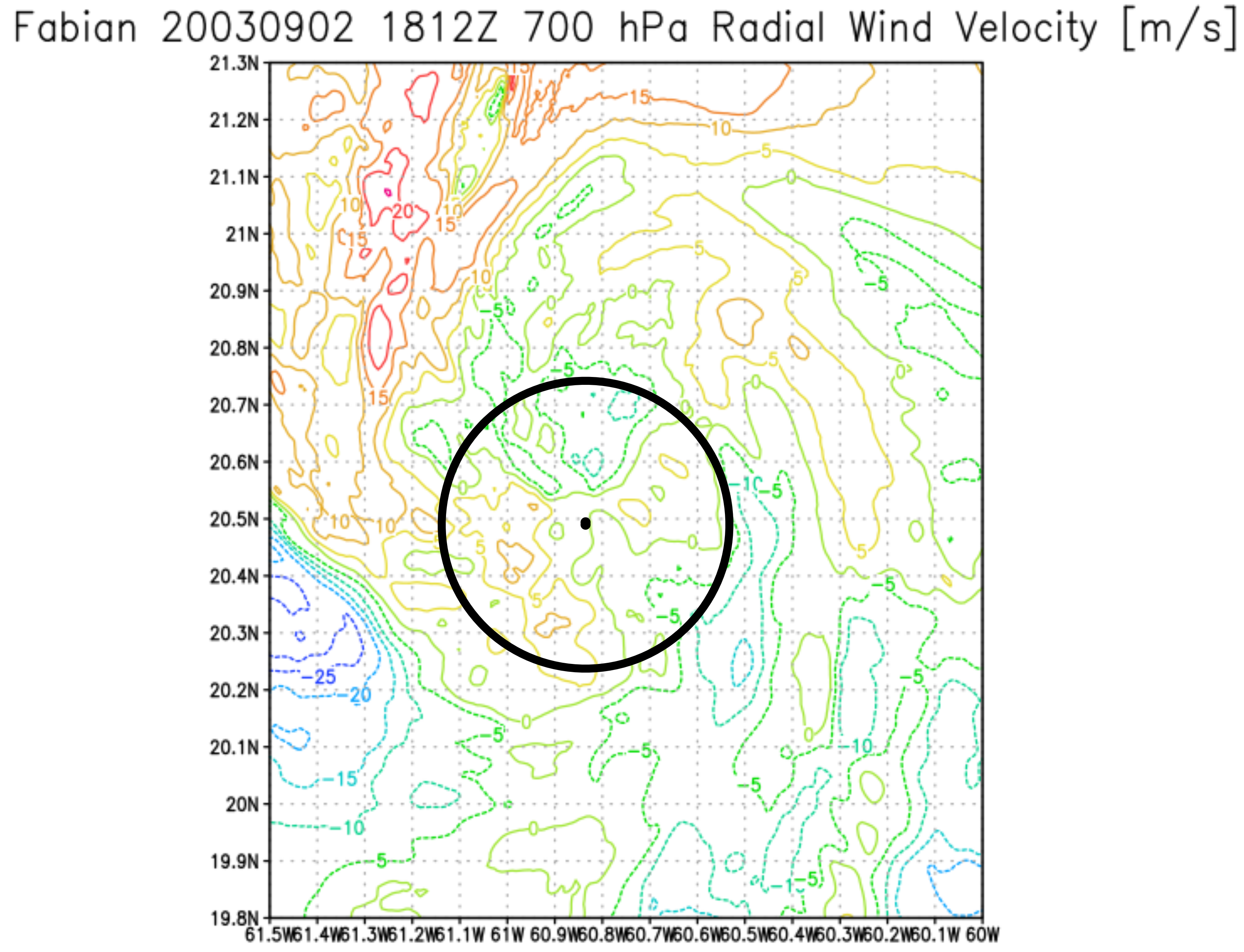
1824 UTC

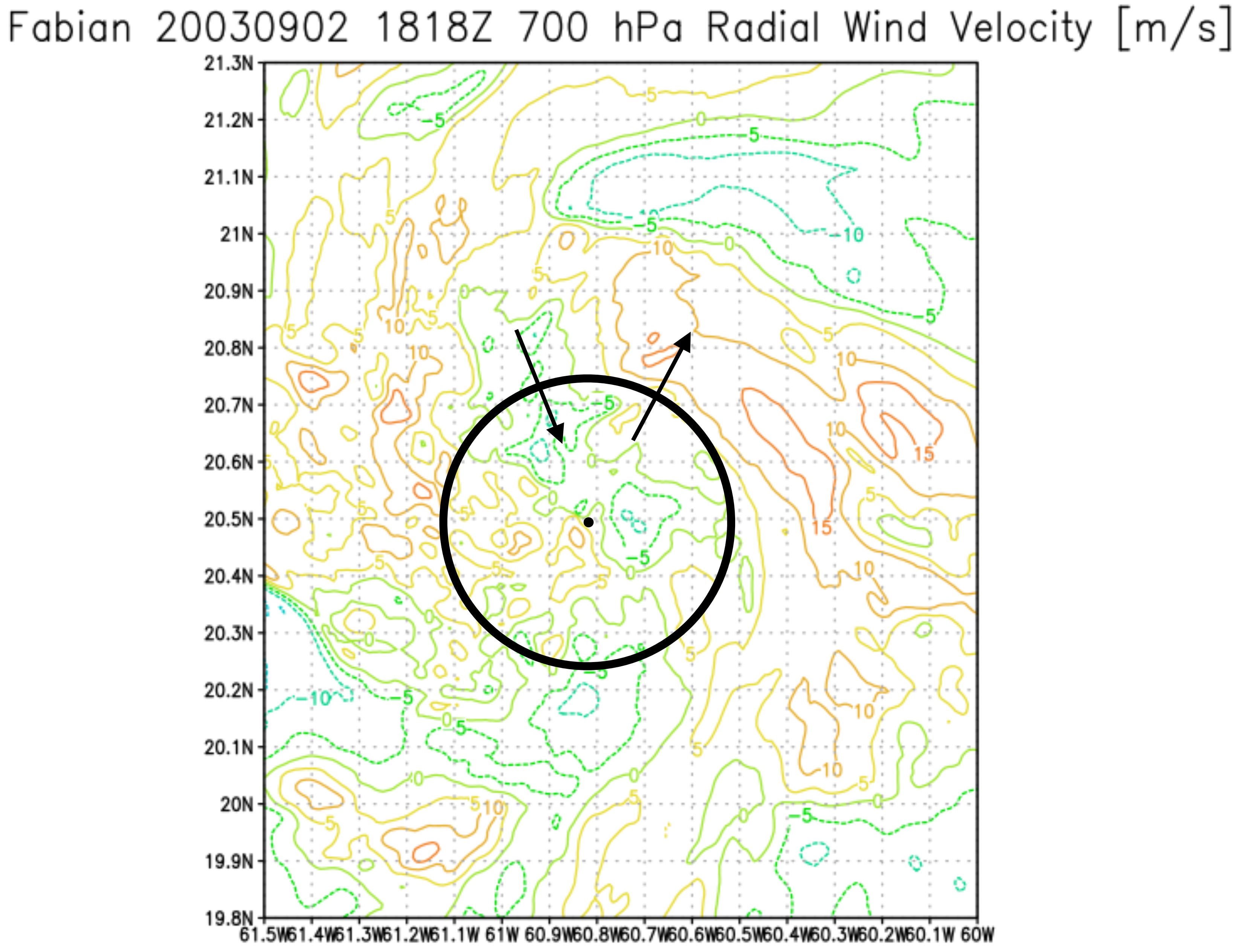


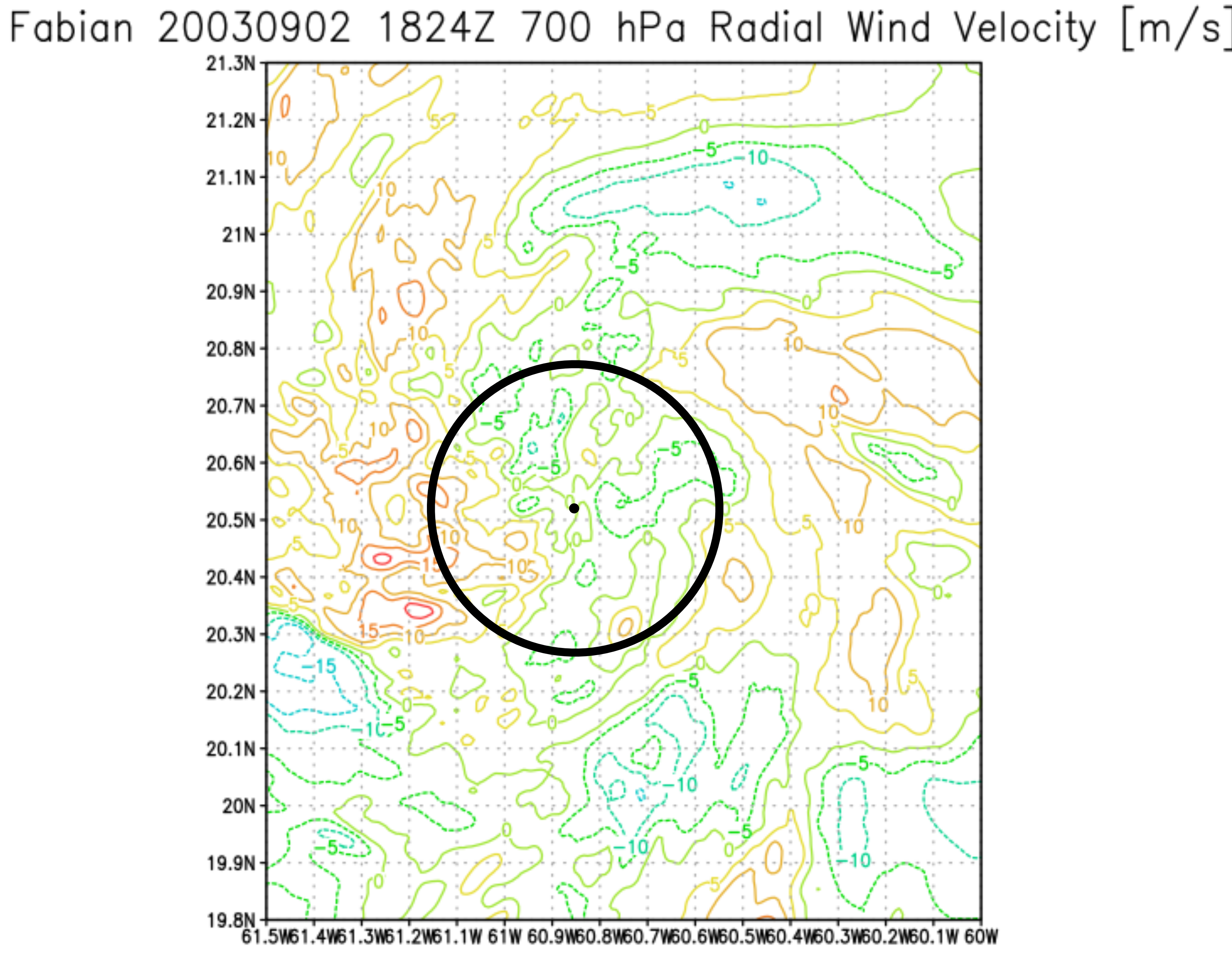
No small-scale vortices



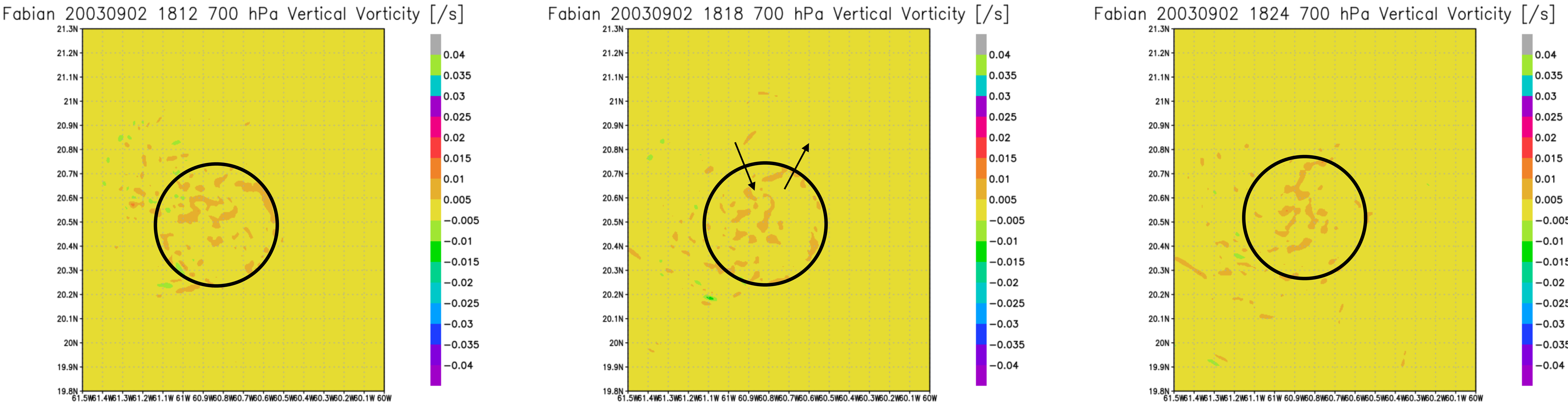
Black circle corresponds to approximate radius of maximum reflectivity, black square to region in reflectivity image.

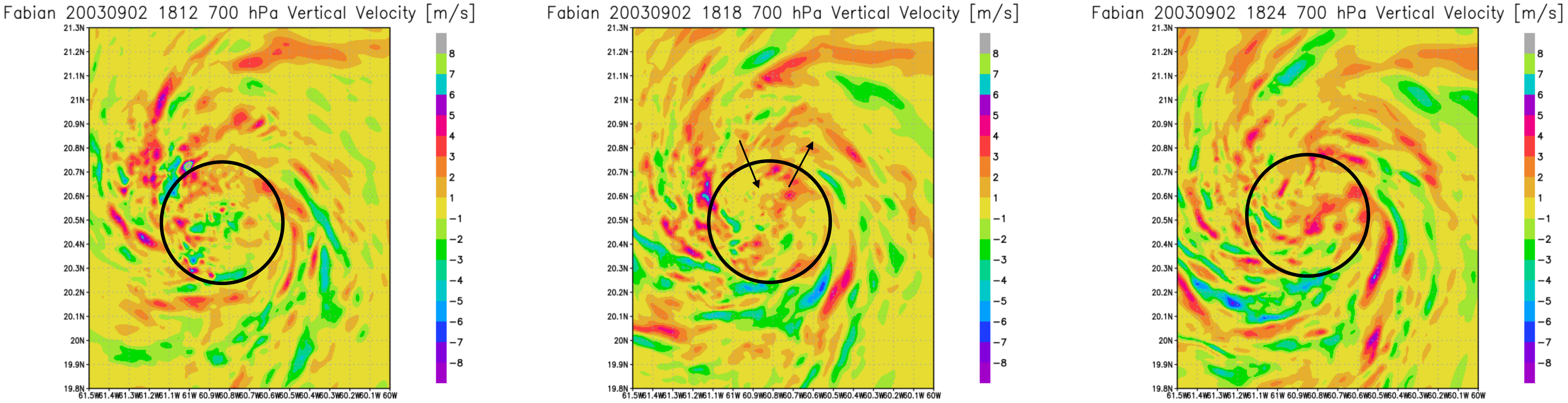

Fabian 20030902 1812Z 700 hPa Radial Wind Velocity [m/s]


Fabian 20030902 1818Z 700 hPa Radial Wind Velocity [m/s]


Fabian 20030902 1824Z 700 hPa Radial Wind Velocity [m/s]

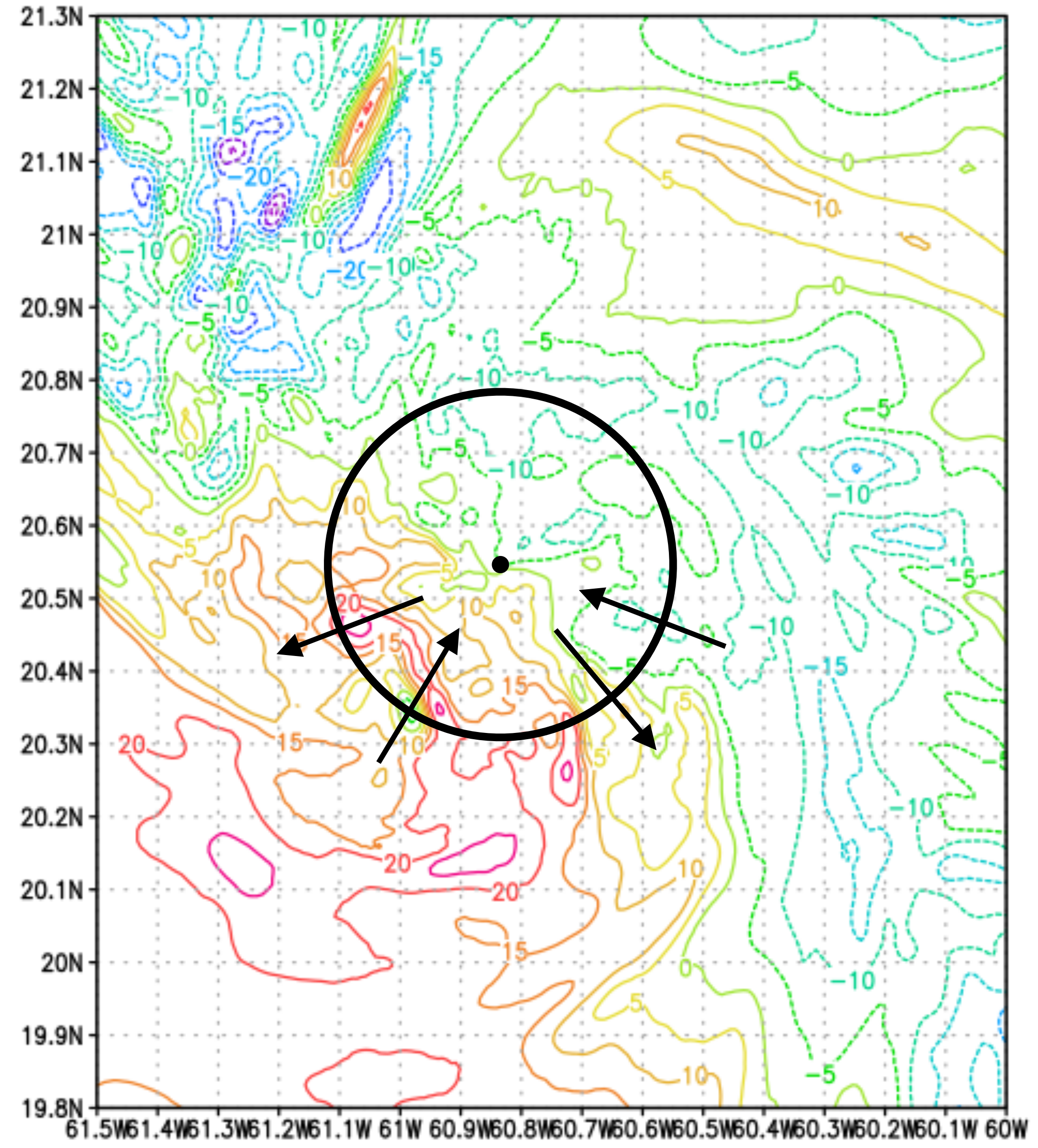
No large vorticity maxima suggesting vortices



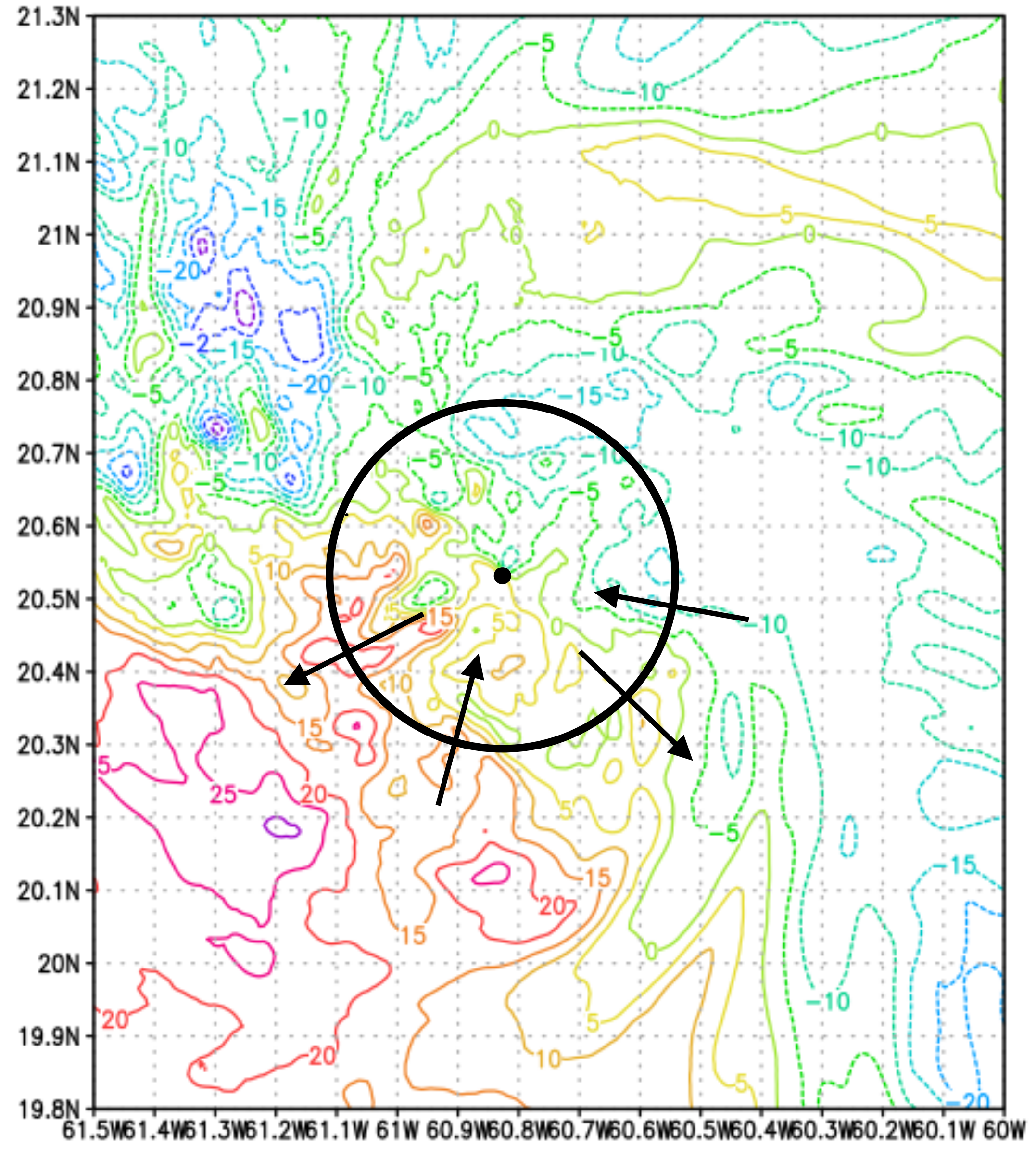


Fabian 20030902 1812 700 hPa Vertical Velocity [m/s]
Fabian 20030902 1818 700 hPa Vertical Velocity [m/s]
Fabian 20030902 1824 700 hPa Vertical Velocity [m/s]
21.3N 21.2N 21.1N 21N 20.9N 20.8N 20.7N 20.6N 20.5N 20.4N 20.3N 20.2N 20.1N 20N 19.9N 19.8N
61.5W 61.4W 61.3W 61.2W 61.1W 61W 60.9W 60.8W 60.7W 60.6W 60.5W 60.4W 60.3W 60.2W 60.1W 60W
8 7 6 5 4 3 2 1 −1 −2 −3 −4 −5 −6 −7 −8

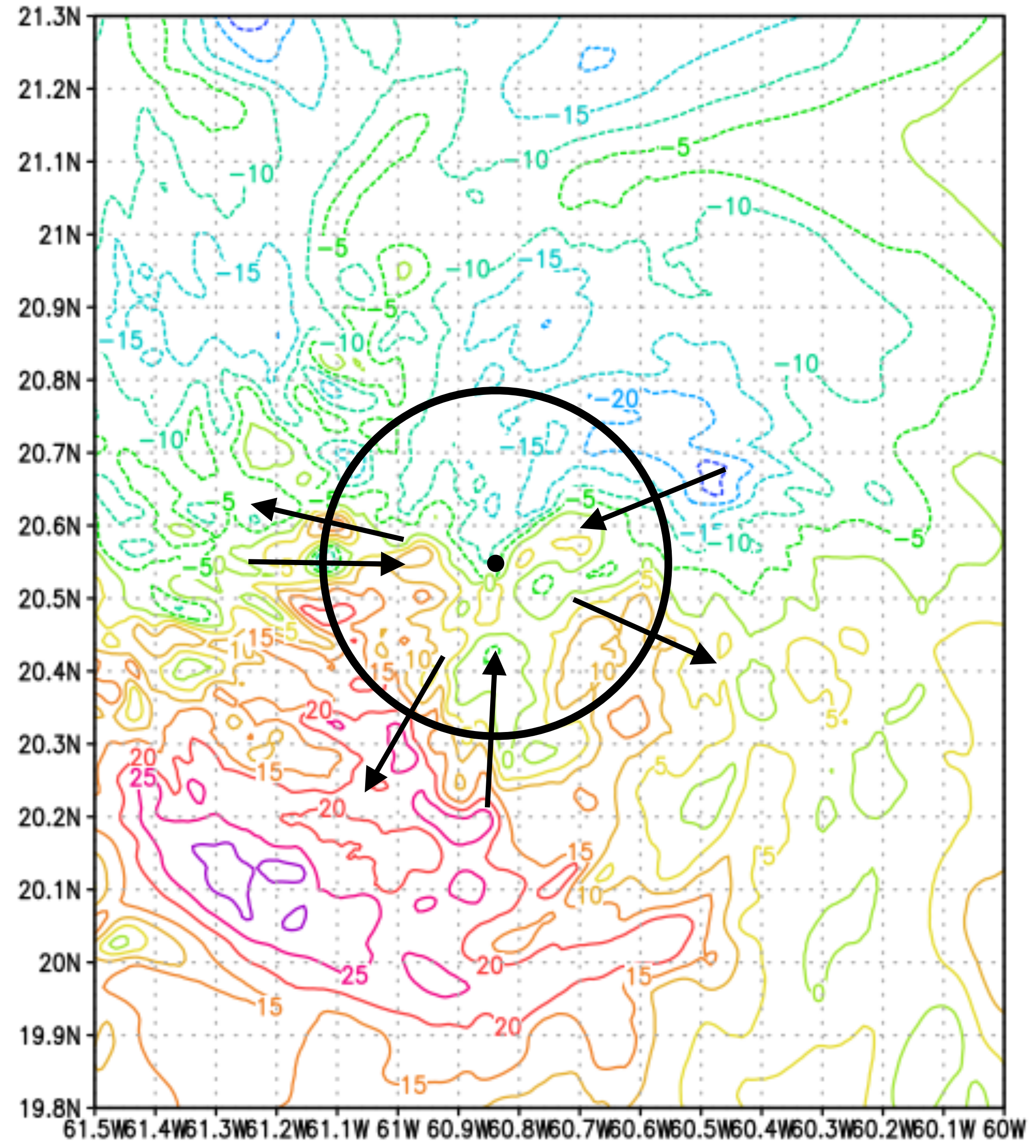
Fabian 20030902 1812Z 900 hPa Radial Wind Velocity [m/s]

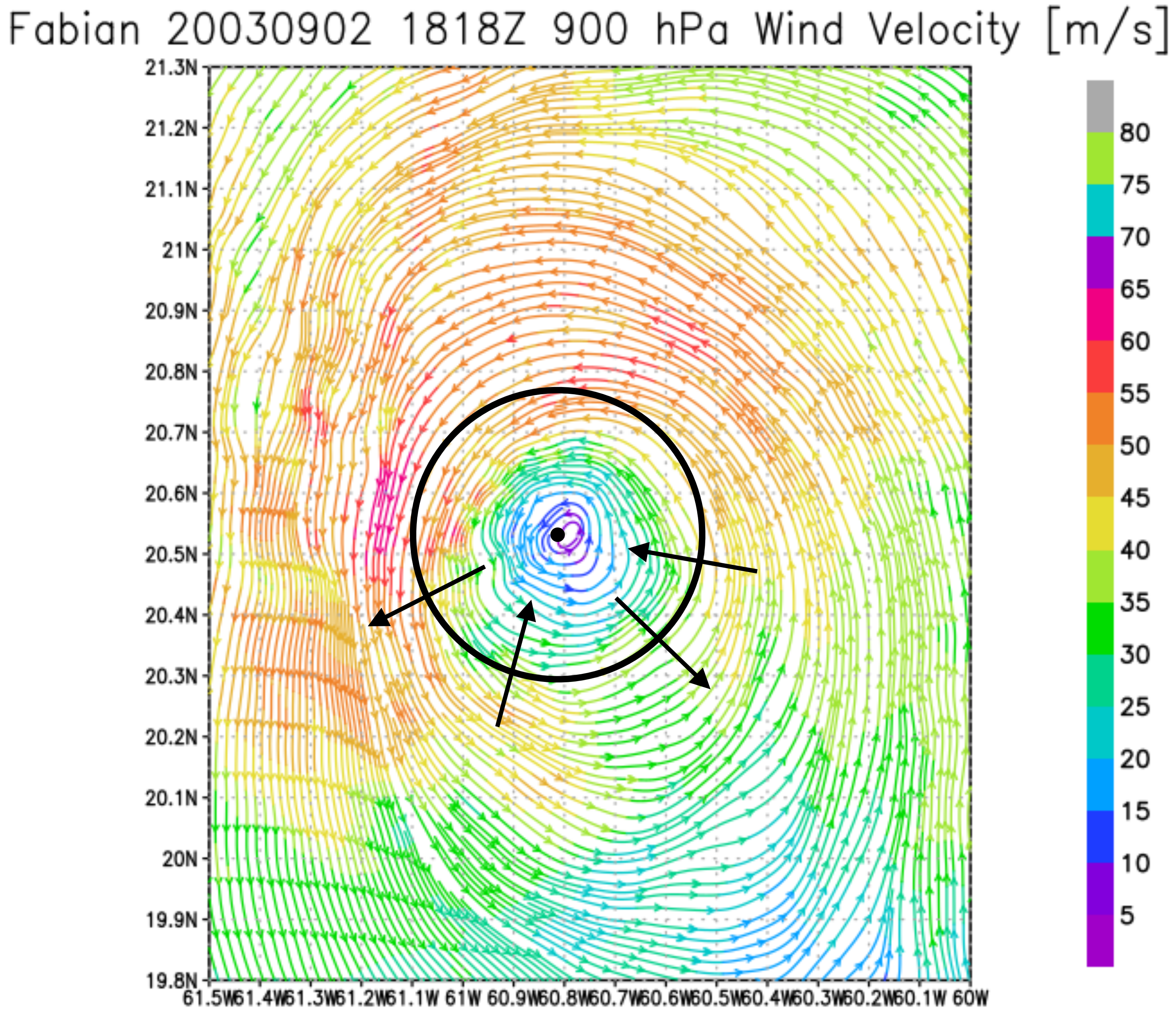


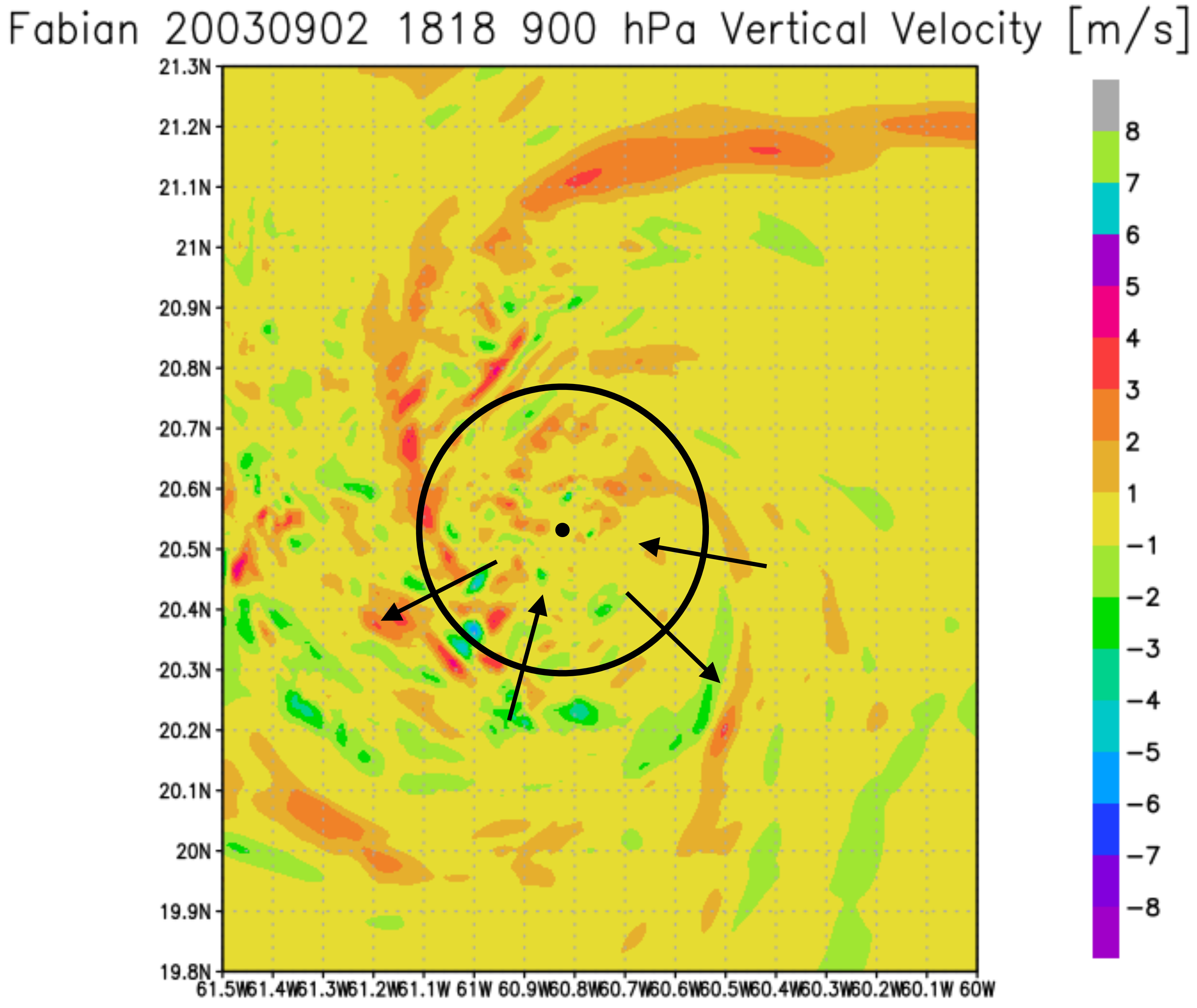
Fabian 20030902 1818Z 900 hPa Radial Wind Velocity [m/s]

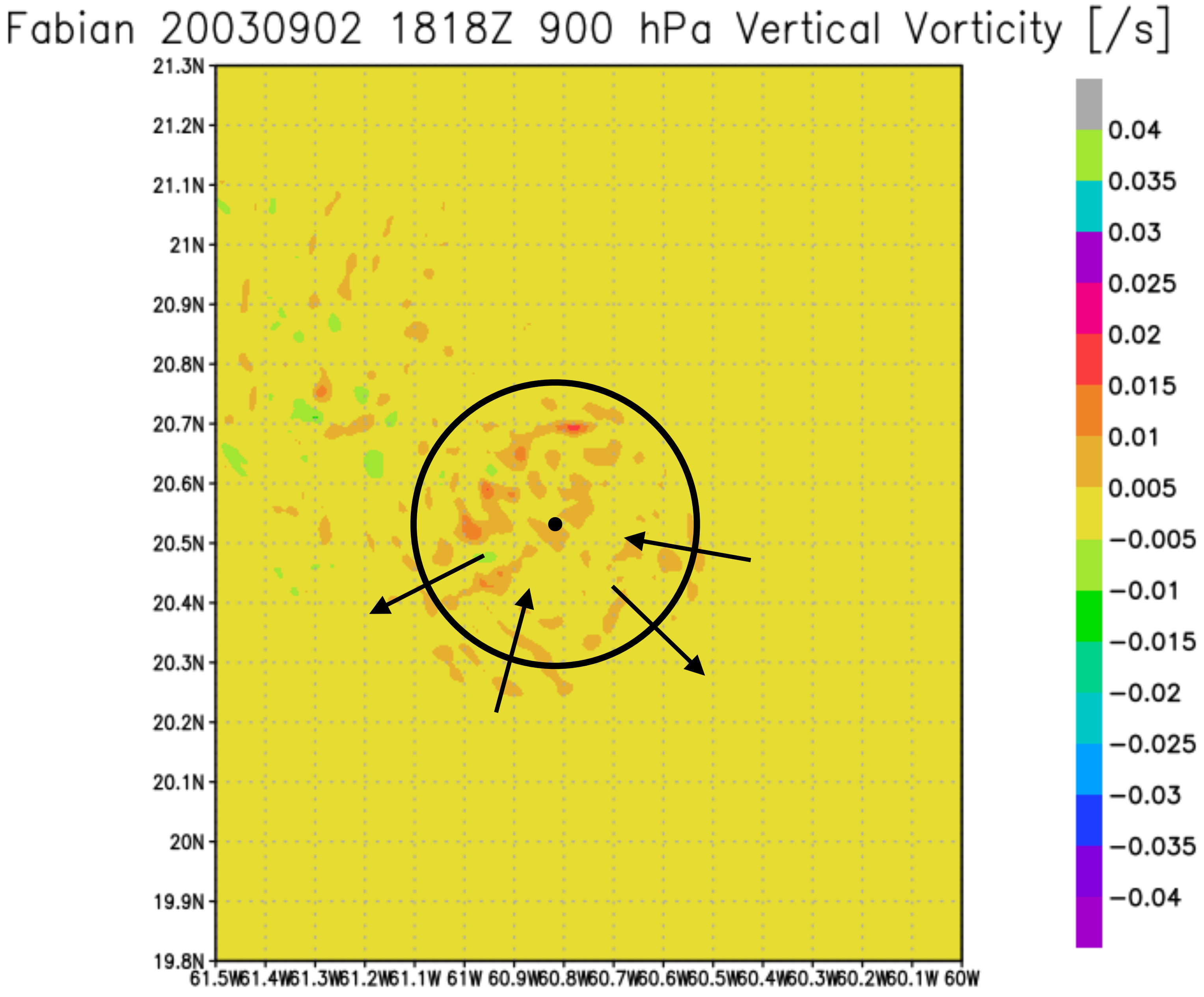


Fabian 20030902 1824Z 900 hPa Radial Wind Velocity [m/s]









There do not seem to be any feature in the thermodynamic fields, but there are very few temperature or moisture observations, so take that with a grain of salt


Fabian 20030902 1818Z 975 hPa Radial Wind Velocity [m/s]
Fabian 20030902 1818Z 950 hPa Radial Wind Velocity [m/s]
Fabian 20030902 1818Z 925 hPa Radial Wind Velocity
Fabian 20030902 1818Z 900 hPa Radial Wind Velocity [m/s]
Fabian 20030902 1818Z 875 hPa Radial Wind Velocity [m/s]
Fabian 20030902 1818Z 850 hPa Radial Wind Velocity

Conclusions:

A wavenumber-3 pattern is clearly visible in the reflectivity field that rotates around the center at approximately the same rate as predicted by theory.

This reflectivity pattern does not seem to be related to anything in the wind-velocity analyses.

The reflectivity pattern does seem to be related to shallow, low-level radial-wind dipoles that also rotate around the center near the two southern triangle vertices.

There do not appear to be any meso-vortices in Fabian’s eyewall during this time.

More cases in which the P-3 circled in the eye need to be analyzed to come to any conclusions.

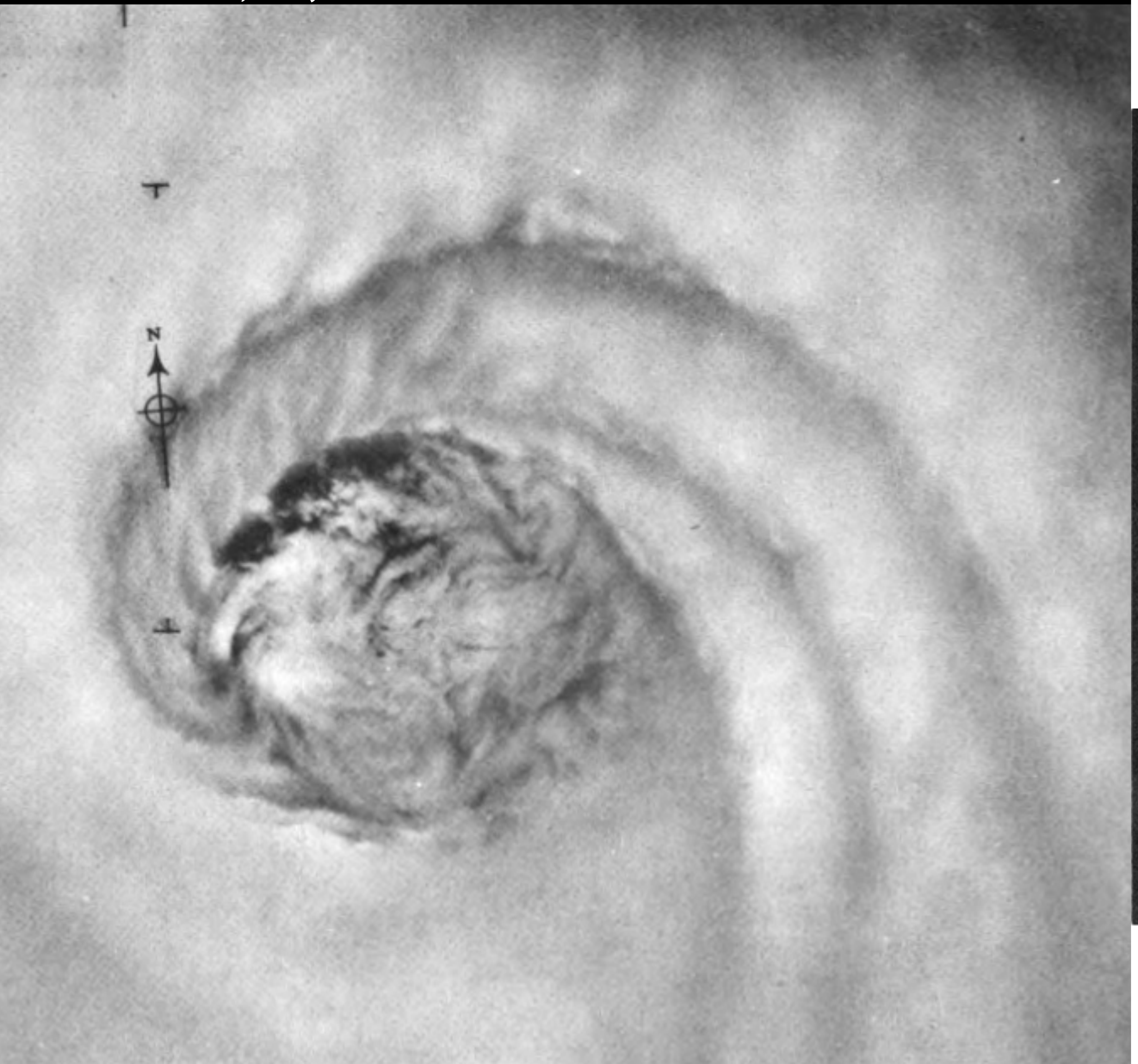
What do we call them?

Vortex: a flow with closed streamlines.

Cyclone: a cyclonic circulation, a closed circulation.

Low: an area of low pressure

Typhoon Ida (1958): First photographic evidence of small-scale features in the eye and eyewall.
Fletcher, R. D., J. R. Smith, and R. C. Bundgaard, 1961: Superior photographic reconnaissance of tropical cyclones. *Weatherwise,* **14,** 102-109.



Numerous intense hurricanes exhibit polygonal eyewalls, like Hurricane Betsy (1965), attributed to horizontally propagating internal gravity waves.

Polygonal Eye Walls and Rainbands in Hurricanes

B. M. Lewis[1] and H. F. Hawkins
National Hurricane Research Laboratory/NOAA
Gables One Tower
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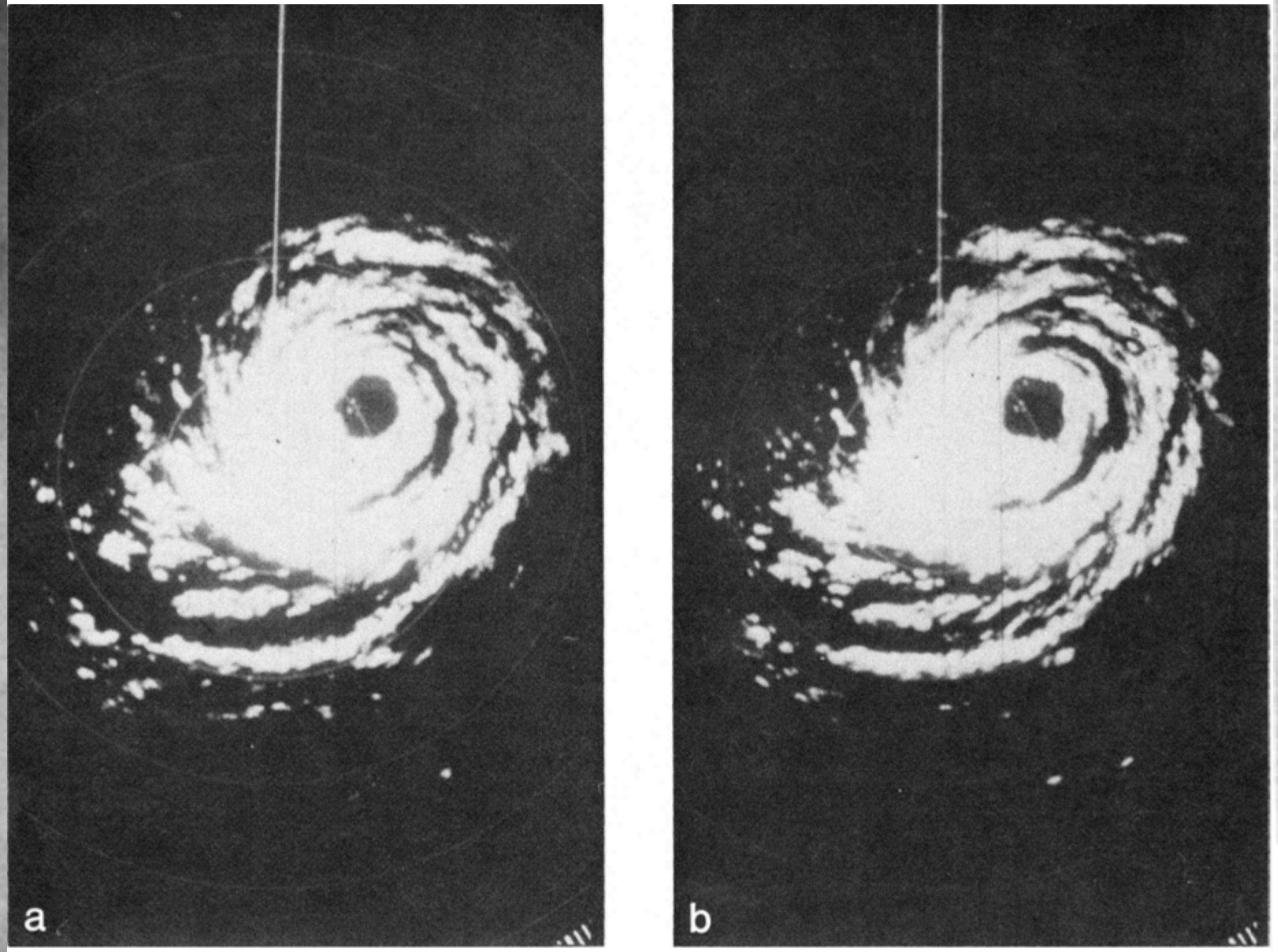

FIG. 1. Two examples of polygonal features observed by the Key West, Fla., WSR-57 radar in Hurricane Betsy: a) hexagonal eye at 0748 GMT on 8 September 1965 and b) square eye at 0803. In both cases, straight-sided bands are evident in the east side of the field of bands. (The polygonal aspect is enhanced for most viewers if the illustrations are rotated 90 degrees clockwise.)

Numerous intense hurricanes exhibit polygonal eyewalls, like Typhoon 8019, attributed to horizontally propagating internal gravity waves.

The Structure of Polygonal Eye of a Typhoon*

By Teruo Muramatsu

Japan Meteorological Agency, Forecast Division

(Manuscript received 10 June 1986, in revised form 8 October 1986)

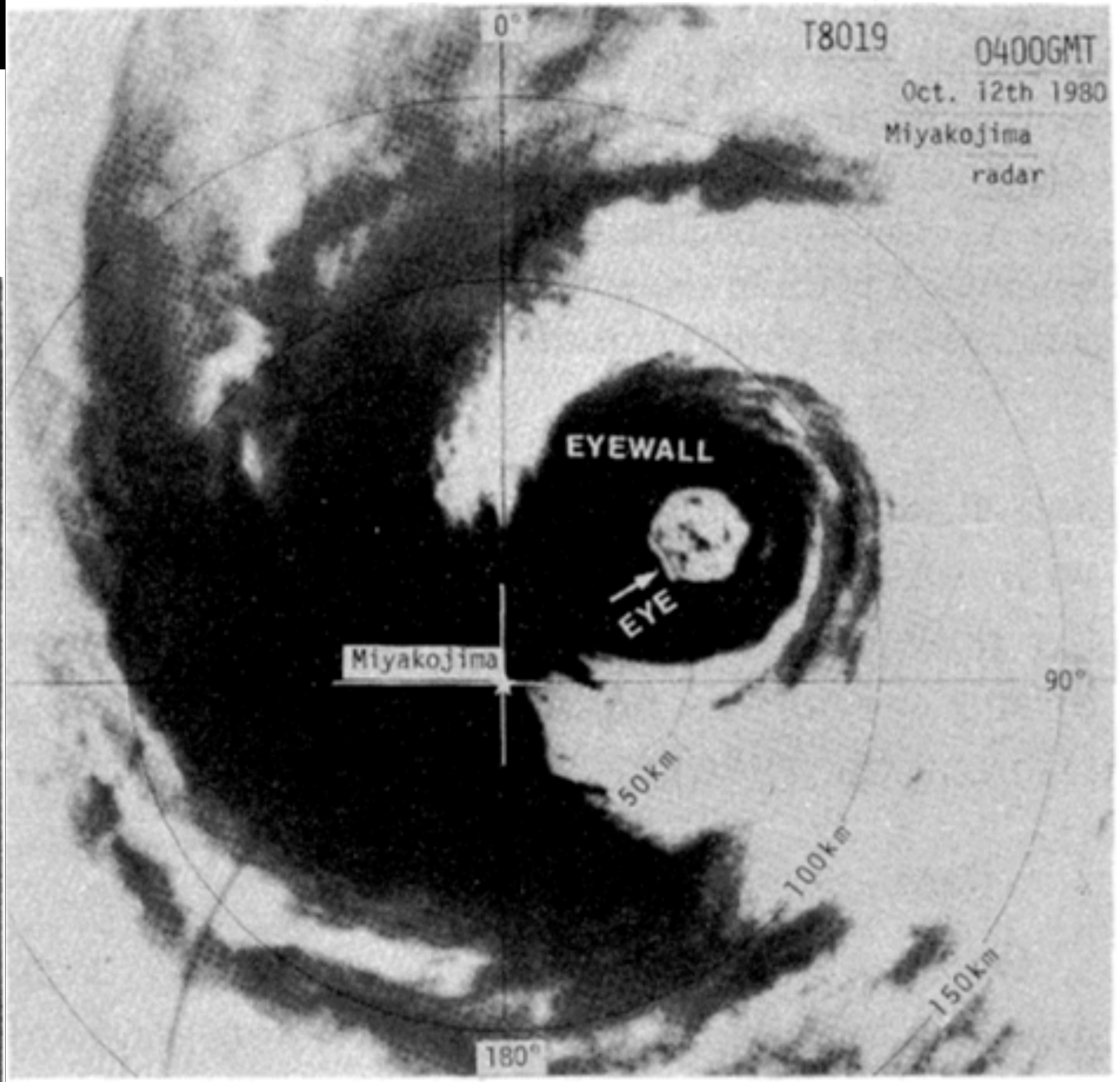

Fig. 2. Polygonal (hexagonal) eye of the typhoon 8019 on the PPI (plain position indicator), original (no-attenuation), at 0400 GMT October 12, 1980, by Miyakojima radar.

Small-scale features seen in eyes of intense tropical cyclones. Study "assumes that the cloud lines are approximately parallel to local streamlines.

Hurricane Debby (1982): Doppler radar analysis shows small-scale circulation in developing eyewall of weak hurricane.

Airborne Doppler Radar Observations in Hurricane Debby

Frank D. Marks, Jr.[1] and Robert A. Houze, Jr.[2]

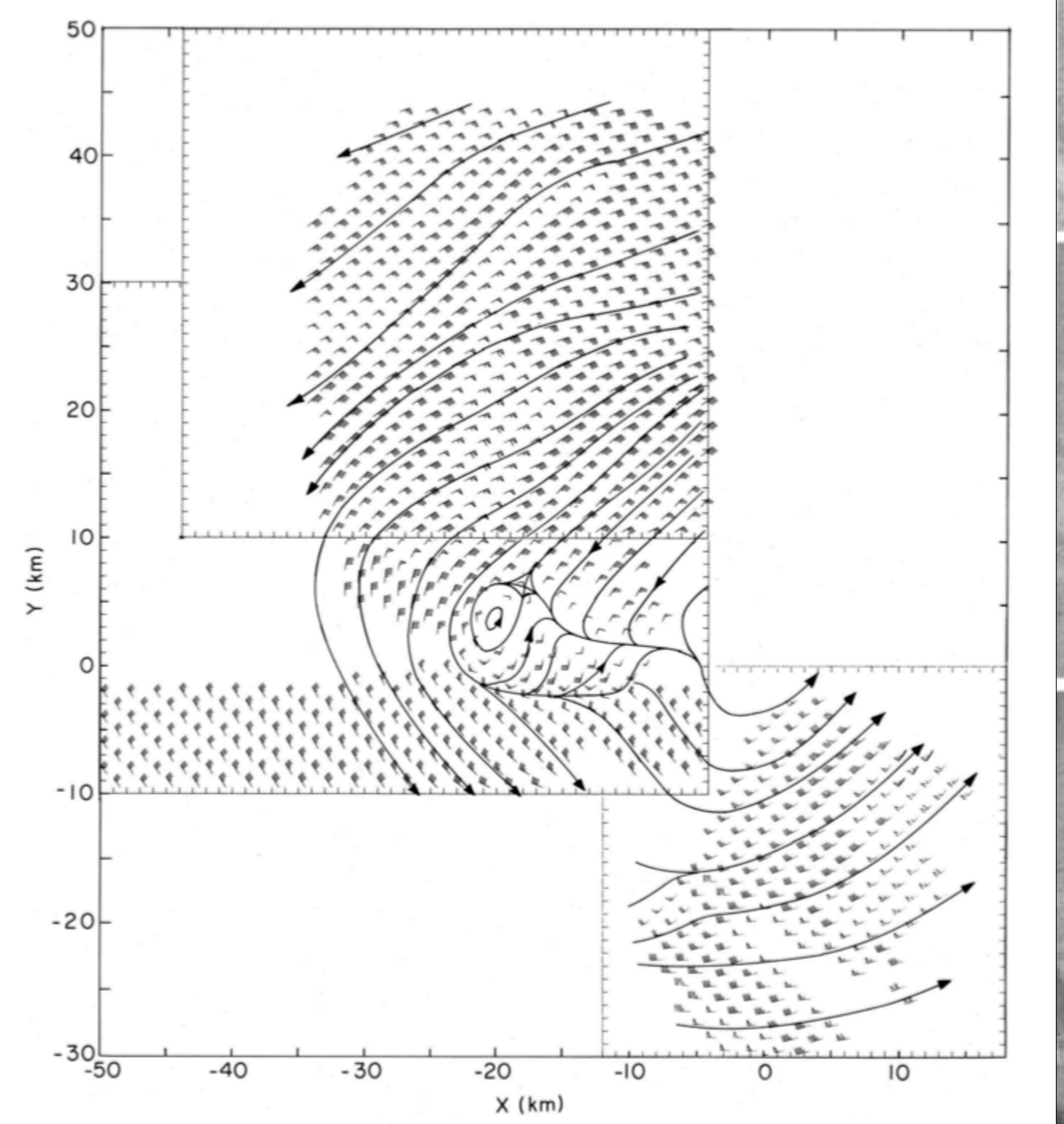

Fig. 7. Analysis of Doppler-derived winds at the 2.5 km level. The field is a mosaic of the wind patterns in Boxes 1, 3, and 4. Plotting convention same as in Fig. 2.

Vortical Swirls in Hurricane Eye Clouds

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Brian D. McNoldy and Wayne H. Schubert
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

11 April 2002 and 14 June 2002

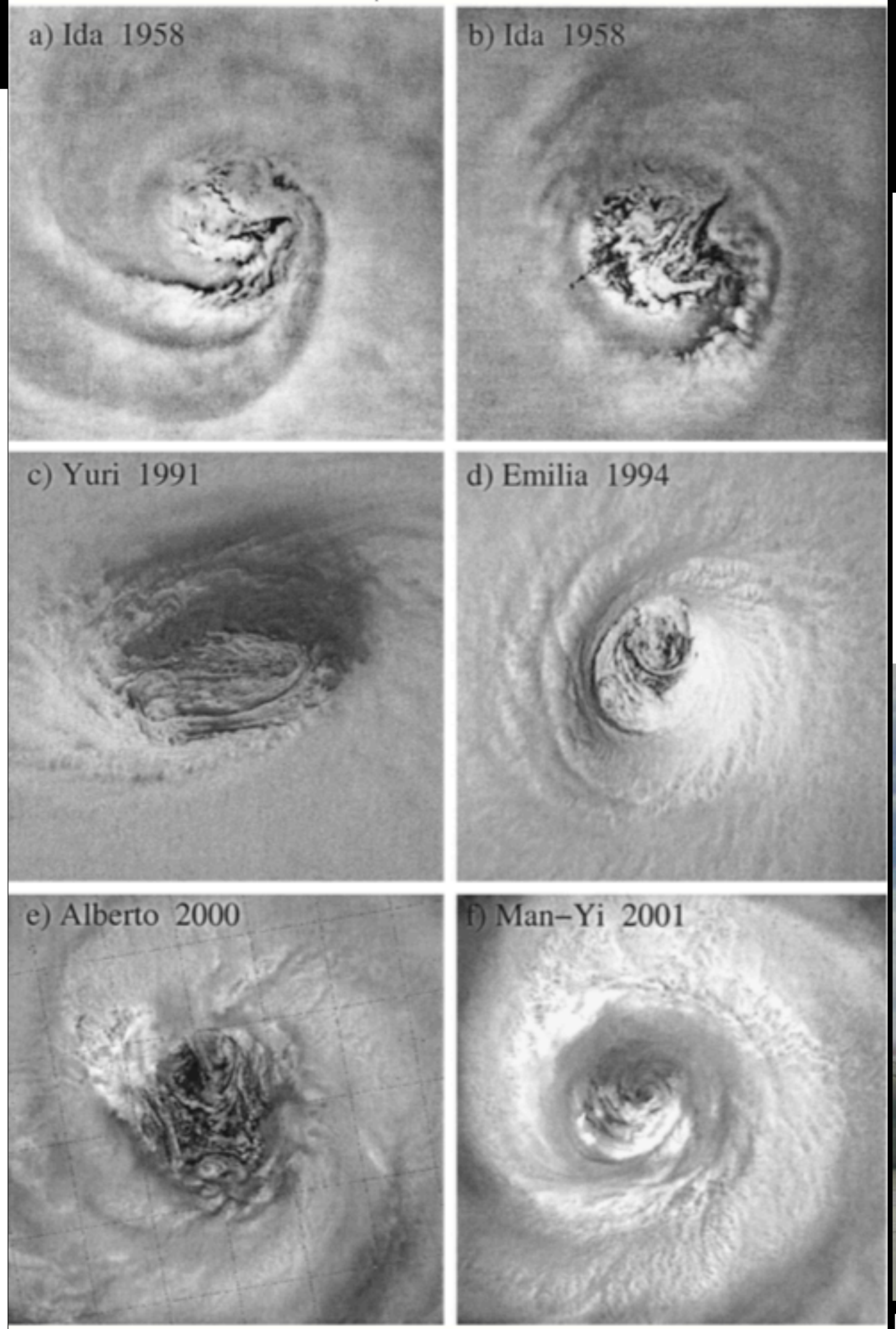

Fig. 2. Montage of images showing a variety of swirling patterns in hurricane eye clouds: (a),(b) high-altitude U-2 aircraft photographic reconnaissance (from Fletcher et al. 1961), (c),(d) photographs taken from the space shuttle, and (e)–(i) MODIS images.

Photograph of a wavenumber-2 pattern in Hurricane Erin (2011), but there was no evidence of vortices in the wind field.

NOTES AND CORRESPONDENCE

A Photograph of a Wavenumber-2 Asymmetry in the Eye of Hurricane Erin

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Jason P. Dunion
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Frank D. Marks Jr.
NOAA/AOML/Hurricane Research Division, Miami, Florida

(Manuscript received 11 November 2003, in final form 1 October 2004)

Photograph taken by the lead author from the right window of the NOAA WP-3D aircraft while circling inside the eye of Hurricane Erin at a flight level of about 4500 m at 1822 UTC 10 Sep 2001.

Buoyancy of Convective Vertical Motions in the Inner Core of Intense Hurricanes. Part II: Case Studies

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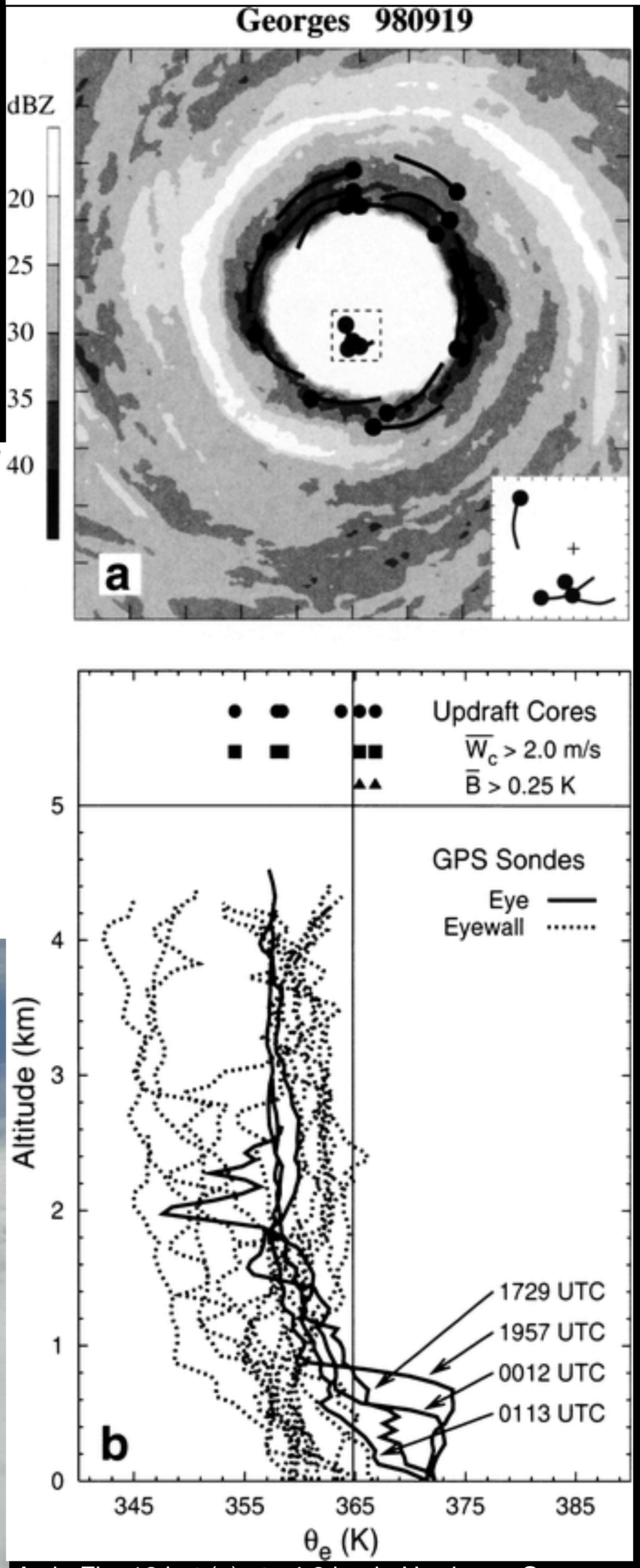
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

Peter G. Black
Hurricane Research Division, NOAA/AOML, Miami, Florida

(Manuscript received 19 December 2003, in final form 19 July 2004)



As in Fig. 12 but (a) at ~4.2 km in Hurricane Georges at 0041 UTC on 20 Sep 1998, and (b) for GPS sondes deployed in Hurricane Georges between 1900 UTC on 19 Sep and 0100 UTC on 20 Sep. Core average equivalent potential temperature θ_e values are only shown for eyewall updraft cores encountered at ~4.2-km altitude by the second aircraft between 2300 and 0100 UTC.

Study suggests that mesovortices may have been responsible for the outward advection of high-θ_e air into the eyewall. However, no mesovortices are seen in the data.

Pattern resembles mesovortices, but they did not look at the Doppler data to confirm circulations.

Rapidly Intensifying Hurricane Guillermo (1997). Part I: Low-Wavenumber Structure and Evolution

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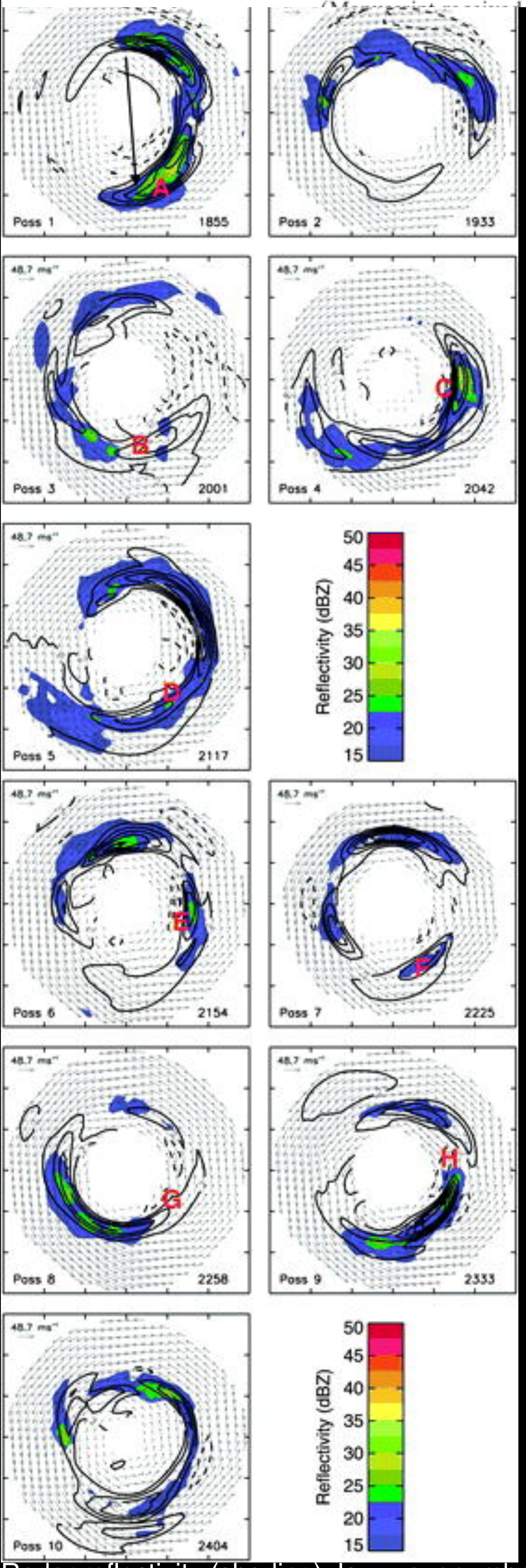
MATTHEW D. EASTIN
Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, North Carolina

JOHN F. GAMACHE
Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, Florida



A look at the low-wavenumber structure of Hurricane Guillermo. Mesovortices are mentioned in the paper in relation to past studies, but not in relation to Guillermo. Wind-field figures too small to find circulations.

Radar reflectivity (shading), low-wavenumber (n = 0–4) vertical velocity (contours), and low-wavenumber horizontal winds (vectors) in the 9–11-km layer: pass 1–10. Only the highest values of reflectivity (>15 dBZ) have been shaded for clarity. The vertical velocity contour interval is 2 m s-1. Negative values are indicated by the dashed contours. The domain is 120 km on a side with tick marks every 20 km. Regions with substantial wind coverage gaps are omitted from the analysis. Locations of convective clusters–bursts discussed in the text are labeled A–H.

PICTURE OF THE MONTH

Observed Inner-Core Structural Variability in Hurricane Dolly (2008)*

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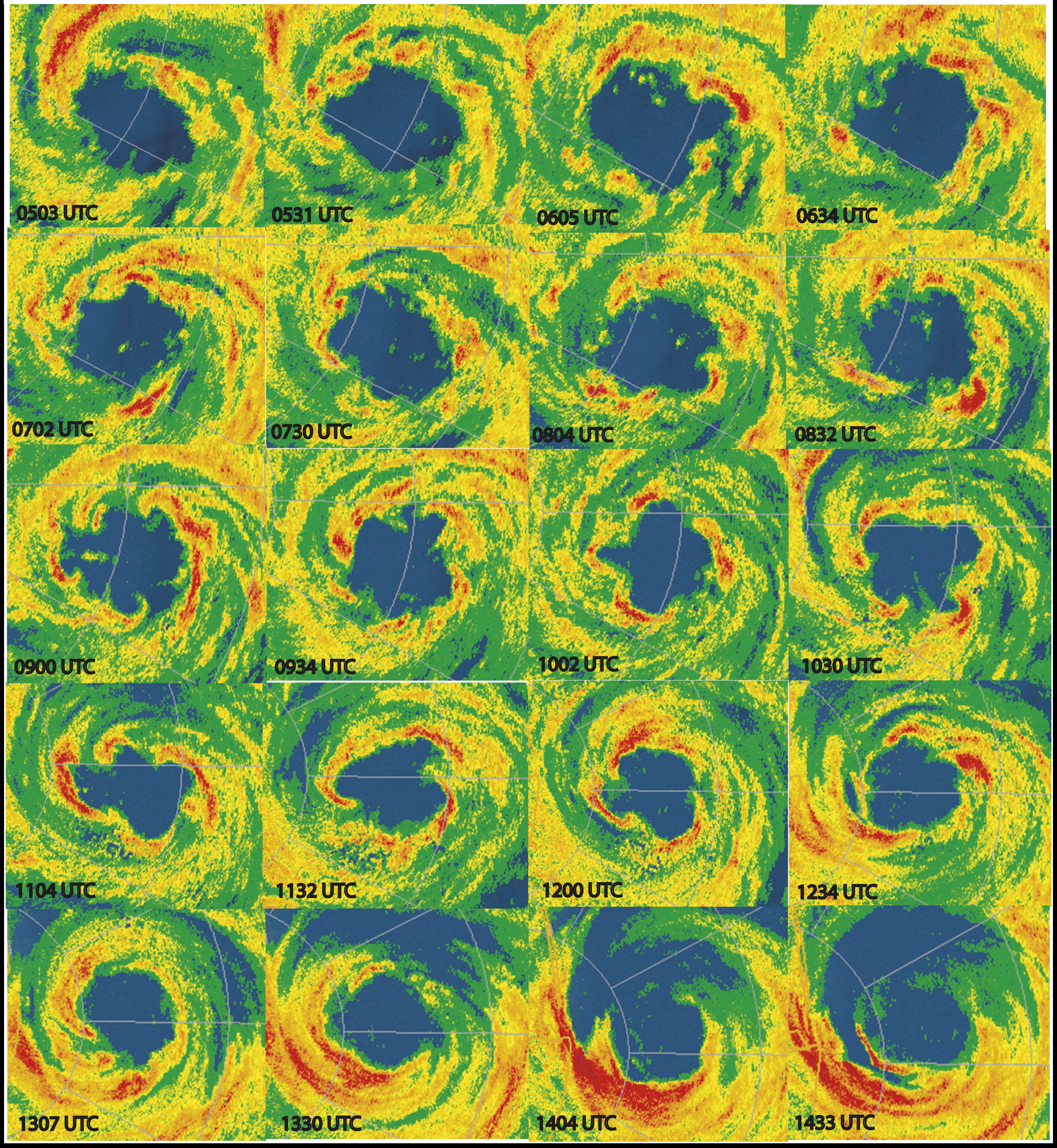
(Manuscript received 17 January 2012, in final form 22 June 2012)



Detailed temporal evolution of the eyewall of Hurricane Dolly. The first panel is at 0503 UTC 23 Jul, and each subsequent panel is approximately 30 min after the previous panel. Panels increase in time in the horizontal. The last panel is at 1433 UTC 23 Jul. The approximate diameter of the eyewall is 45–50 km.

Study describes mesovortices, but no closed circulations are found.

Estimation of the Tangential Winds and Asymmetric Structures in Typhoon Inner Core Region Using Himawari-8

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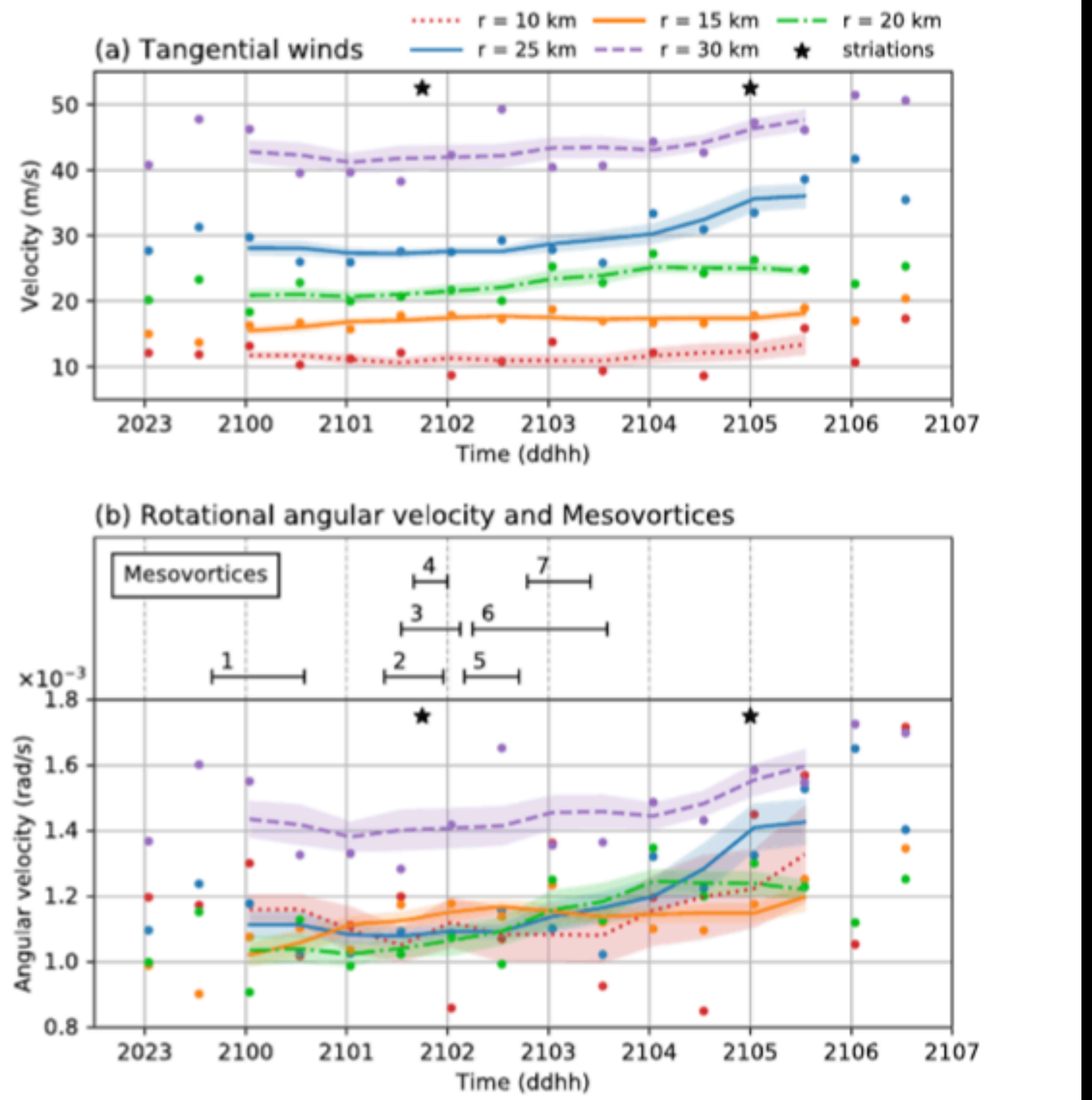

Figure 4. (a) Time variation of tangential winds and (b) rotational angular velocities at the radii of 10 (red), 15 (orange), 20 (green), 25 (blue), and 30 km (purple), respectively. Dots indicate the v_E every 30 min, while the solid curves show the running means with time over the five samples of v_E. The shading indicates ± the standard error computed from the variance among the five samples of v_E. Stars indicate the manually derived (angular) velocities of the cloud striations alongside the eyewall. The black lines at the top of (b) show the durations when the seven mesovortices were observed.

Small- (miso?-) scale features

Sloping striations seen on the inner edge of the eyewall in Hurricane Diana (1984).

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NOTES AND CORRESPONDENCE

On the Structure of the Eyewall of Hurricane Diana (1984): Comparison of Radar and Visual Characteristics

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18 December 1986 and 1 April 1987

FIG. 3. Photograph of the inside edge of the eyewall of Hurricane Diana at 1708 UTC 11 September 1984. The view is of the northeast side of the eye through a 28 mm lens (photograph by Howard B. Bluestein).

Kelvin-Helmholtz instability on the inner edge of the eyewall in Hurricane Erin (2001).

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PICTURE OF THE MONTH

Kelvin–Helmholtz Billows in the Eyewall of Hurricane Erin

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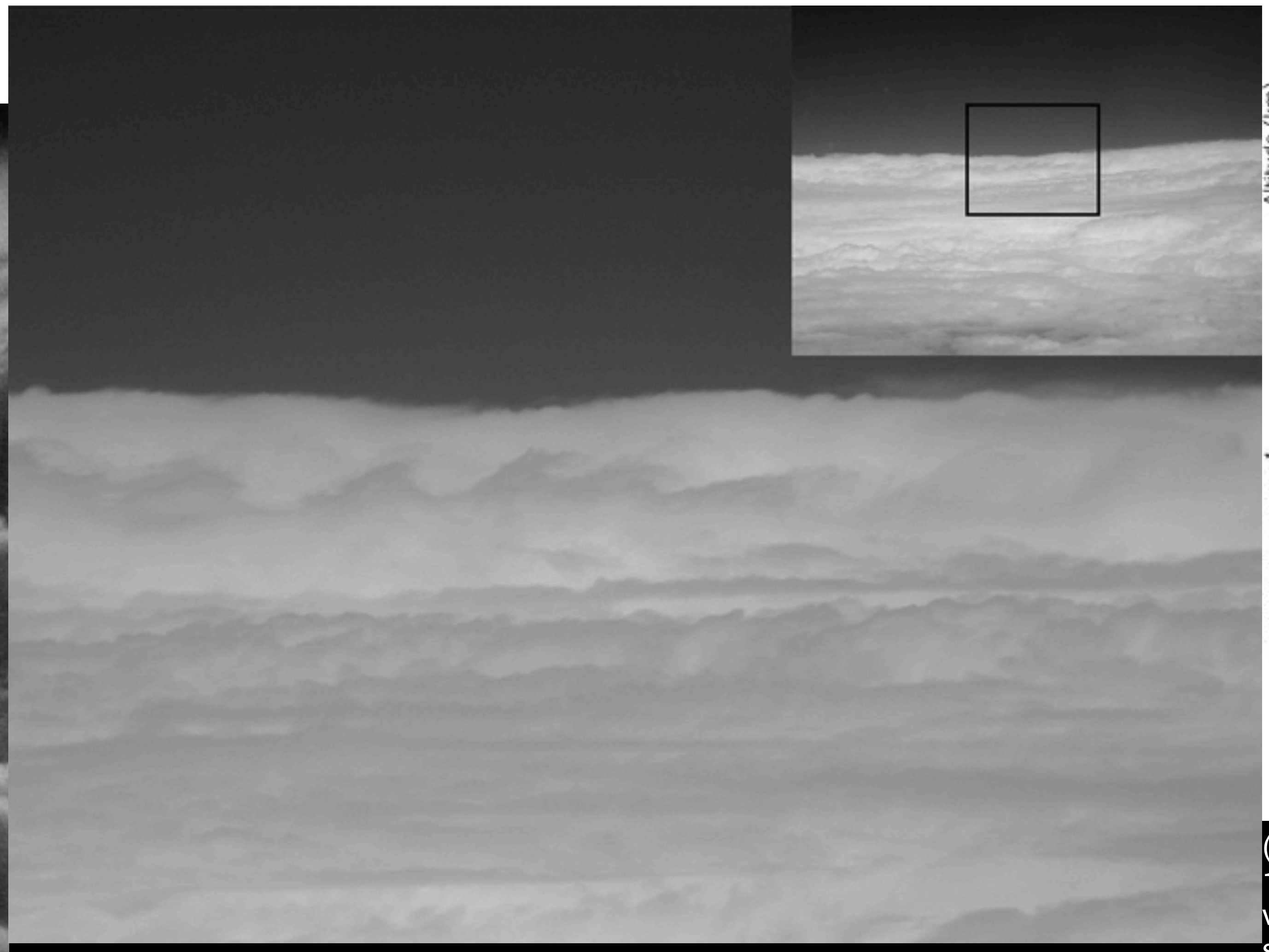
(Manuscript received 12 April 2005, in final form 27 July 2005)



Photograph of the eyewall of Hurricane Erin with Kelvin–Helmholtz waves at approximately 1815 UTC 10 Sep 2001. The image was taken from the NOAA P3 aircraft from an altitude of approximately 4500 m. The inset shows the entire photograph, with the approximate region of the close-up marked by the rectangle.

Distinct vorticity maximum ~6 km across. Wavenumber-1 wind-speed and pressure minima are tracked around the eye, though it is not a closed circulation. They are described as roll vortices or vortex tubes.

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Structure of the Eye and Eyewall of Hurricane Hugo (1989)

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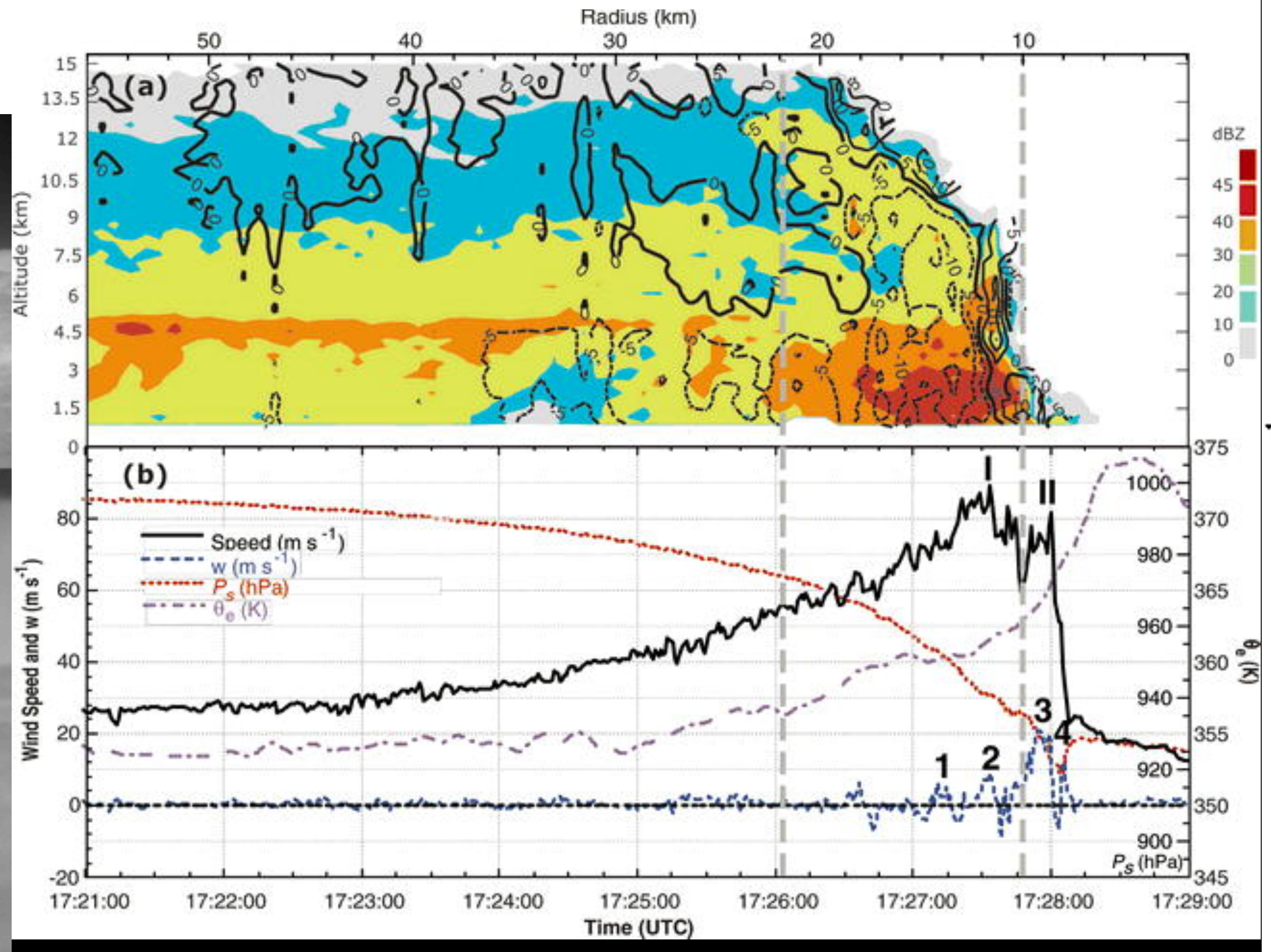

(a) Time–height cross section of vertical incidence tail radar reflectivity (dBZ) from LA for 1721–1728 UTC. The LA flight track was at 450 m. Solid and dashed lines denote vertical velocity, and radar reflectivity is denoted by colors using the color scale on the right. (b) Time series plots of w, horizontal wind speed, P_s, and θ_e for the period 1721–1730 UTC. Updrafts labeled 1, 2, 3, and 4 and wind speed peaks I and II are described in the text. The thick dashed lines in (b) approximately delineate the outer and inner radii of strong eyewall reflectivity maxima in the lower troposphere (1 < z < 5-km altitude).

Event similar to Hugo in Hurricane Felix

JUNE 2017 ABERSON ET AL. 2083

An Extreme Event in the Eyewall of Hurricane Felix on 2 September 2007

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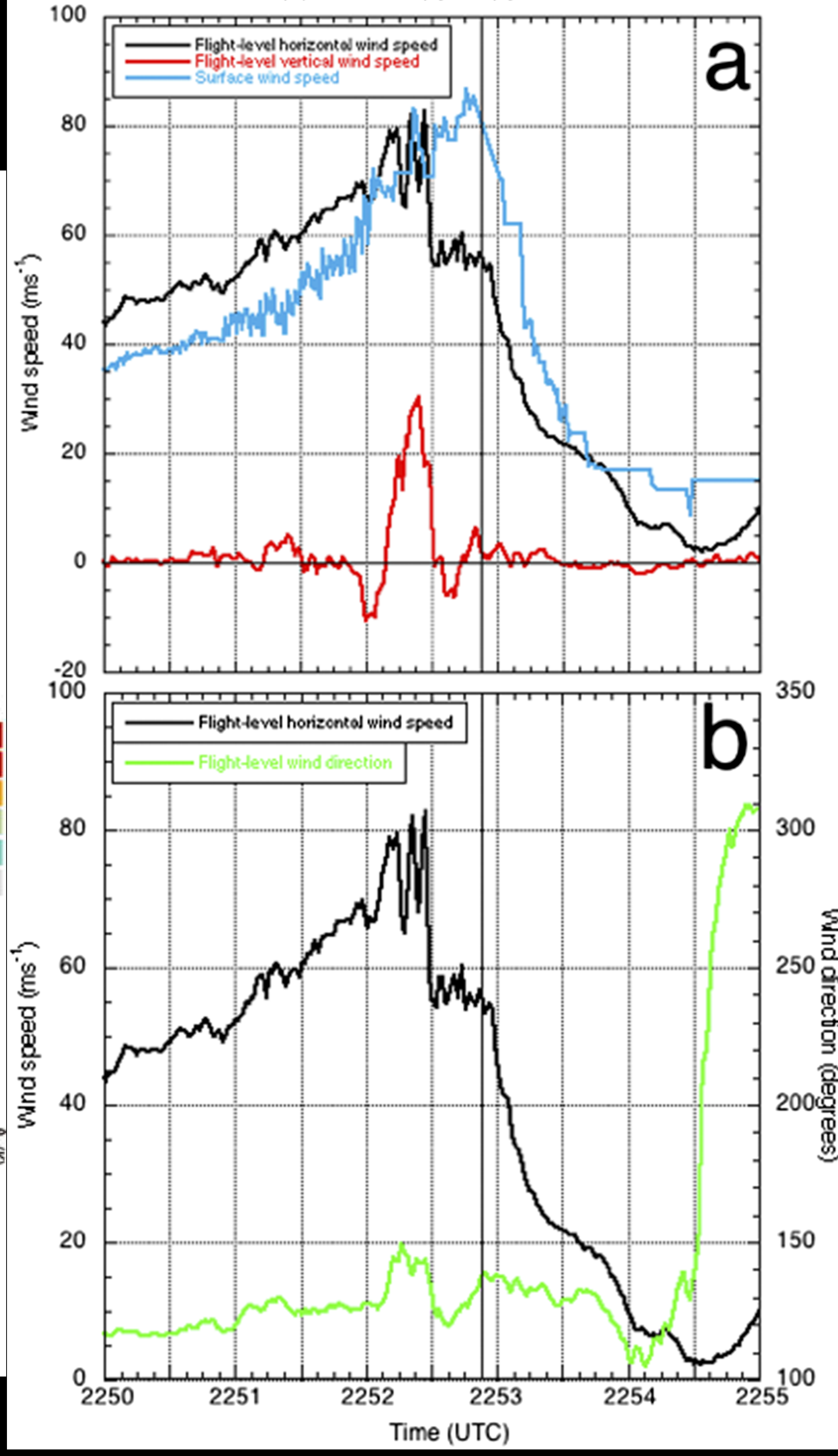

Flight-level and surface wind data during the inbound leg into Hurricane Felix: (a) flight-level horizontal wind speed, vertical wind velocity, and surface wind speed; and (b) flight-level horizontal wind speed and direction. The black vertical line corresponds to the time of the release of a dropwindsonde.