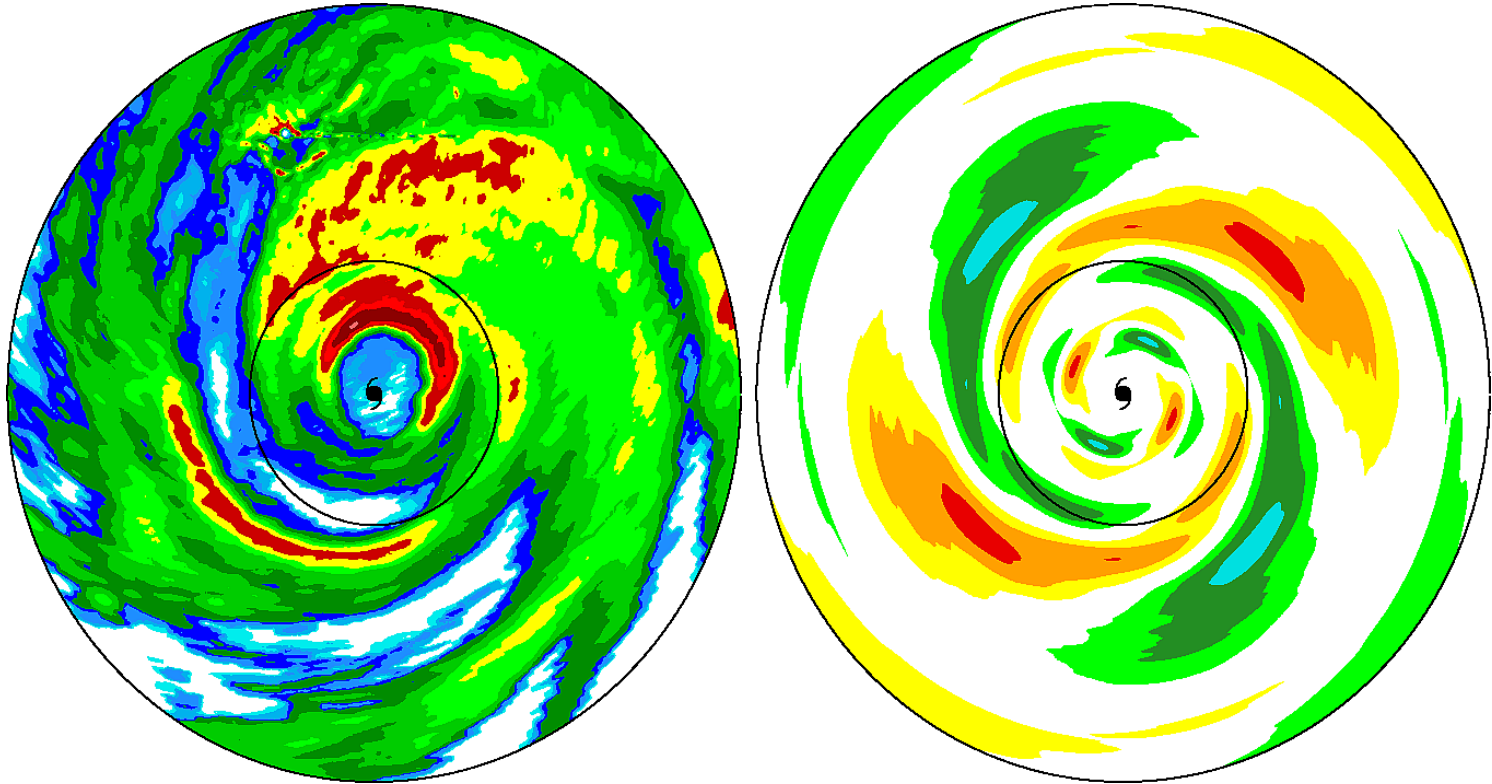


# The Inner Core Structure and Intensity Change of Hurricane Elena (1985)



**Kristen L. Corbosiero**  
*National Center for Atmospheric Research*

**Small Scales and Extreme Events: The Hurricane**  
**February 13, 2007**

## ★ Why study Hurricane Elena (1985)? ★

- Unprecedented radar and aircraft reconnaissance data set collected over a 56 hour period during which Elena underwent significant changes in structure and intensity
- Use this data to provide a more complete picture of the structural changes and dynamic processes associated with intensity change in tropical cyclones

## The Data:

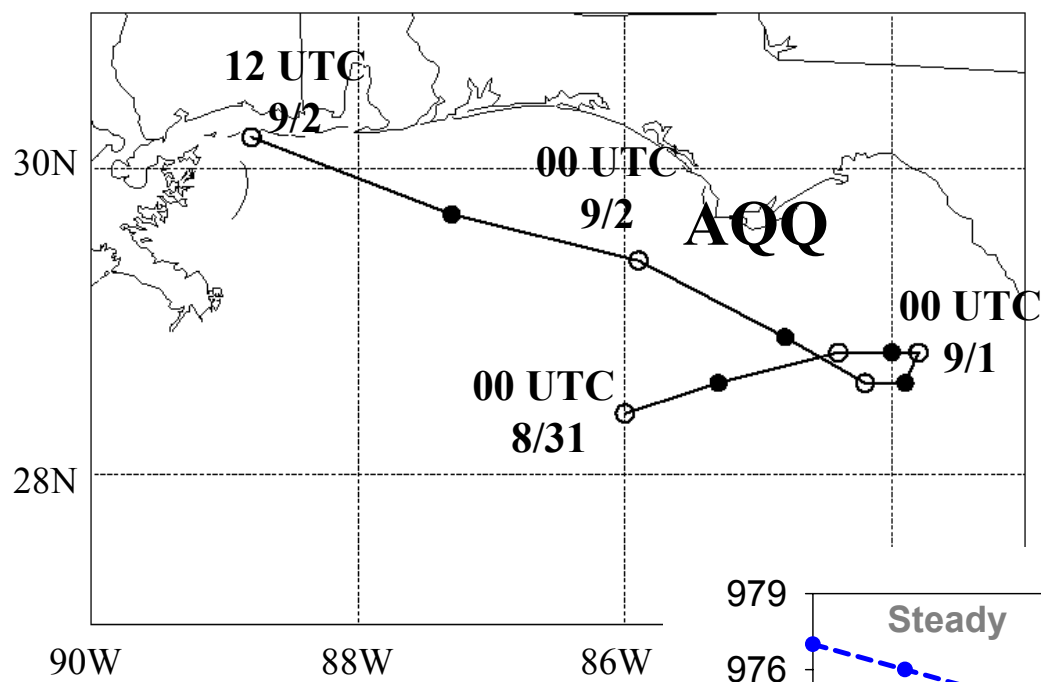
- 1,142 ground-based radar scans
  - ~ WSR-57 radar at Apalachicola, Florida (AQQ)
  - ~ Every 5 minutes, with 750 m resolution
- 86 radial flight legs
  - ~ NOAA P-3 aircraft flown at 850 hPa
  - ~ Temperature, dew point, wind speed and direction
- 47 vertically pointing radar scans from the NOAA P-3
  - ~ Radius-height cross sections of radar reflectivity and vertical motion

**This unprecedented amount of data allowed for the investigation of three separate, but interrelated topics of tropical cyclone development and intensity change:**

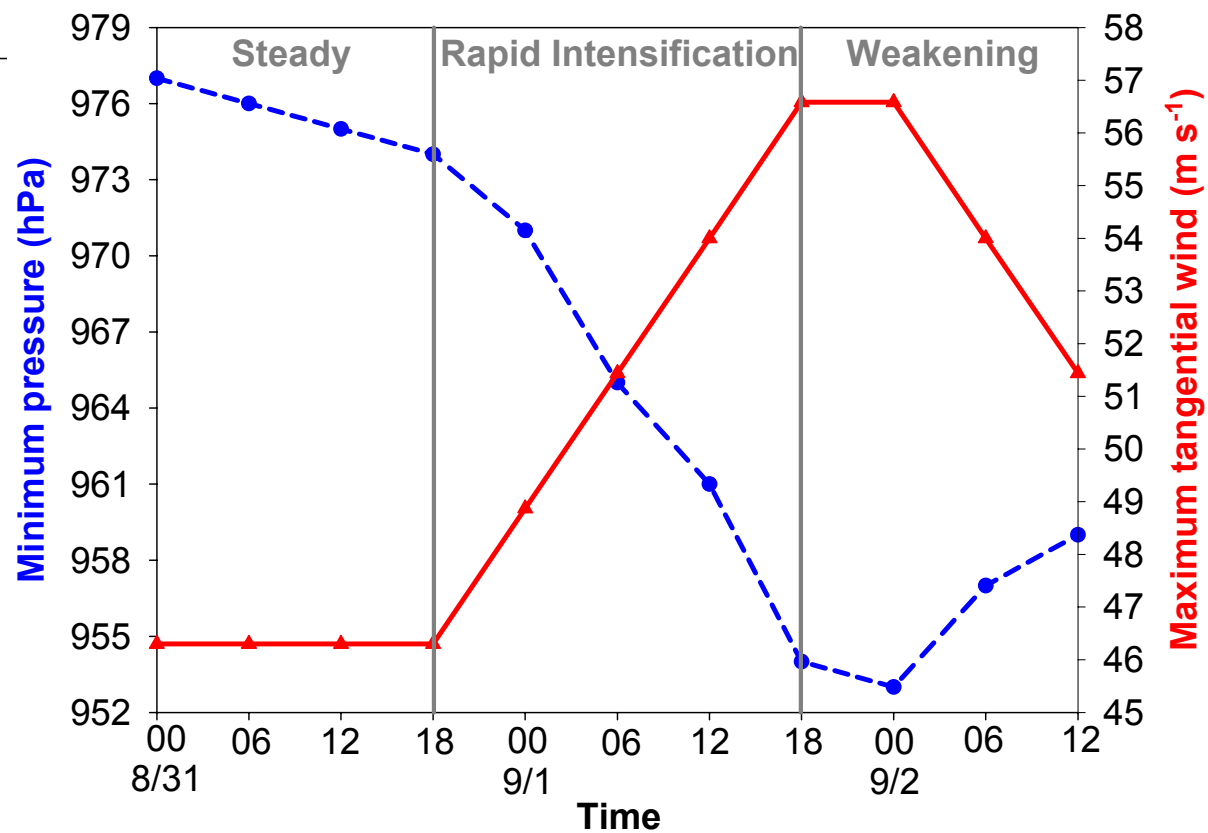
- 1) The evolution of the symmetric storm structure as Elena underwent changes in intensity**
- 2) The distribution of convection, and of kinematic and thermodynamic variables, with respect to the direction of the environmental vertical wind shear**
- 3) The realization of inner core instabilities, asymmetries and the existence of vortex Rossby waves**

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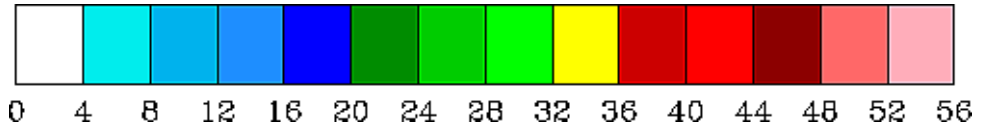
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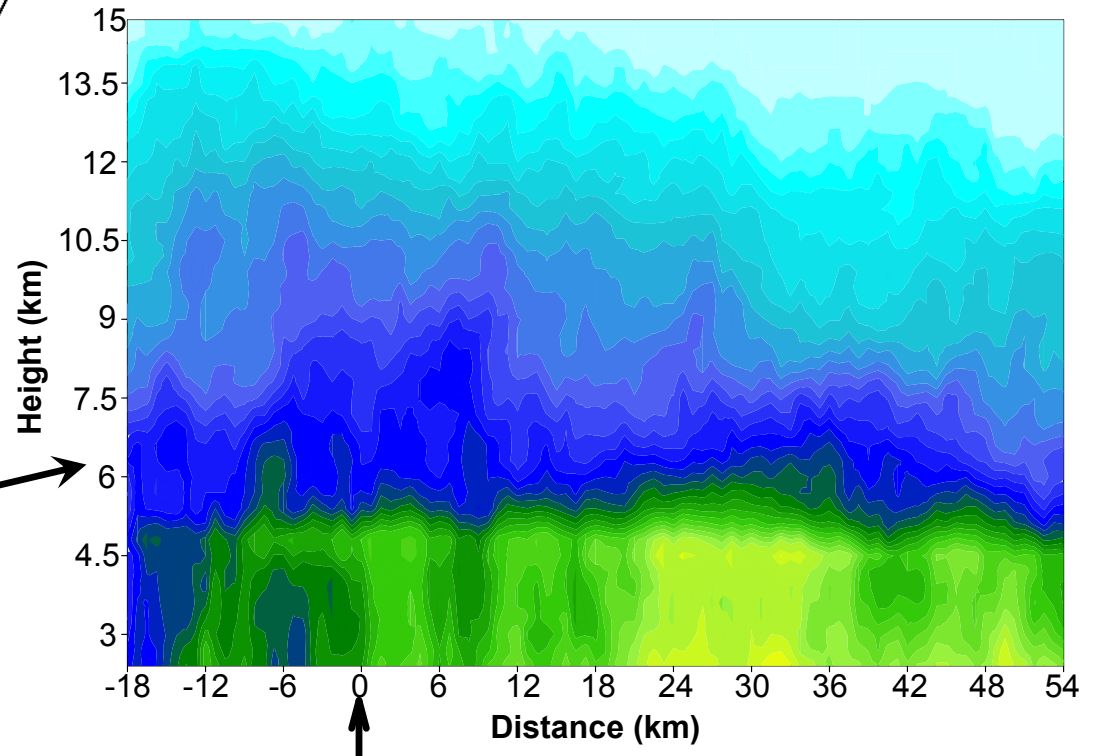
**NHC minimum surface pressure and maximum surface wind speed**



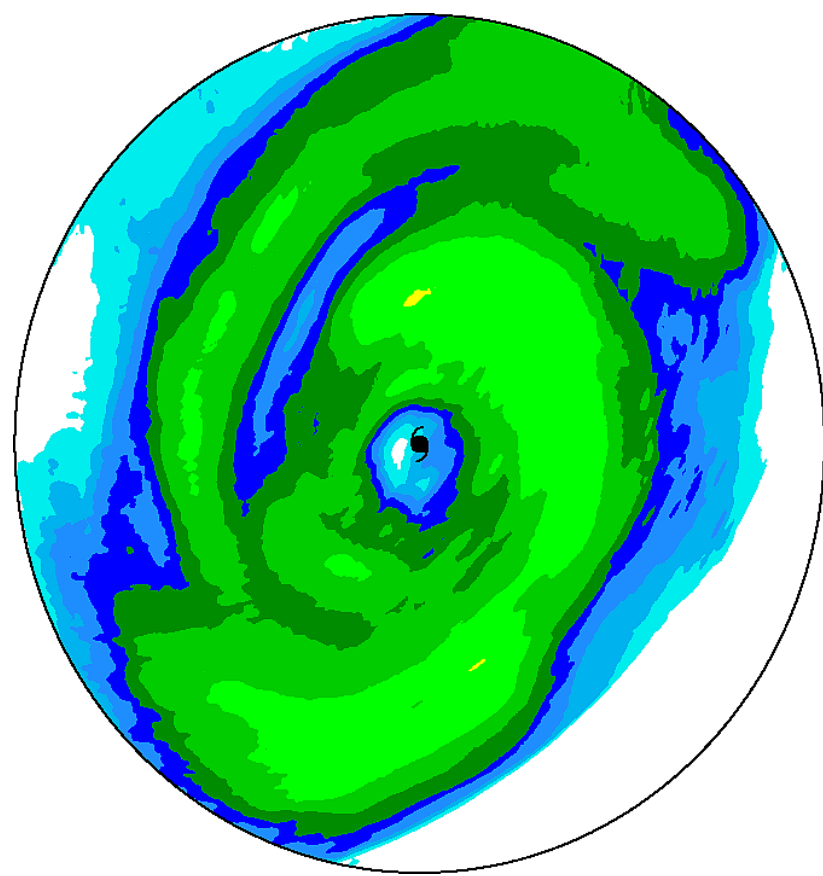
# Average reflectivity structure of Elena 22 UTC 8/31 – 05 UTC 9/1



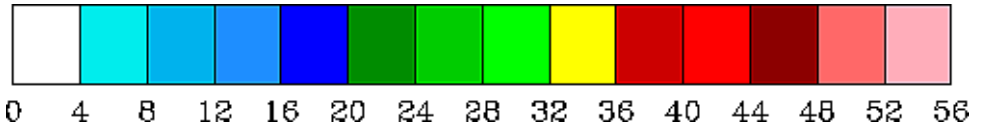
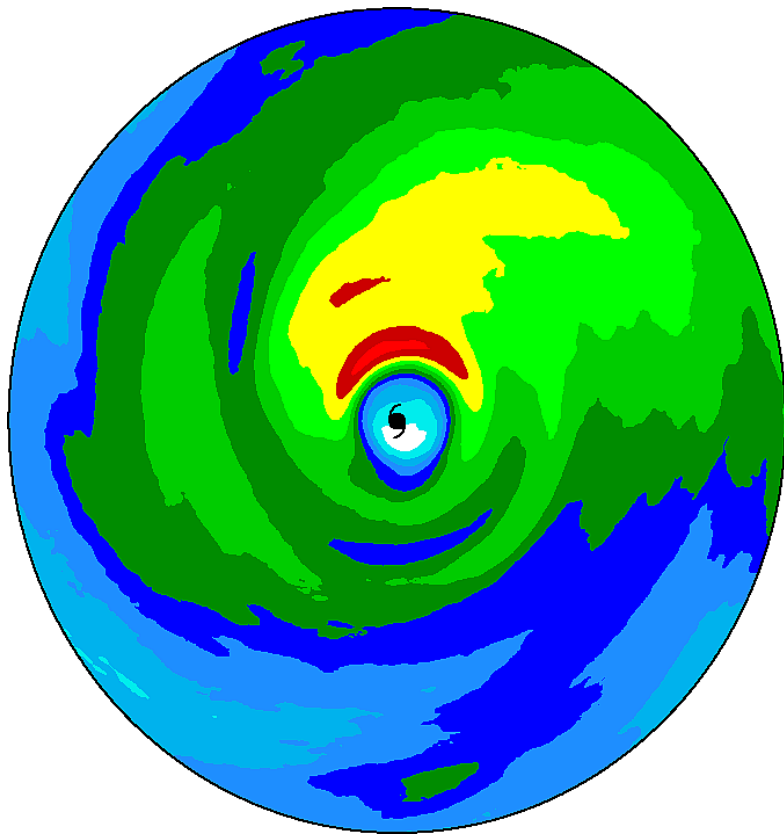
← **AQQ radar reflectivity**



**Radius-height  
cross section of  
the vertically  
pointing radar  
reflectivity**

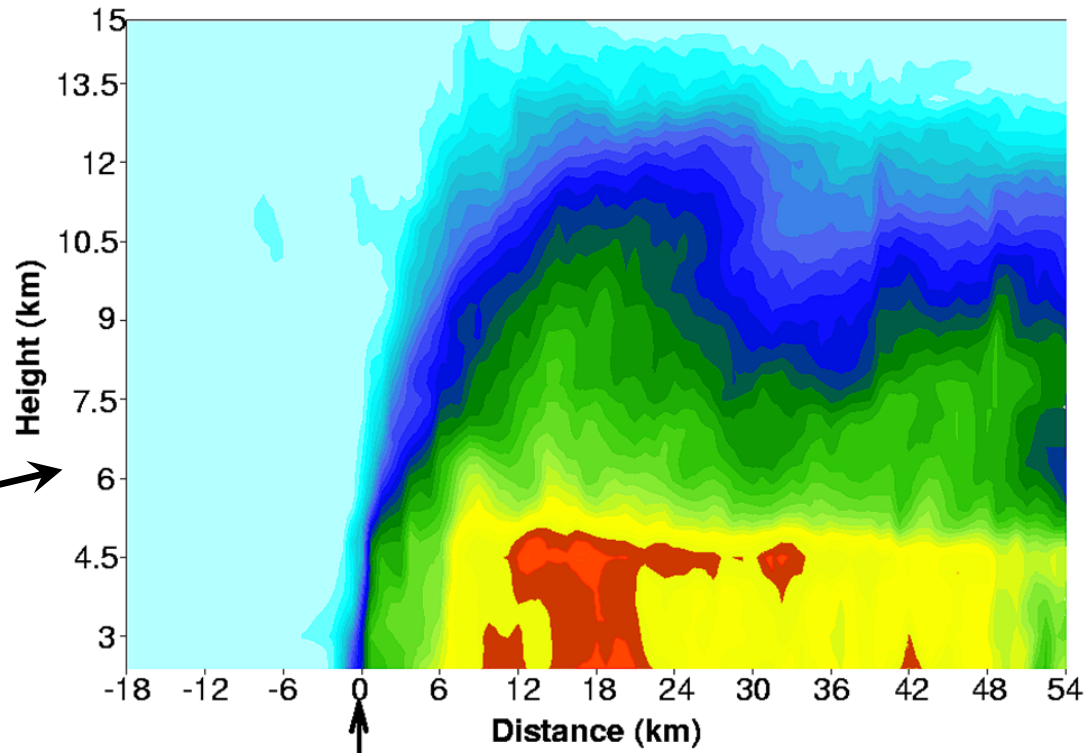


# Average reflectivity structure of Elena 12 UTC – 20 UTC 9/1

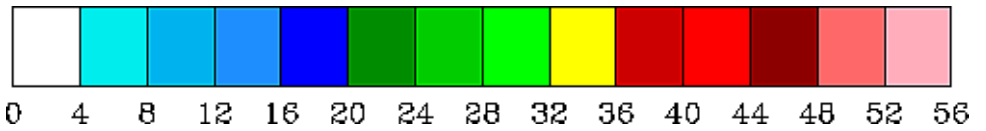
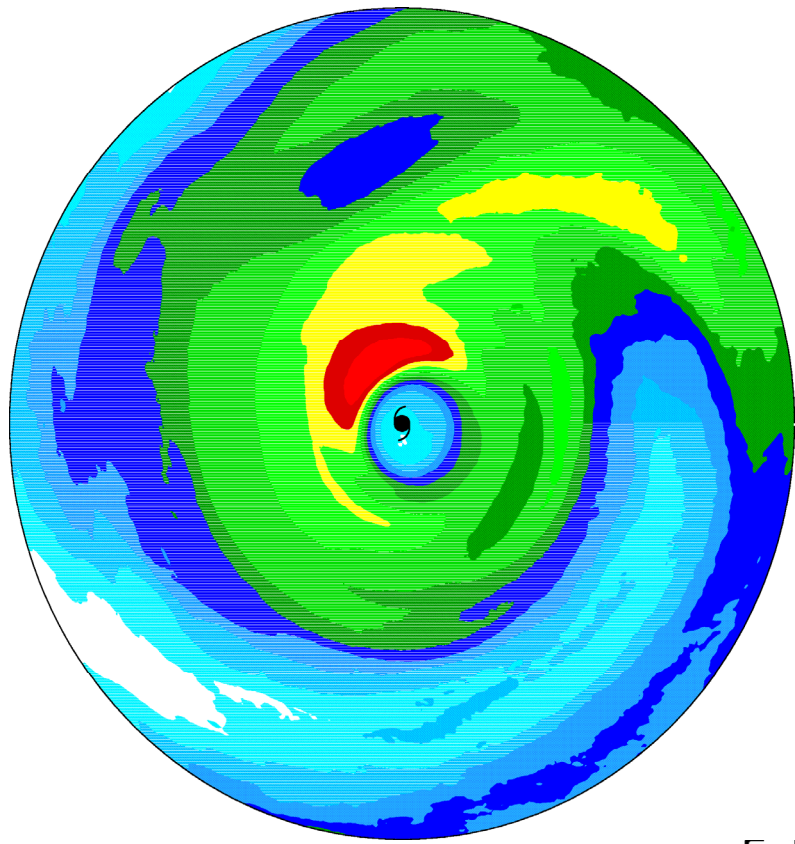


← AQQ radar reflectivity

Radius-height  
cross section of  
the vertically  
pointing radar  
reflectivity

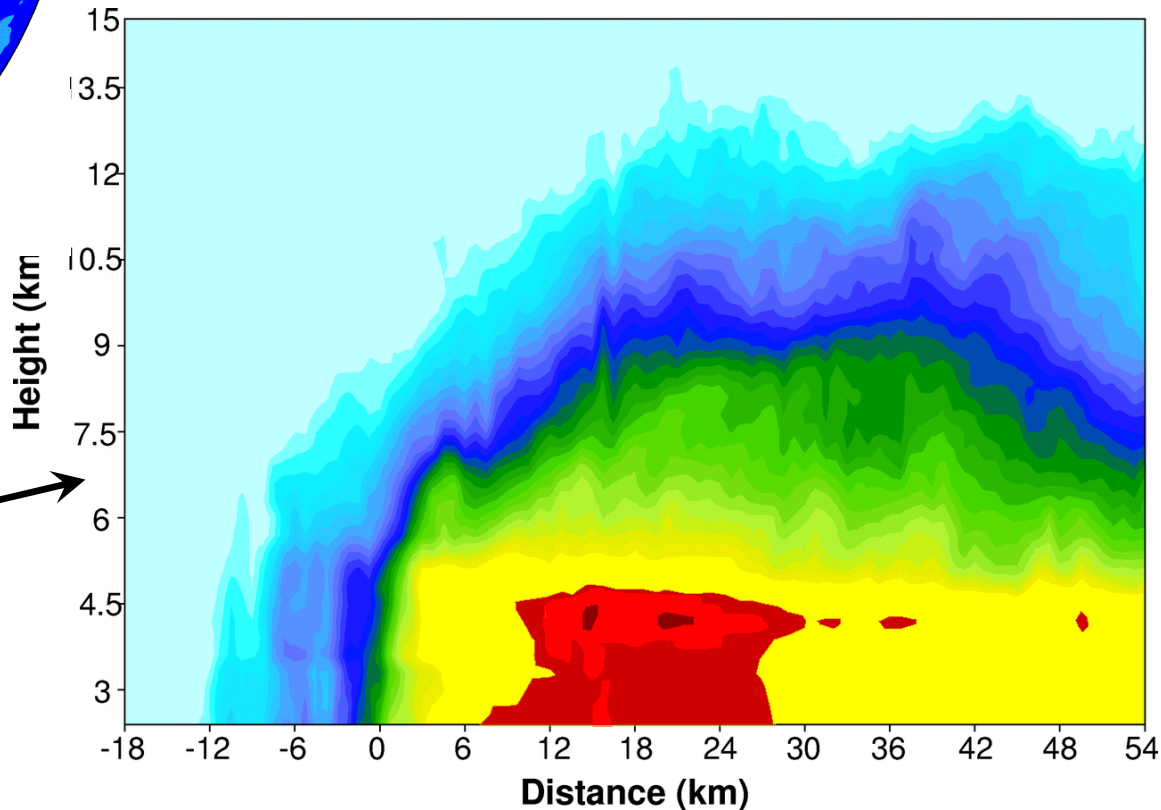


# Average reflectivity structure of Elena 21 UTC 9/1 – 03 UTC 9/2

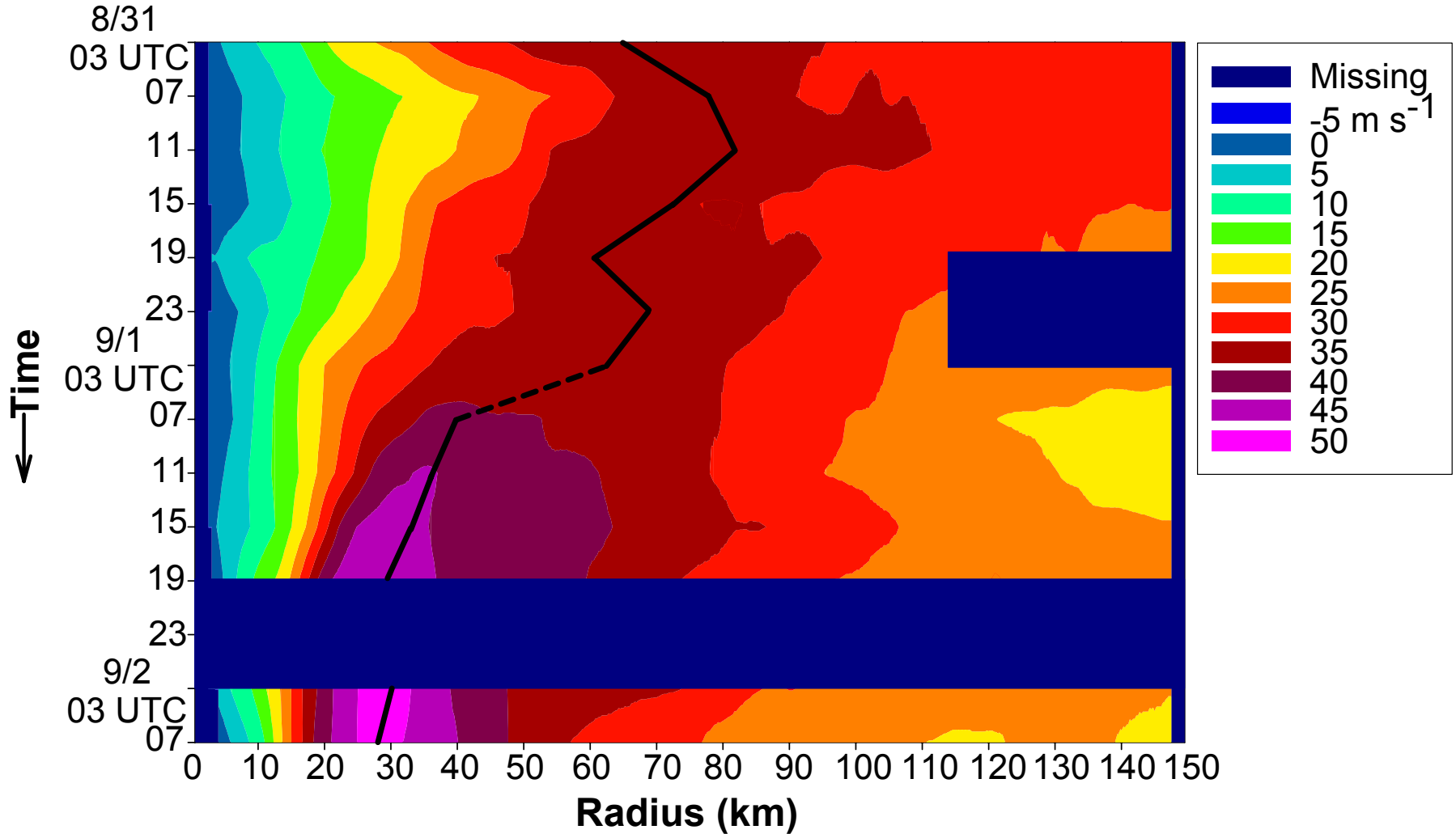


AQQ radar reflectivity

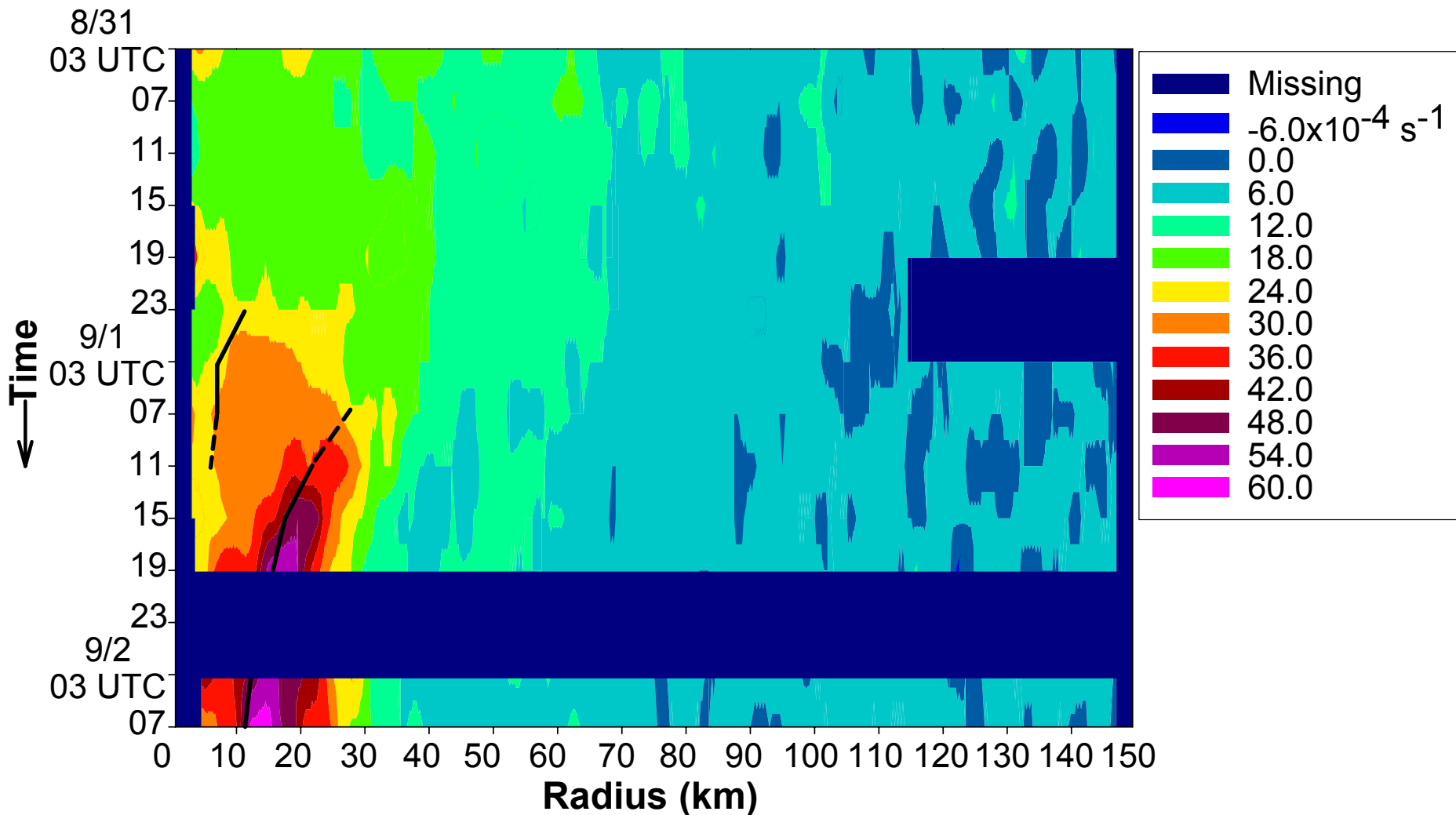
Radius-height  
cross section of  
the vertically  
pointing radar  
reflectivity

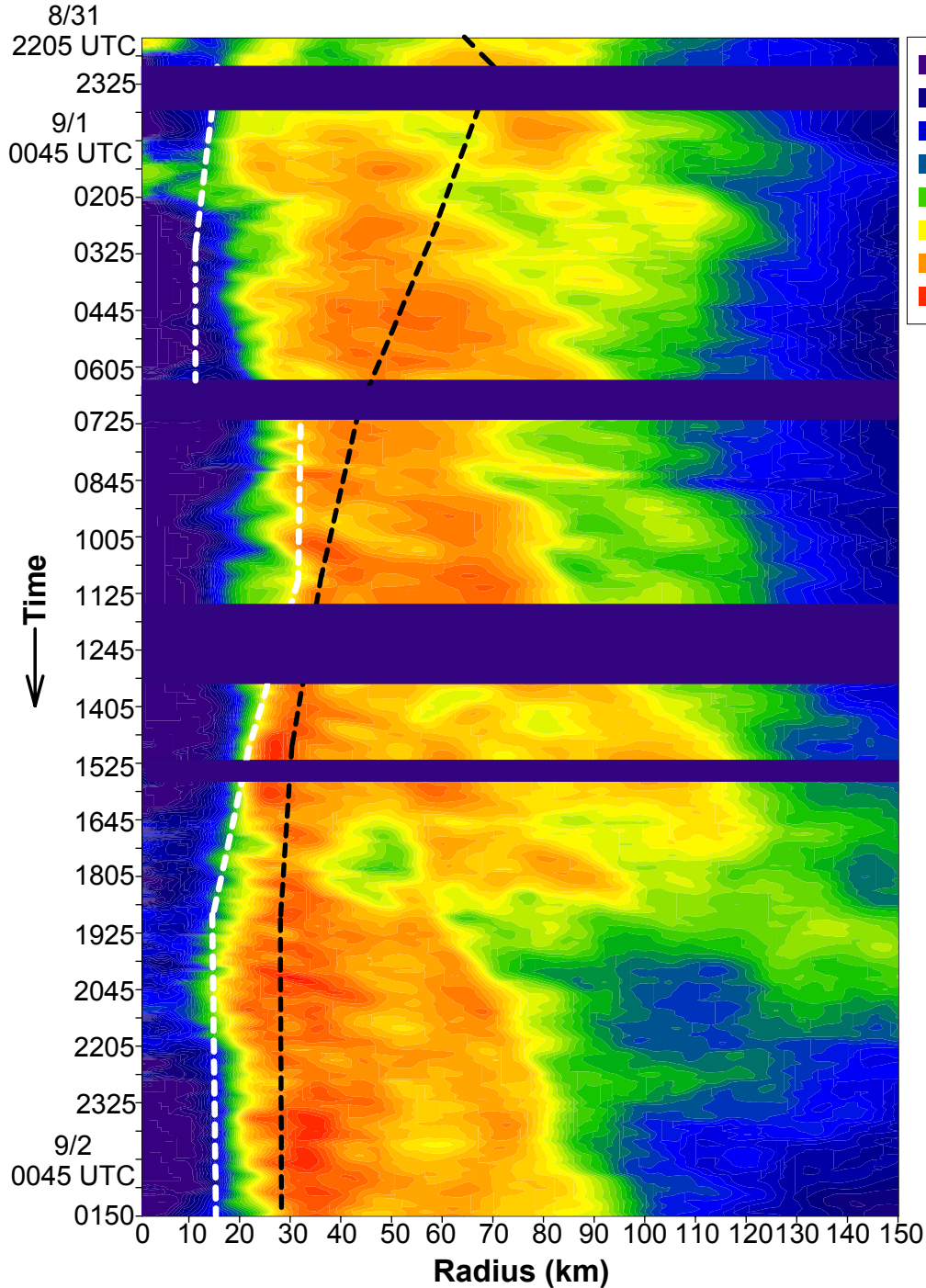


# Radius-time plot of azimuthally averaged 850 hPa tangential winds



# Radius-time plot of azimuthally averaged 850 hPa relative vorticity

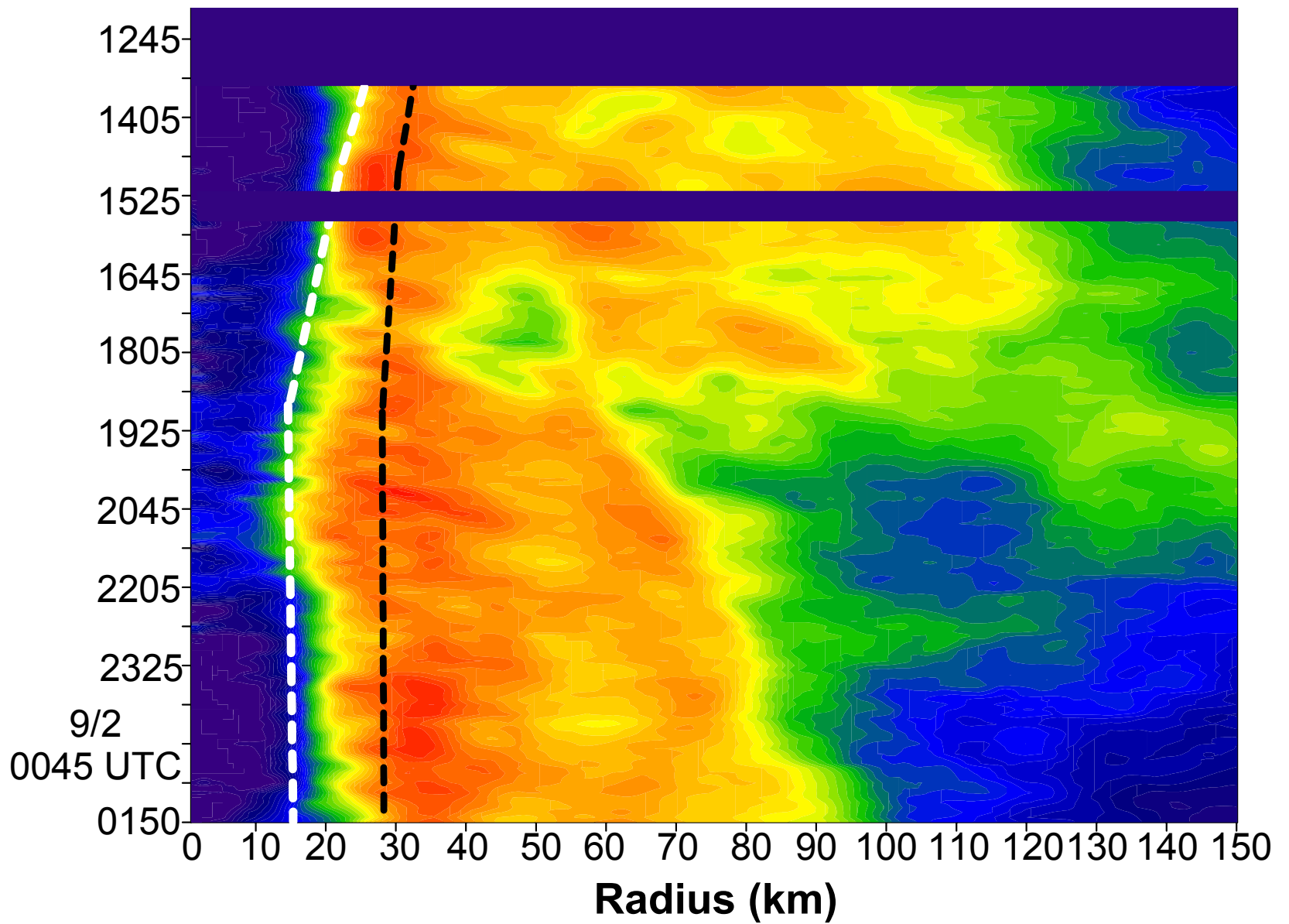


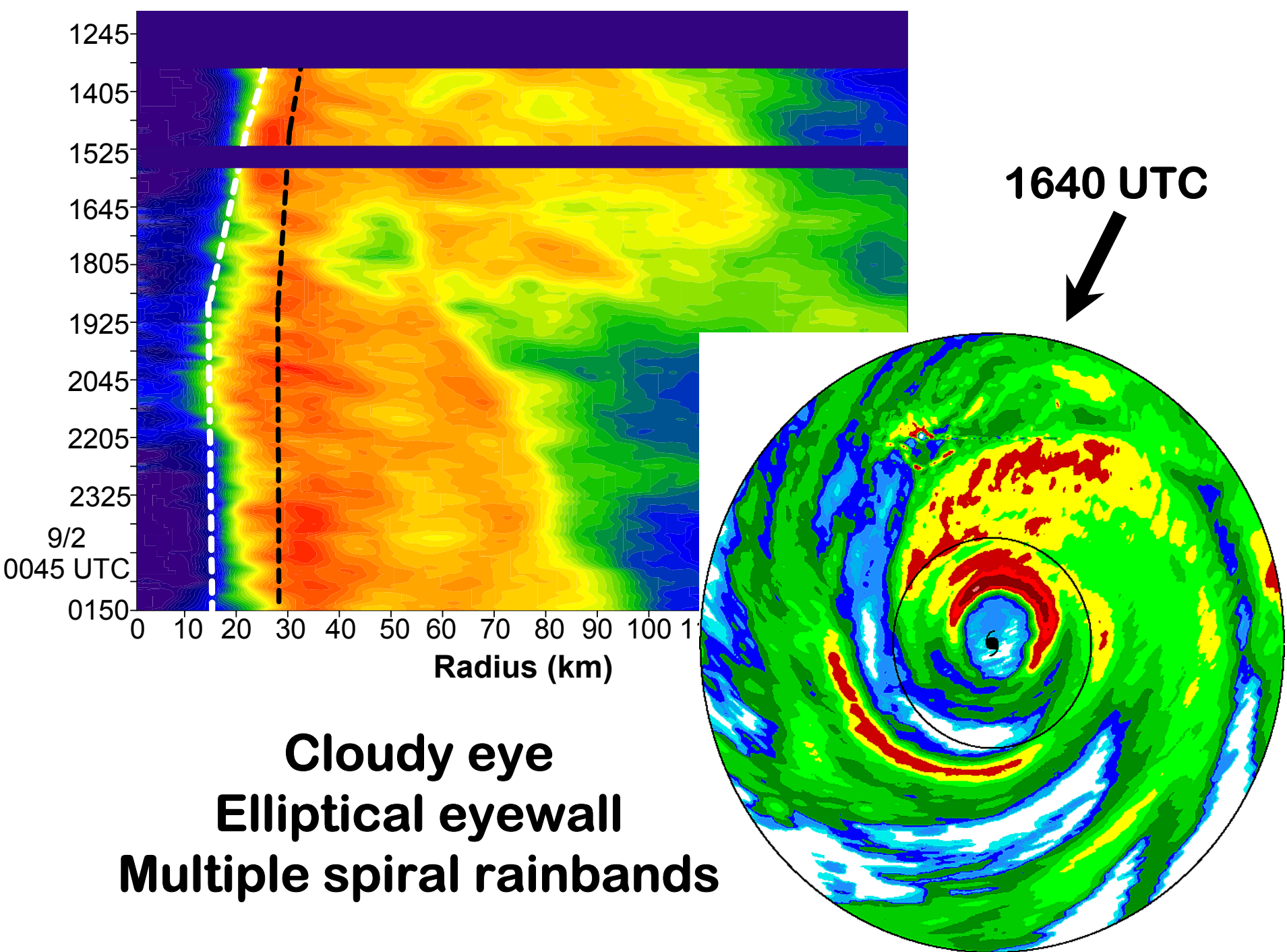


**Radius-time plot  
of azimuthally  
averaged AQQ  
radar reflectivity**

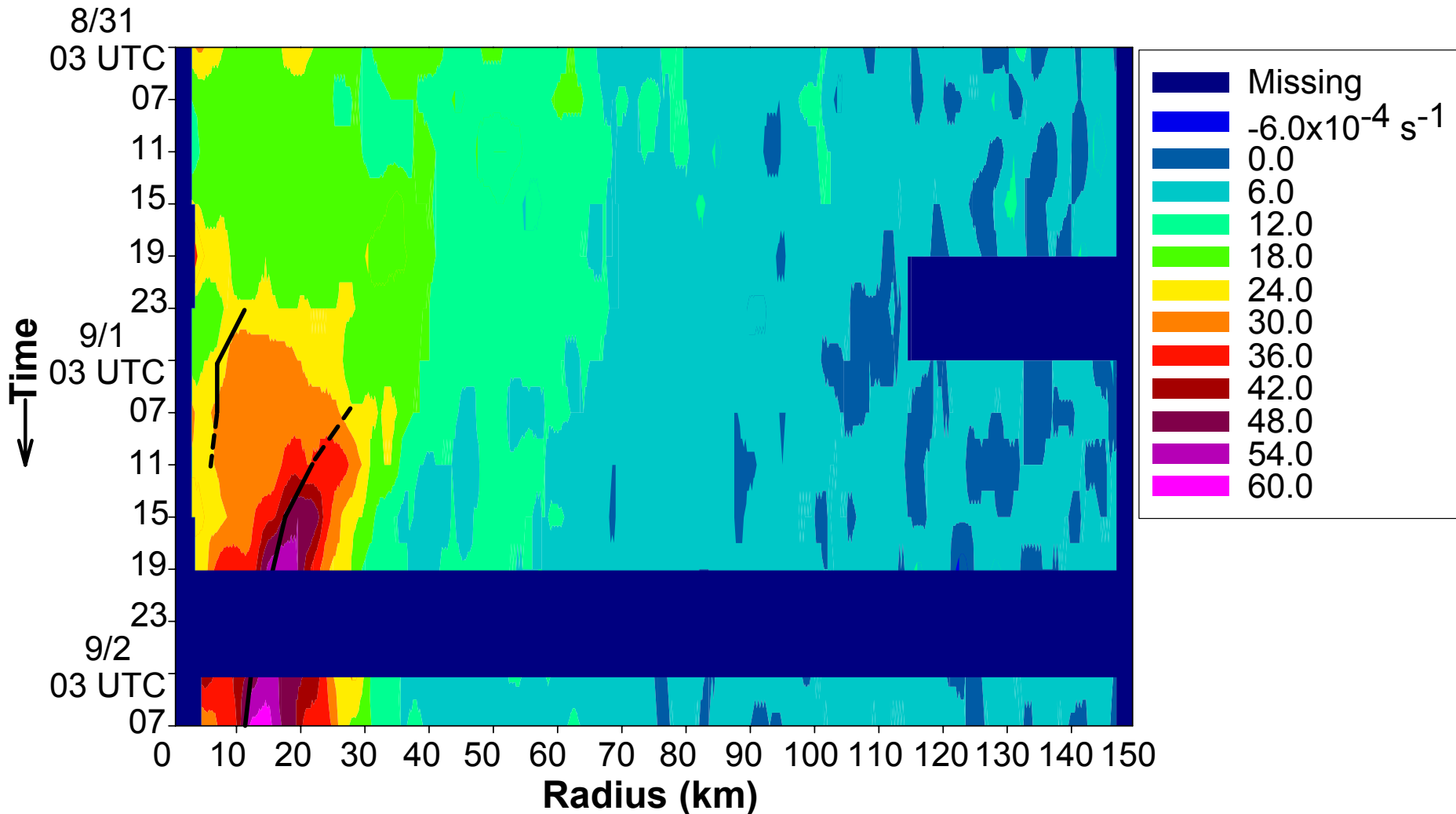
**Black line is the  
radius of  
maximum winds**

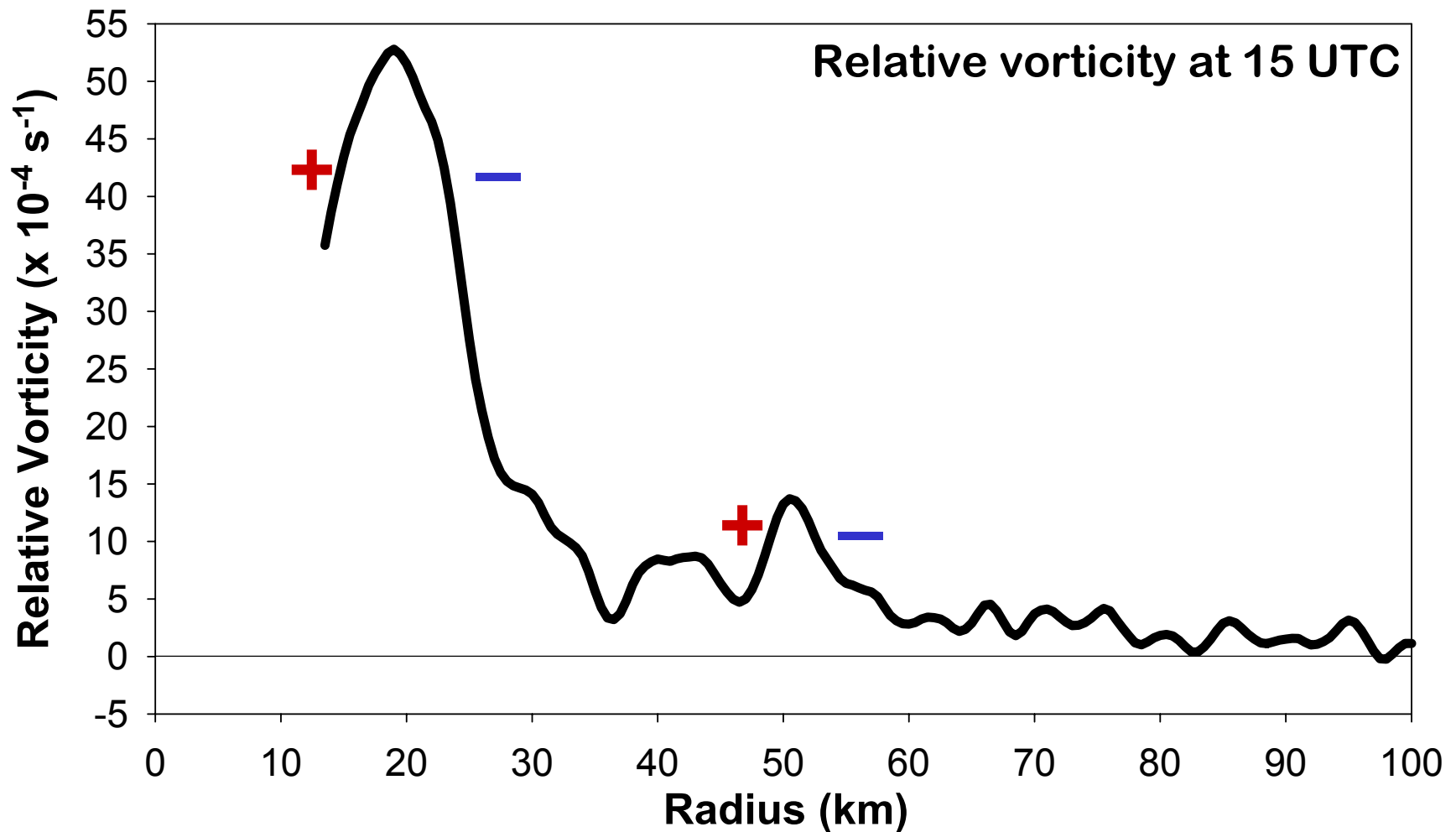
**White line is the  
radius of  
maximum  
vorticity**





# Radius-time plot of azimuthally averaged 850 hPa relative vorticity

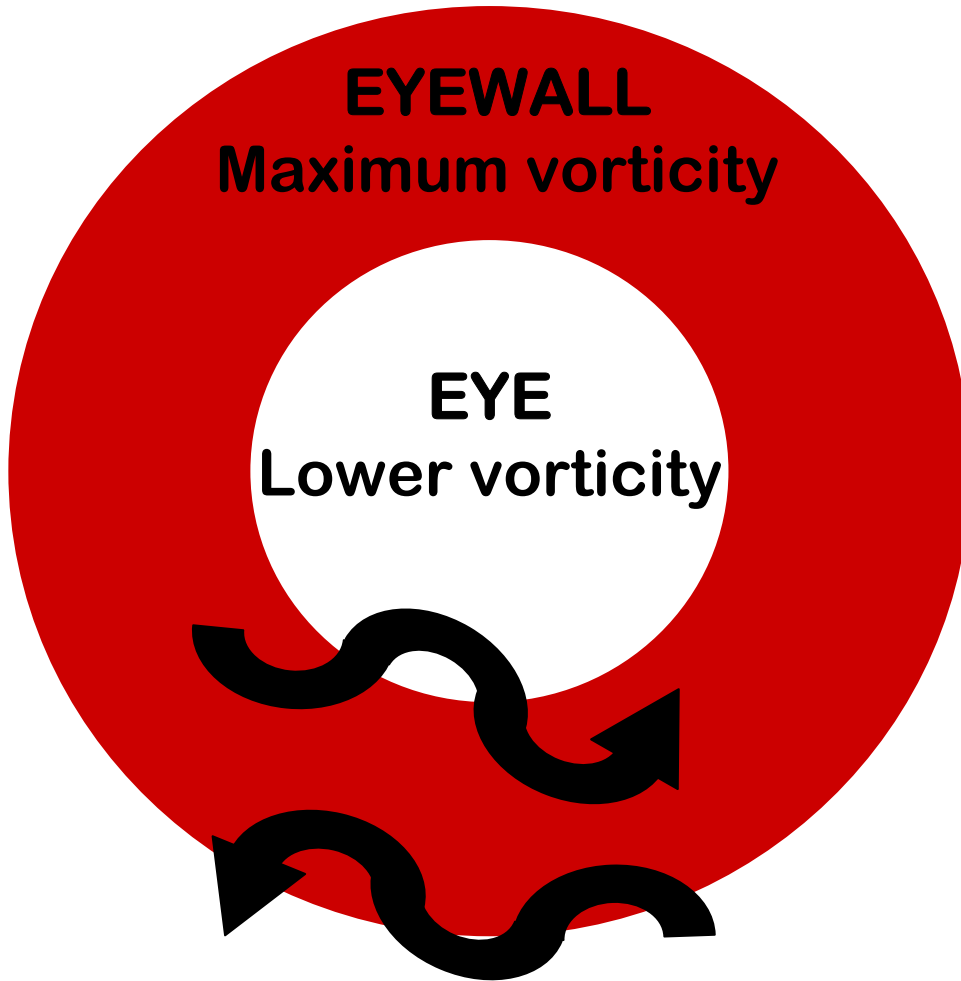




**The radial vorticity profile in Elena exhibited sharp gradients and multiple changes in sign.**

**Such profiles support the propagation of waves along the gradients and at least two types of instability.**

**Low vorticity**



**These waves are analogous to Rossby waves in the large scale circulation propagating on gradient of Earth's vorticity, and were thus called vortex Rossby waves.**

**MacDonald (1968)  
Montgomery & Kallenbach (1997)  
McWilliams et al. (2003)**

Möller and Montgomery (2000) give the dispersion relation for vortex Rossby waves:

$$\omega = n\bar{\Omega} + \frac{n \bar{\xi}}{R \bar{q}} \frac{\frac{\partial \bar{q}}{\partial r}}{[k^2 + n^2 / R^2 + (\bar{\eta} \bar{\xi} m^2) / N^2]}$$

$n$ = azimuthal wavenumber	$\bar{\xi}$ = inertia parameter
$k$ = radial wavenumber	$N^2$ = static stability
$m$ = vertical wavenumber	$\bar{\eta}$ = relative vorticity
$\bar{\Omega}$ = angular velocity	$\frac{\partial \bar{q}}{\partial r}$ = radial derivative of potential vorticity
$R$ = reference radius	

Möller and Montgomery (2000) give the dispersion relation for vortex Rossby waves:

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Rossby waves on the **outer** eyewall vorticity gradient propagate cyclonically around the storm, **slower** than the local mean tangential wind.

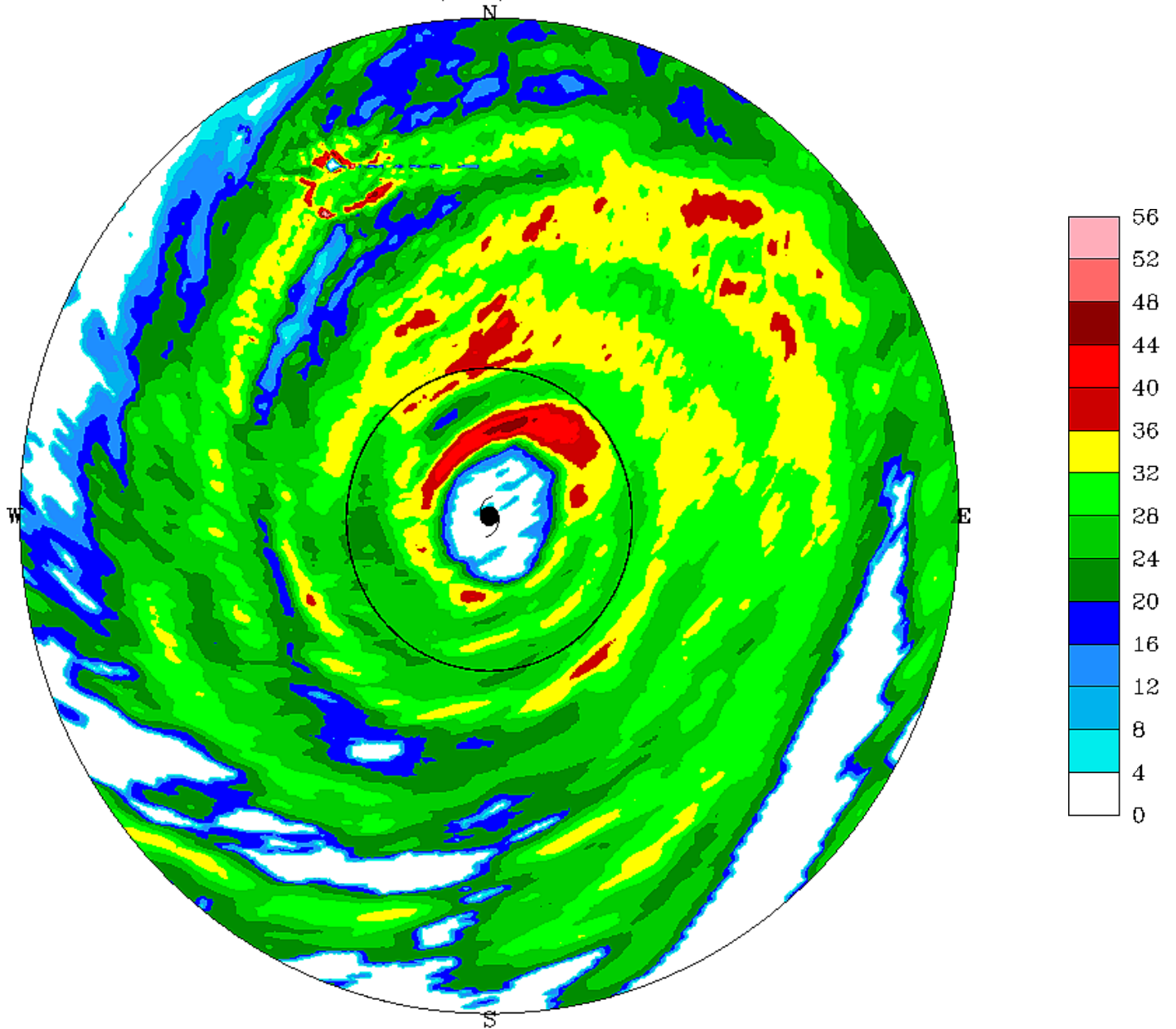
The waves also propagate radially **outward**, against the mean low level inflow.

As these waves propagate outward, they have been found to initiate inner spiral rainbands *in “full physics” numerical models.*

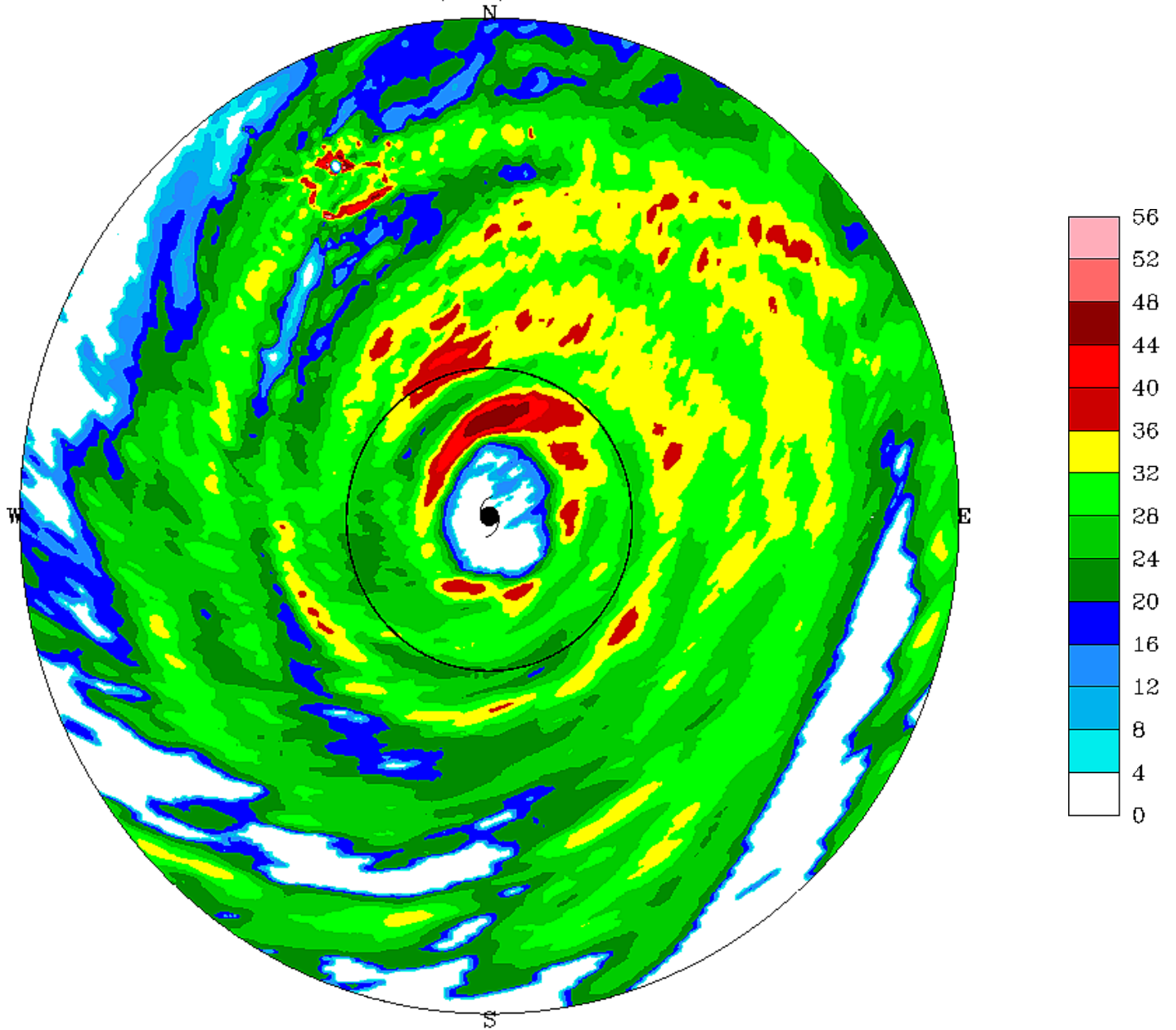
However, Montgomery and Kallenbach (1997) state, “With radar data of fine enough resolution, inner rainbands with vortex Rossby wave characteristics should be seen in real data cases...”

With 750 m spatial and 5 minute time resolution, if vortex Rossby waves do exist in nature, we should be able to see them in Elena.

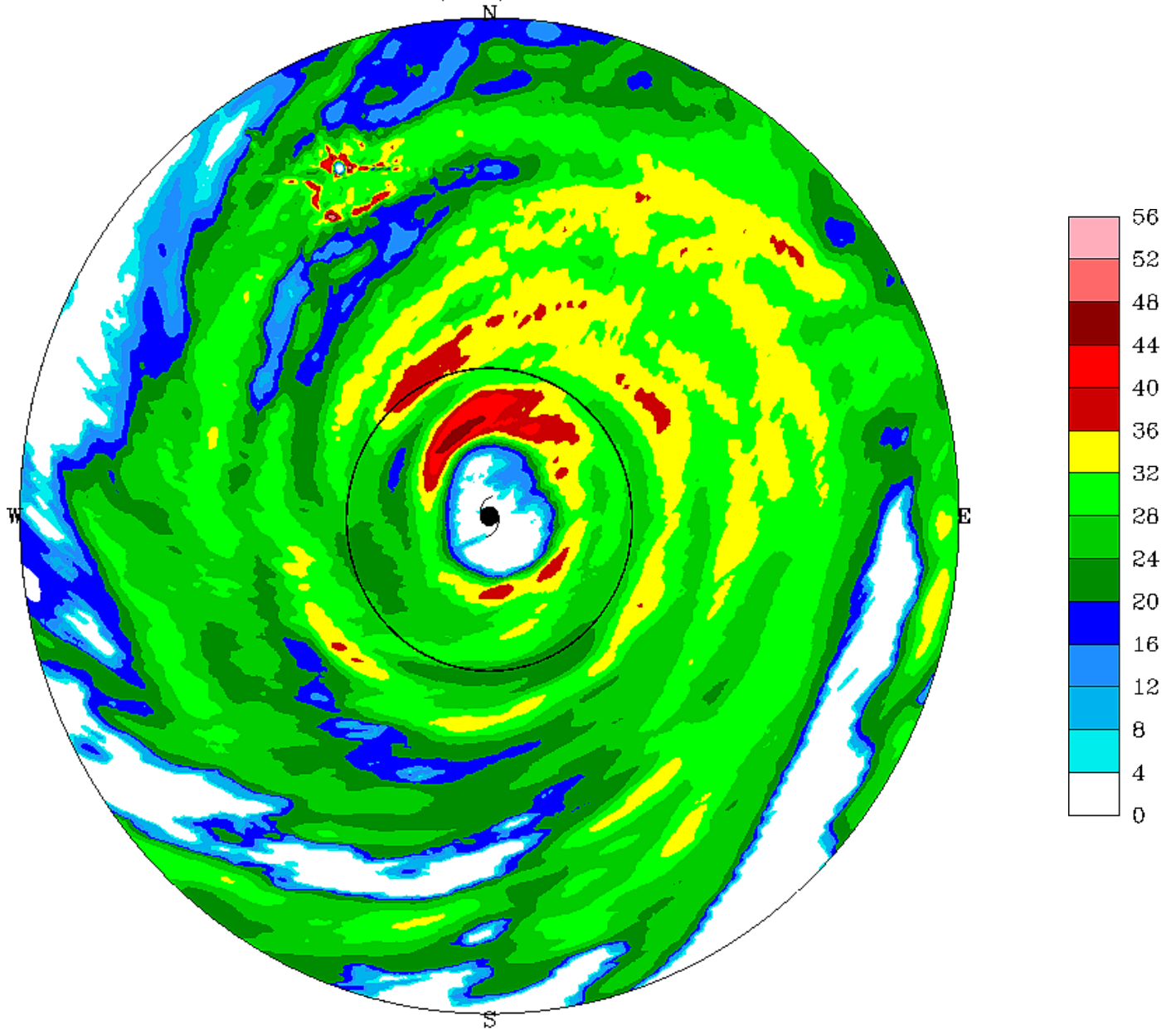
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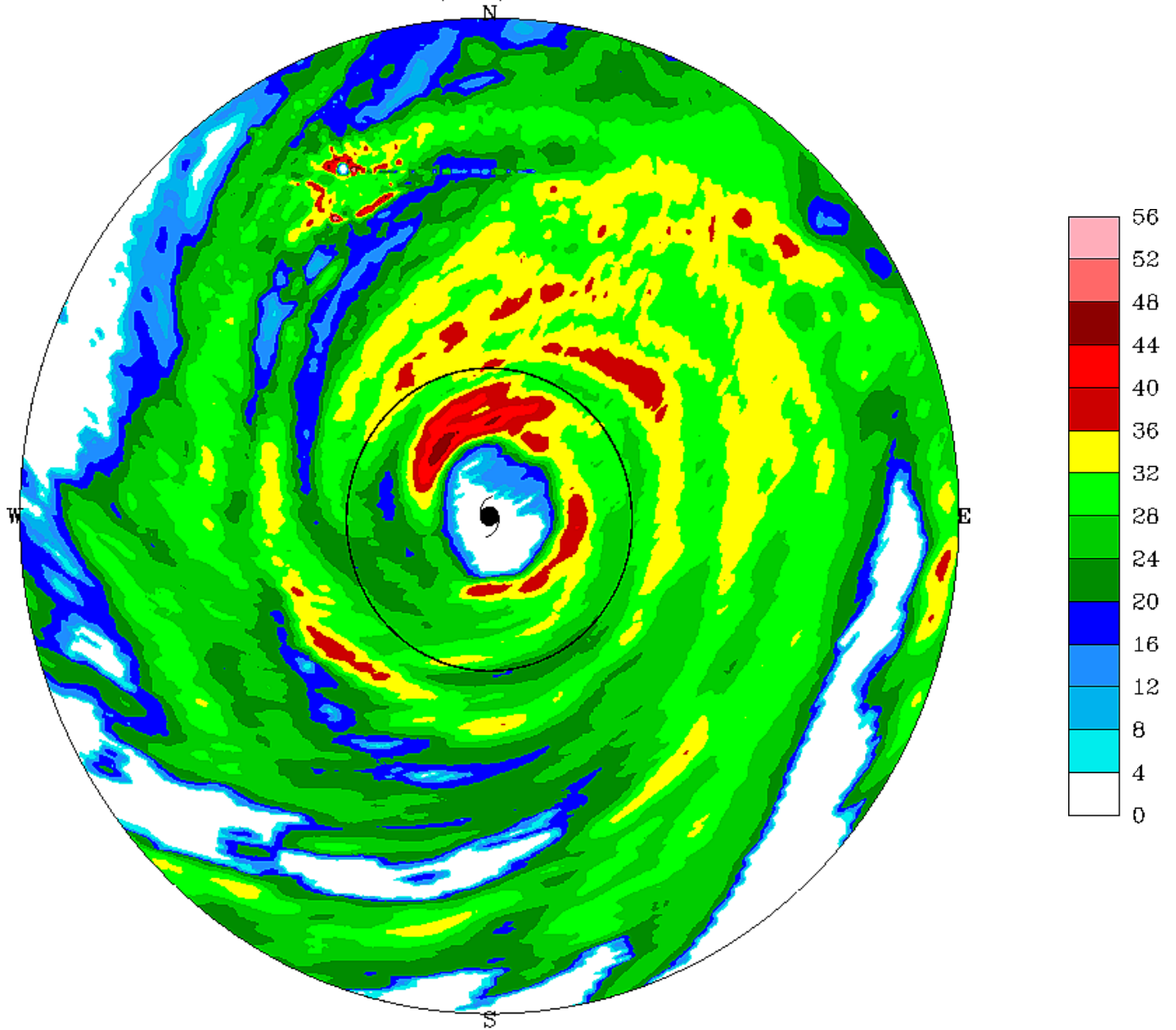
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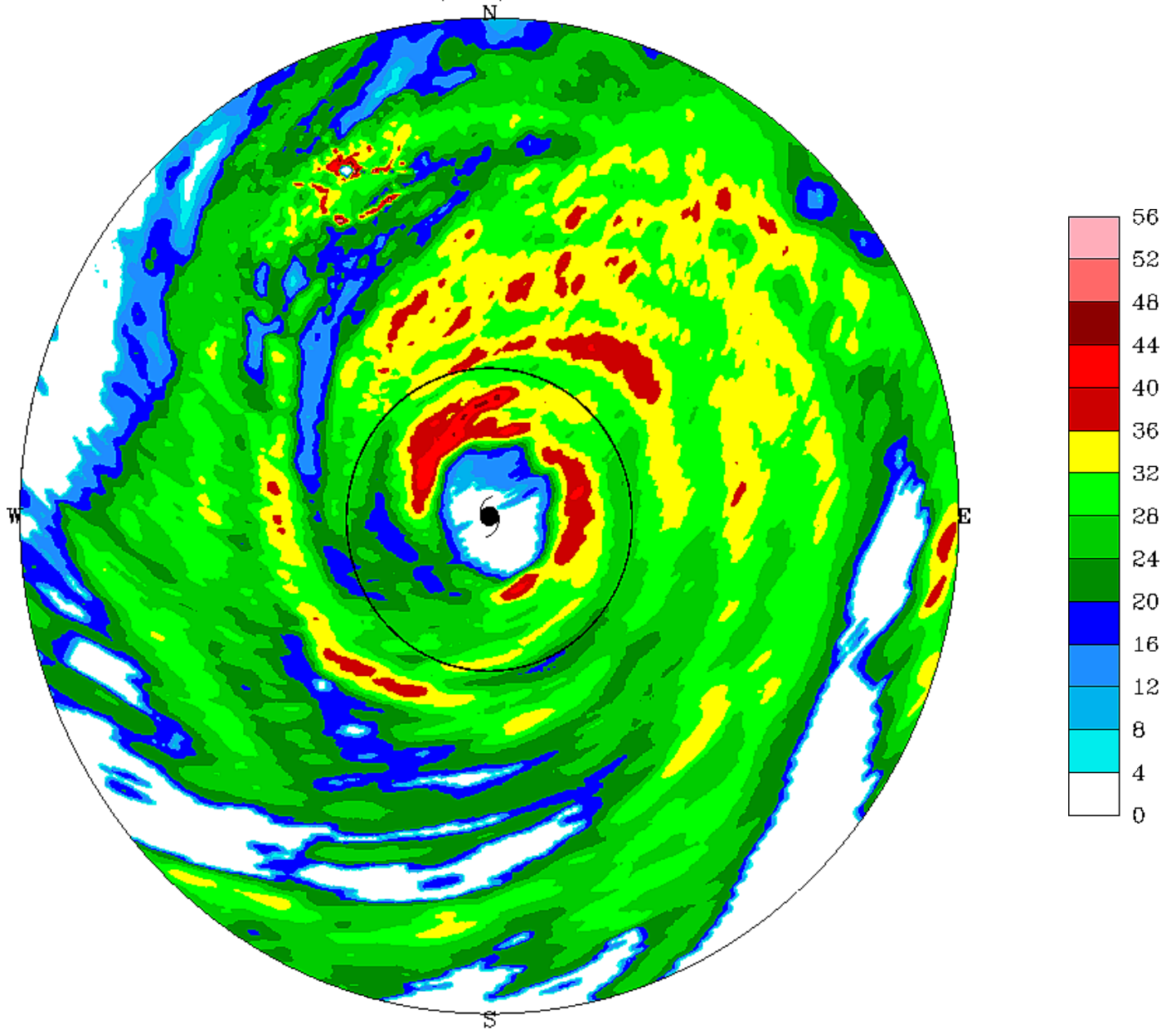
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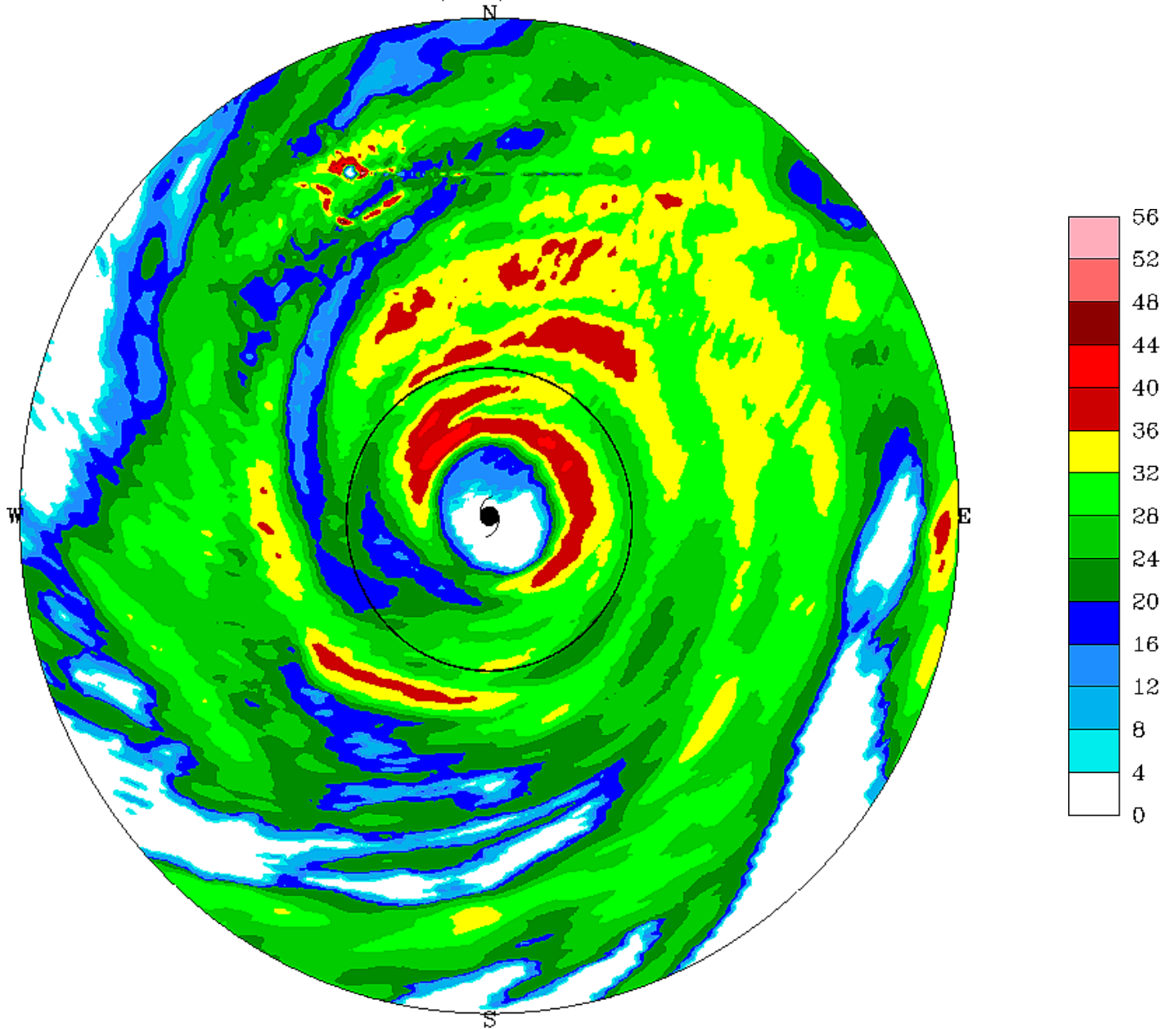
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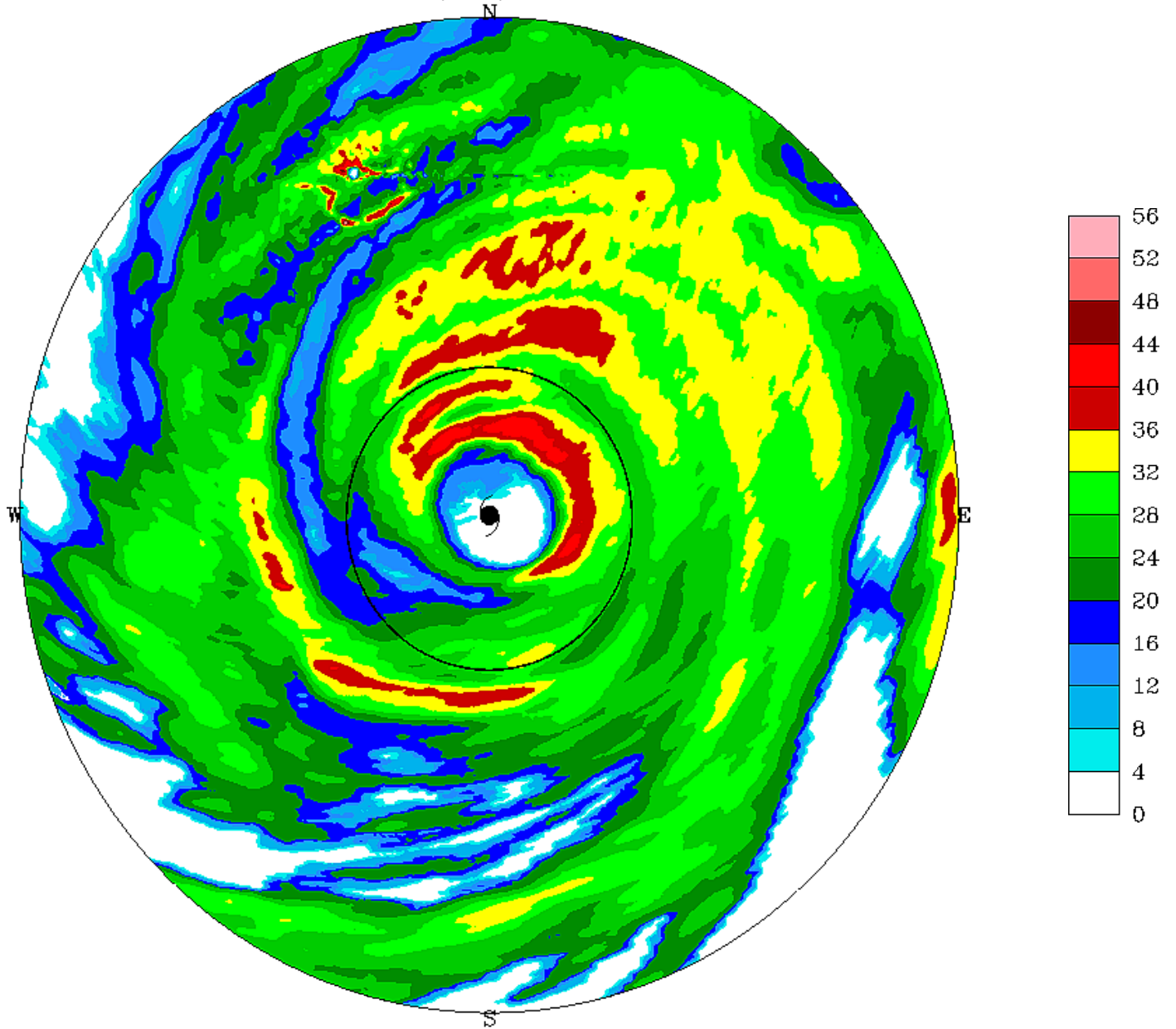
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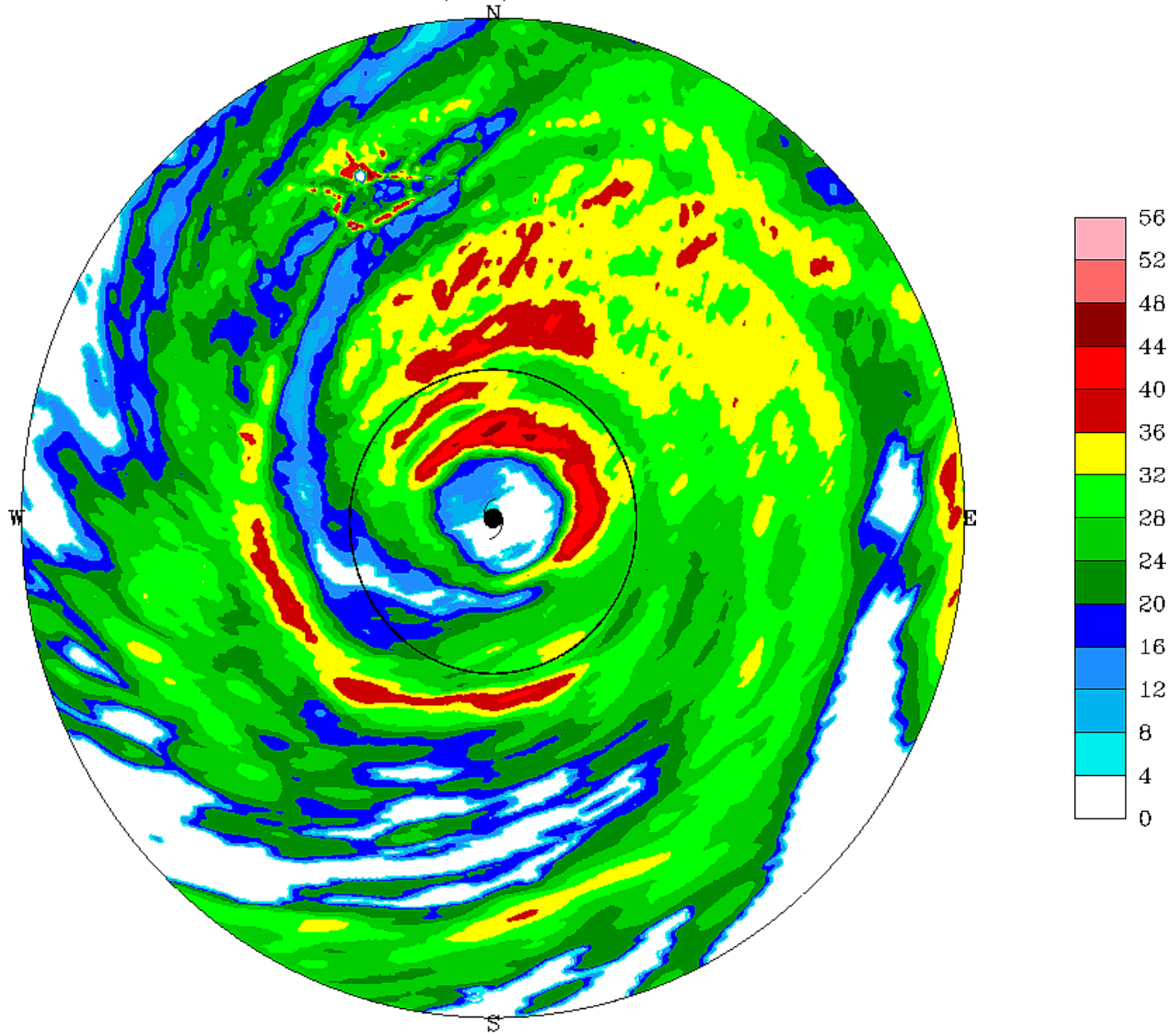
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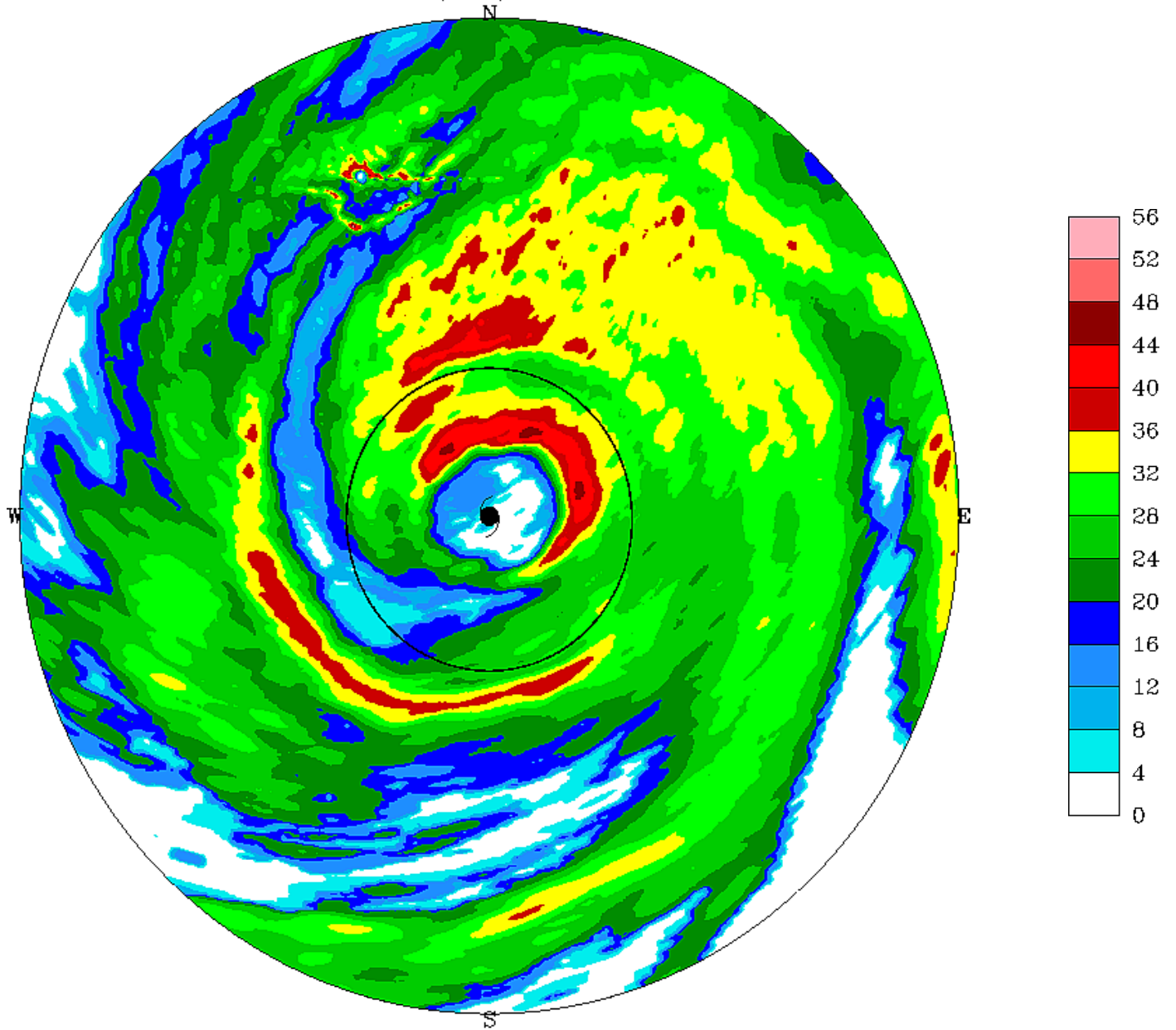
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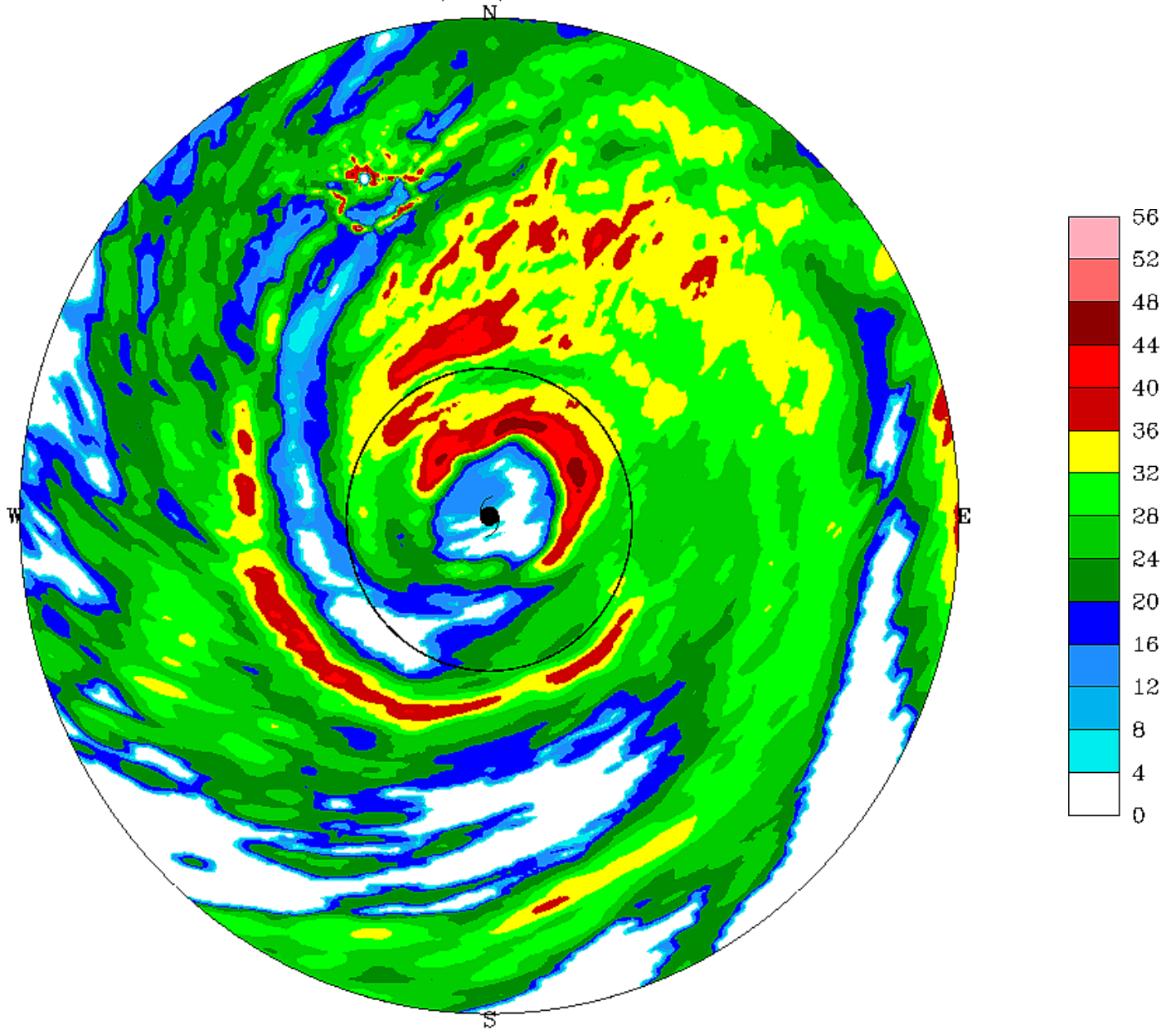
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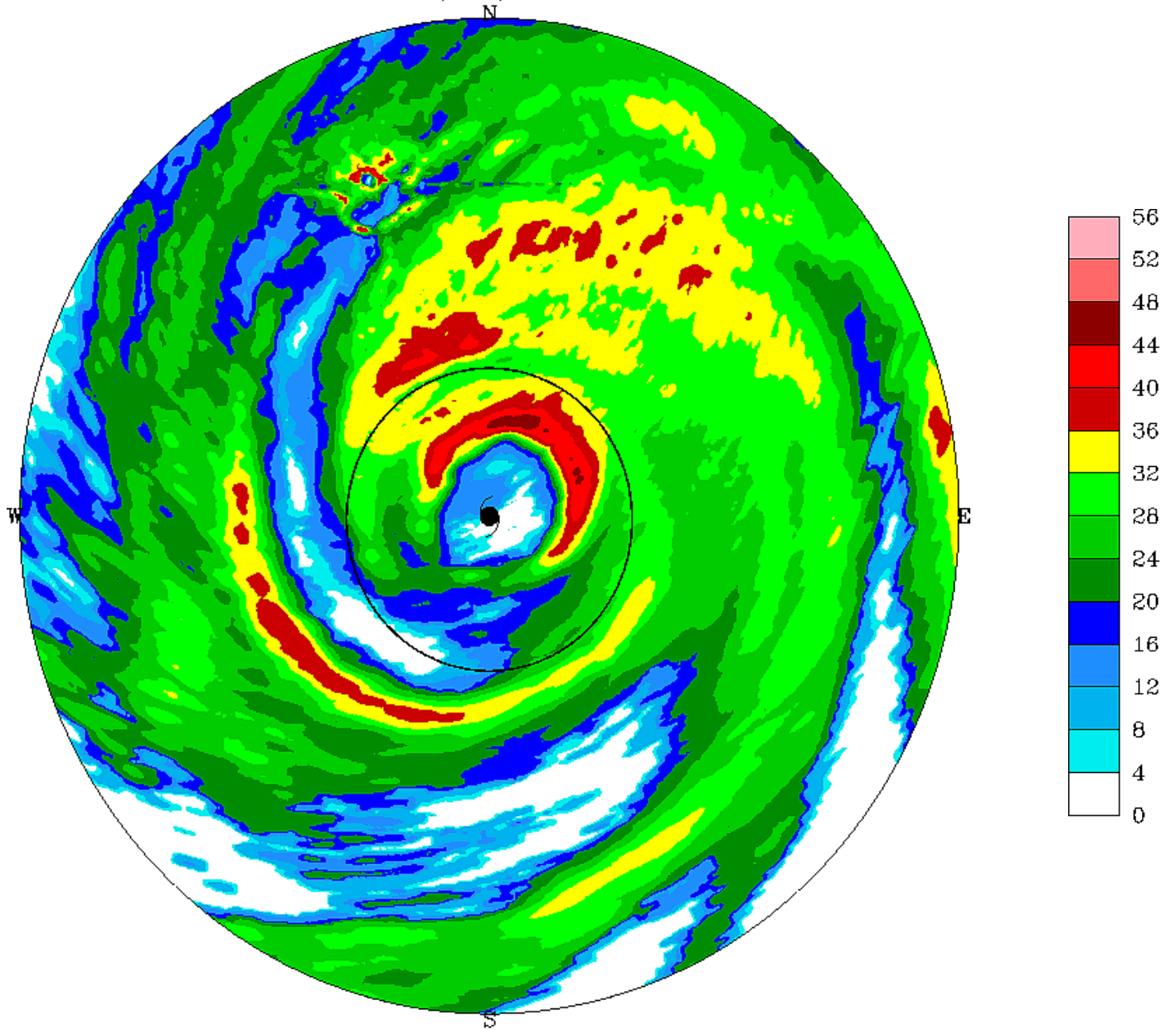
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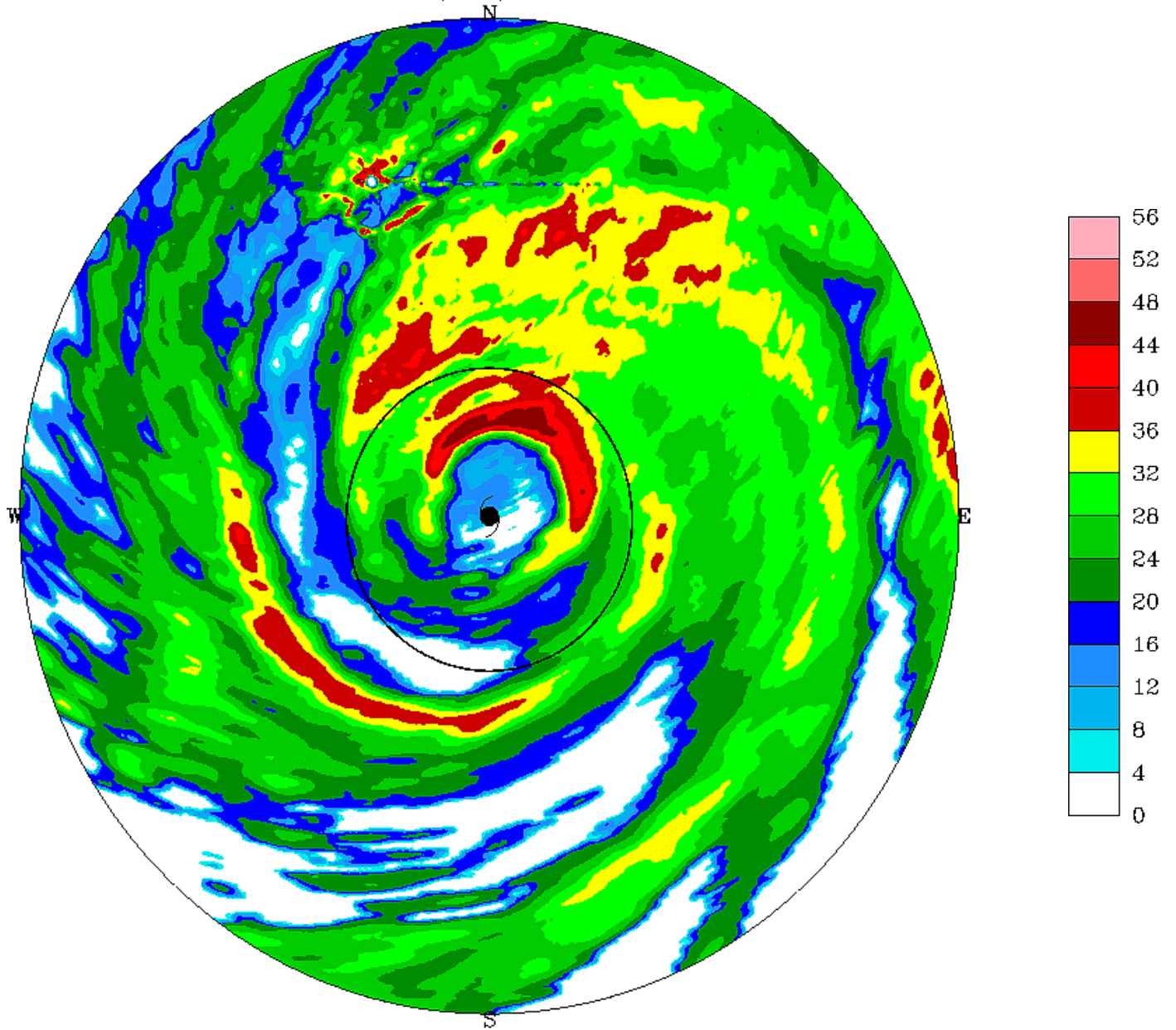
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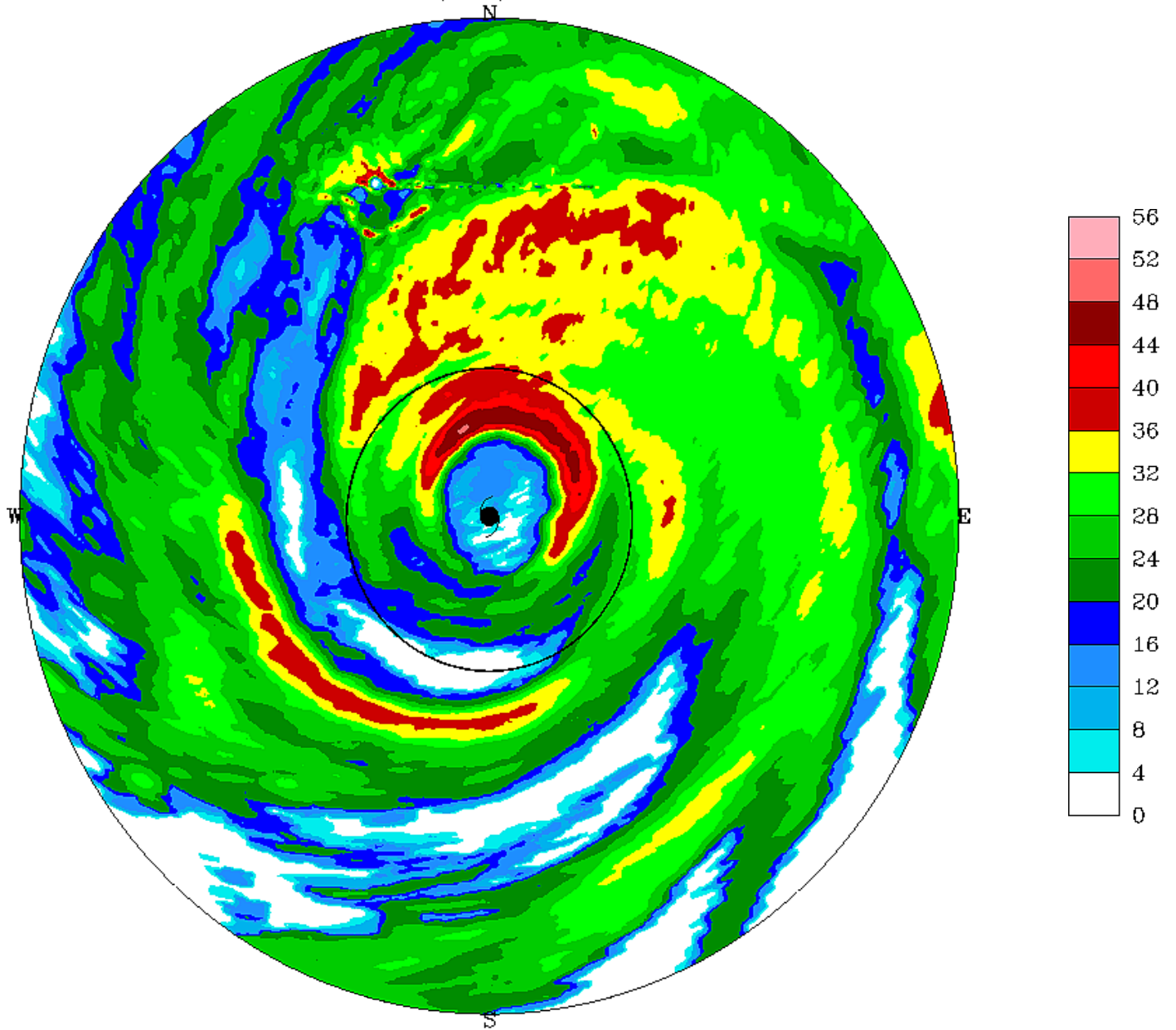
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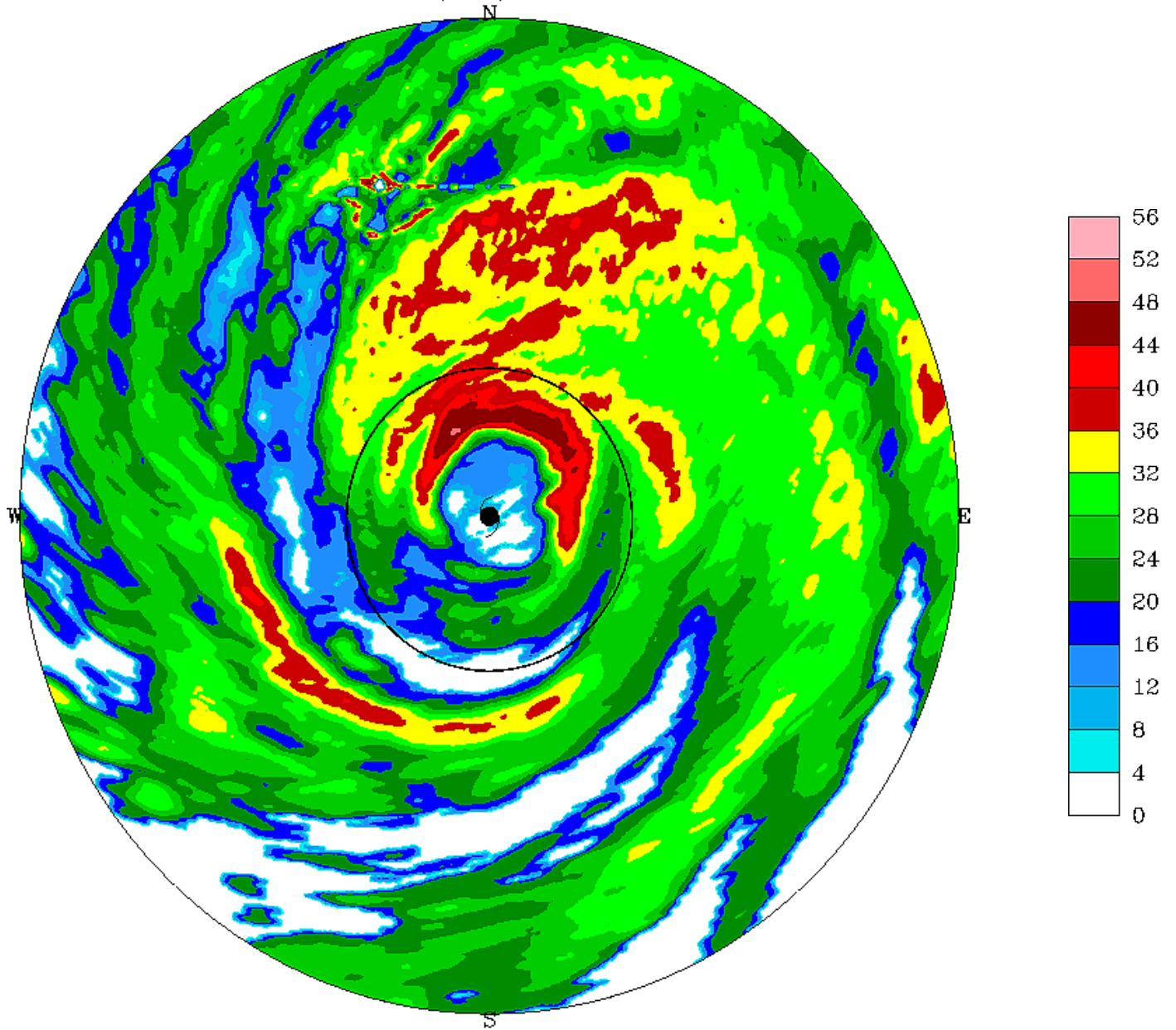
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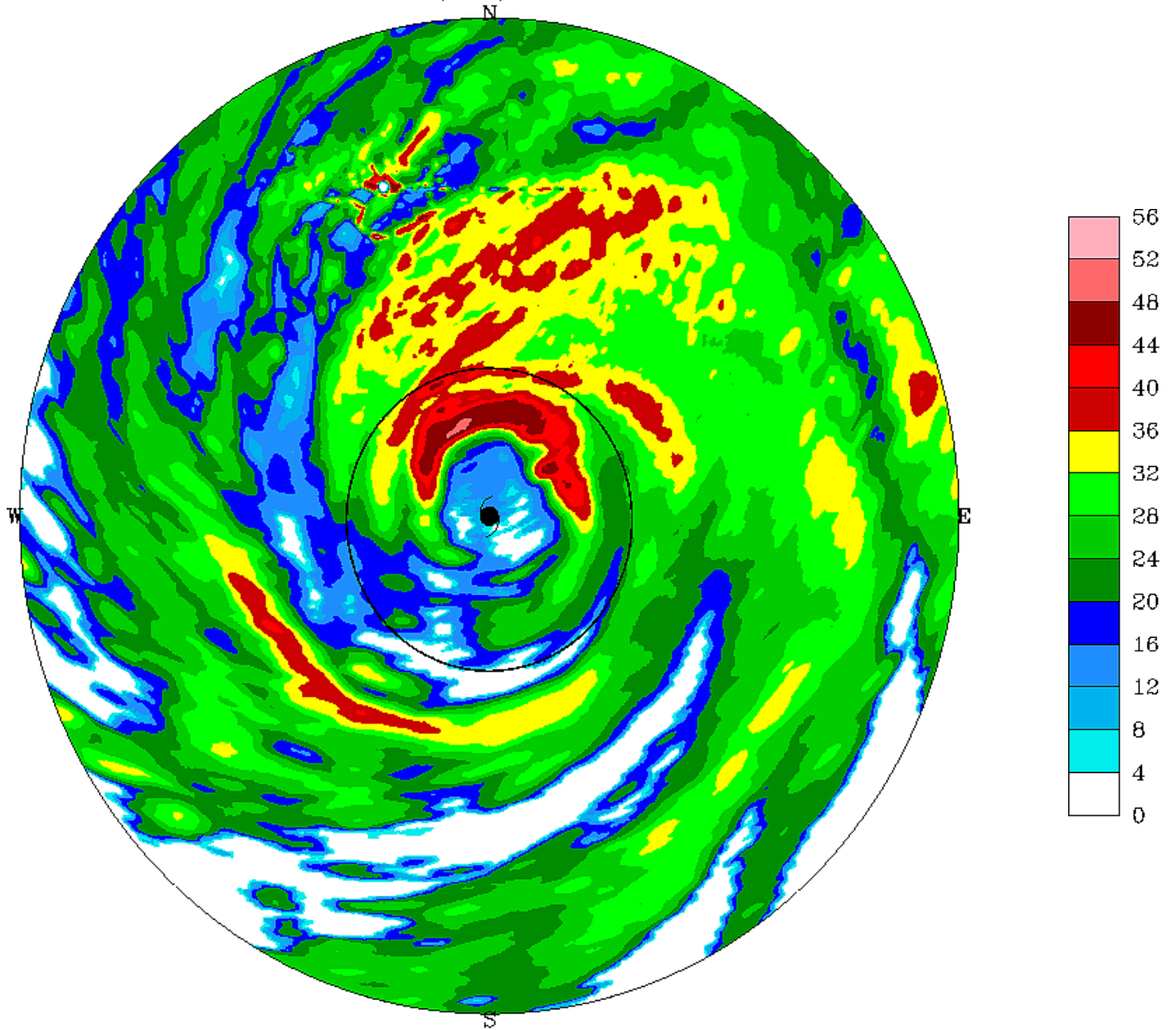
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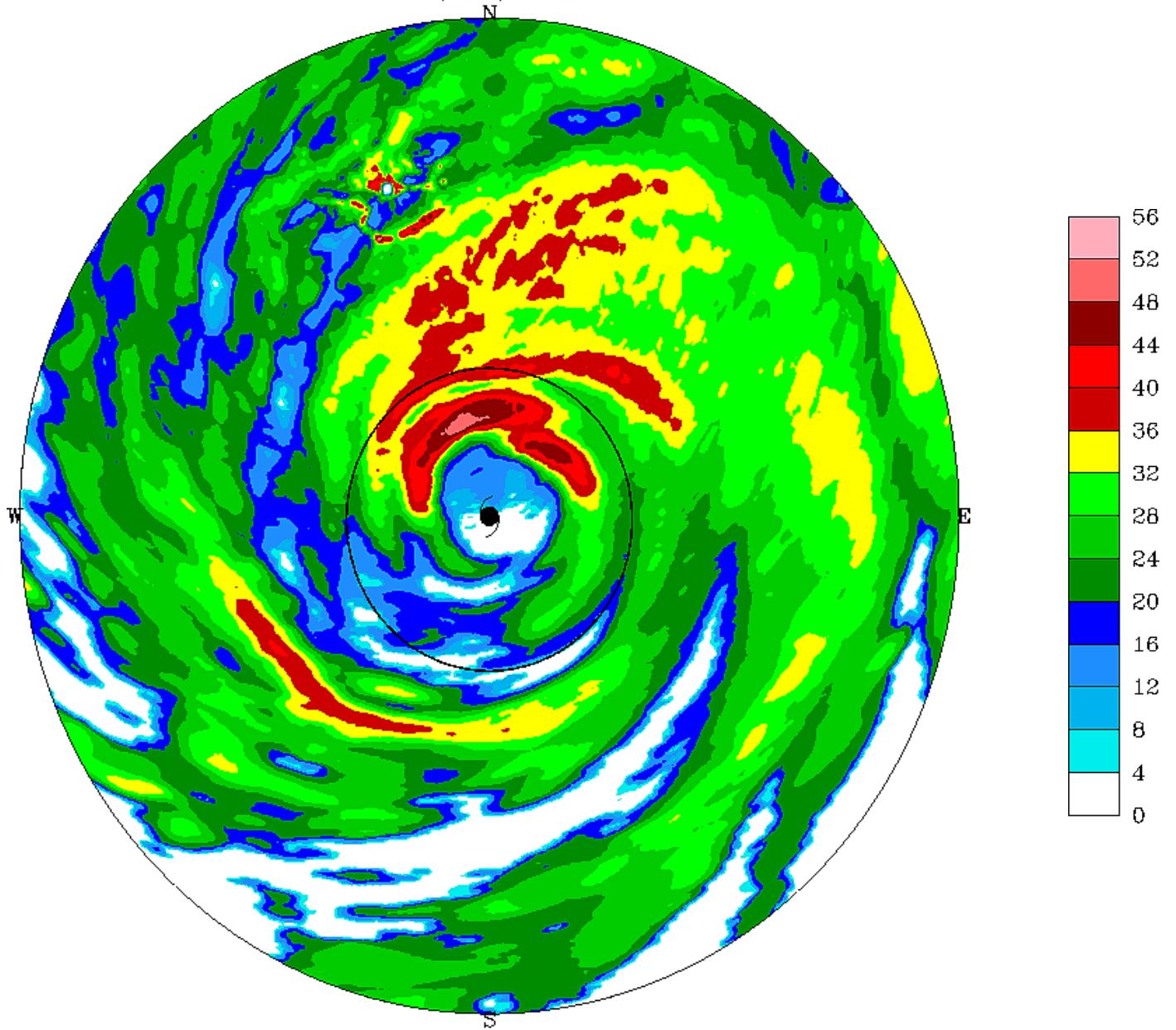
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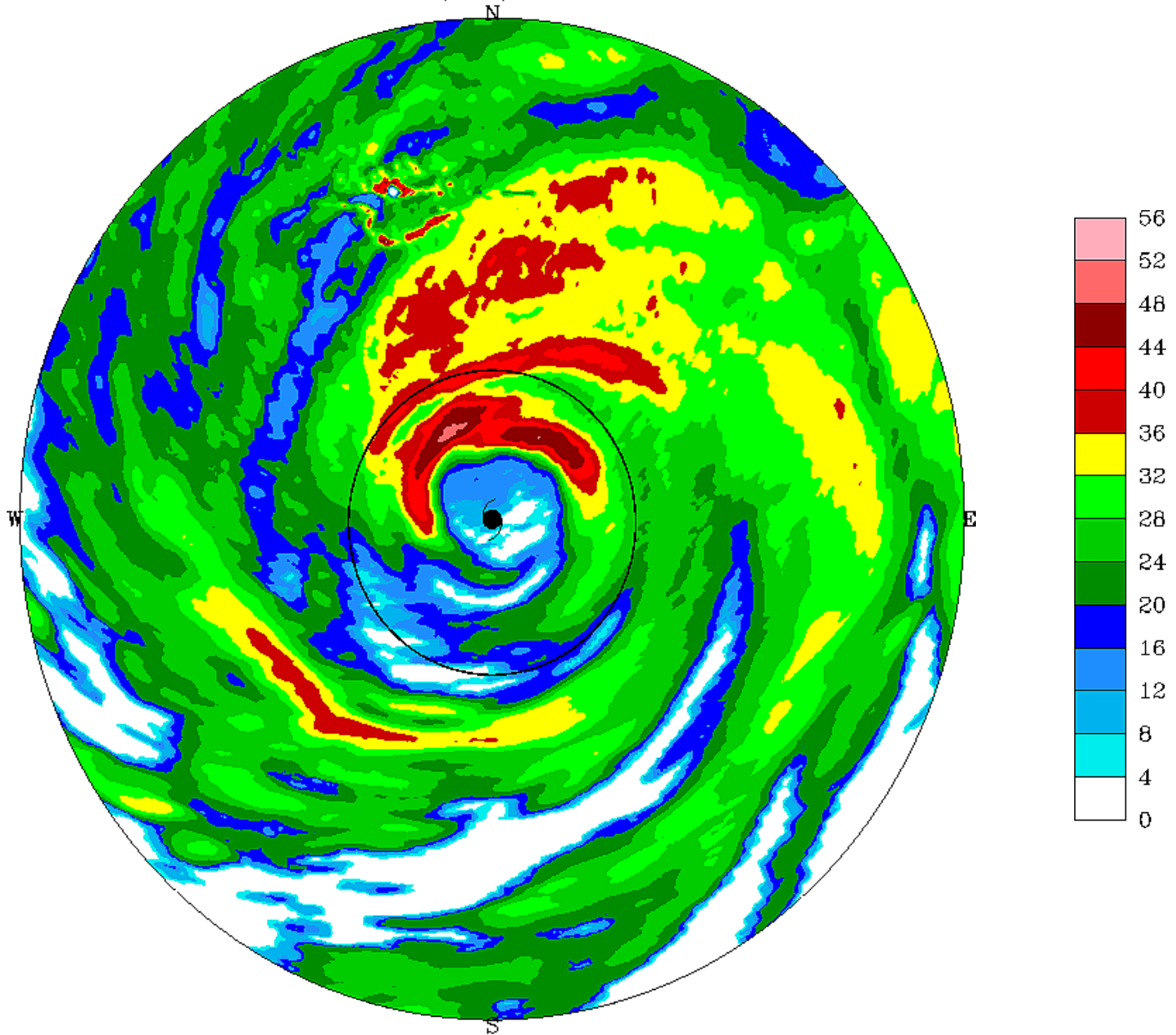
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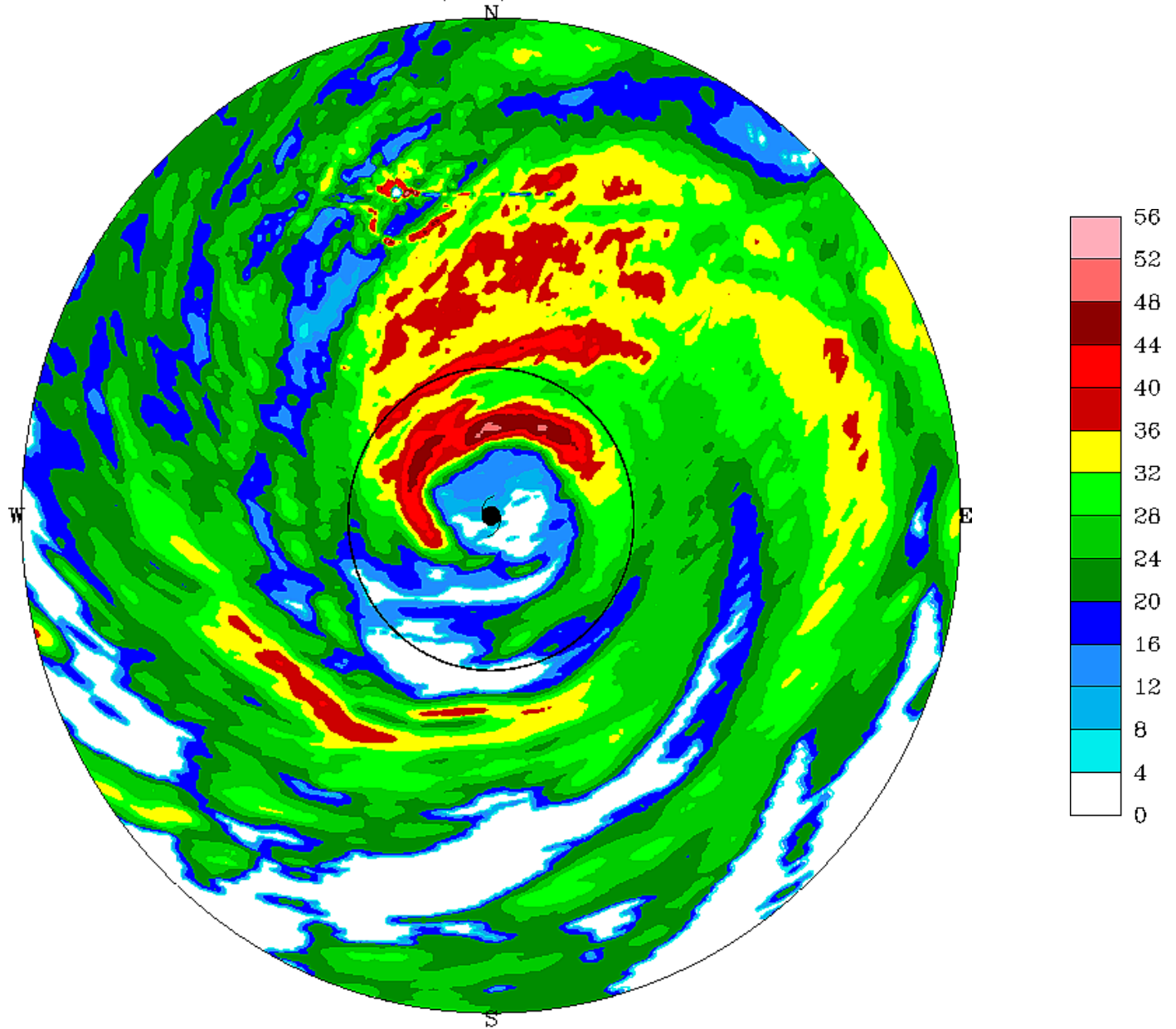
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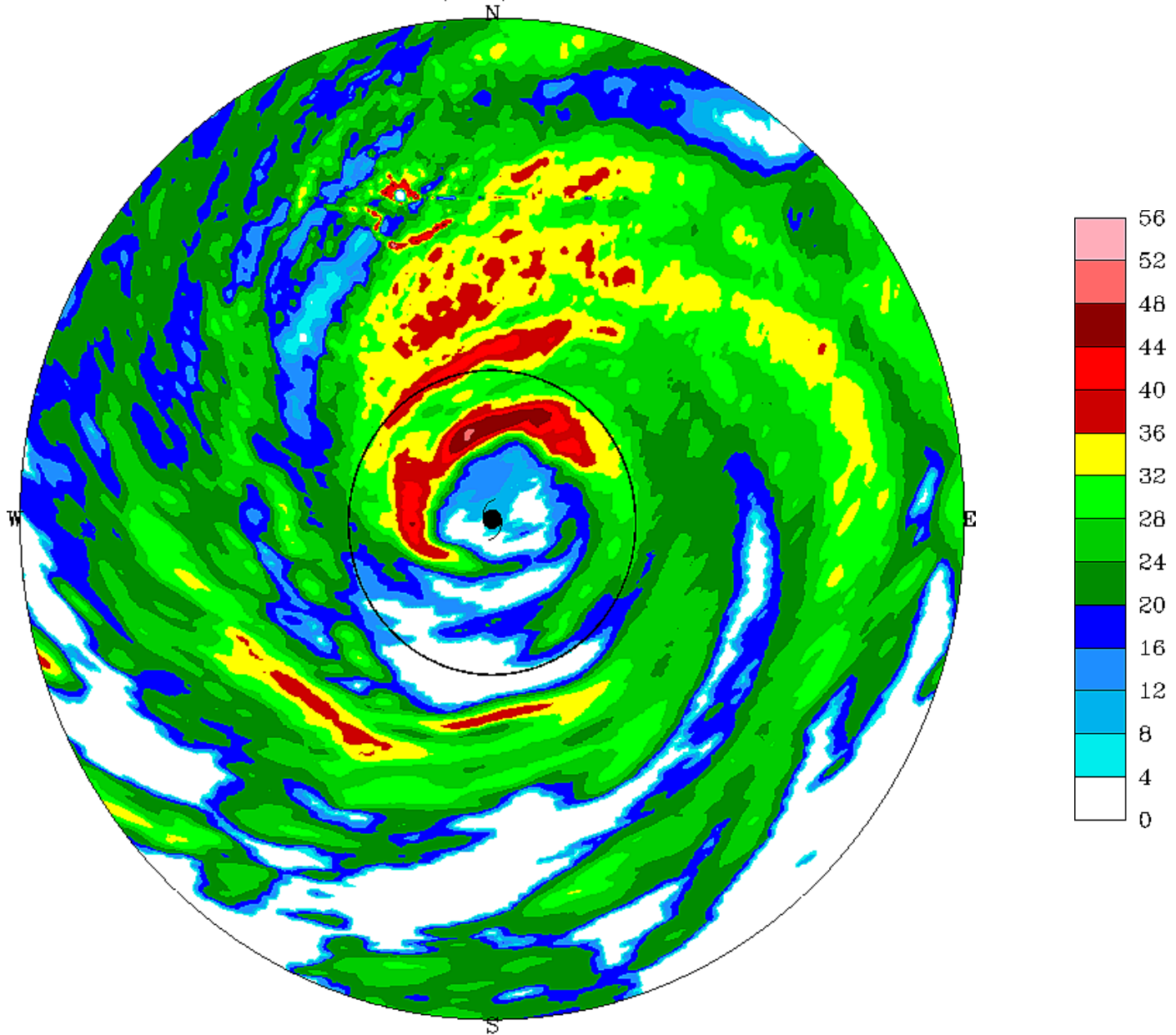
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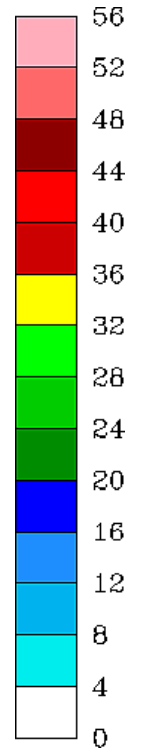
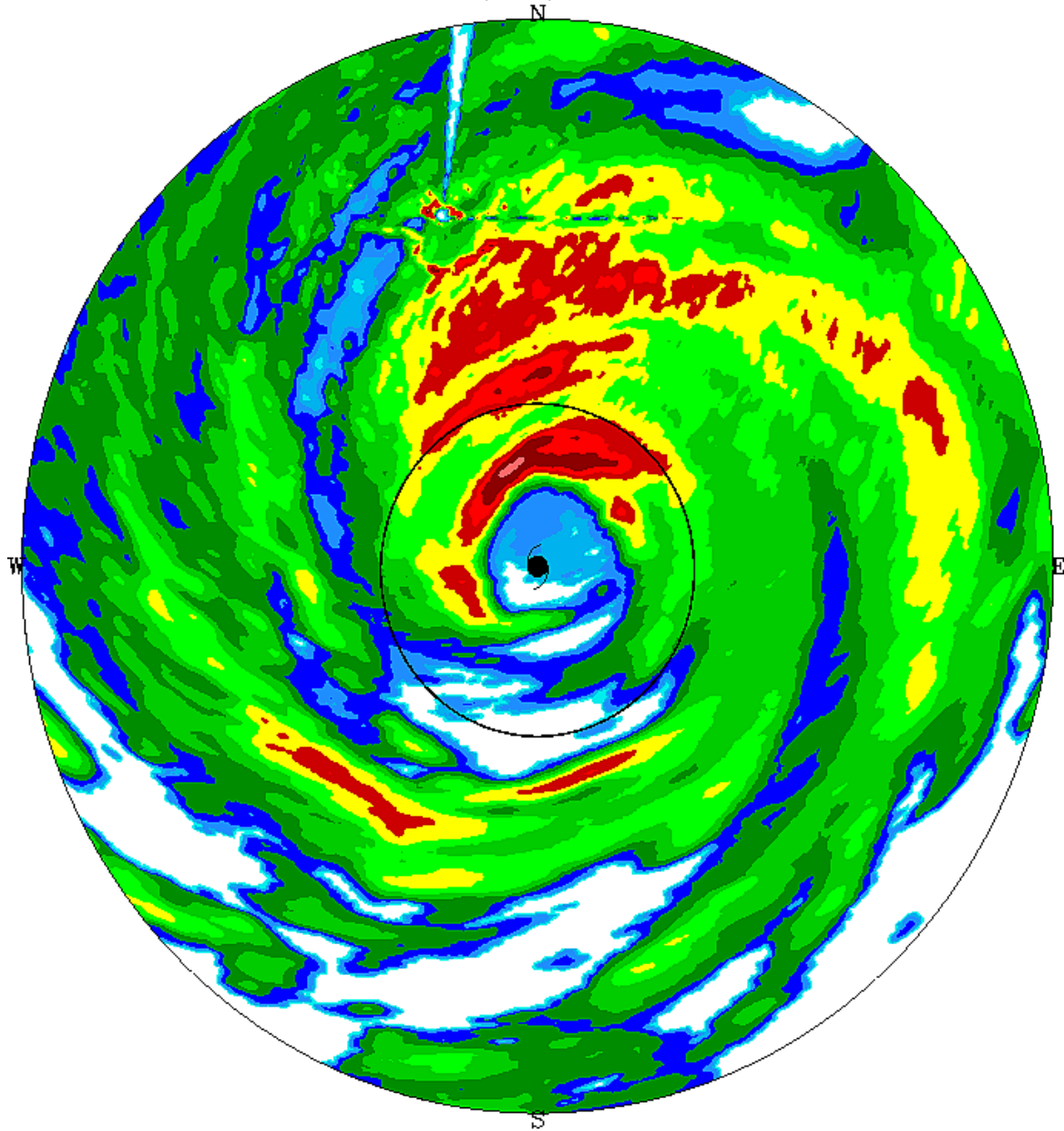
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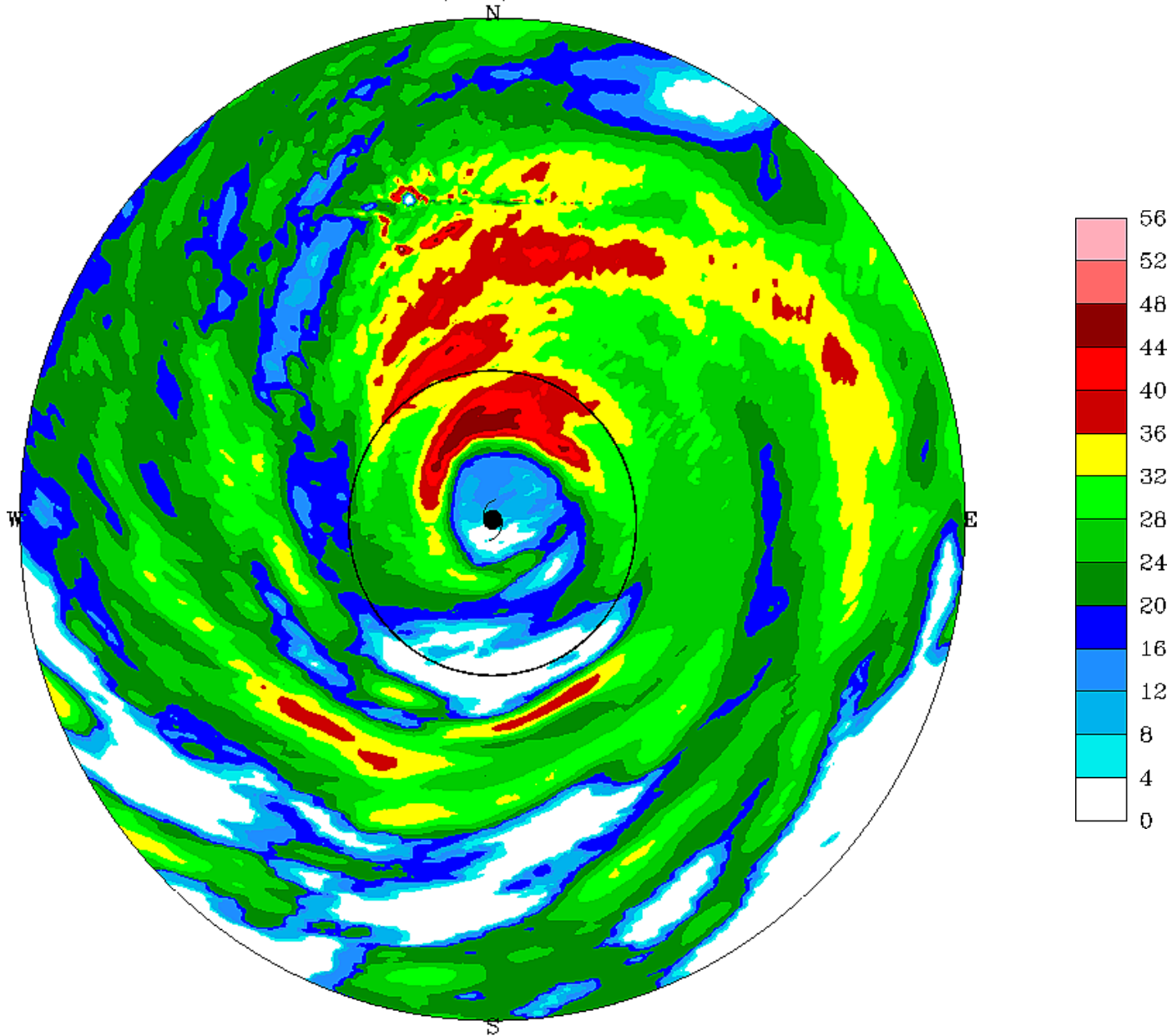
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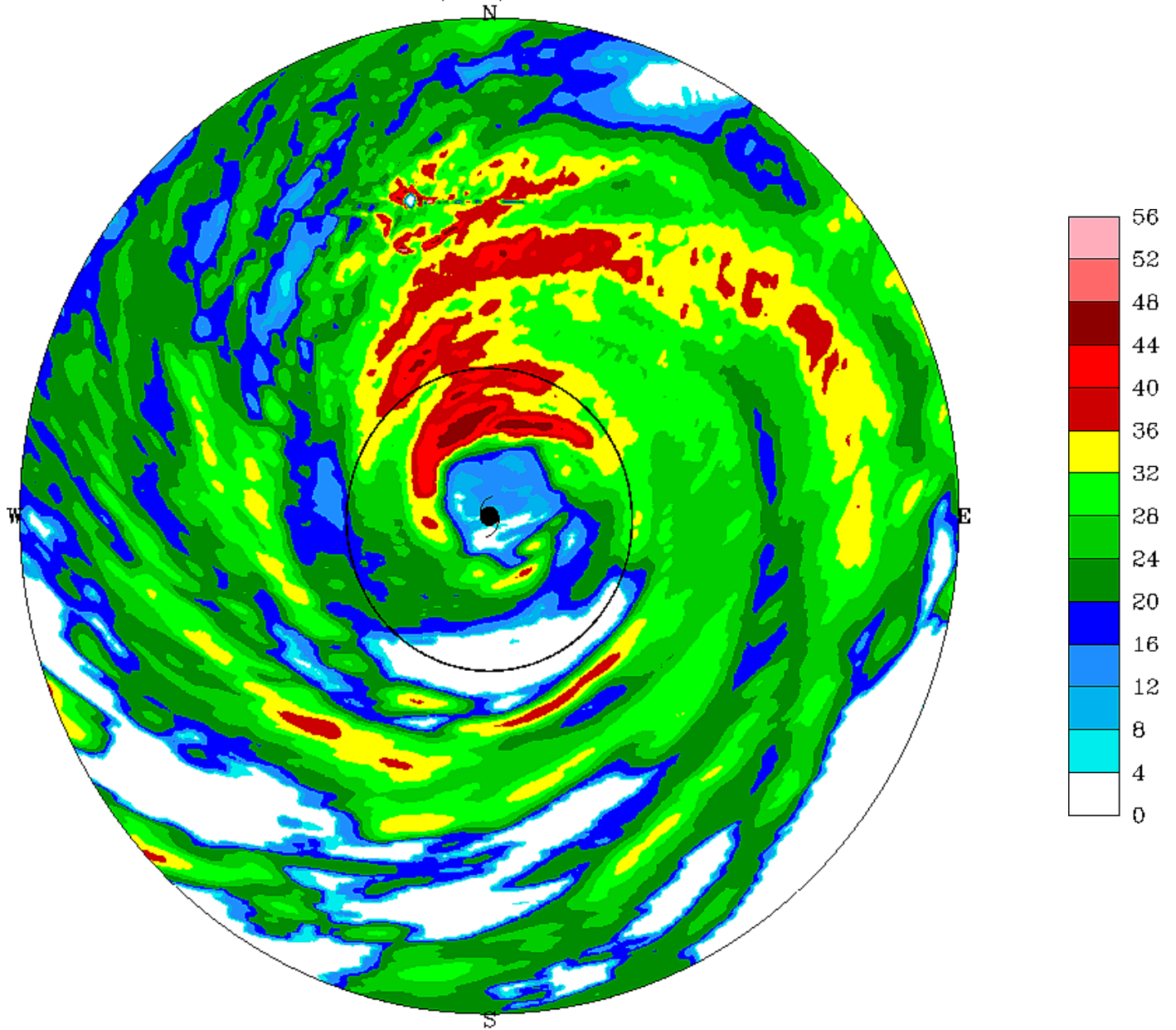
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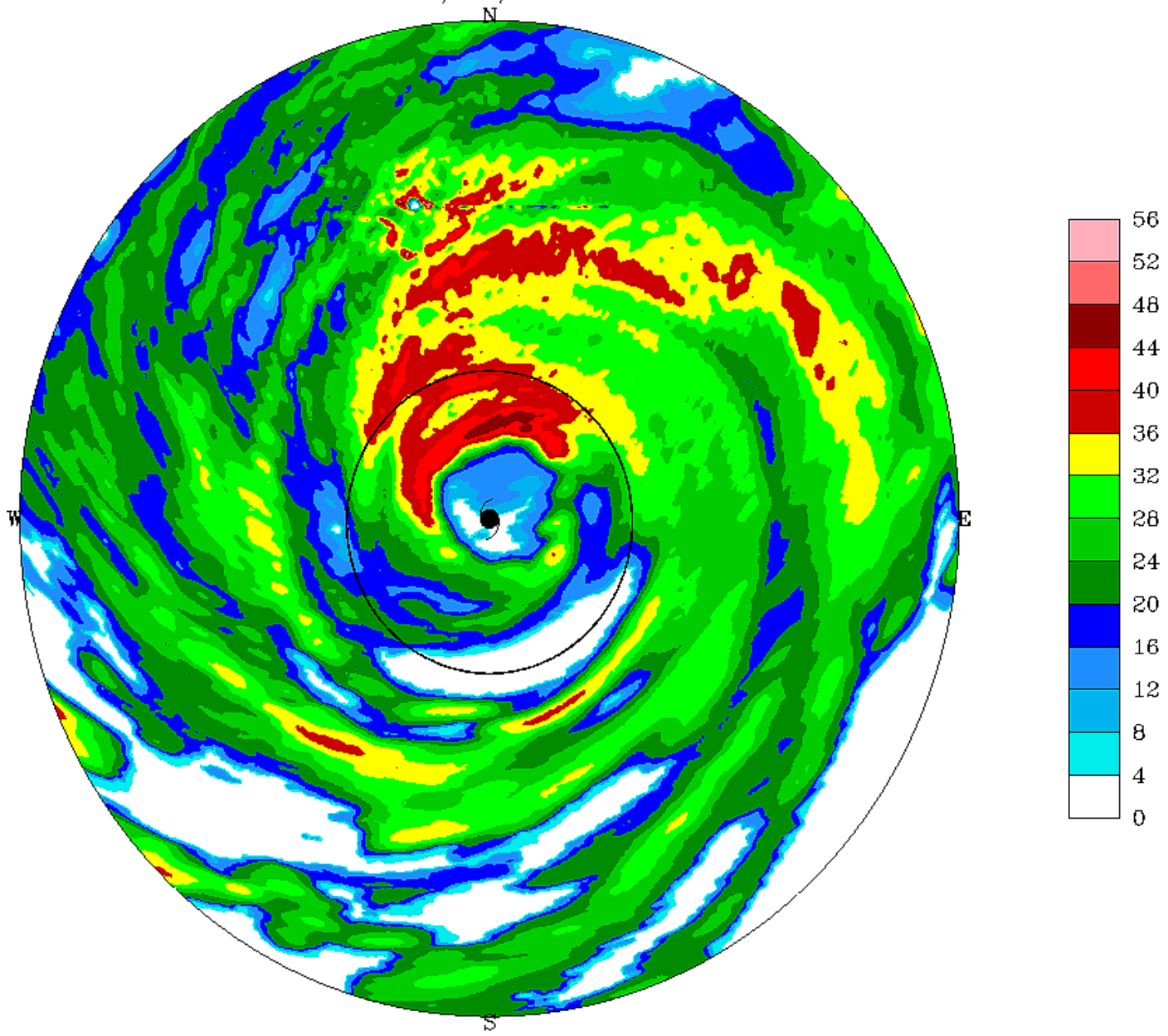
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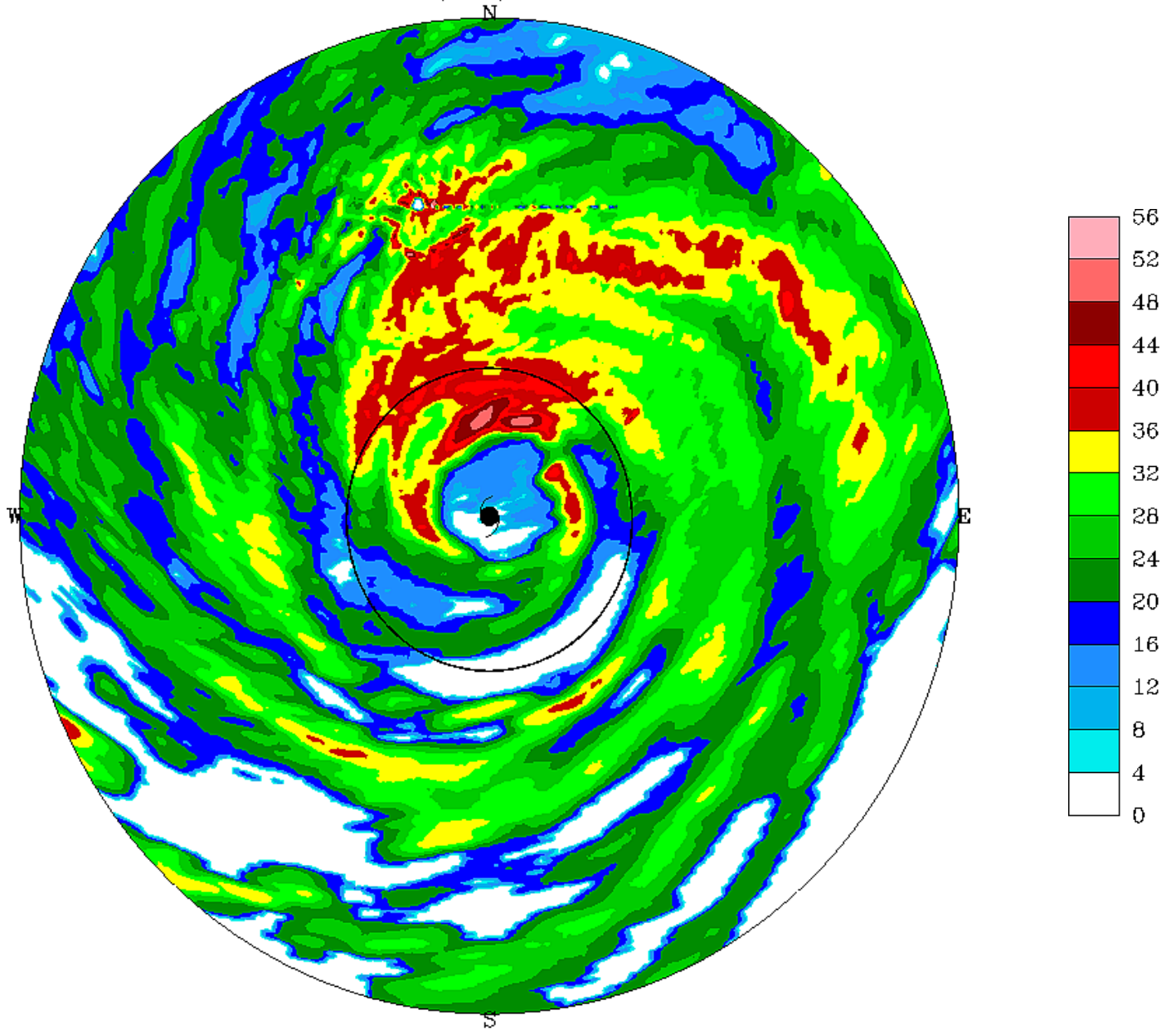
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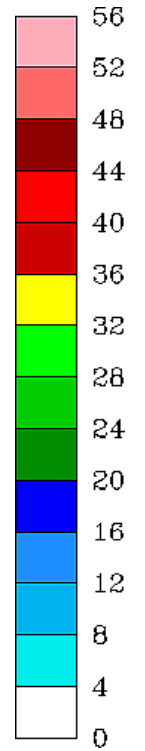
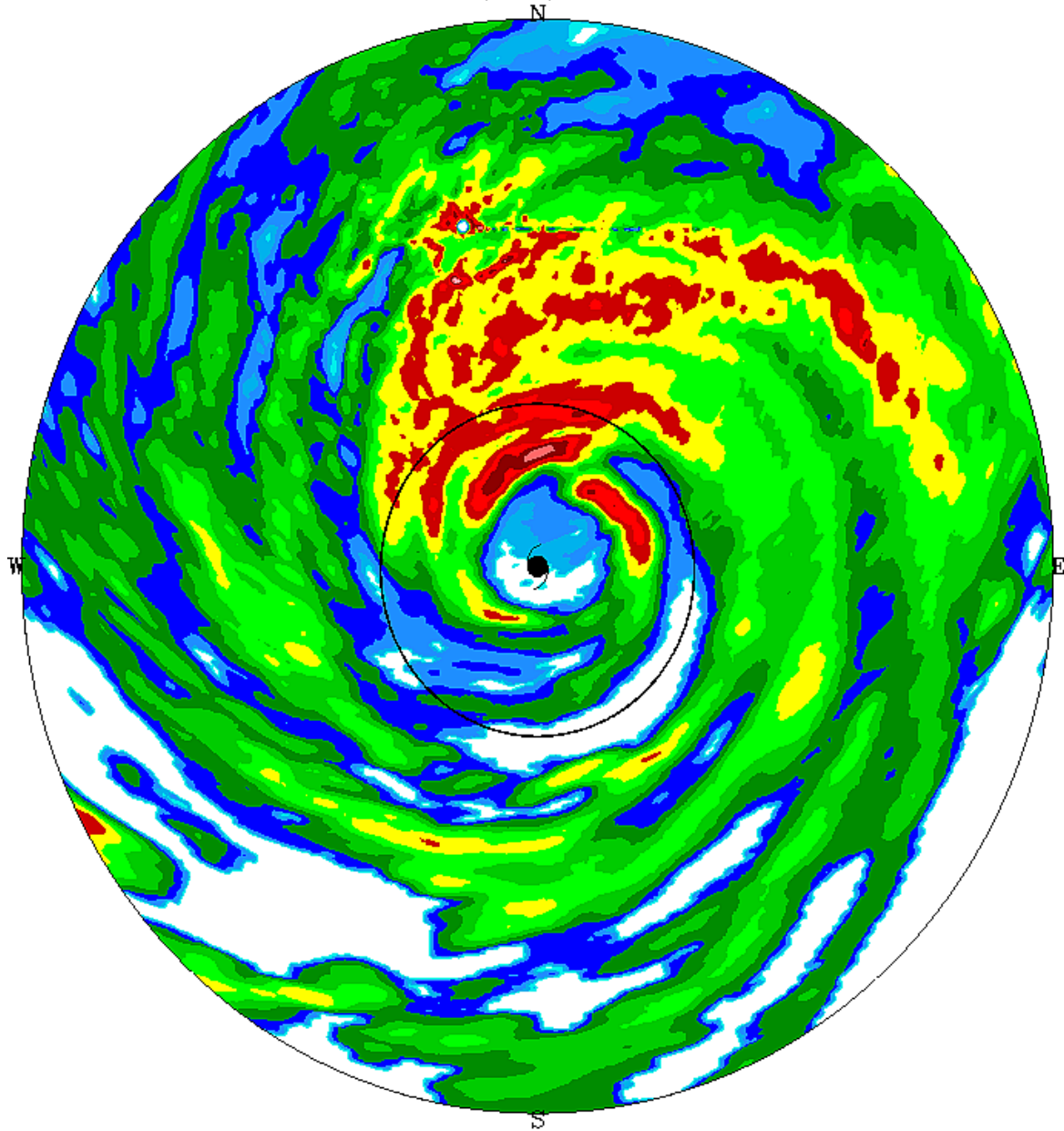
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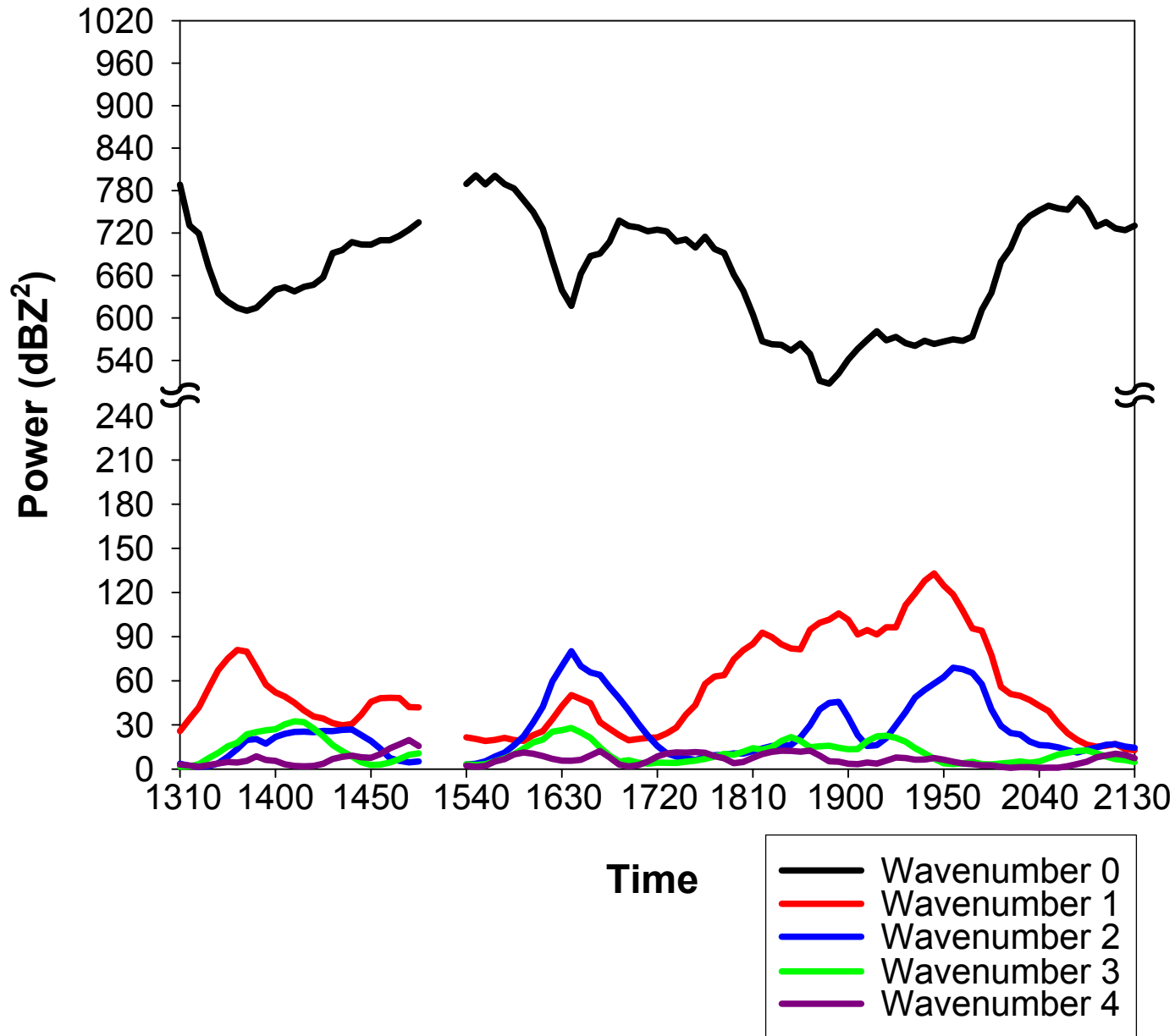
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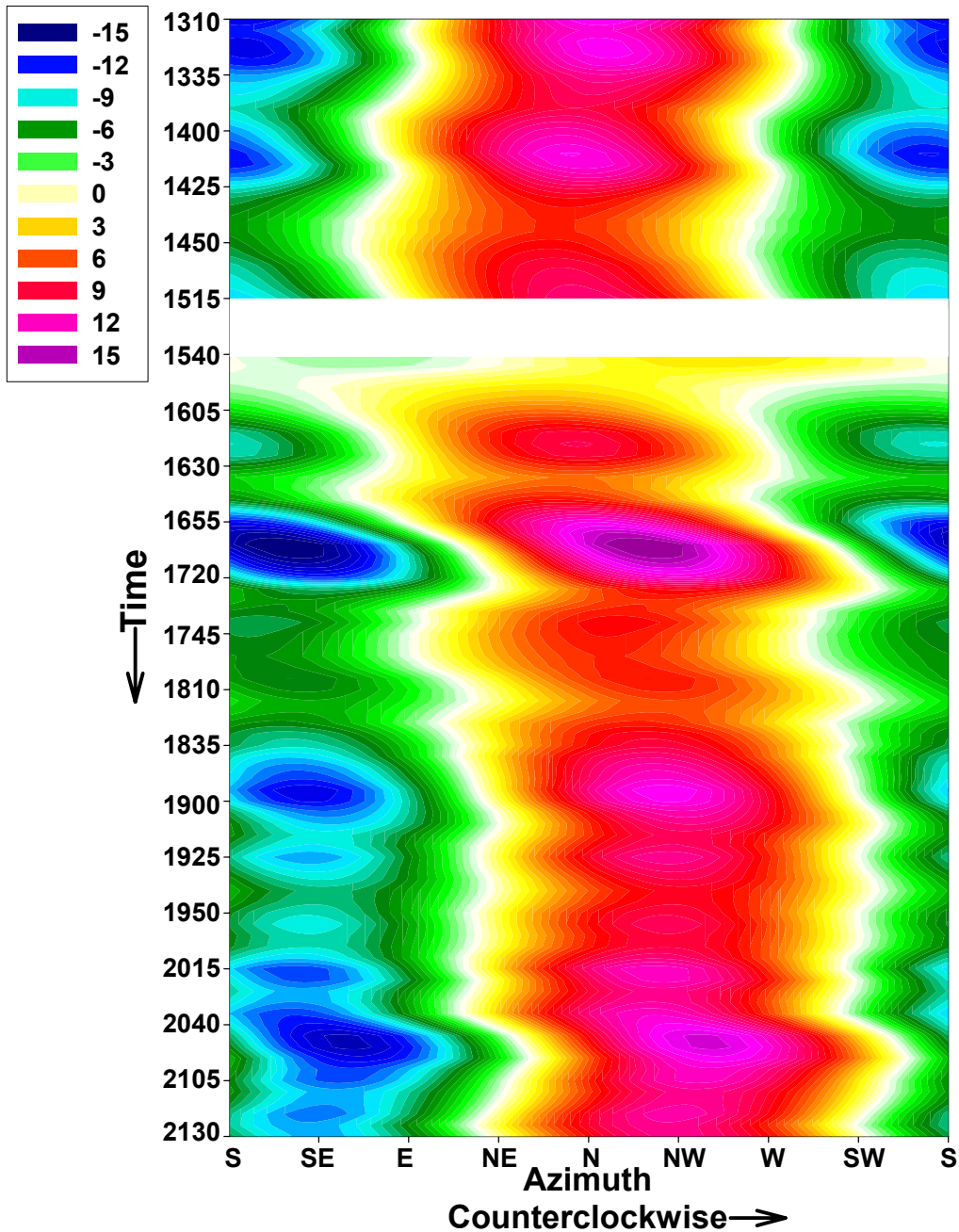


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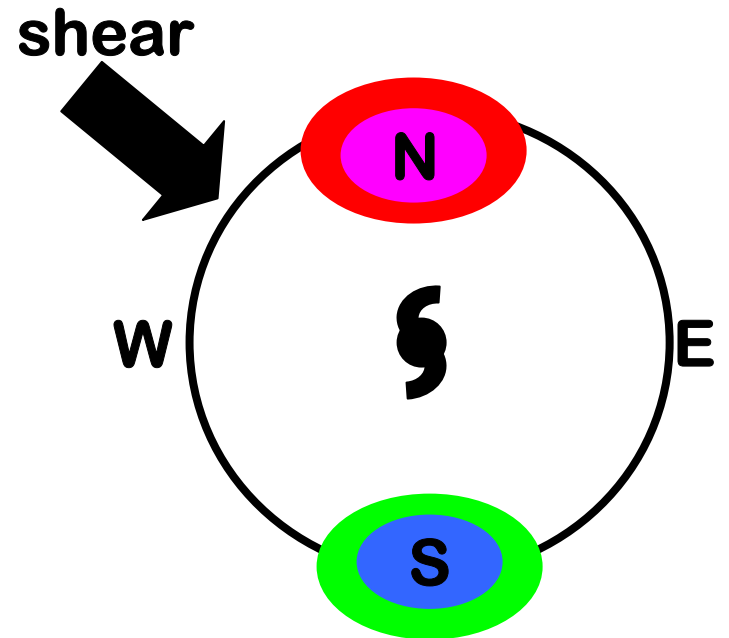


# Power spectrum (dBZ<sup>2</sup>) averaged 55-80 km from the center of Elena

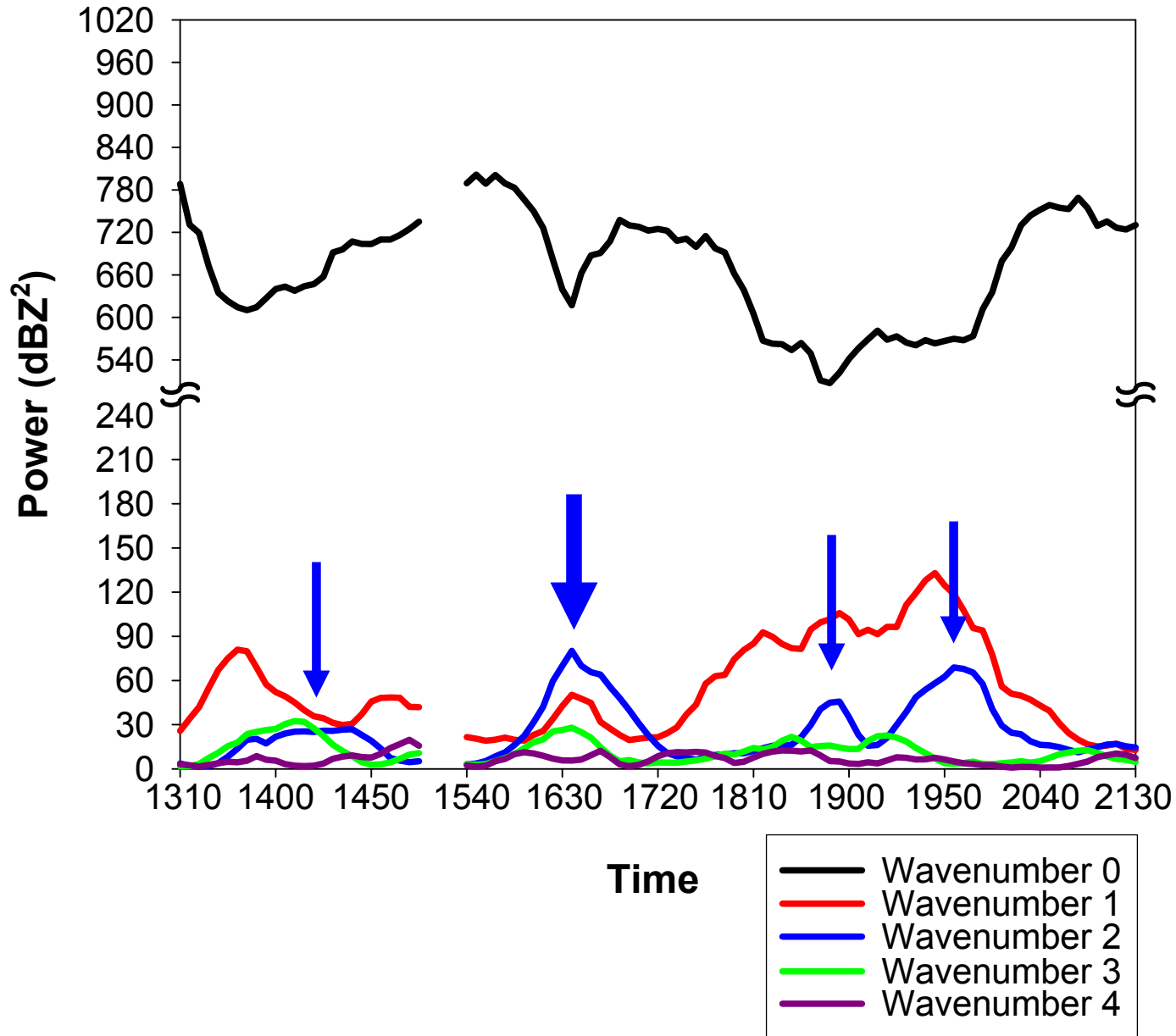




# Azimuth-Time Hovmöller of Wavenumber One Reflectivity

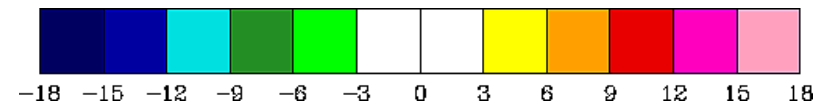
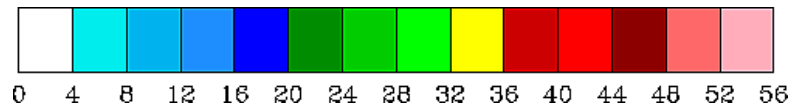
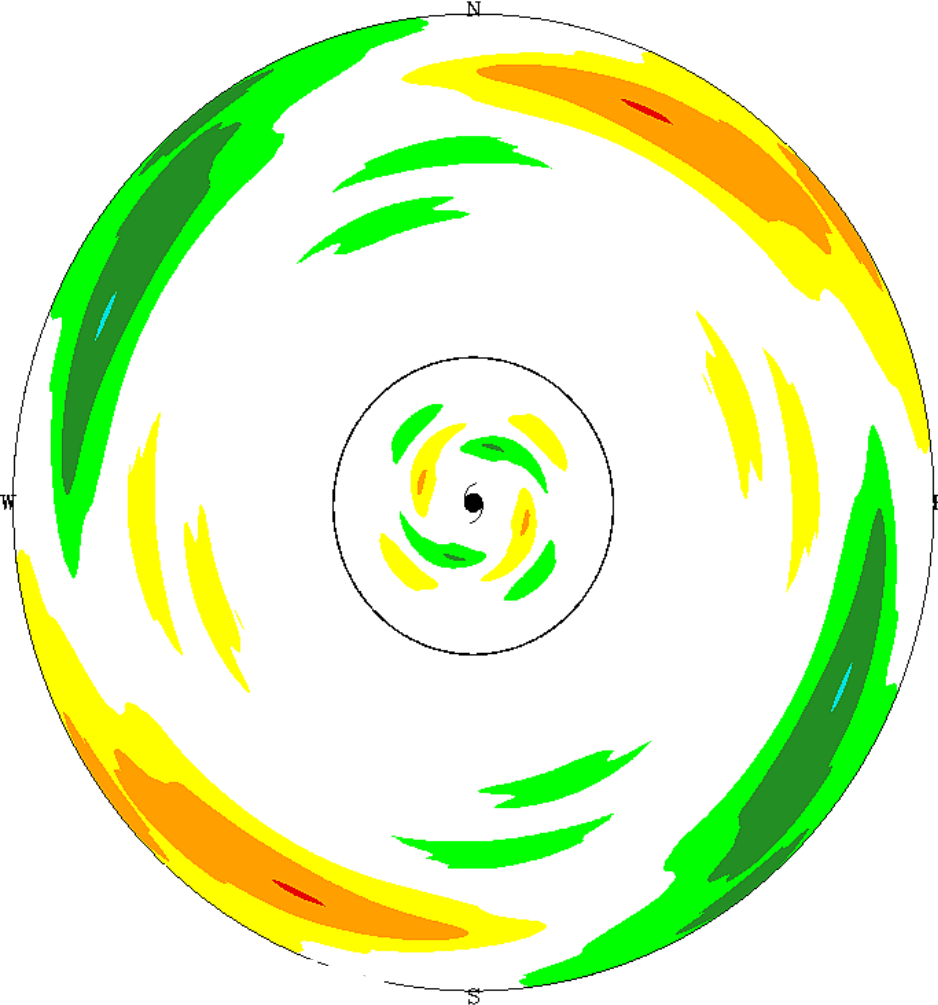
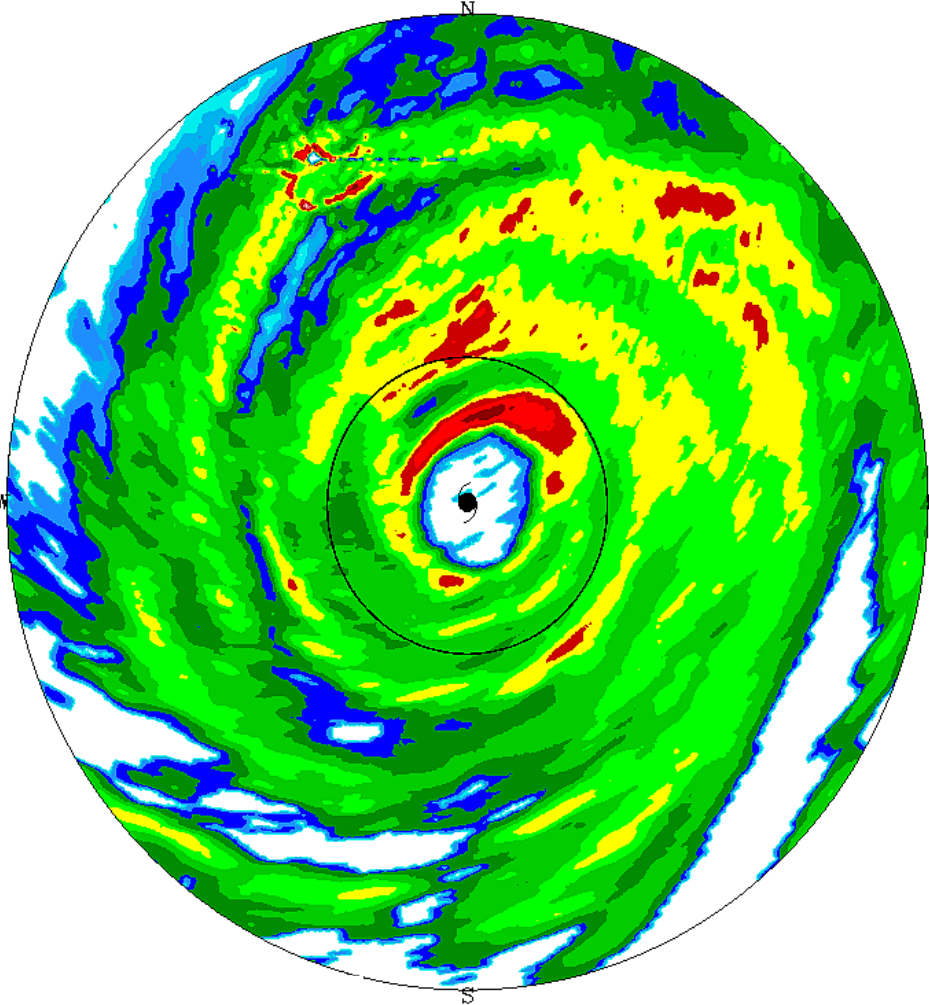


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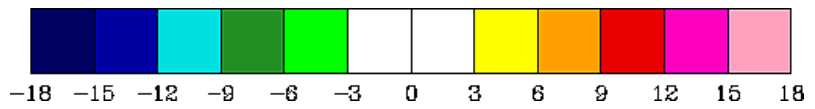
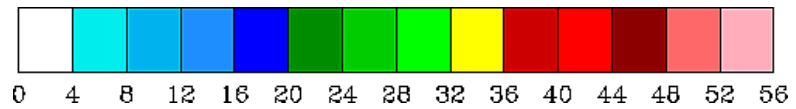
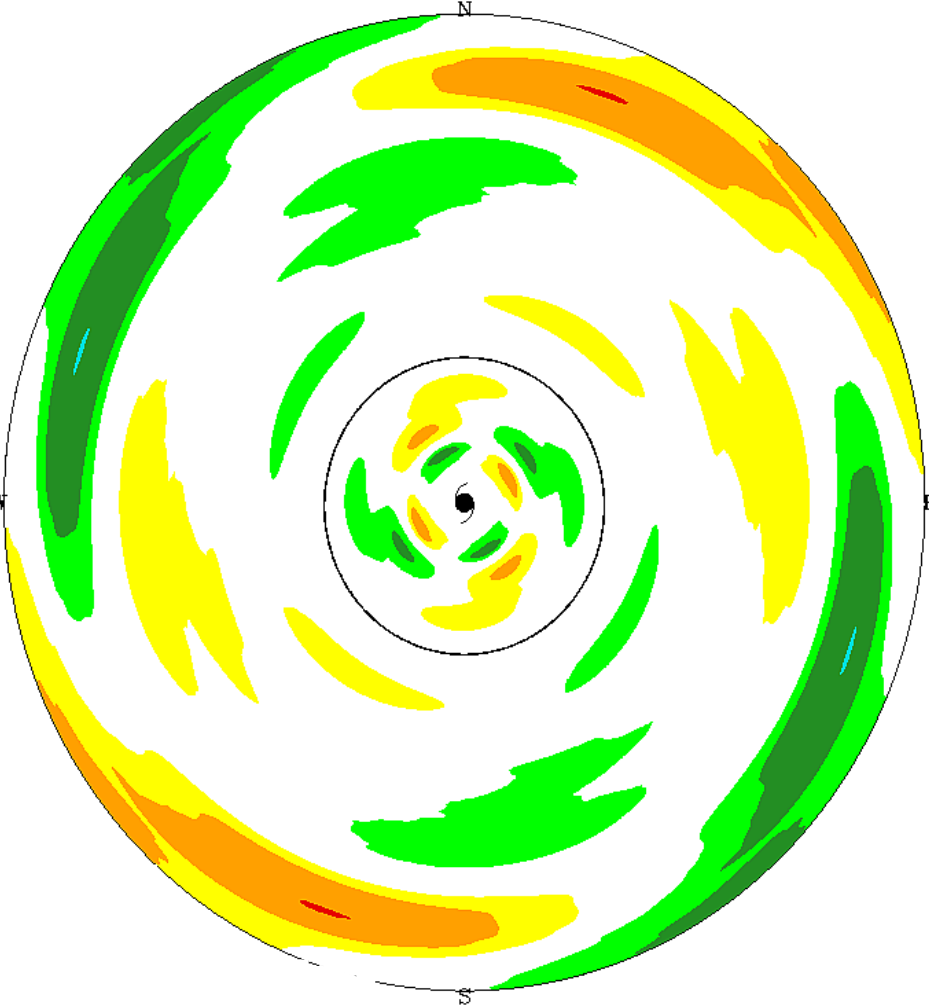
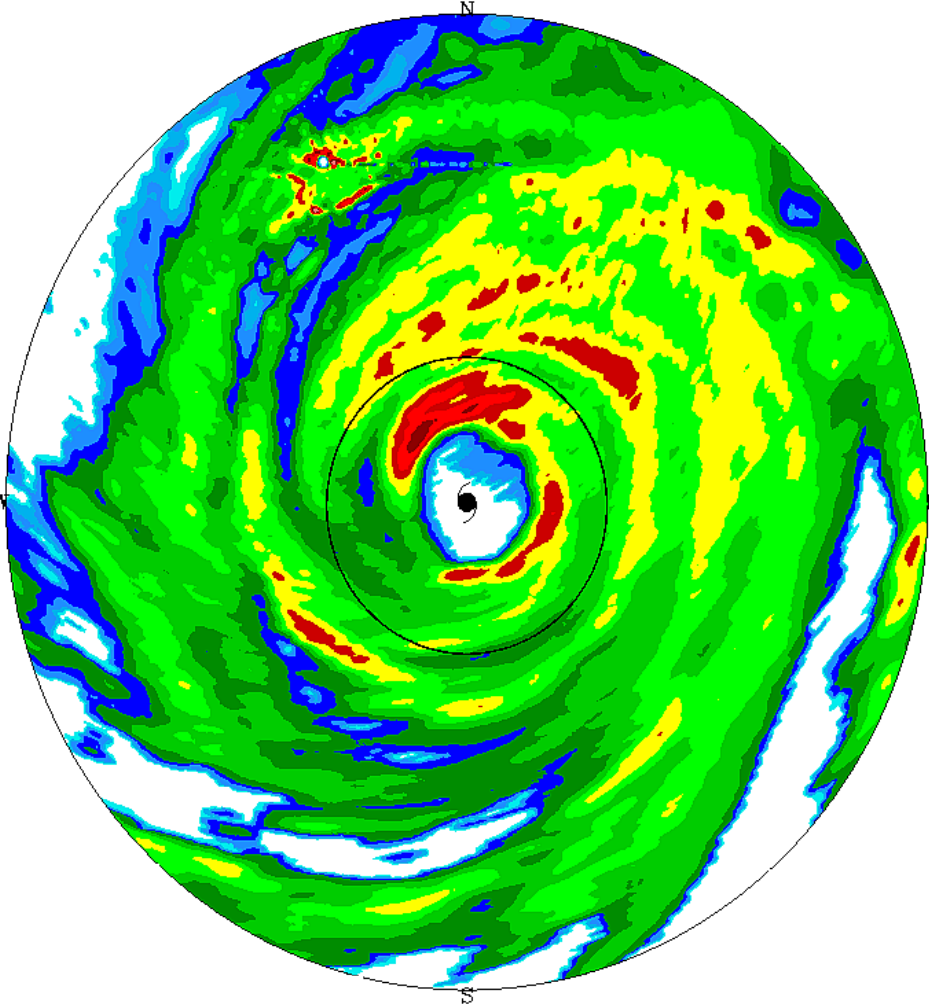
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Wave #2 9/1 1540 UTC



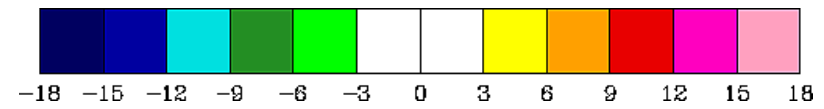
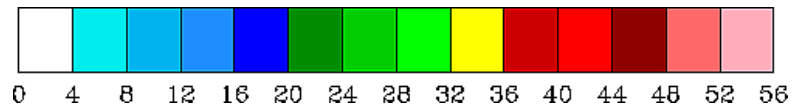
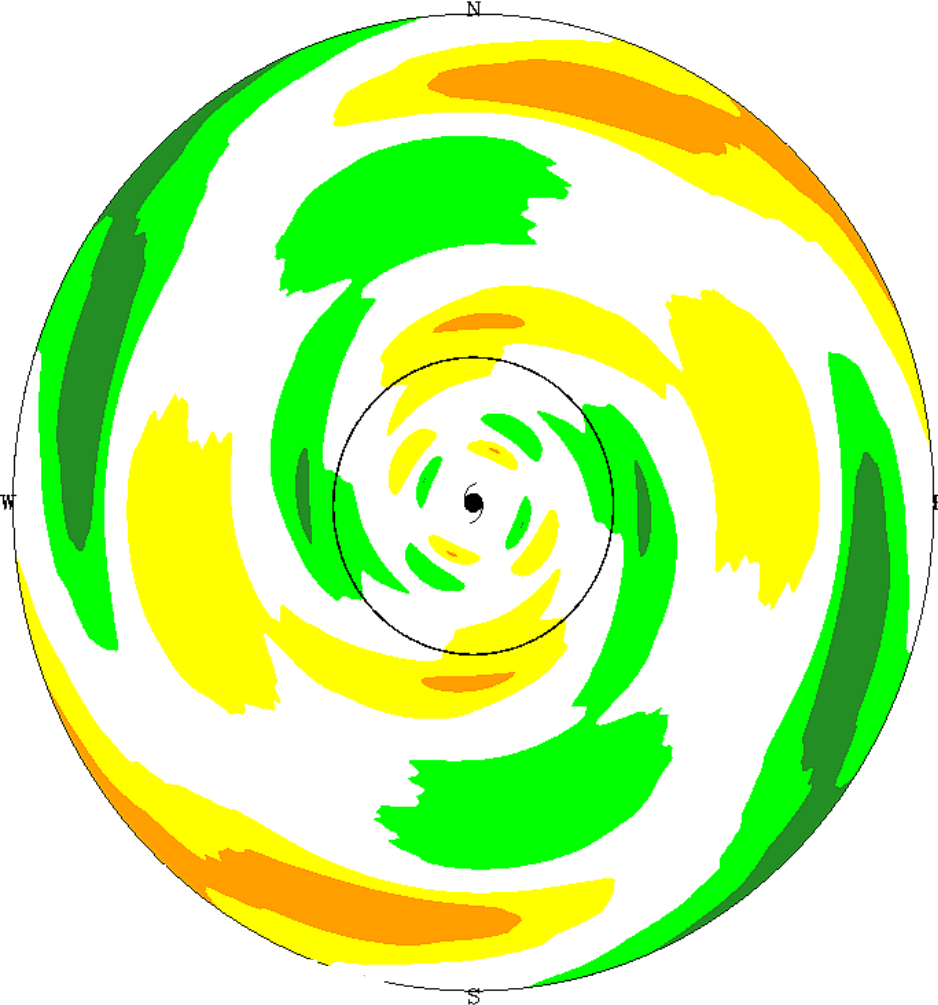
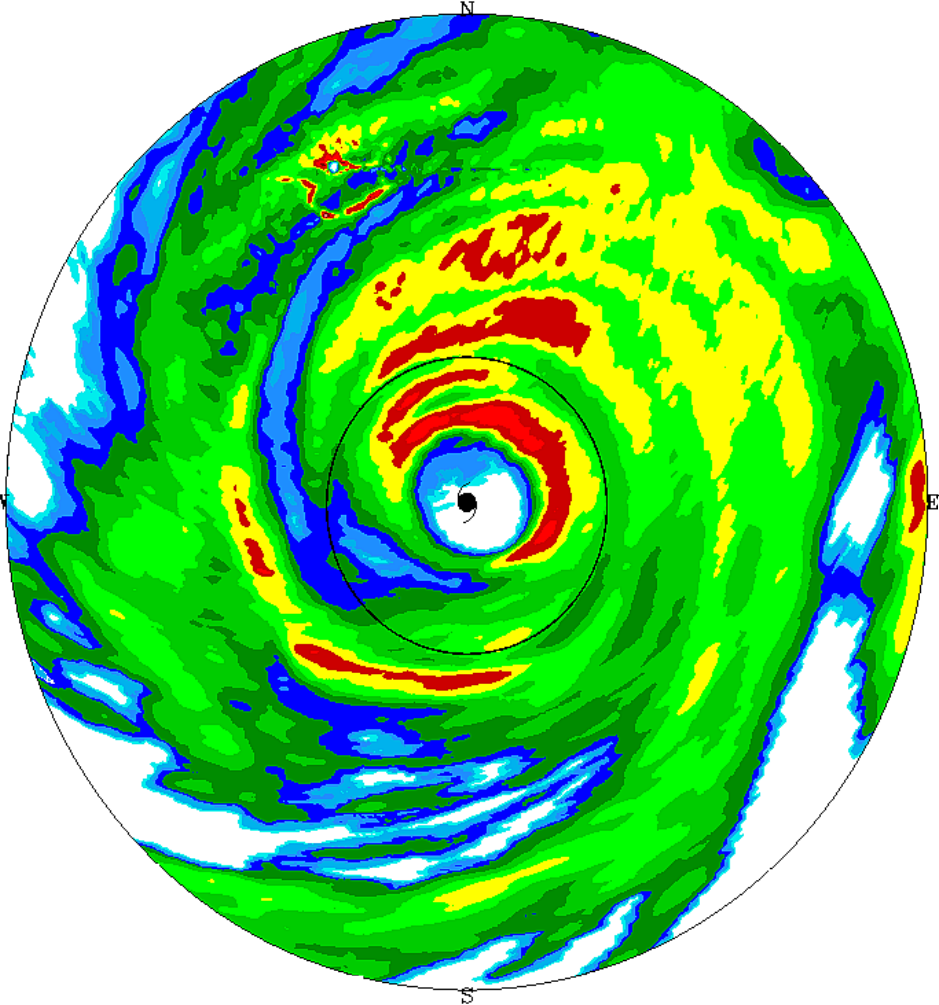
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Wave #2 9/1 1555 UTC



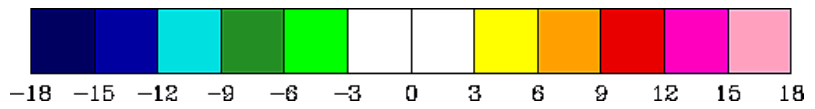
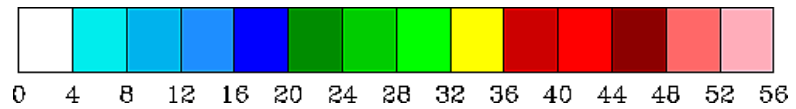
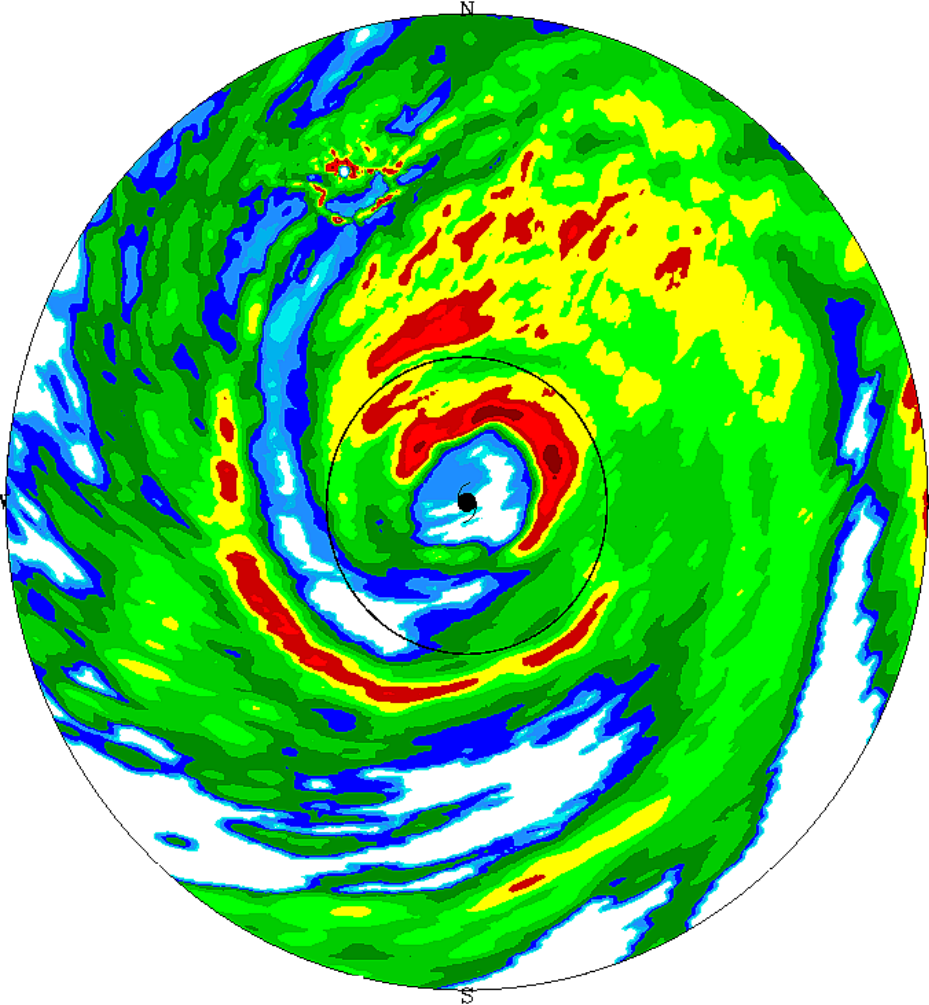
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Wave #2 9/1 1610 UTC



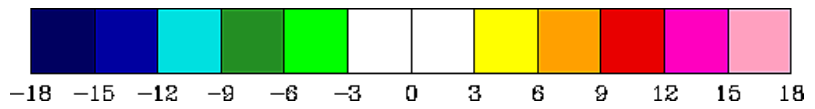
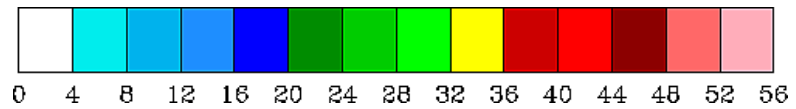
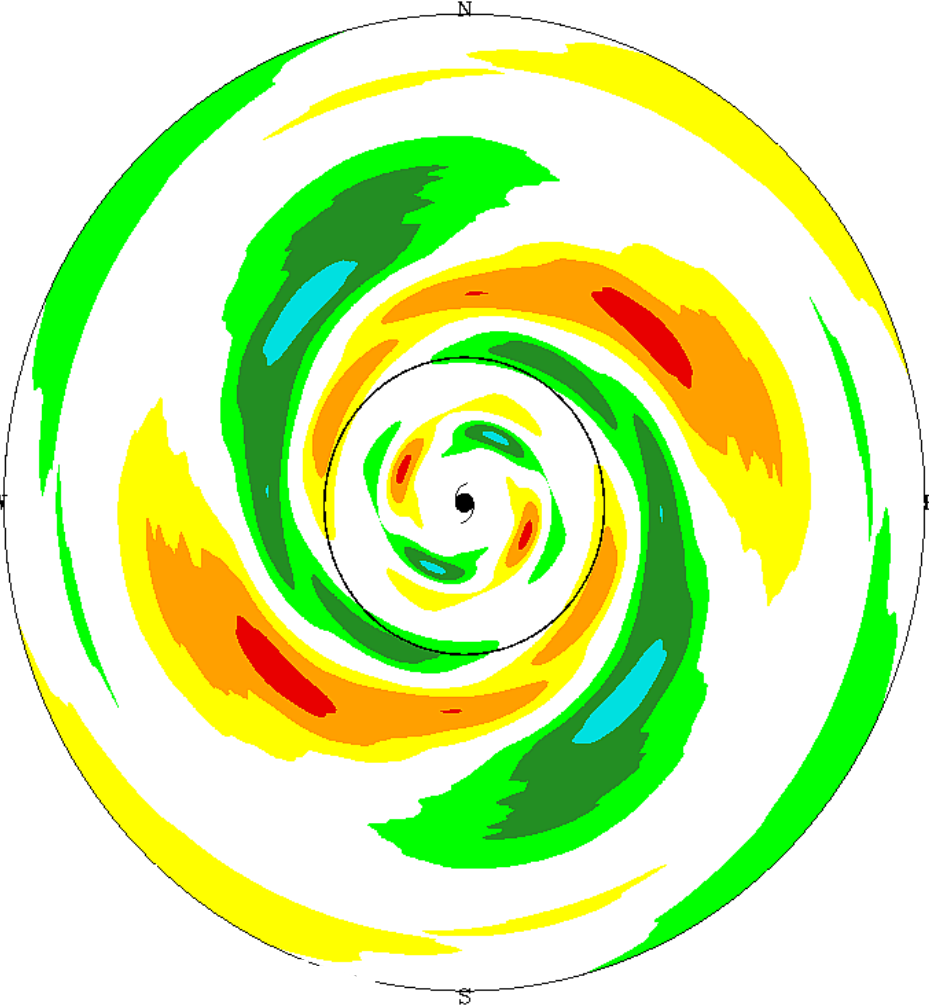
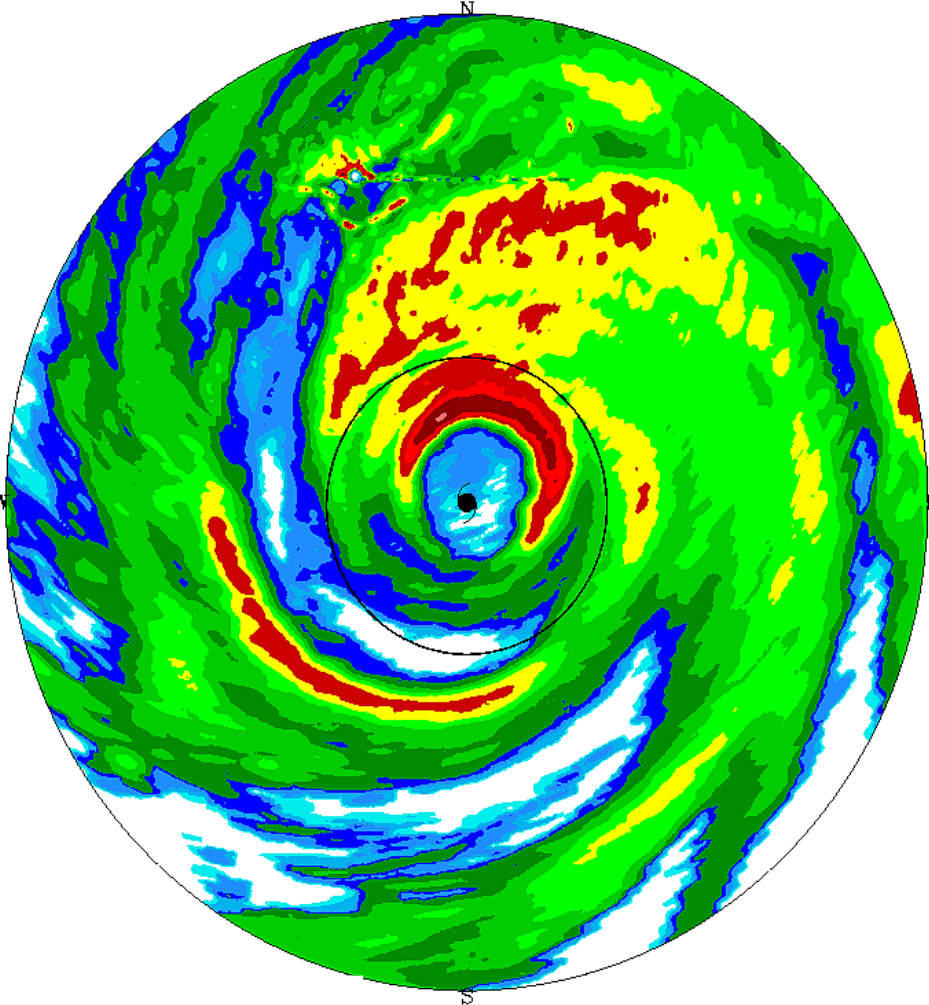
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Wave #2 9/1 1625 UTC



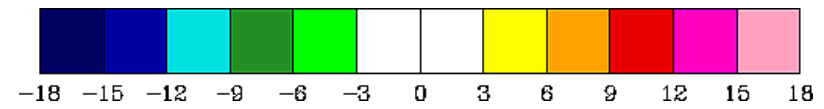
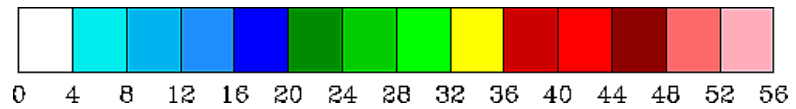
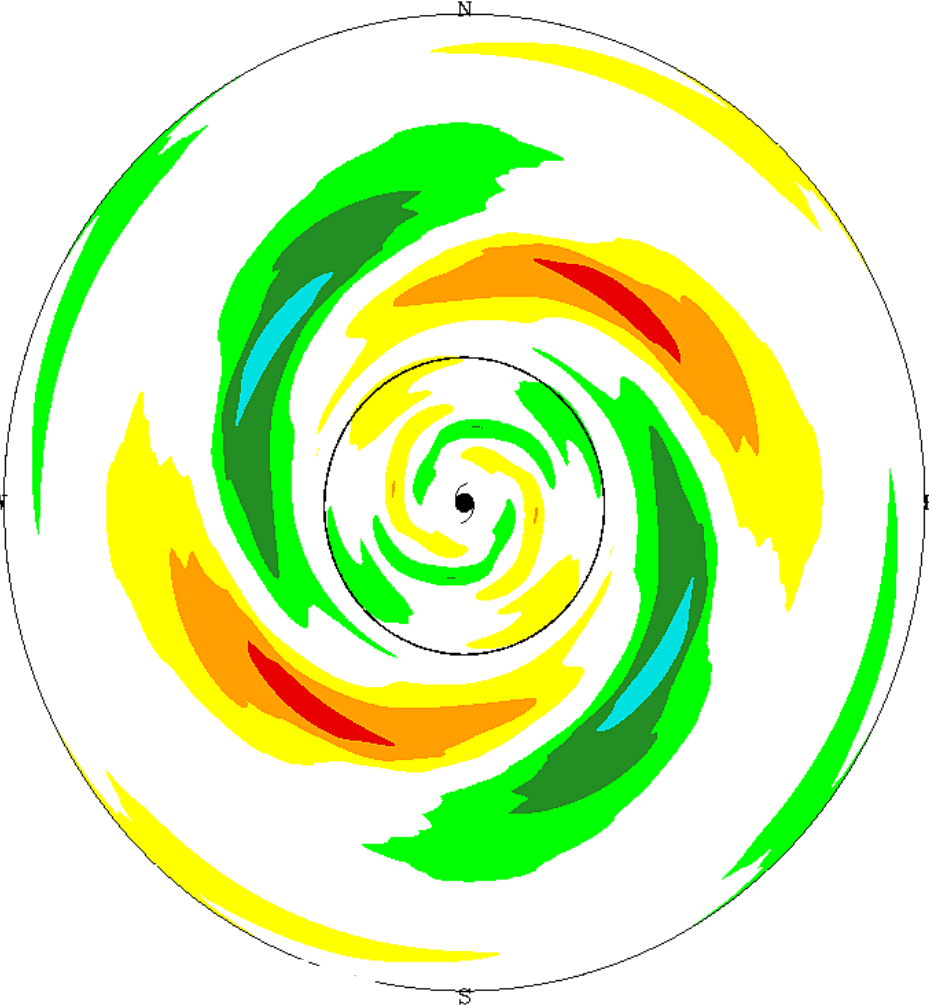
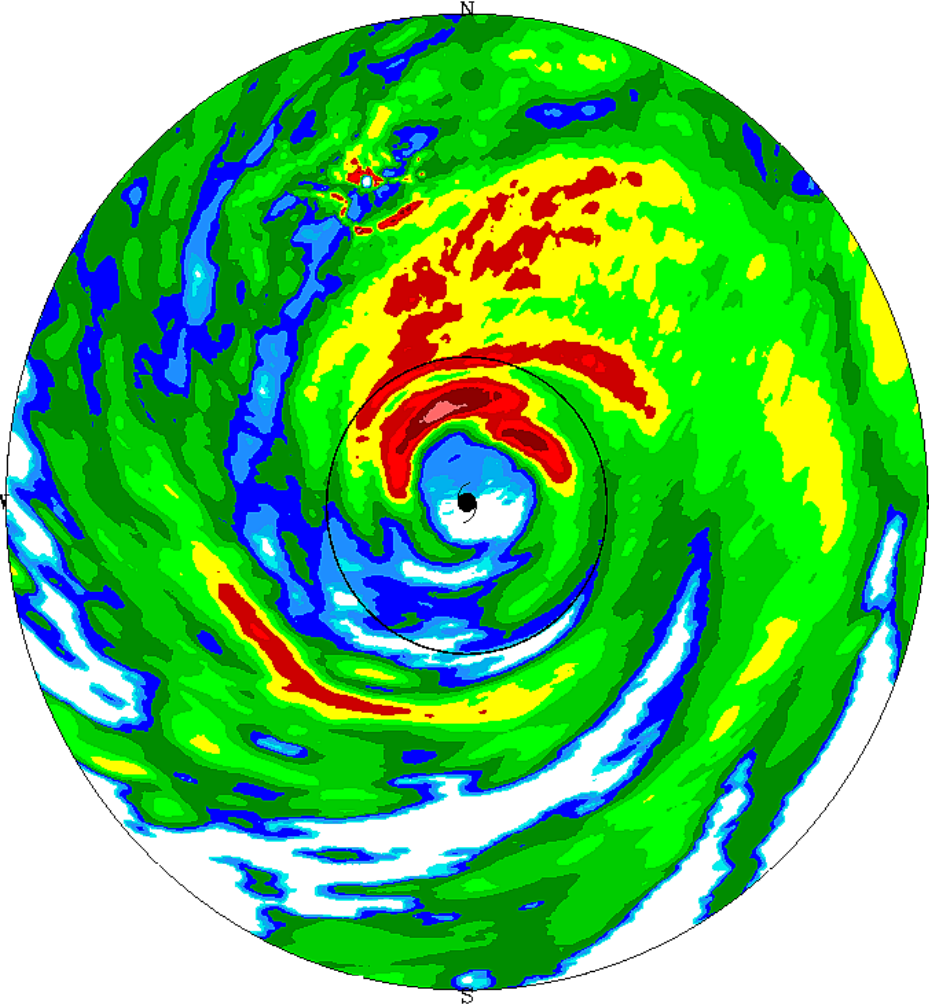
DBZ ELENA 85/09/01 1640Z 0.75

Wave #2 9/1 1640 UTC



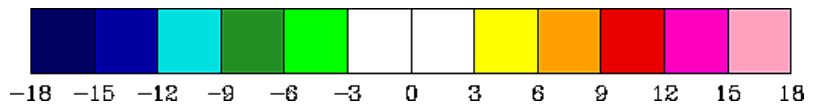
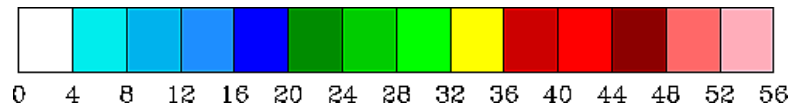
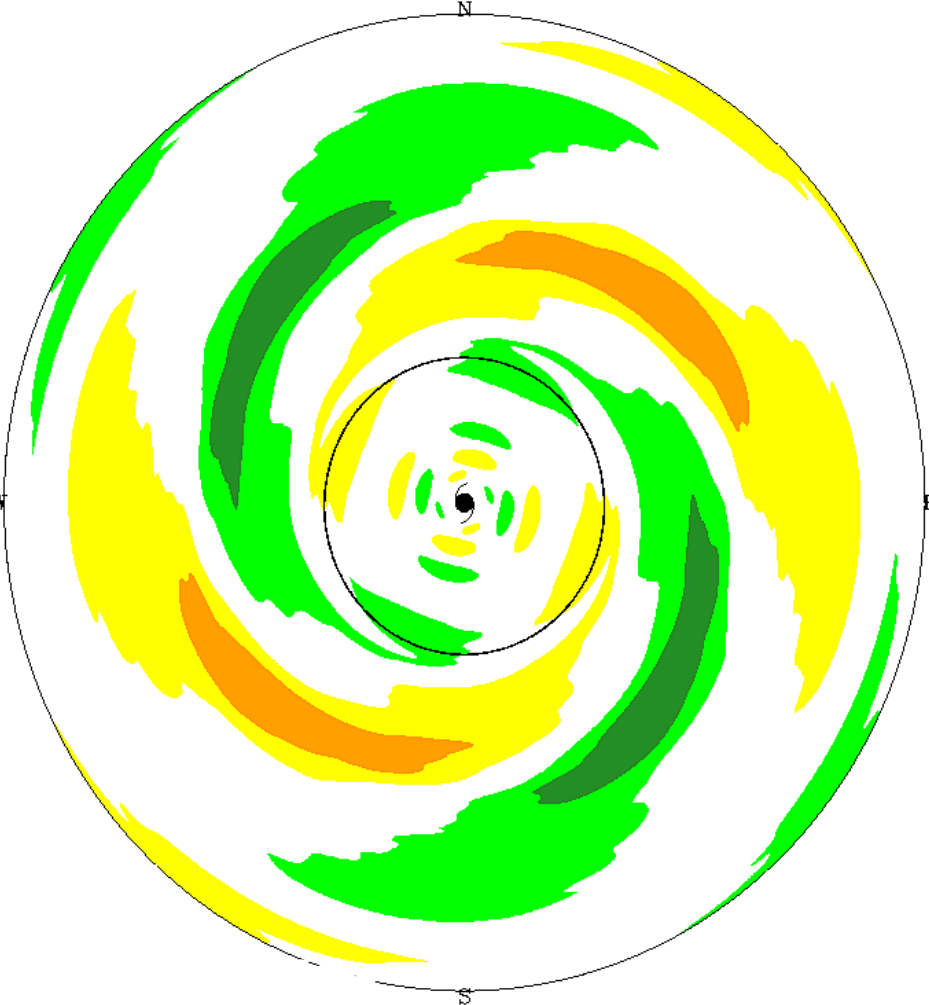
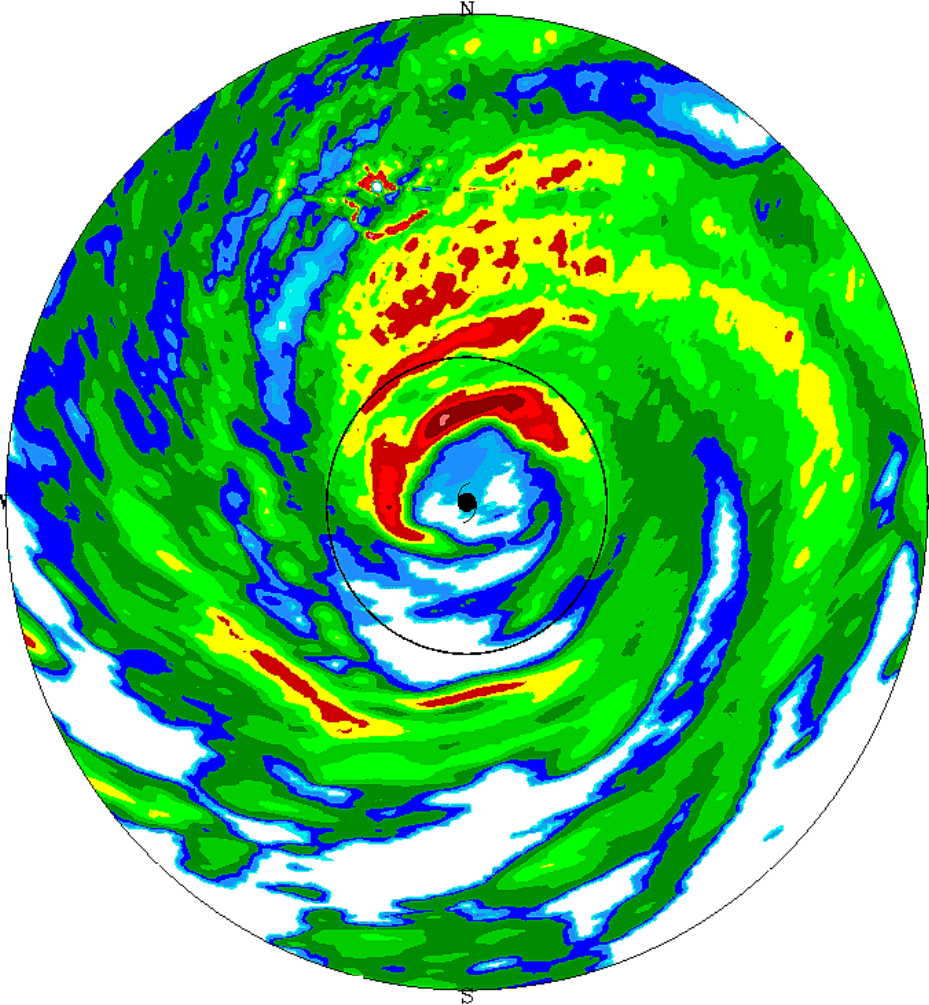
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Wave #2 9/1 1655 UTC



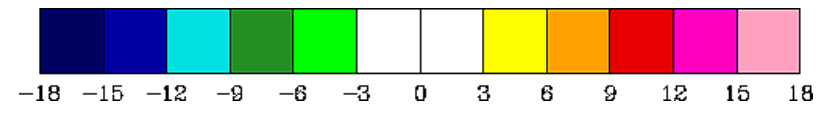
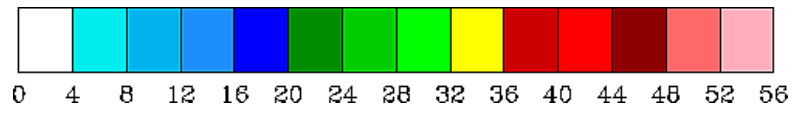
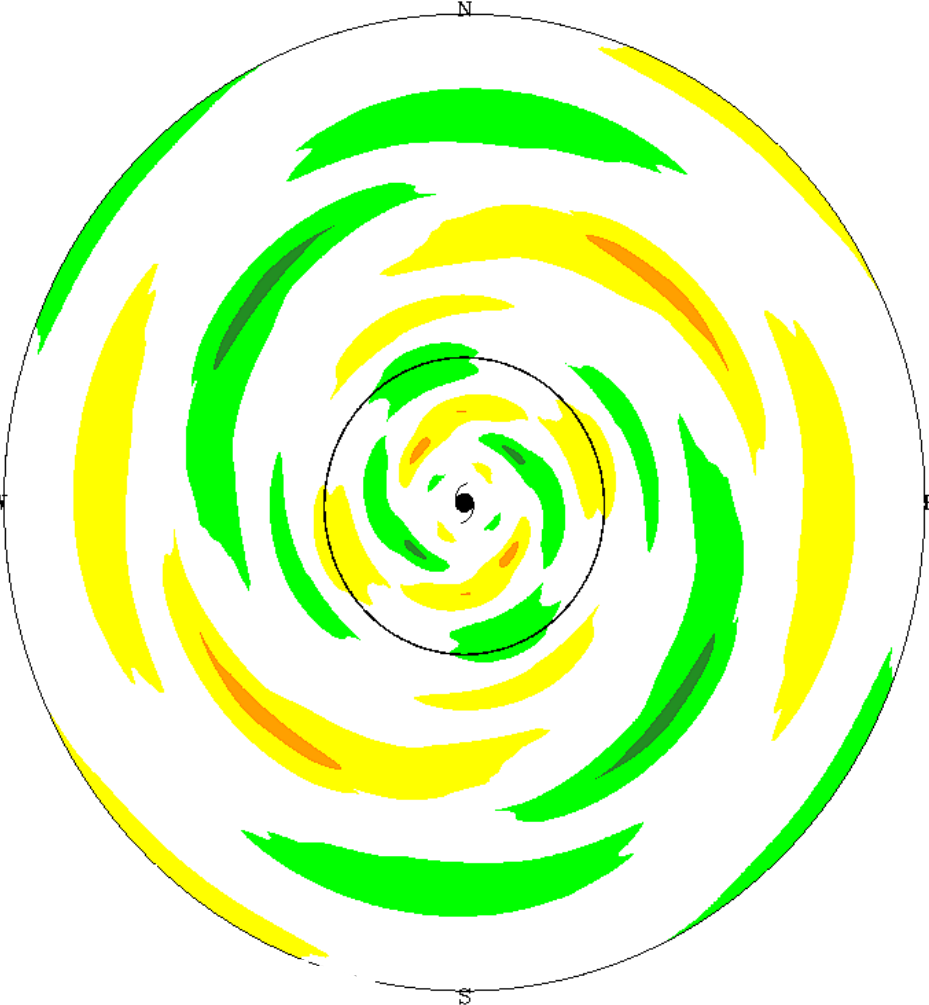
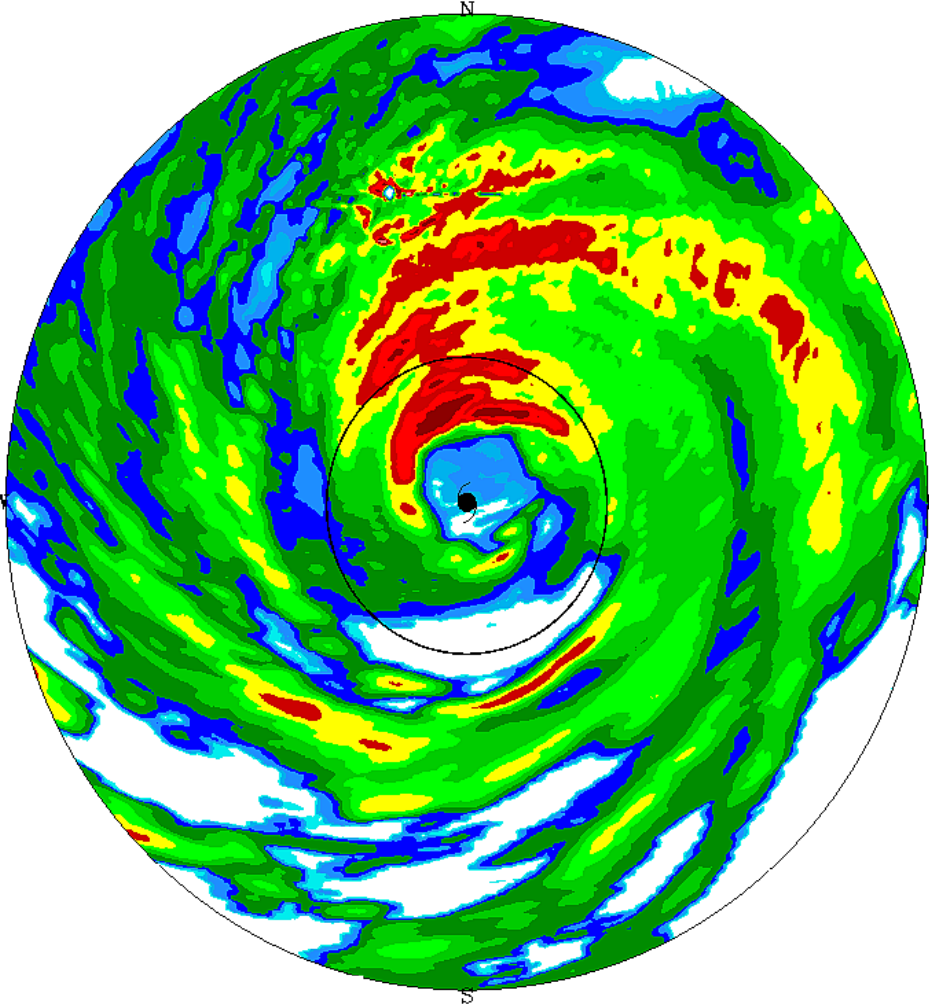
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Wave #2 9/1 1710 UTC



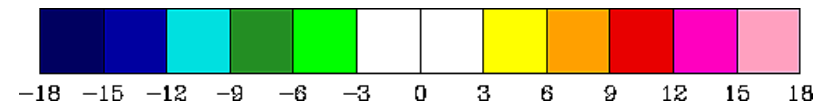
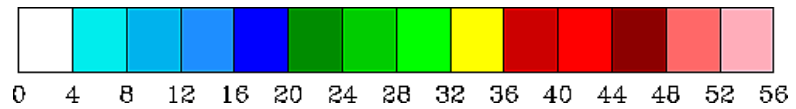
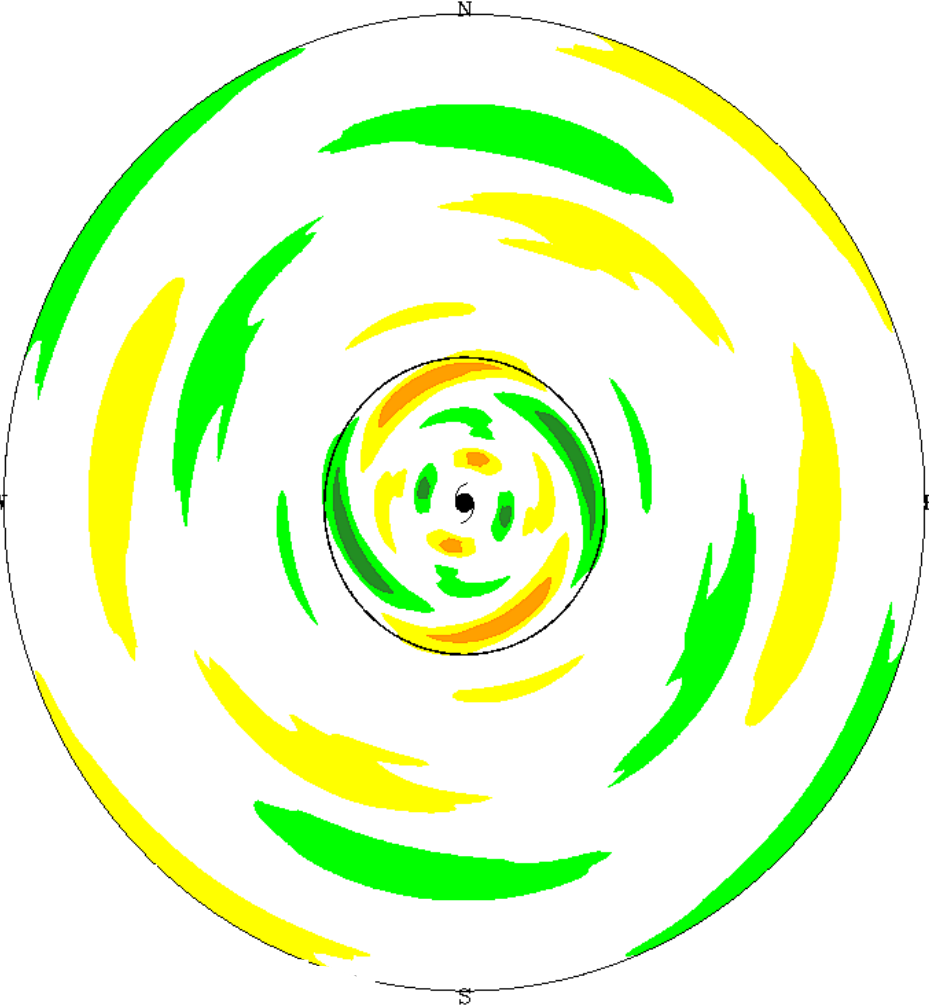
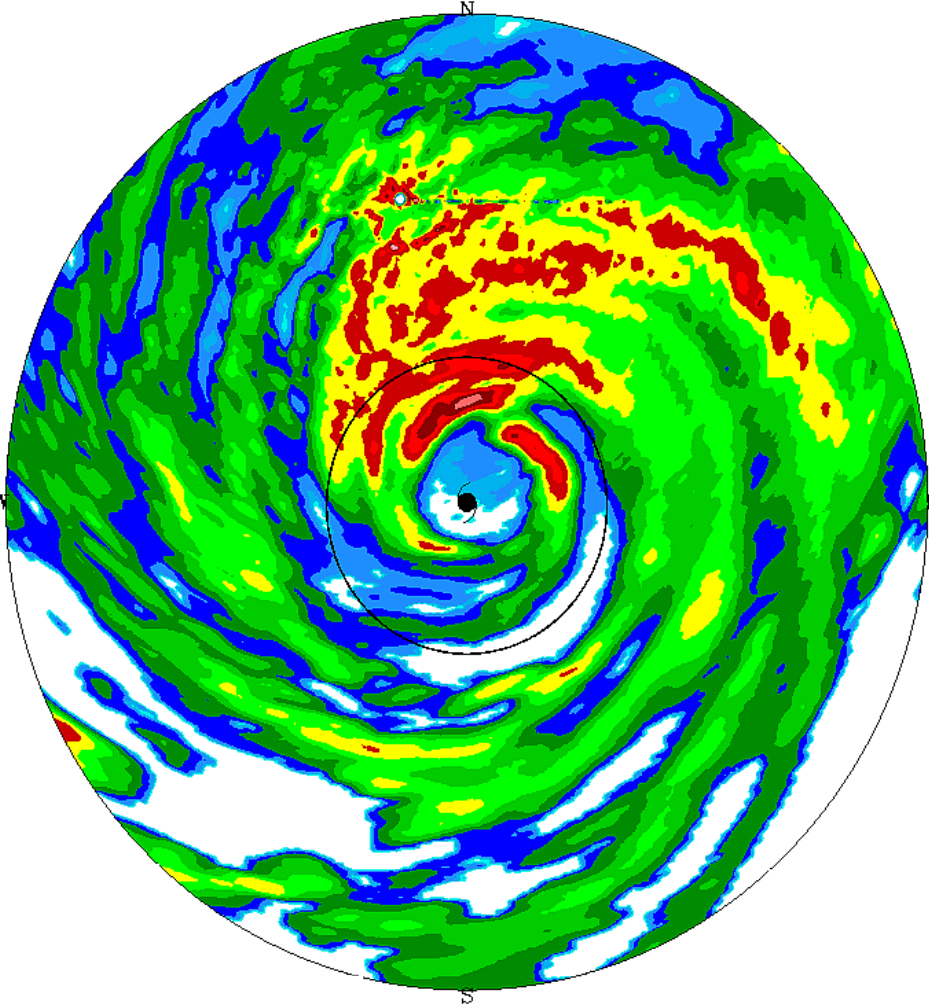
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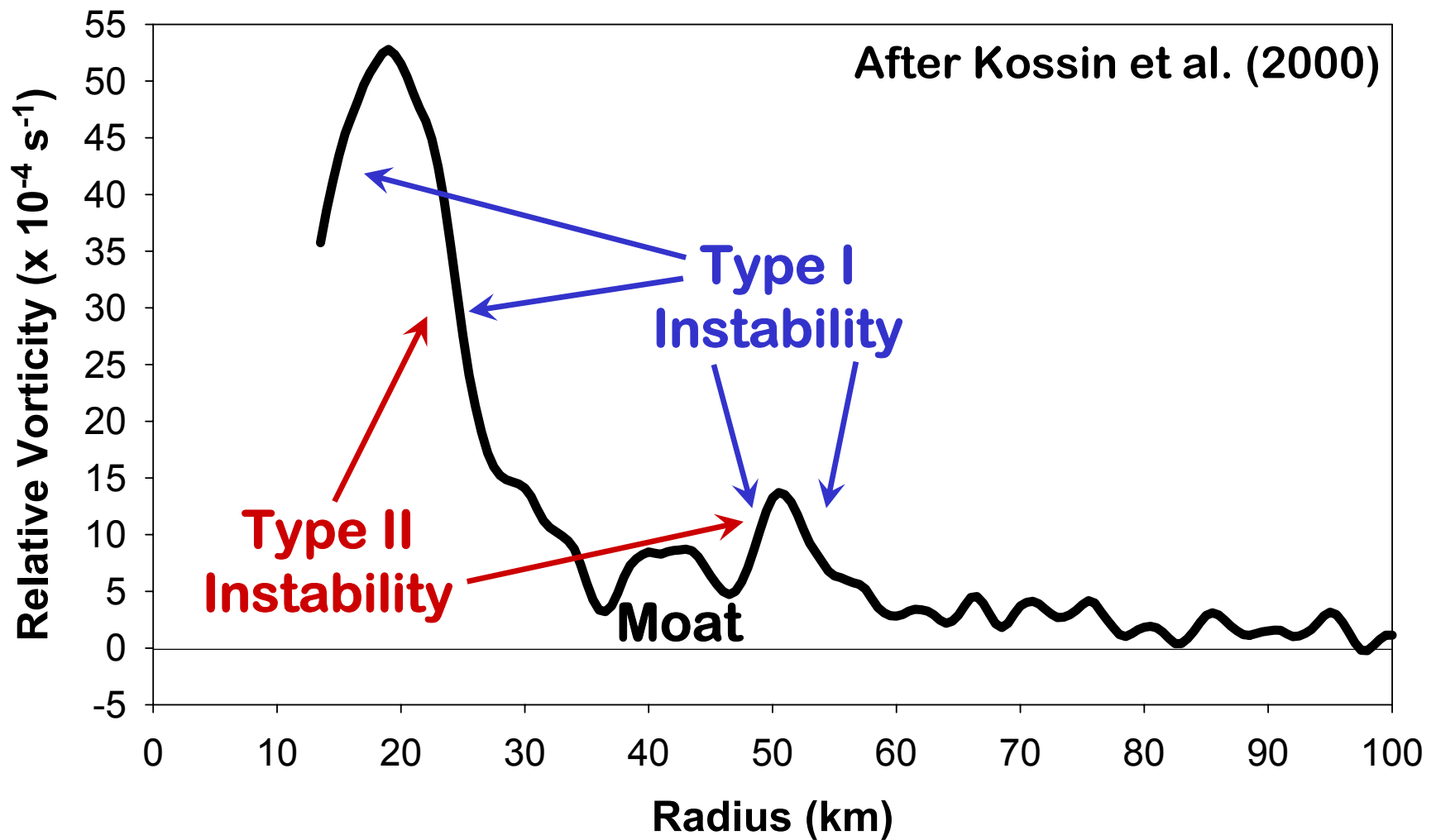
Wave #2 9/1 1725 UTC



DBZ ELENA 85/09/01 1740Z 0.75

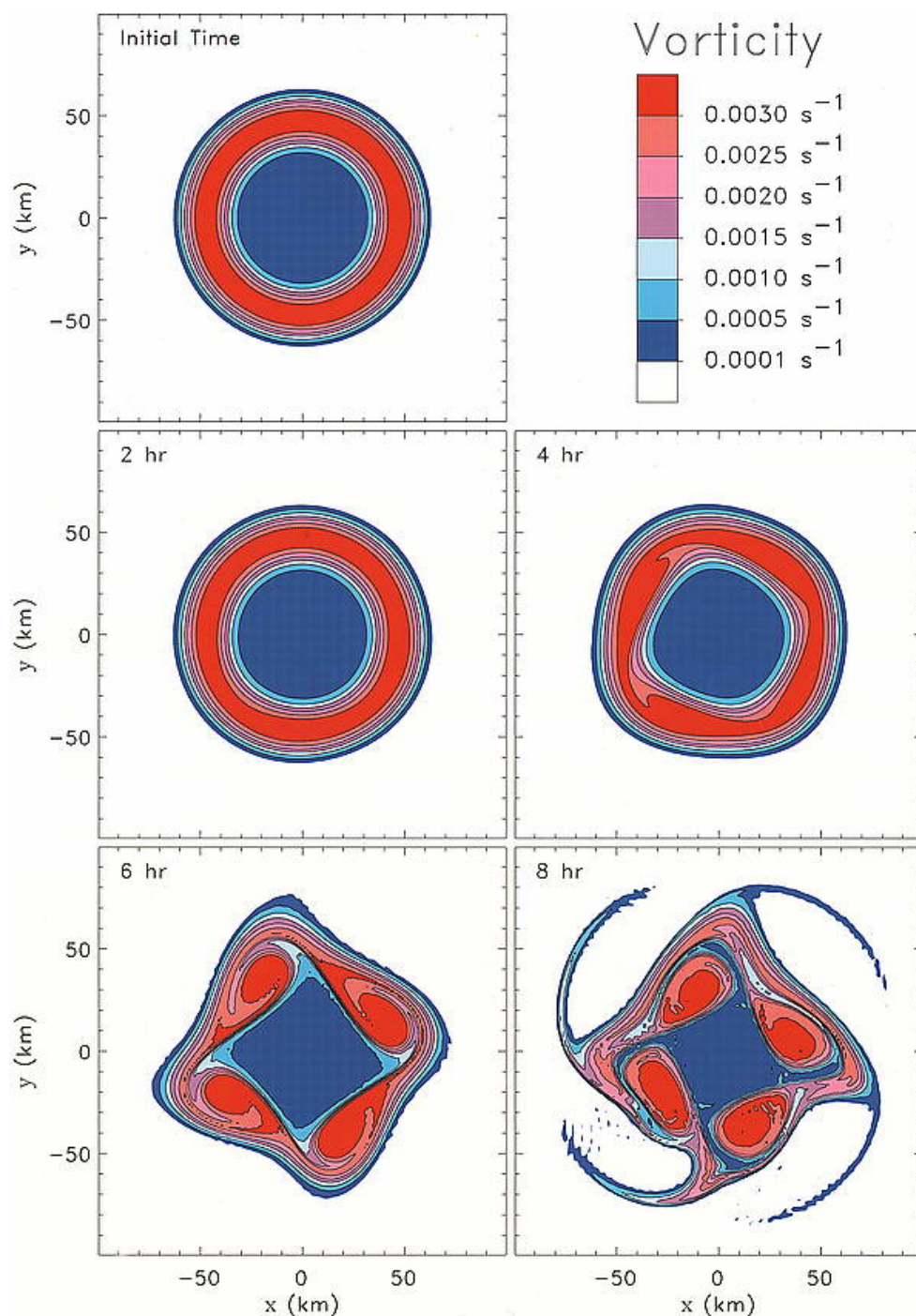
Wave #2 9/1 1740 UTC





**Type I** : Between the gradients on either side of the eyewall or outer ring vorticity maximum

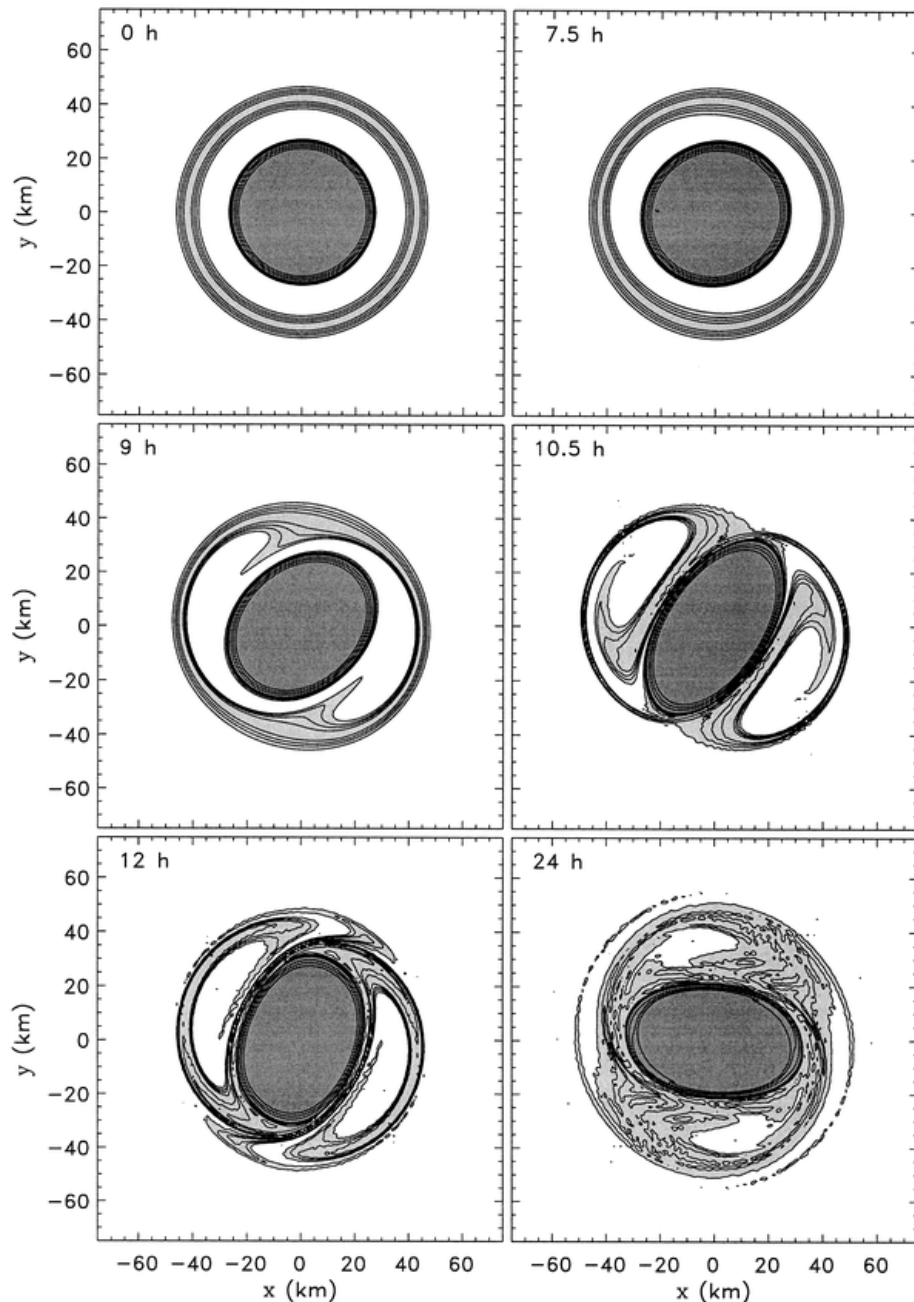
**Type II** : Between the negative eyewall and positive ring vorticity gradients, across a low vorticity moat



The **Type I instability** involves the pooling of eyewall vorticity into discrete **mesovortices**, initiating **asymmetric mixing** between the eye and eyewall

To conserve angular momentum, some **high vorticity** must be **mixed outward**, taking the form of **vorticity filaments**

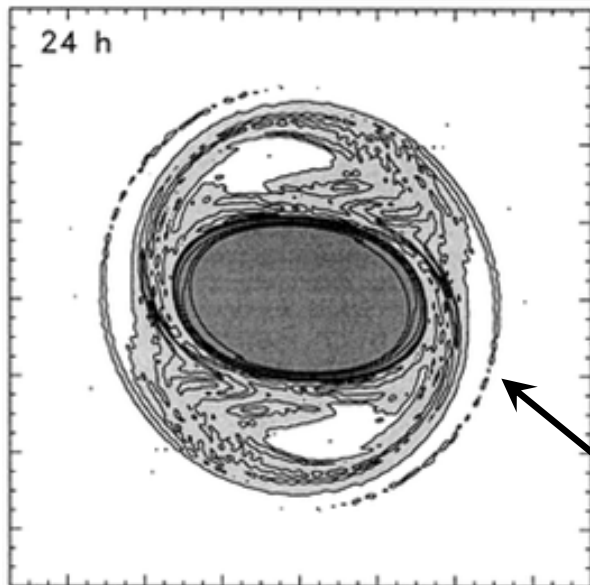
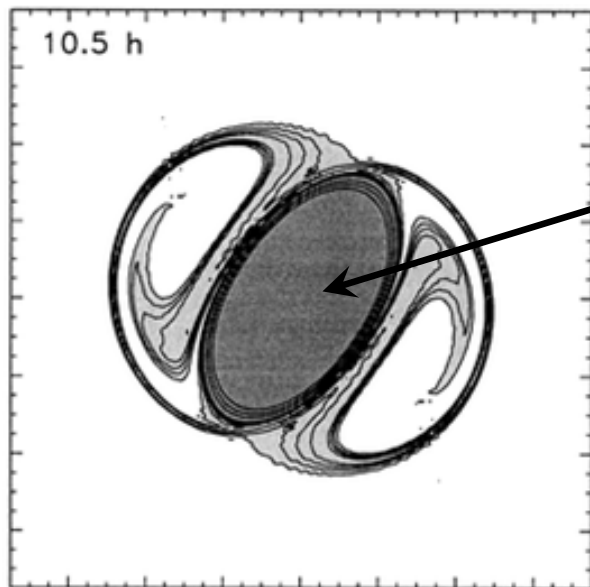
Schubert et al. (1999)



Azimuthal **wavenumber 2** was found to be the most likely manifestation of the **Type II instability**

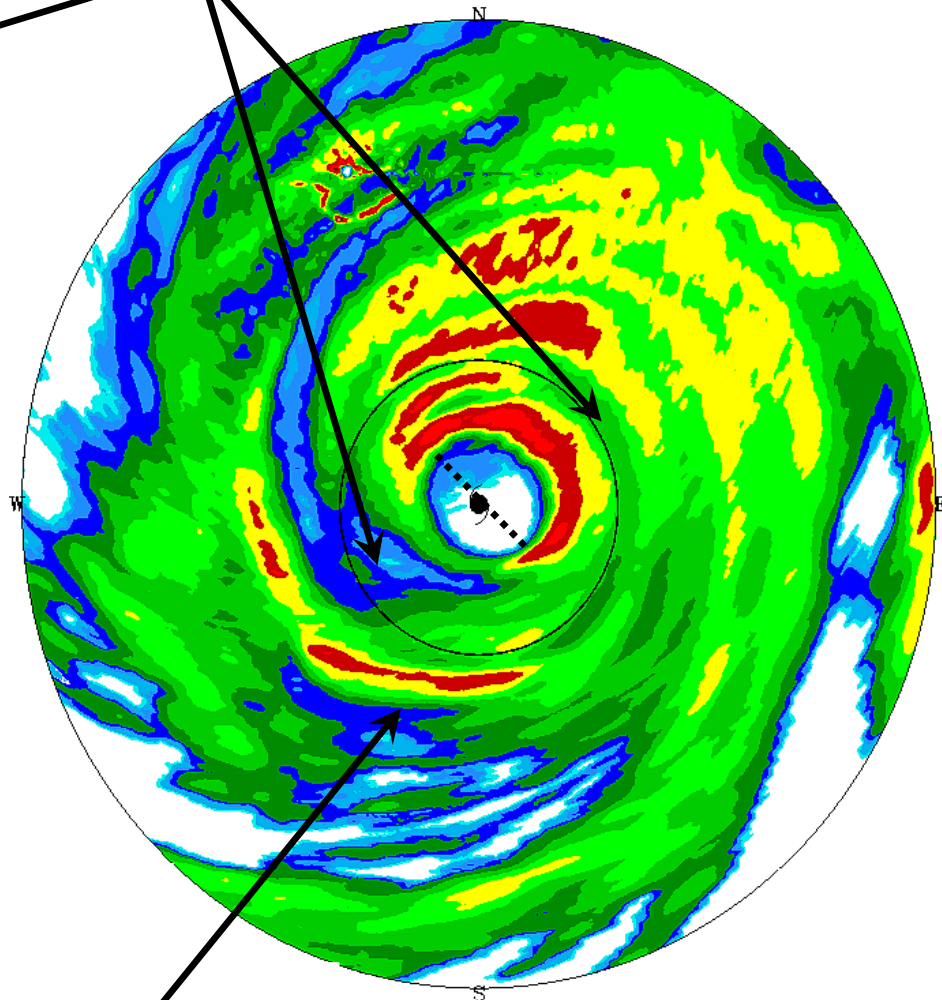
Rearrangement of the near core vorticity field into a tripole, with an **elliptical eyewall** and **filaments** of high vorticity **outside of the core**.

Figure 13 Kossin et al. (2000)



-60 -40 -20 0 20 40 60  
x (km)

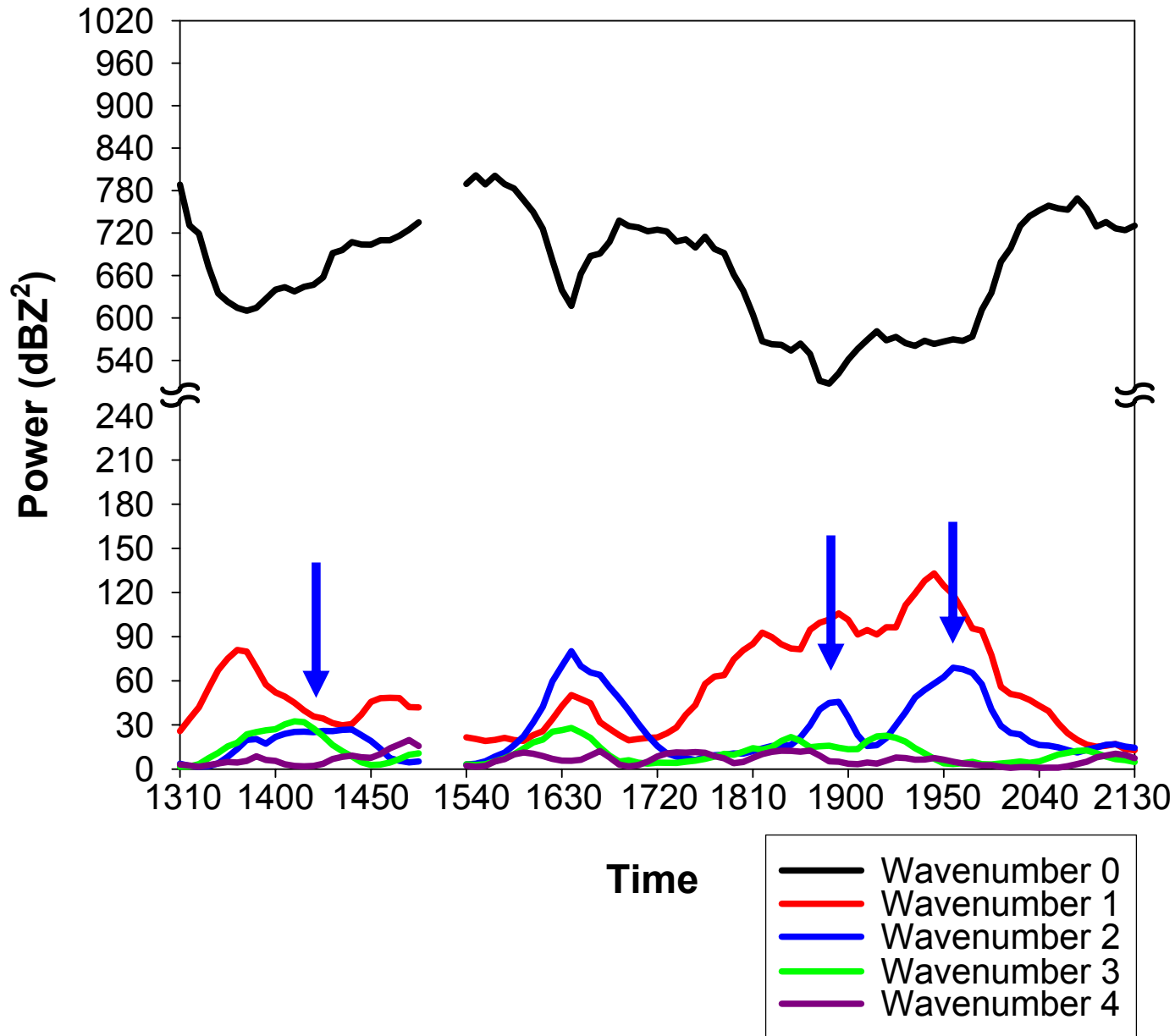
**Tripole and elliptical eyewall**

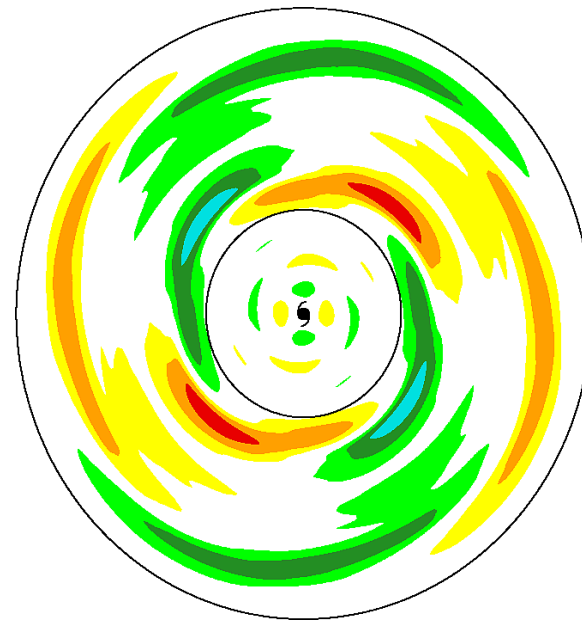
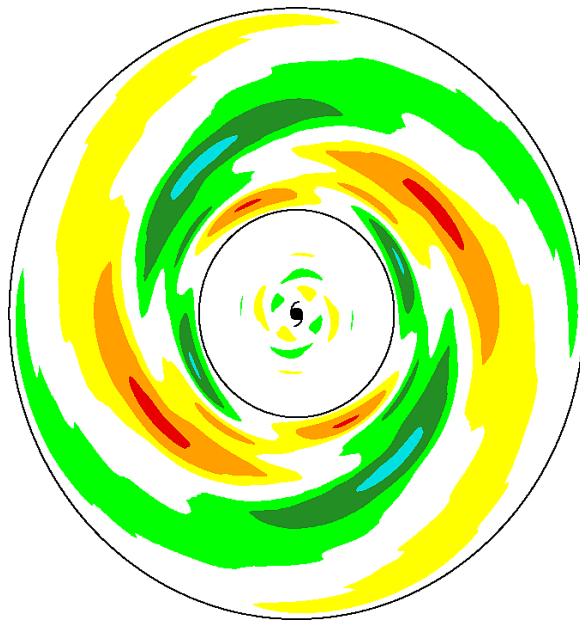
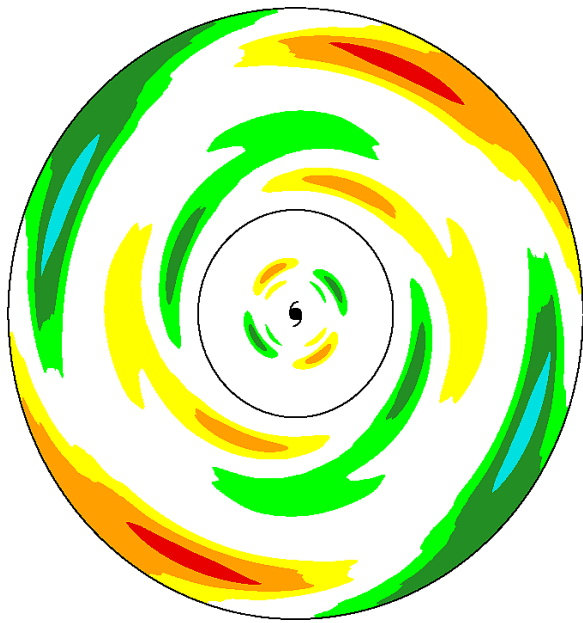
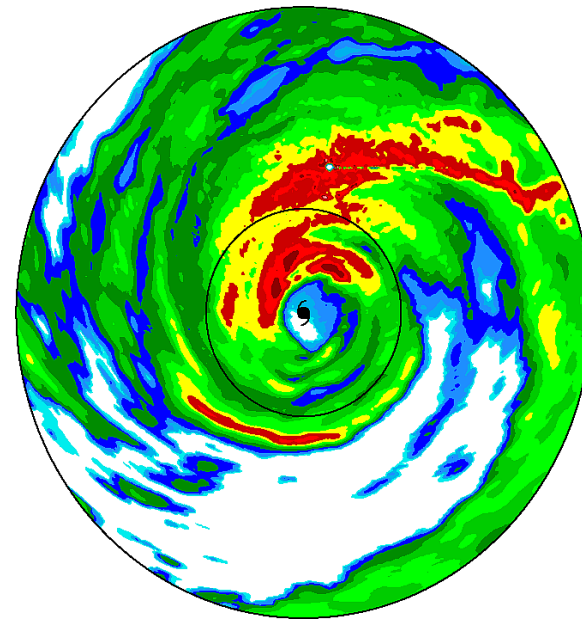
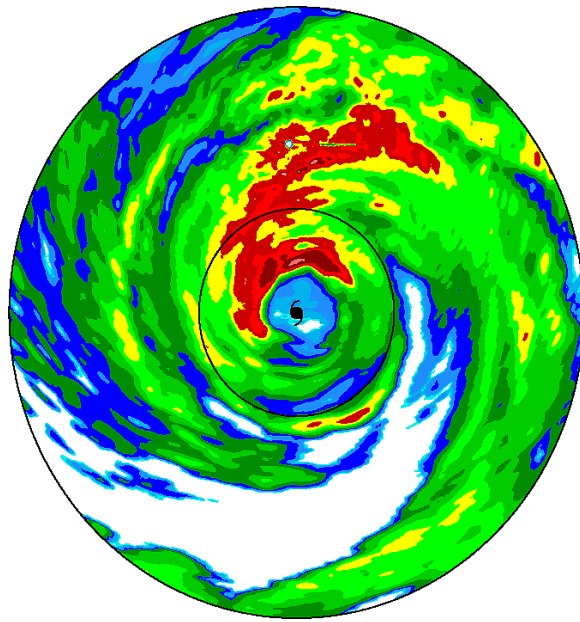
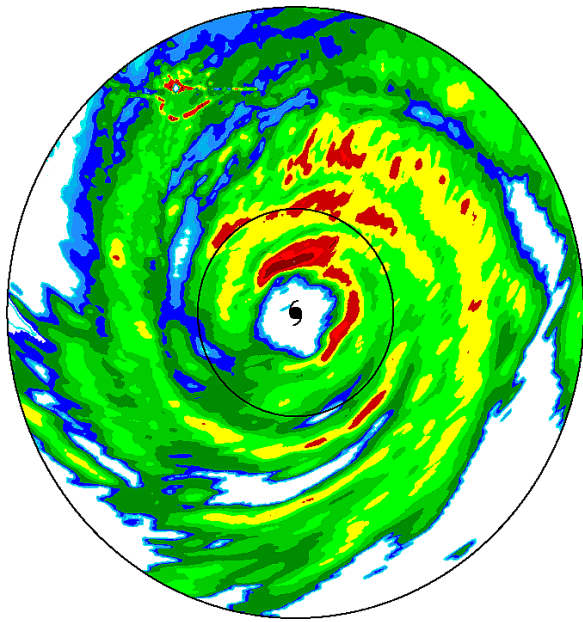


**Vorticity filaments**

**Kossin et al. (2000)**

# Power spectrum (dBZ<sup>2</sup>) averaged 55-80 km from the center of Elena

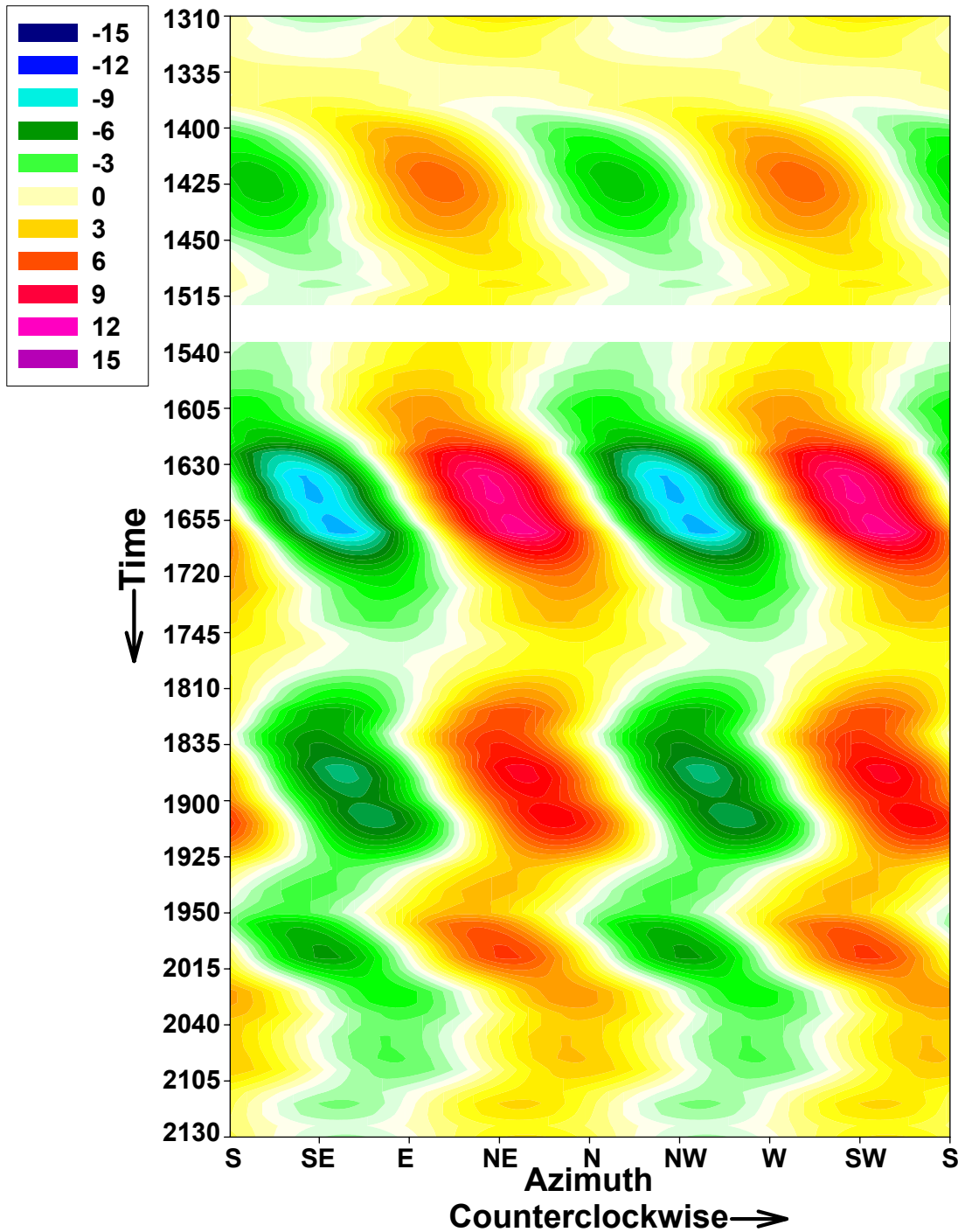




**1440 UTC**

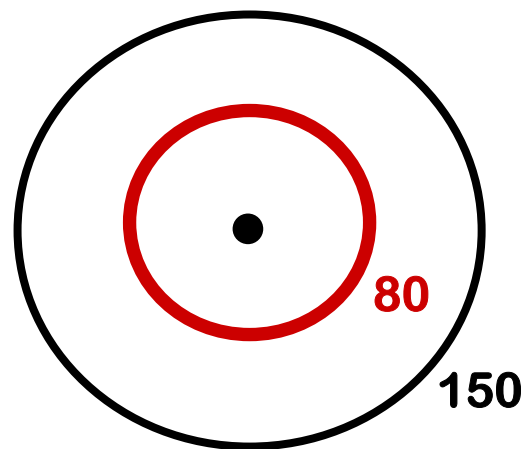
**1850 UTC**

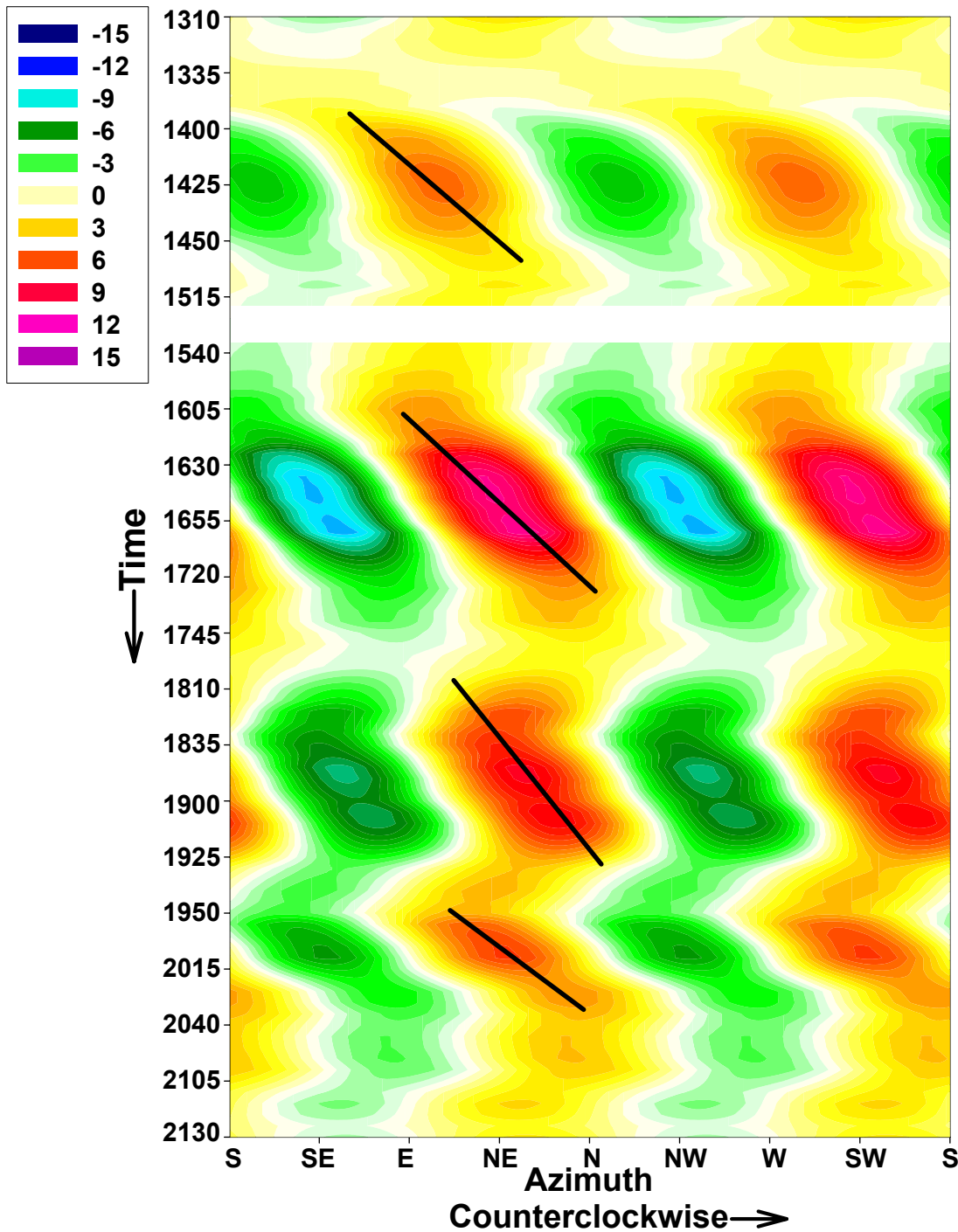
**1955 UTC**



# Azimuth-Time Hovmöller of Wavenumber Two Reflectivity

Radius = 80 km





**Phase speed = 24 m/s**  
**73% of  $\vec{V}_T$**

**Phase speed = 23 m/s**  
**64% of  $\vec{V}_T$**

**Phase speed = 20 m/s**  
**53% of  $\vec{V}_T$**

**Phase speed = 31 m/s**  
**81% of  $\vec{V}_T$**

$$\omega = n\bar{\Omega} + \frac{n \bar{\xi}}{R \bar{q}} \frac{\frac{\partial \bar{q}}{\partial r}}{[k^2 + n^2 / R^2 + (\bar{\eta} \bar{\xi} m^2) / N^2]}$$

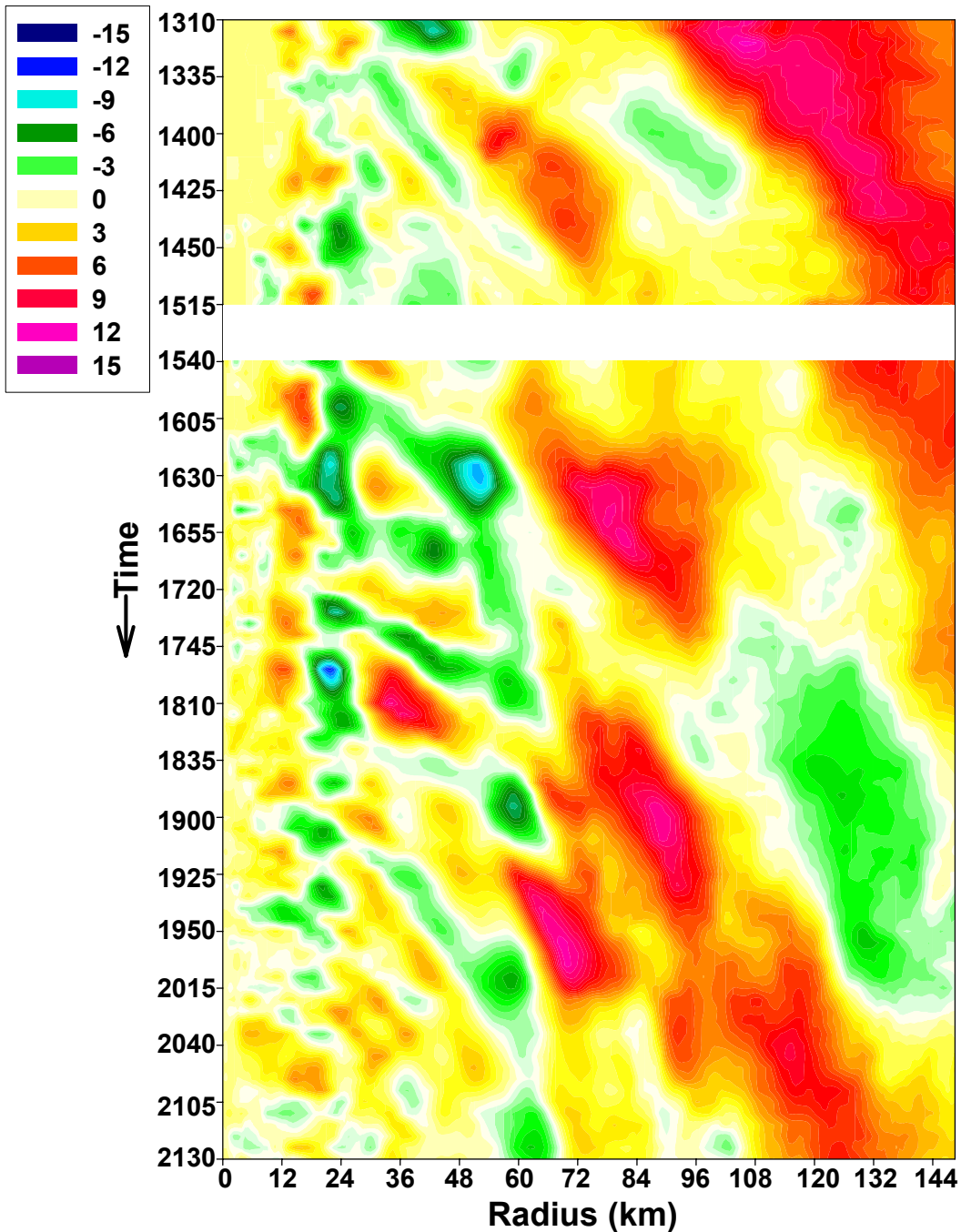
The azimuthal phase speed is  $C_\lambda = \omega R/n$

Neglect horizontal variations in static stability and assume

$$\frac{1}{\bar{q}} \frac{\partial \bar{q}}{\partial r} \approx \frac{1}{\bar{\eta}} \frac{\partial \bar{\eta}}{\partial r}$$

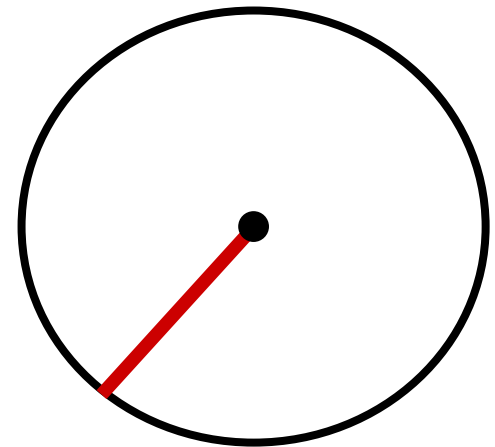
Estimate all quantities from the reconnaissance flight data and Fourier decomposed reflectivity, except for  $N^2$  and  $m$  which we take from Chen and Yau (2001) and Wang (2002)

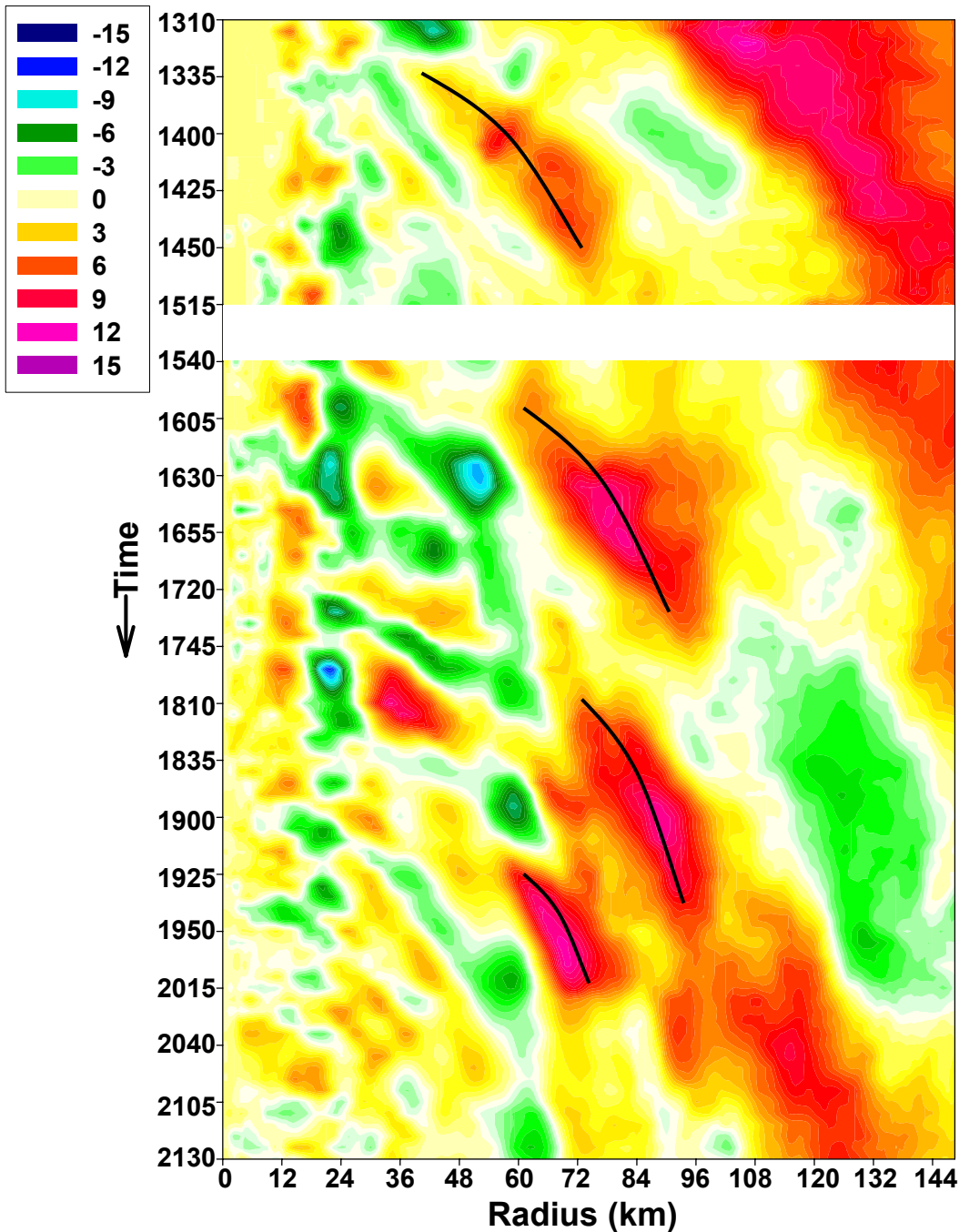
For the second rainband  $C_\lambda = 26 \text{ m/s}$ , nearly equal to the  $23 \text{ m/s}$  deduced from the azimuth-time Hovmöller



# Radius-Time Hovmöller of Wavenumber Two Reflectivity

Azimuth shown is a  
radial to the southwest  
of the center



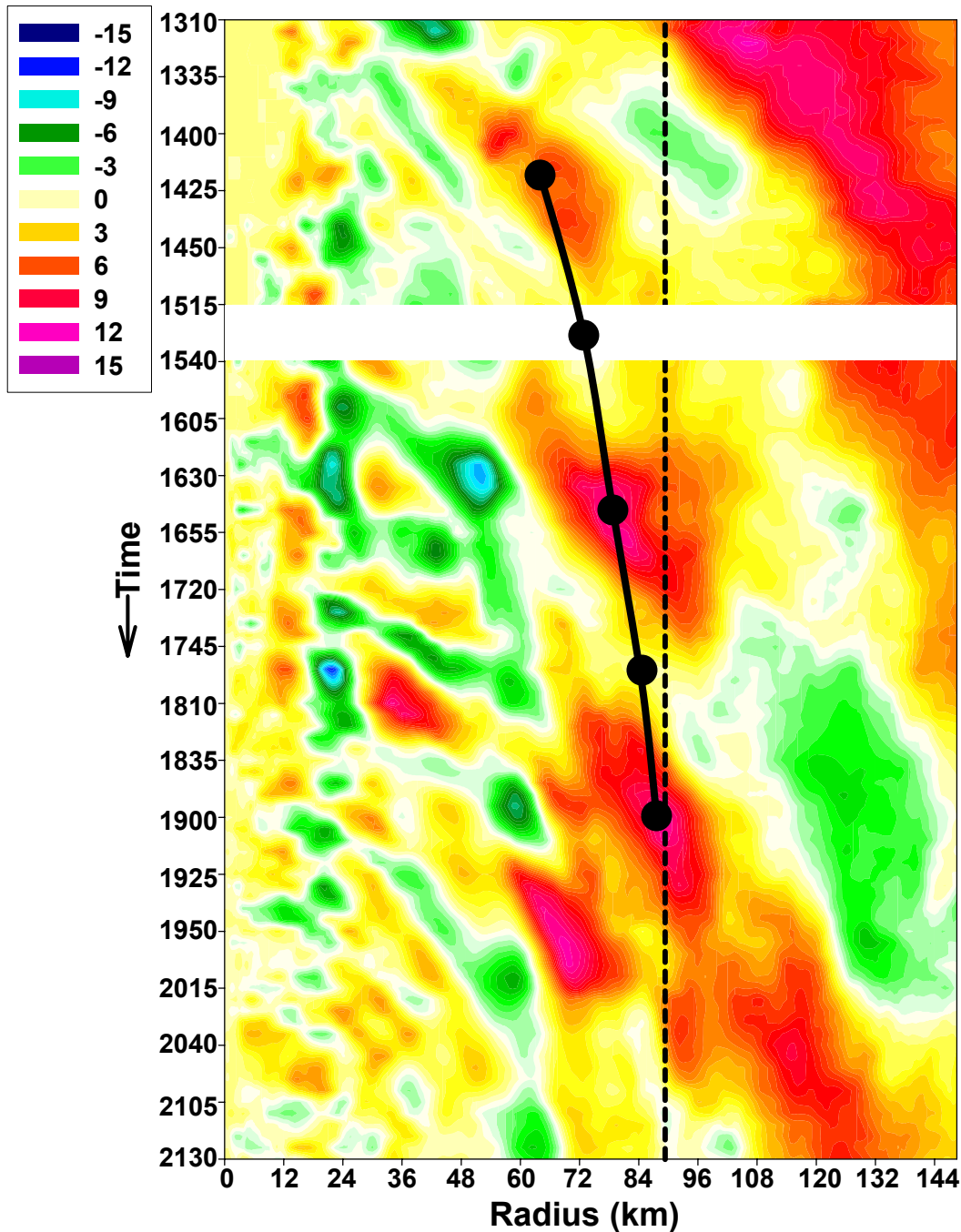


As the waves propagate outward, they are continuously thinned by the shear of the angular velocity, increasing their radial wavenumber  $k$

Radial phase speed is

$$C_r = \omega/k$$

For the second rainband at  $R = 80$  km,  $C_r = 7.2$  m/s, close to the 5.4 m/s estimated from the Hovmöller



Evidence of a radius at which the outward radial group velocity of the waves ceased

Group velocity  $\sim O(k^{-3})$

Phase speed  $\sim O(k^{-1})$

Stagnation radius of vortex Rossby waves  
 $\sim 3 \times \text{RMW}$

Tuttle and Gall (1995)  
 Montgomery and Kallenbach (1997)

## Summary:

- Elena was a disorganized category 2 hurricane of nearly steady intensity on 31 August
- Around 00 UTC 1 September, heights began to rapidly fall, winds increased, and upward vertical motion became concentrated within the developing eyewall leading to rapid intensification of the vortex
- During this period of rapid intensification, Elena's radial vorticity profile exhibited two concentric rings of high vorticity known to support two types of barotropic instability

## Summary:

- Four distinct peaks in wavenumber 2 power were associated with four outward and cyclonically propagating rainbands that exhibited the properties of vortex Rossby waves
- The evolution of one of these peaks in wavenumber 2 closely resembled the realization of the Type II instability of Kossin et al. (2000)
- The other bands were noted to emanate from the asymmetric deep convection in the northern eyewall and may have been the result of the Type I instability or through the axisymmetrization of asymmetric, diabatically generated vorticity