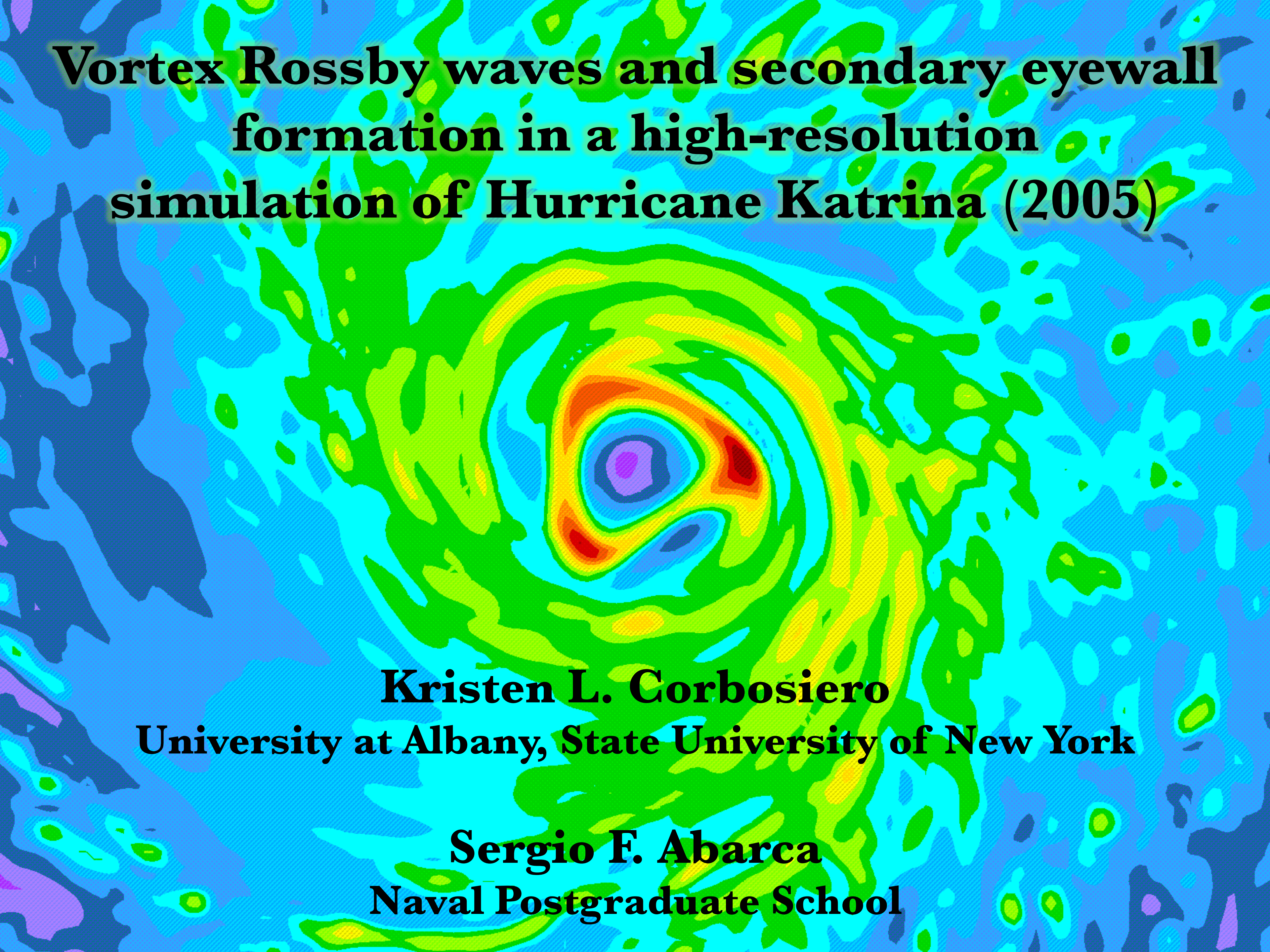
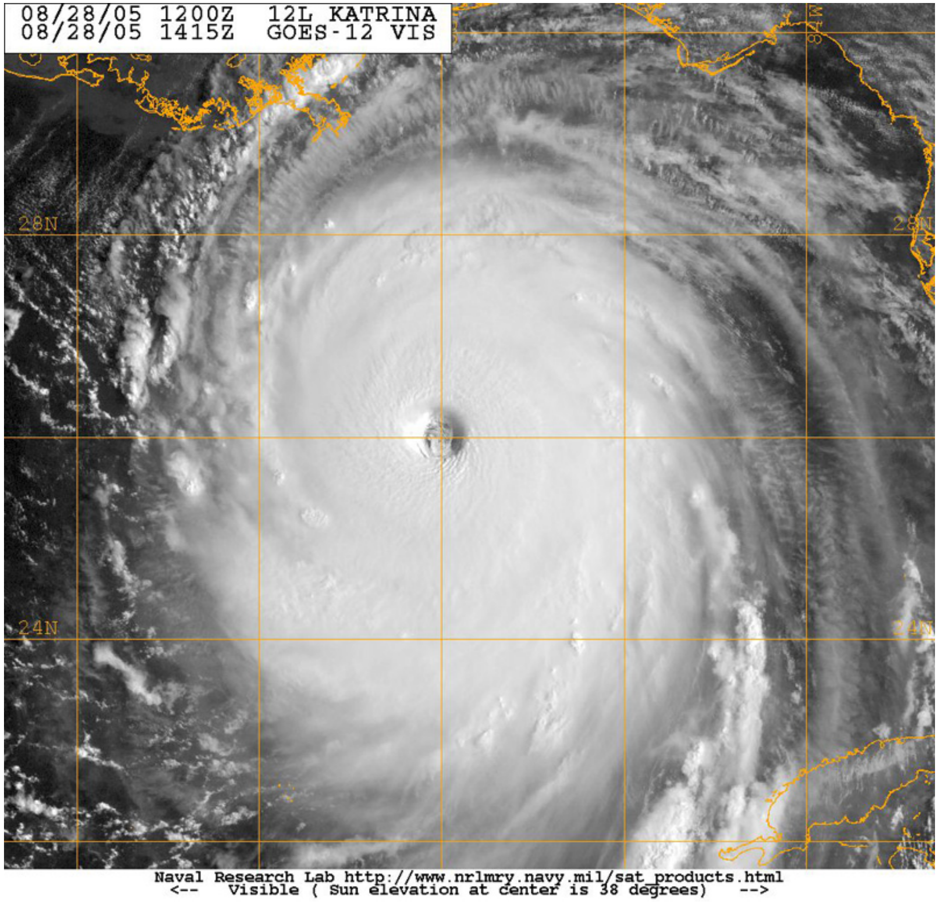
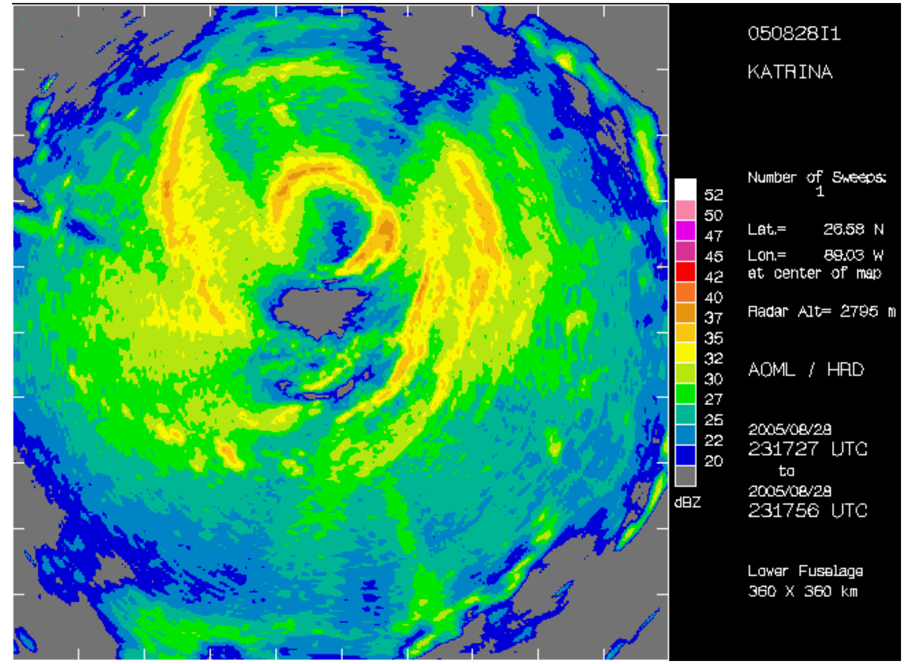


Vortex Rossby waves and secondary eyewall formation in a high-resolution simulation of Hurricane Katrina (2005)

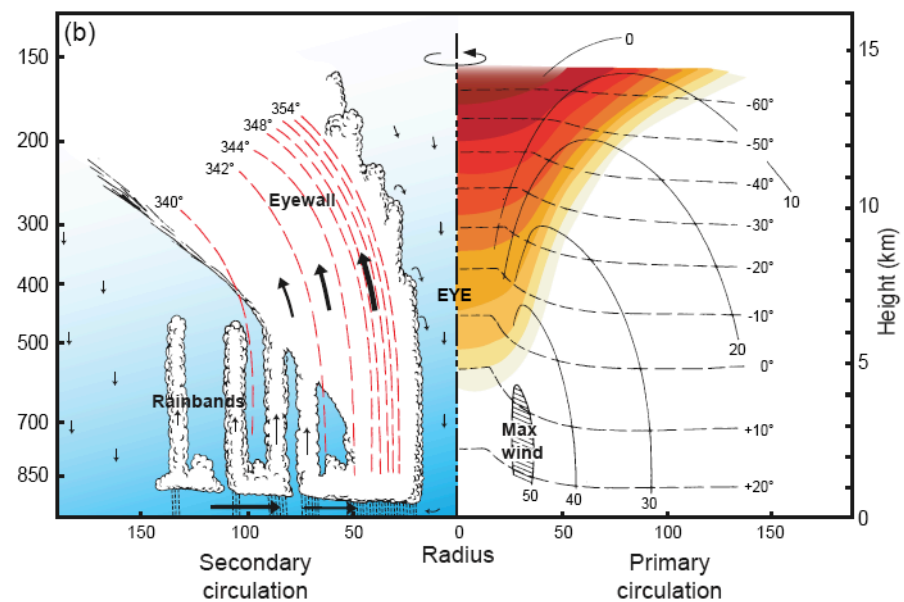
Kristen L. Corbosiero
University at Albany, State University of New York

Sergio F. Abarca
Naval Postgraduate School

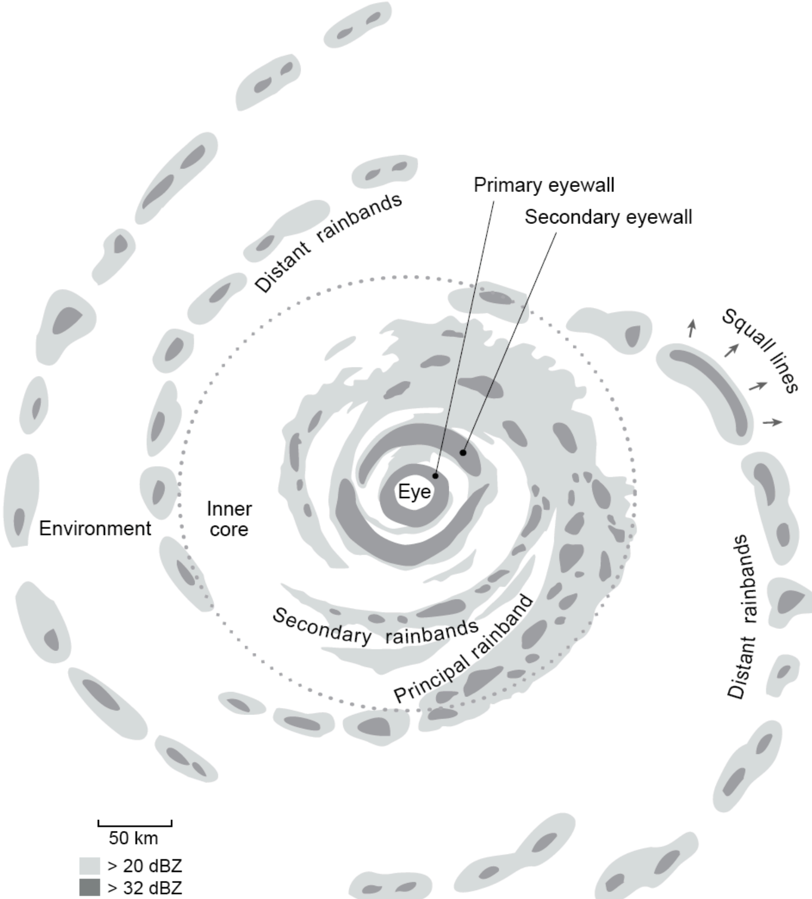




Tropical cyclones:
Structure, satellite and radar presentation

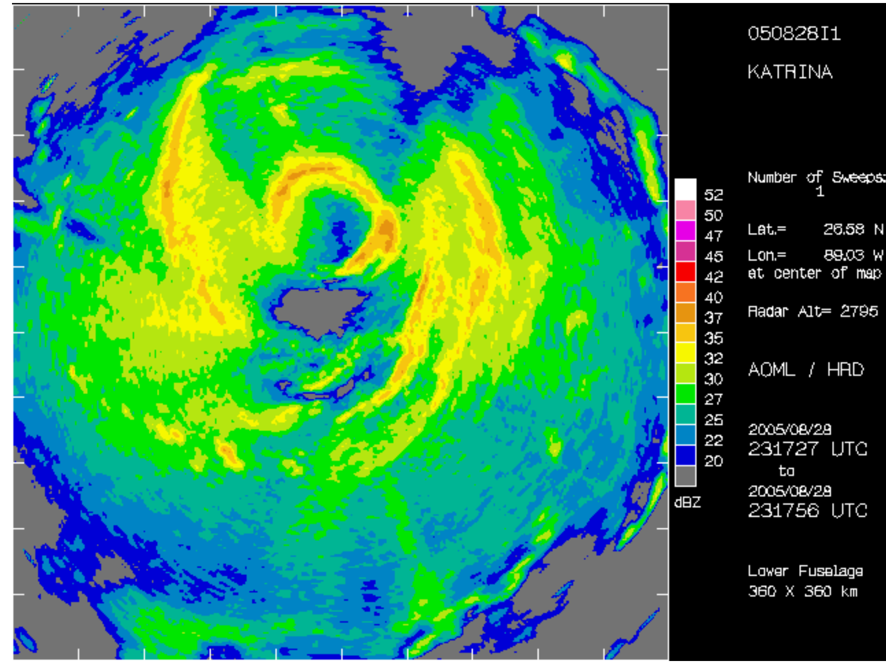


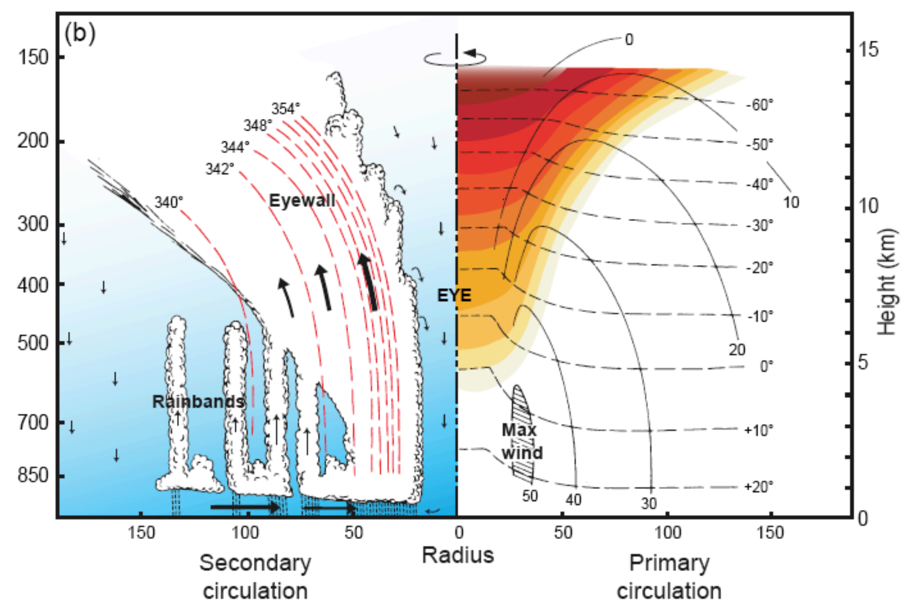
Houze (2010)



Tropical cyclones:

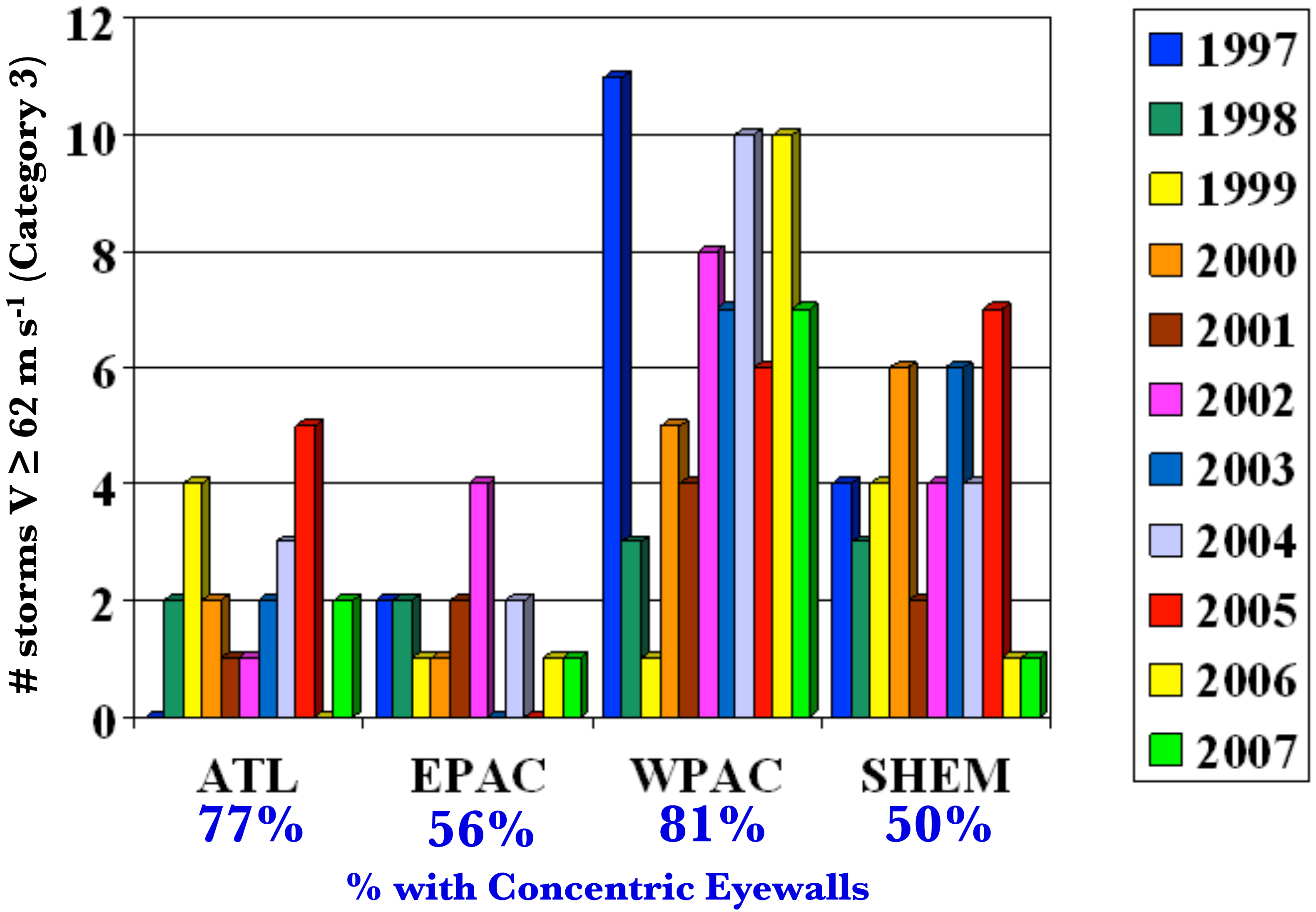
Structure, satellite and radar presentation





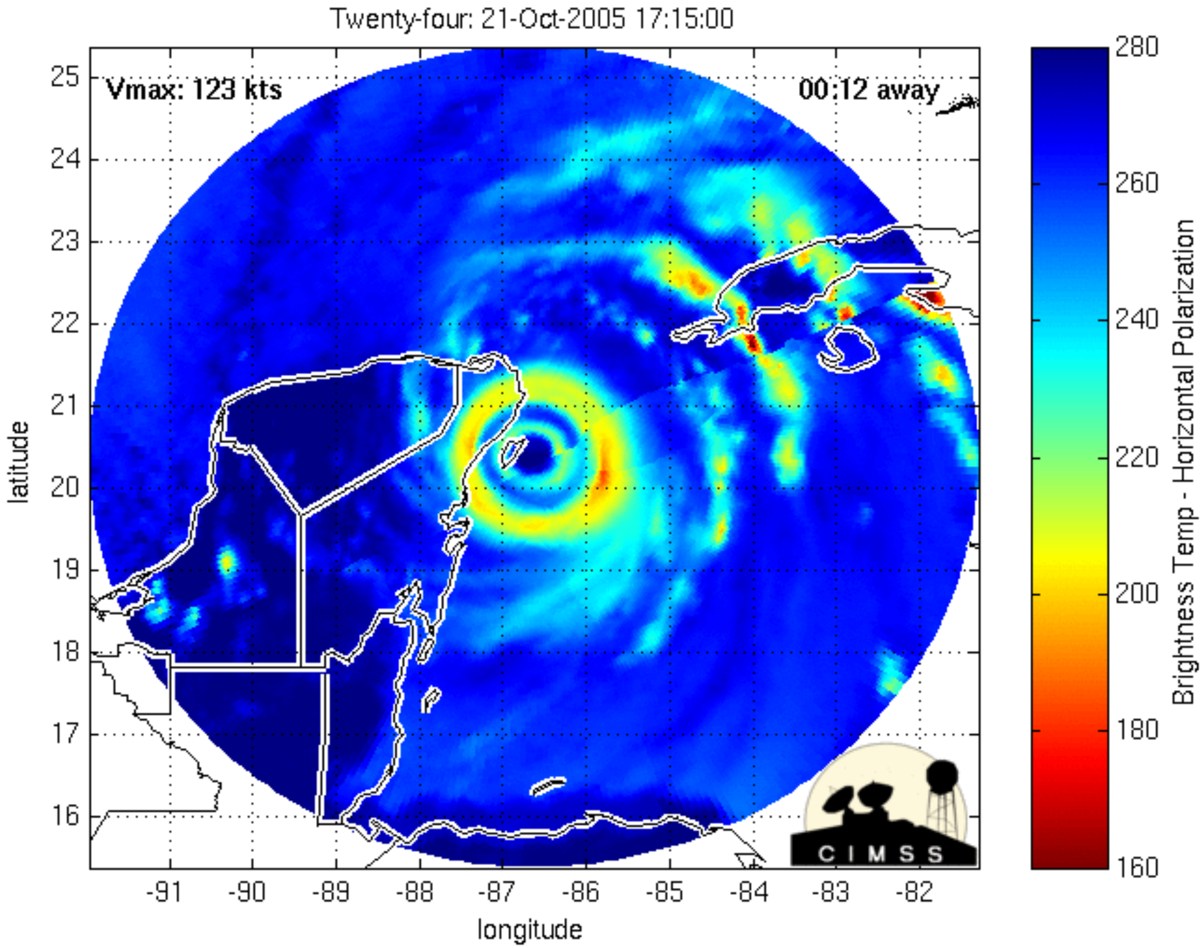
Houze (2010)

Secondary eyewalls are a common feature of intense hurricanes



Hawkins and Helveston (2008)

Hurricane Wilma (2005)

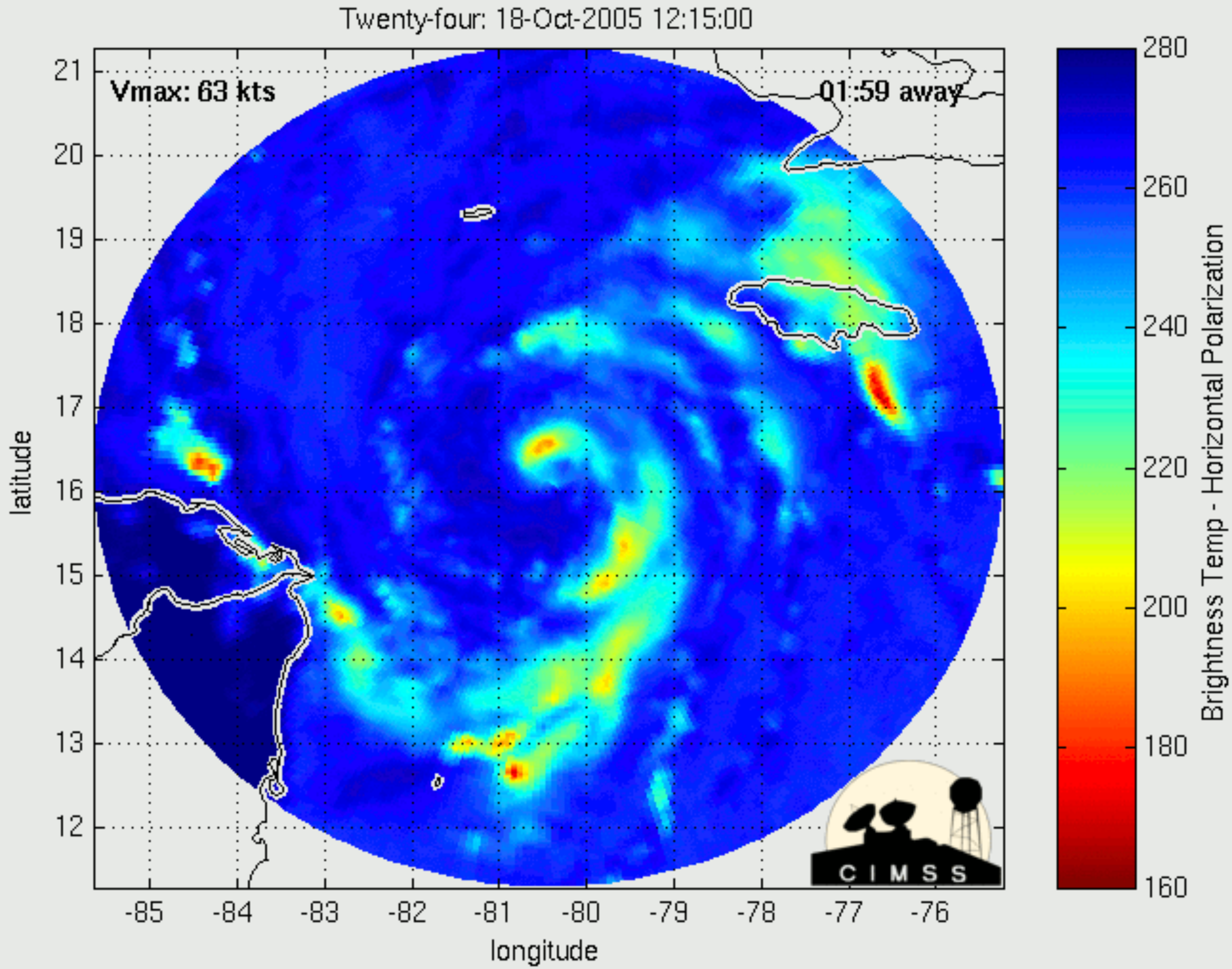


http://cimss.ssec.wisc.edu/tropic/real-time/marti/marti.html

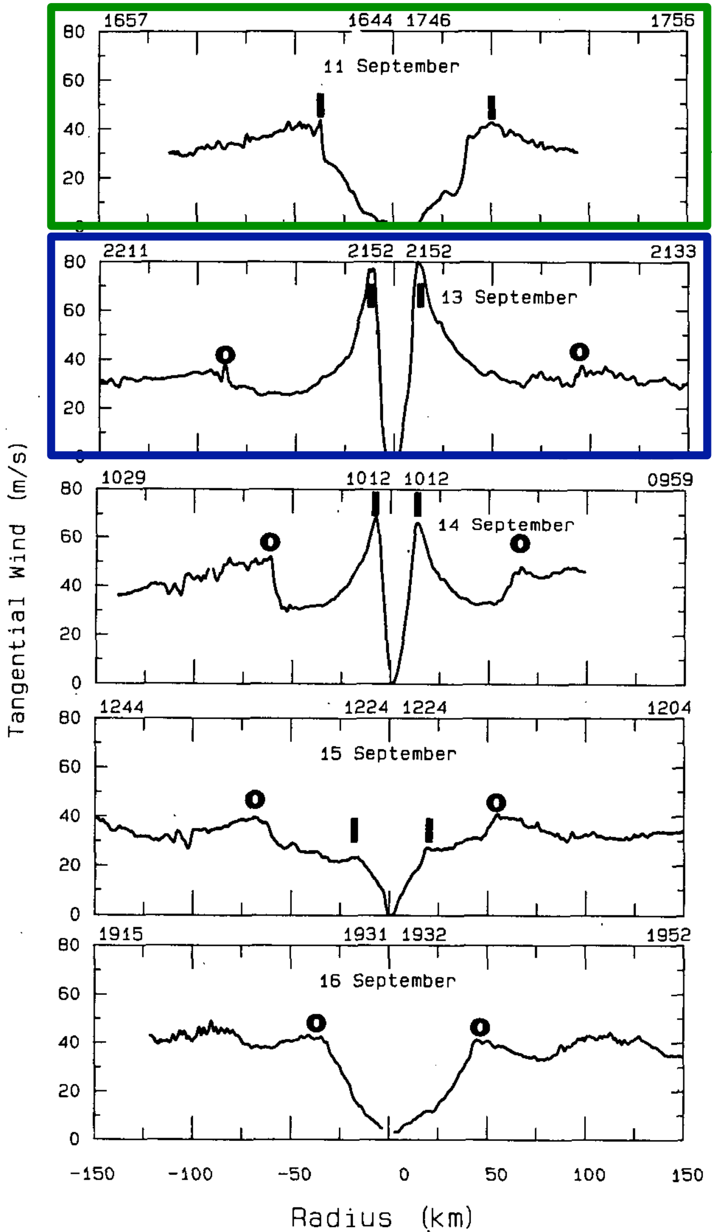
MIMIC

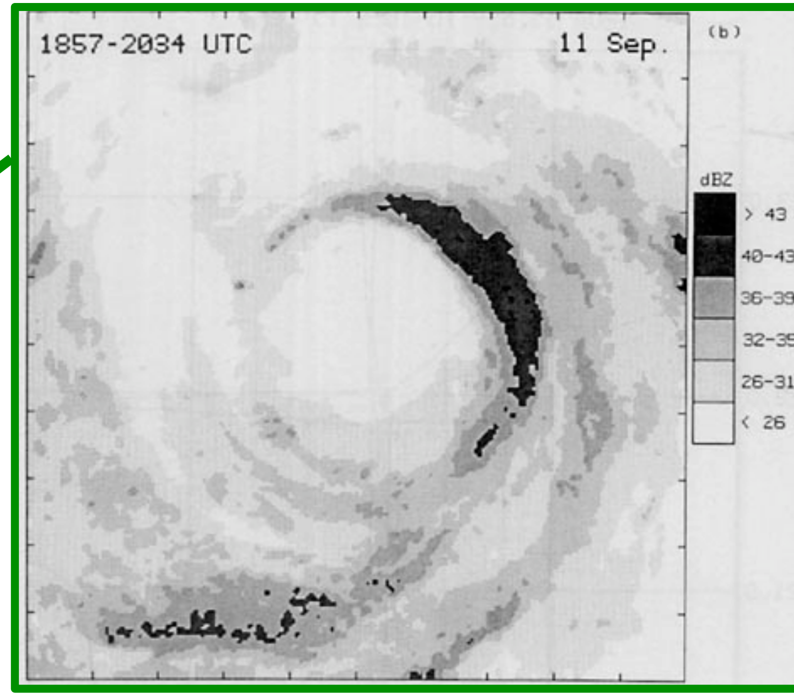
(Morphed Integrated Microwave Imagery at CIMSS)

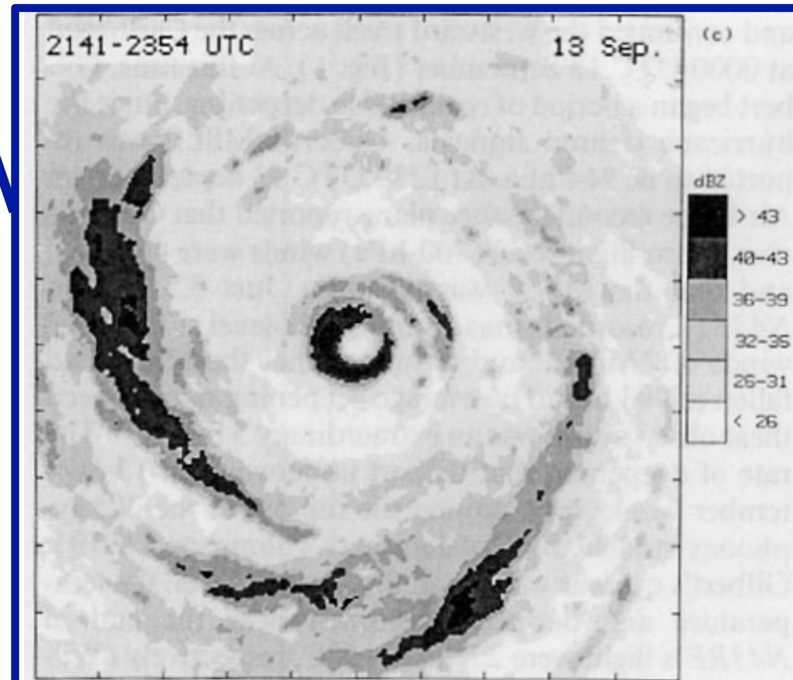
Blend of microwave satellite images


Twenty-four: 18-Oct-2005 12:15:00
Vmax: 63 kts
01:59 away
latitude
longitude
Brightness Temp - Horizontal Polarization
280
260
240
220
200
180
160
21
20
19
18
17
16
15
14
13
12
-85
-84
-83
-82
-81
-80
-79
-78
-77
-76
CIMSS

Gilbert (1988)

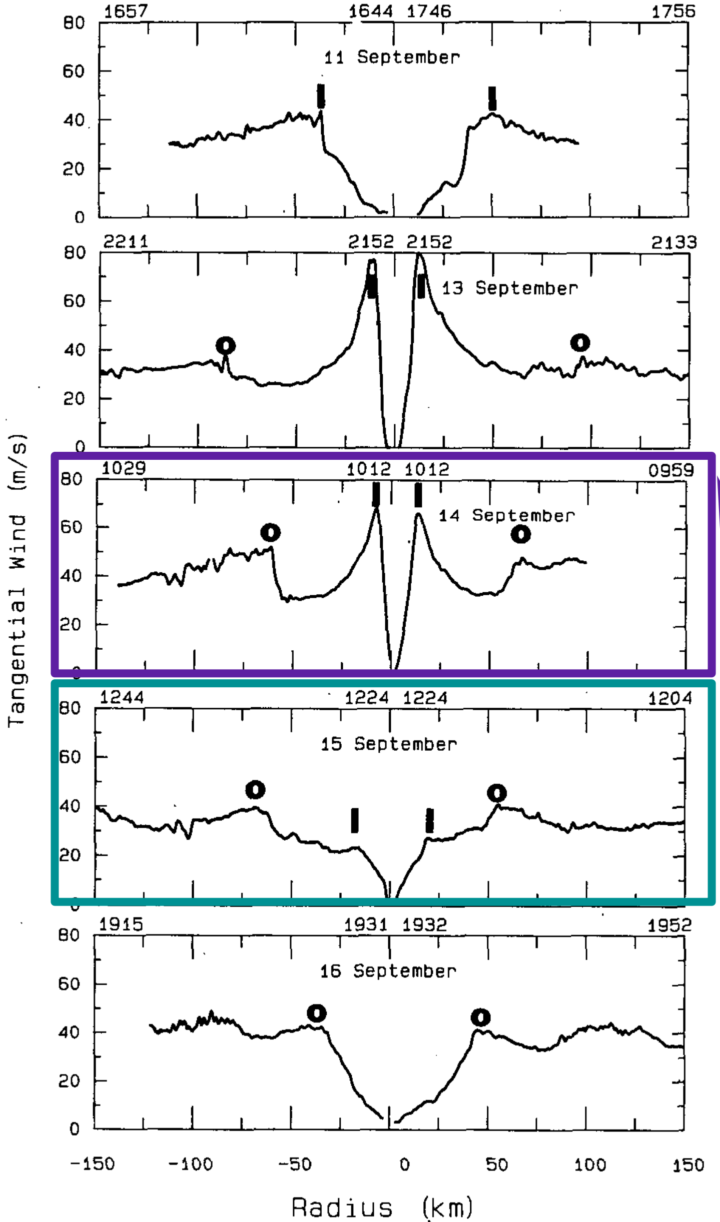


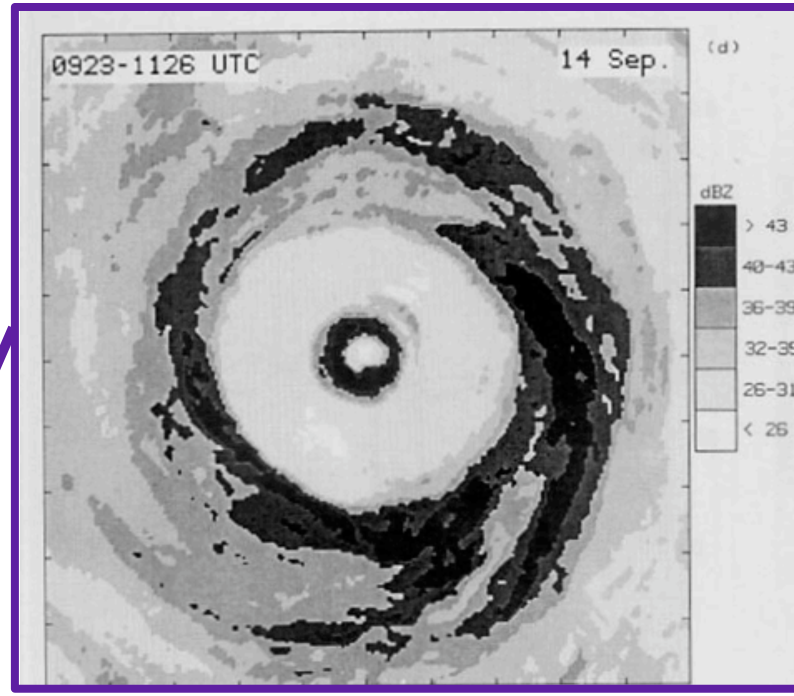


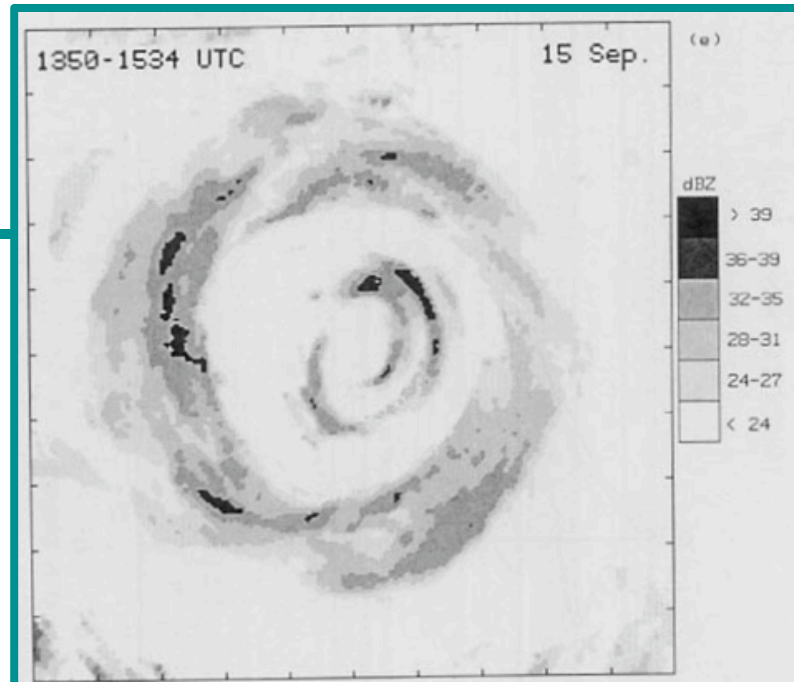


Black and Willoughby (1992)

Gilbert (1988)

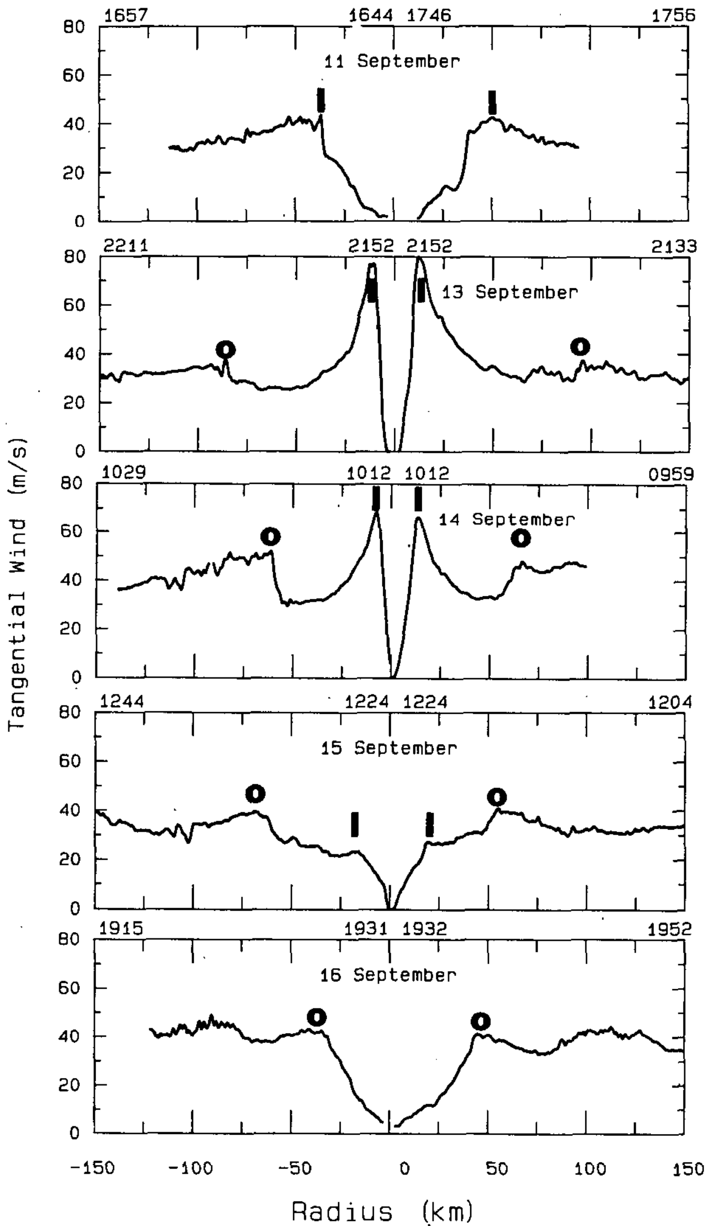




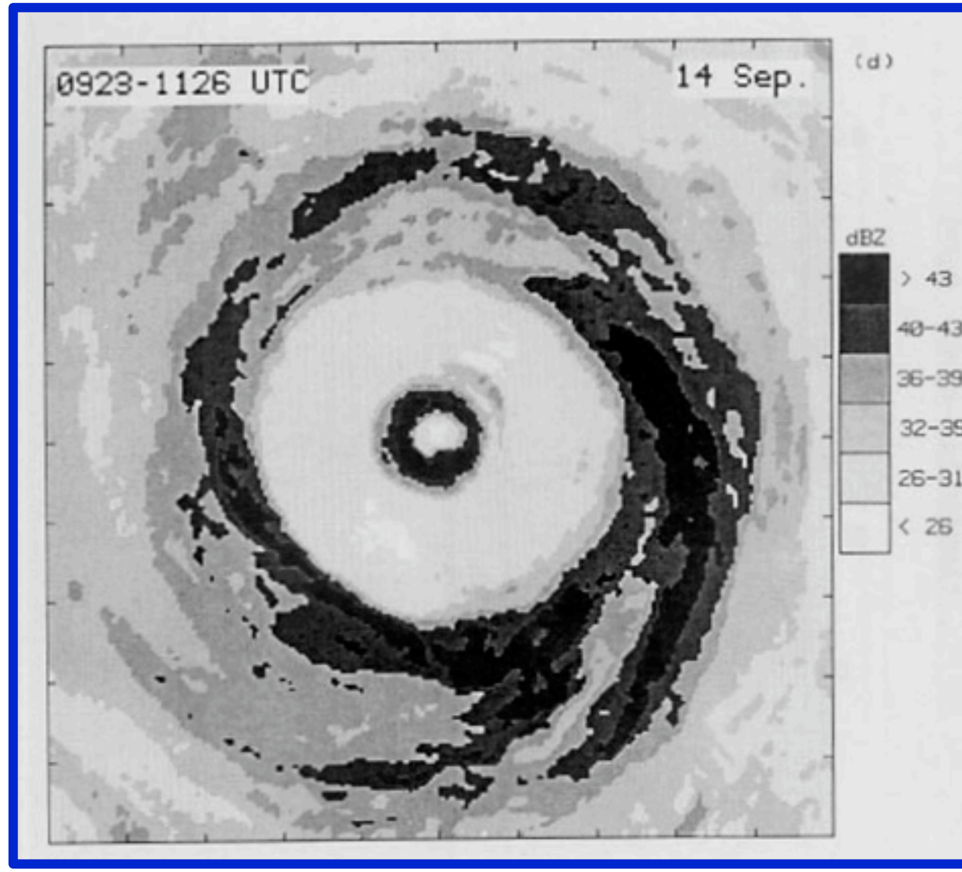


Black and Willoughby (1992)

Gilbert (1988)



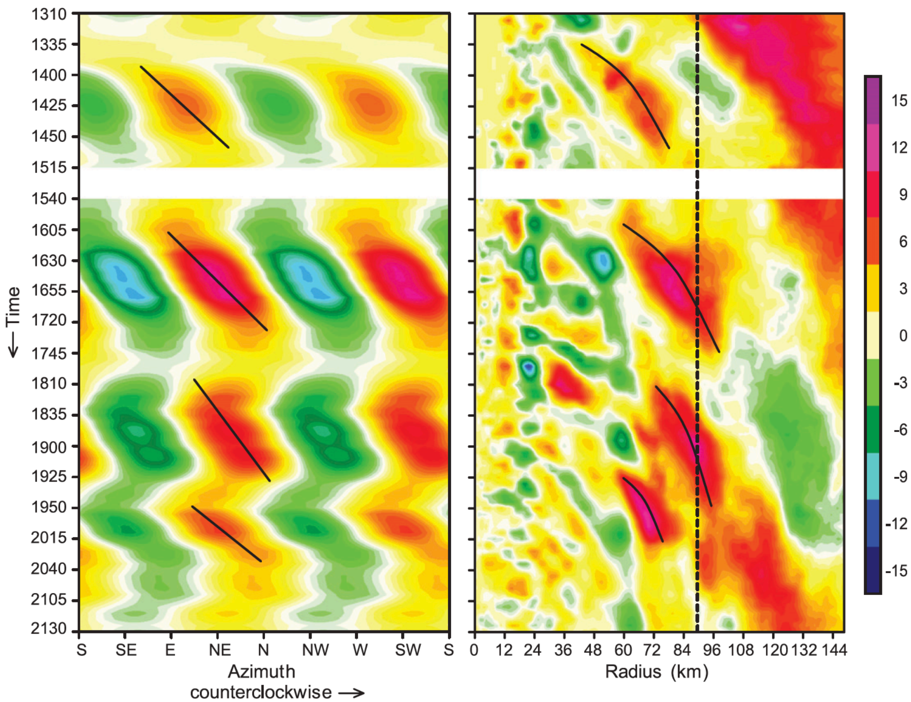
Black and Willoughby (1992)



The formation of a secondary eyewall is followed by an understood series of structural and intensity changes called an eyewall replacement cycle.

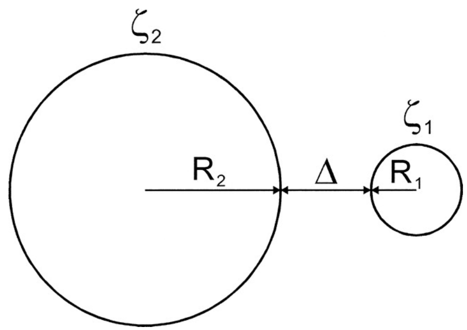
Secondary eyewall formation hypotheses: Internal dynamics

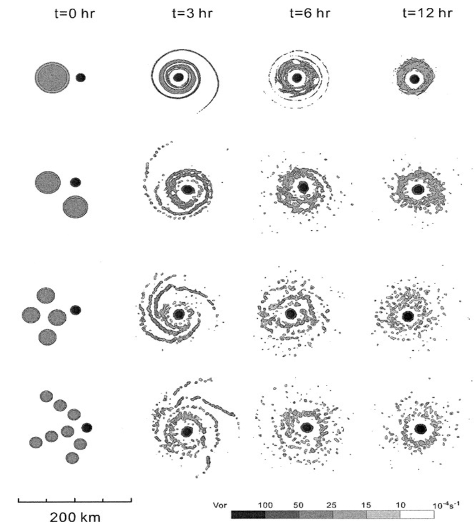
Vortex Rossby waves (VRWs)



Montgomery and Kallenbach (1997)
Camp and Montgomery (2001)
Corbosiero et al. (2005)

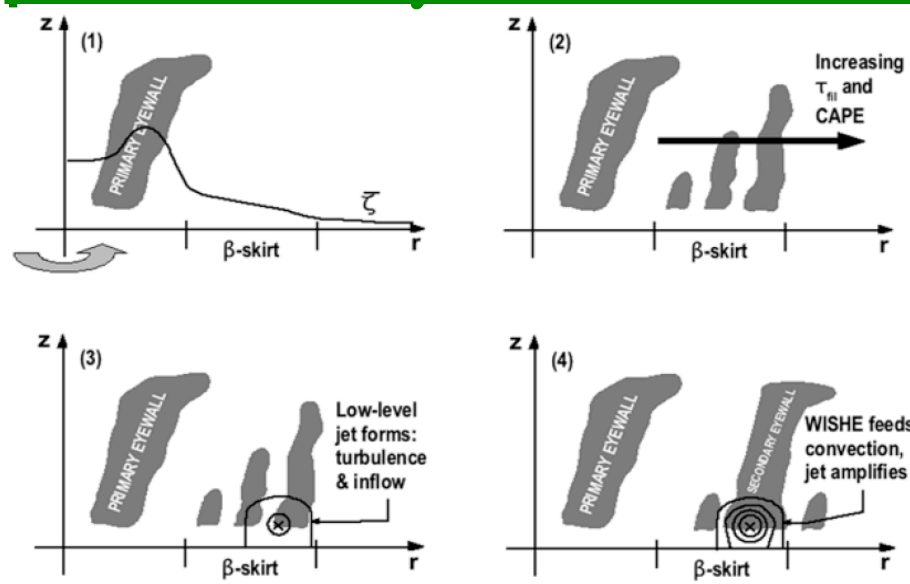
Barotropic vortex interactions





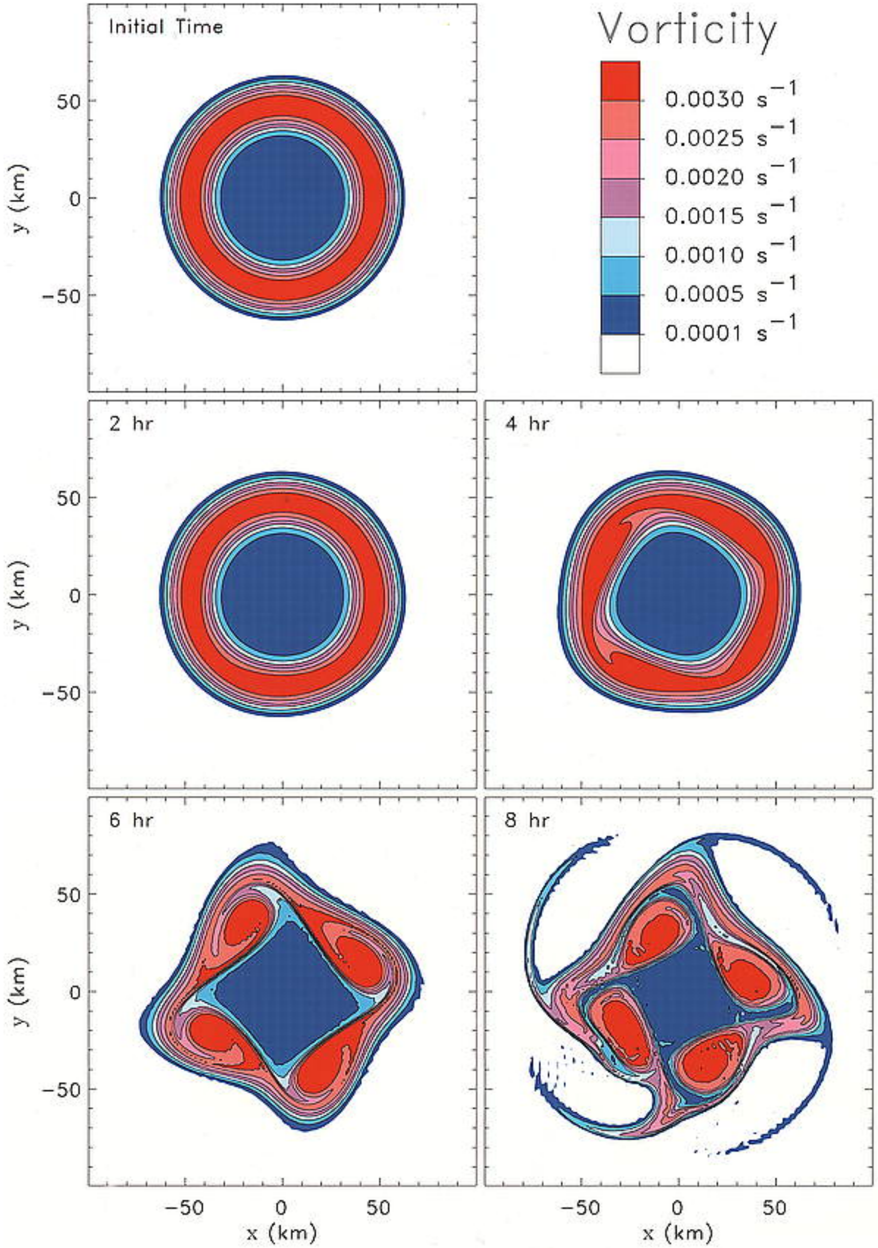
Kuo et al. (2004, 2008)

β-Skirt axisymmetrization

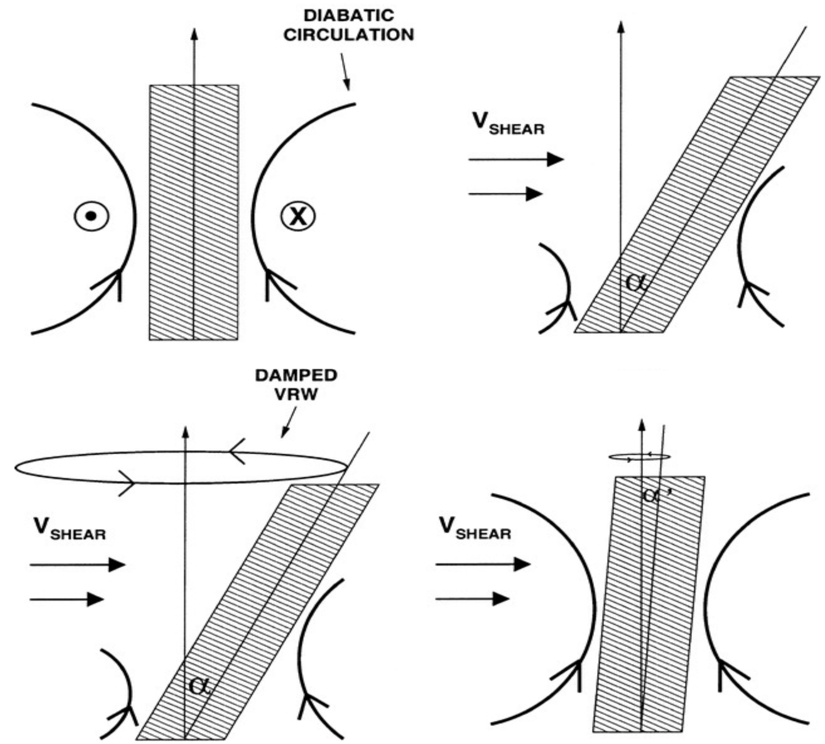


Terwey and Montgomery (2008)

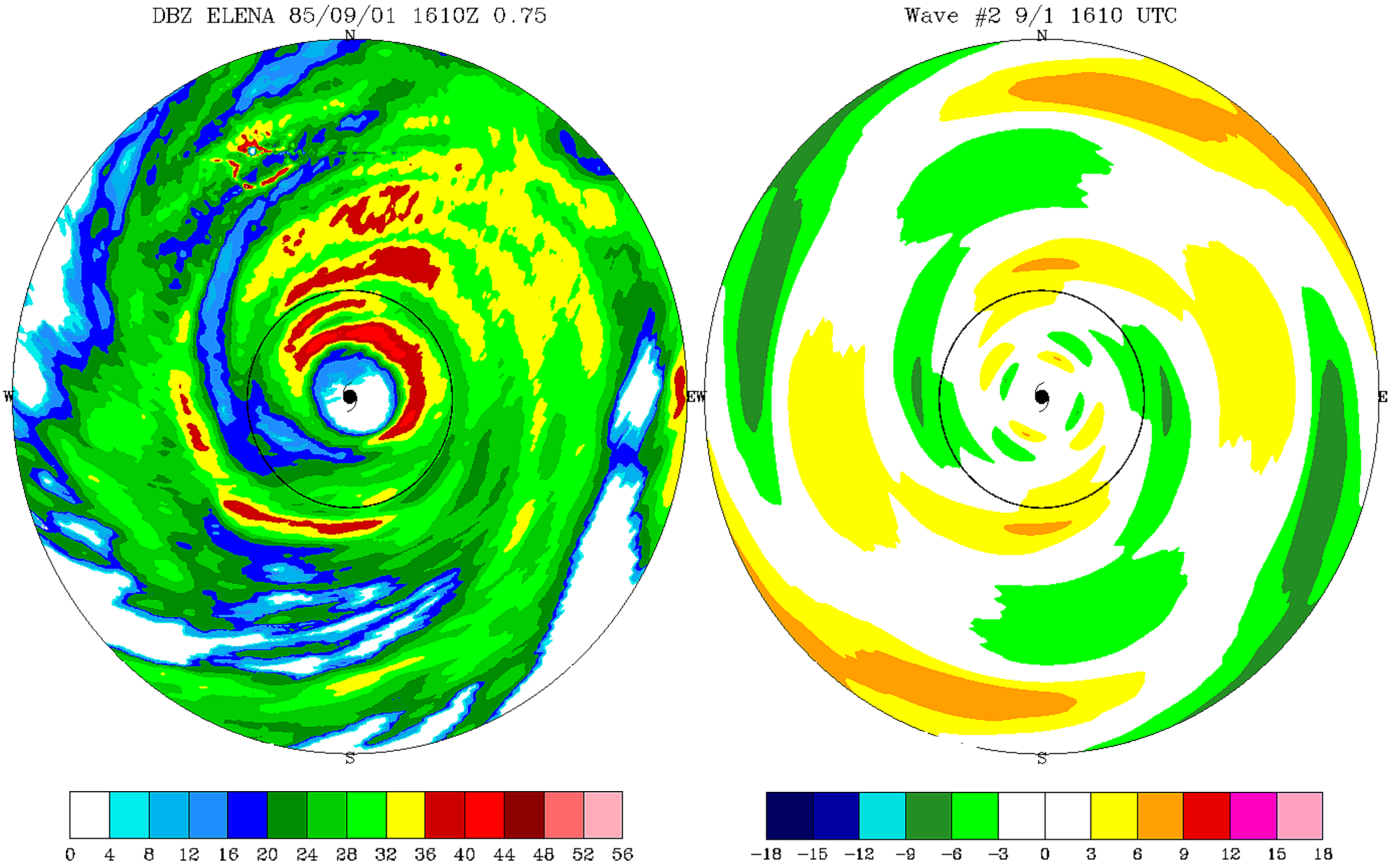
VRW generation mechanisms include barotropic instability in the eyewall and tilt induced by vertical wind shear

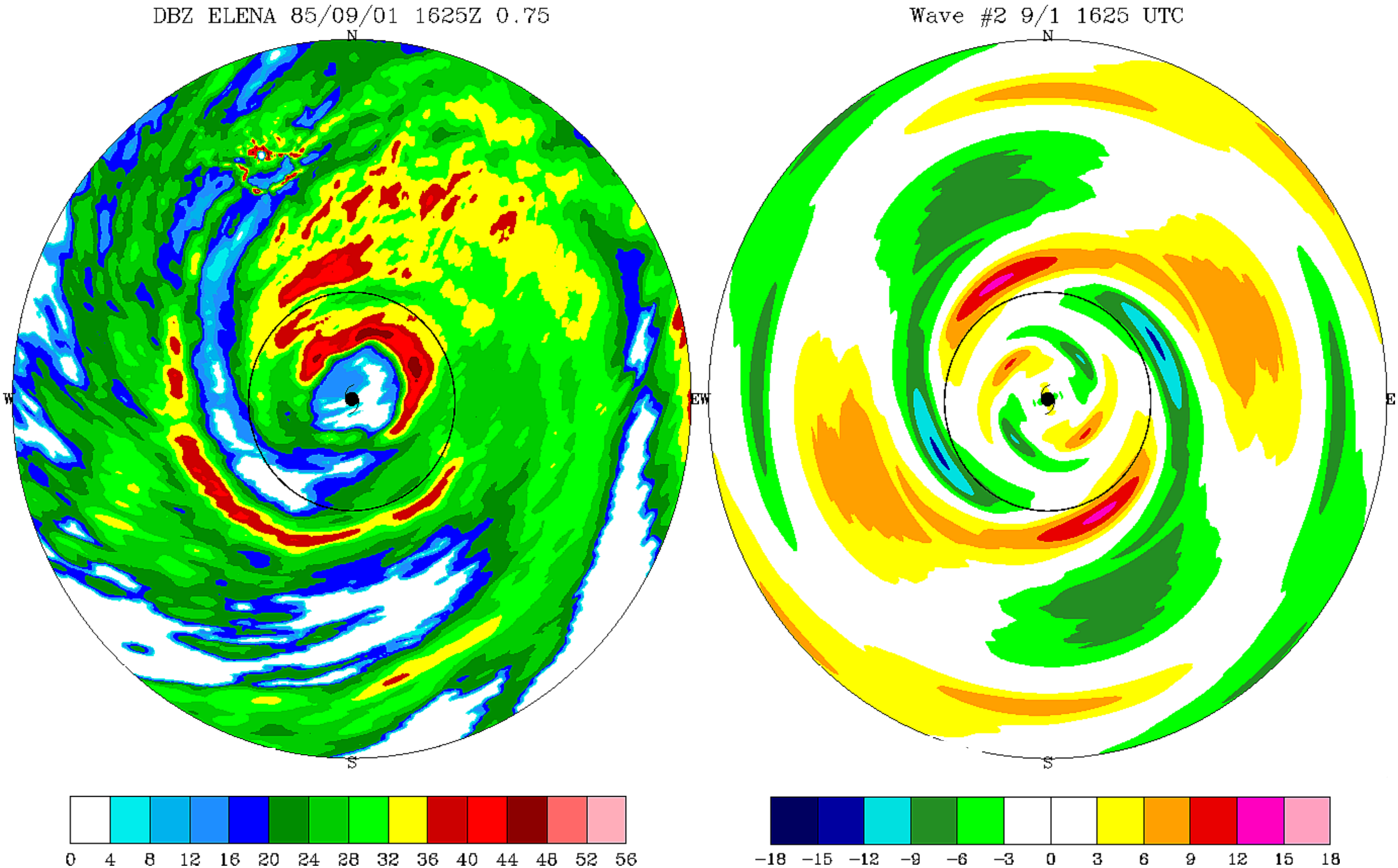


Schubert et al. (1999)



Reasor et al. (2004)


DBZ ELENA 85/09/01 1610Z 0.75
N
W
E
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
Wave #2 9/1 1610 UTC
N
W
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18


DBZ ELENA 85/09/01 1625Z 0.75
N
W
E
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
Wave #2 9/1 1625 UTC
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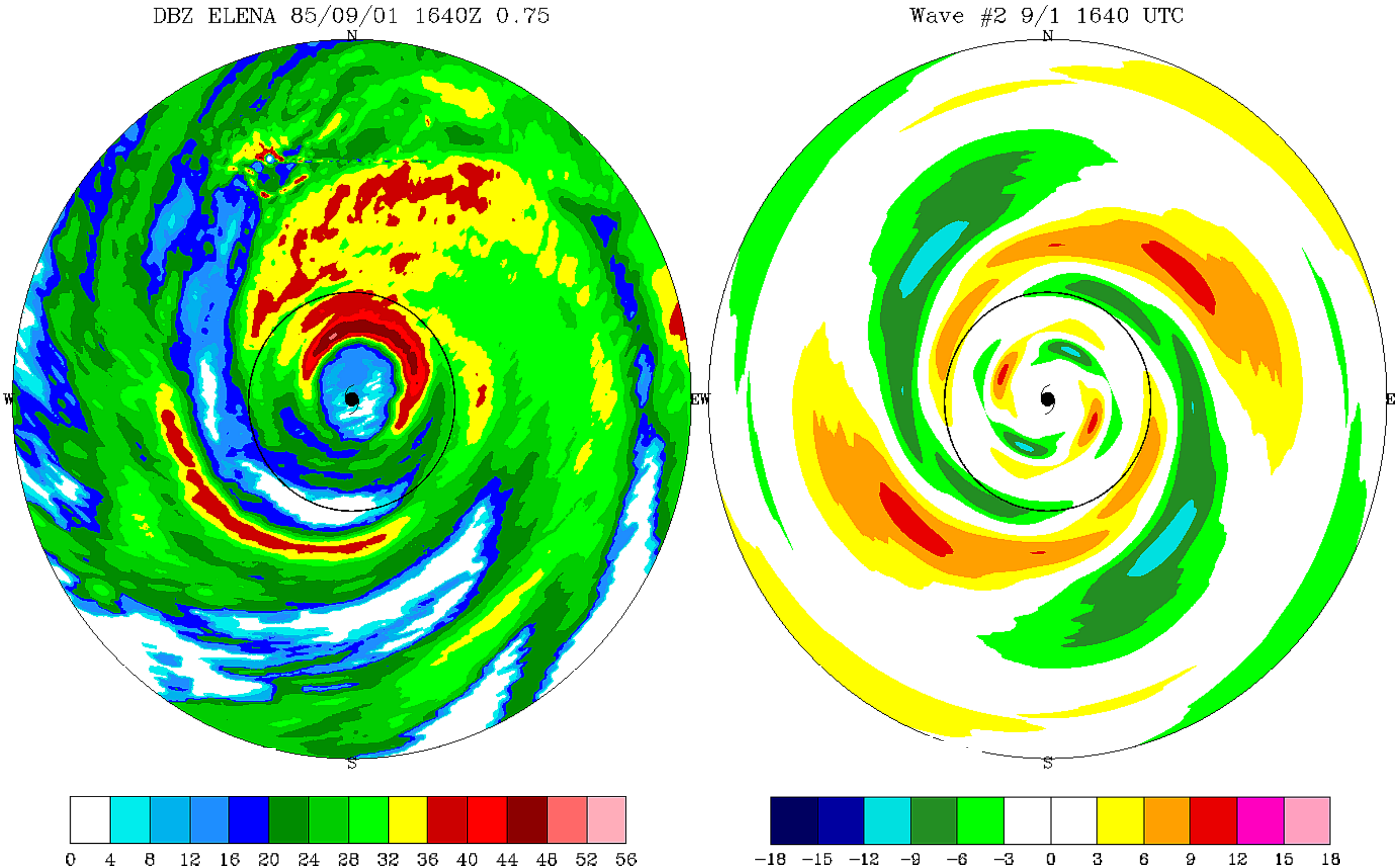
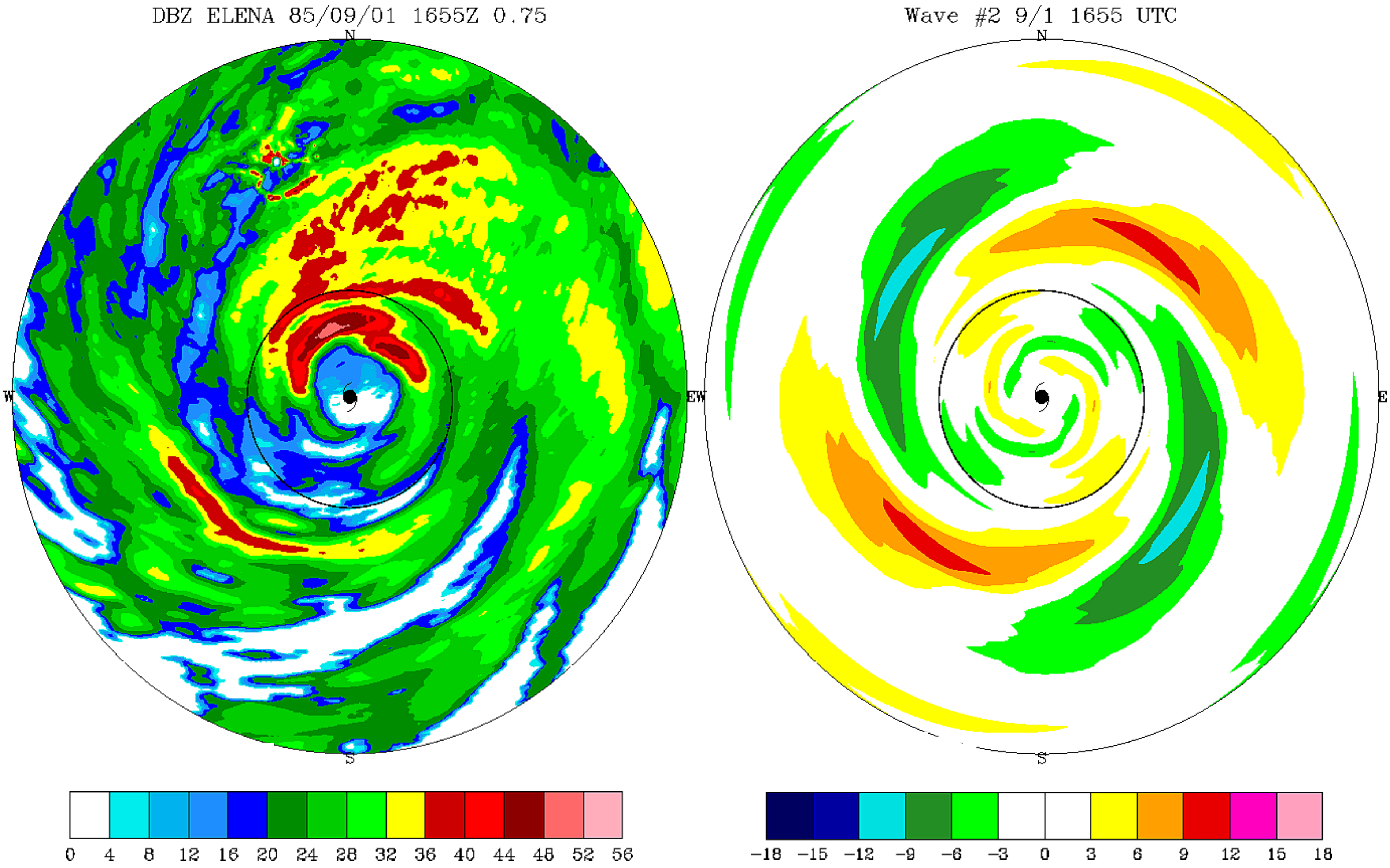
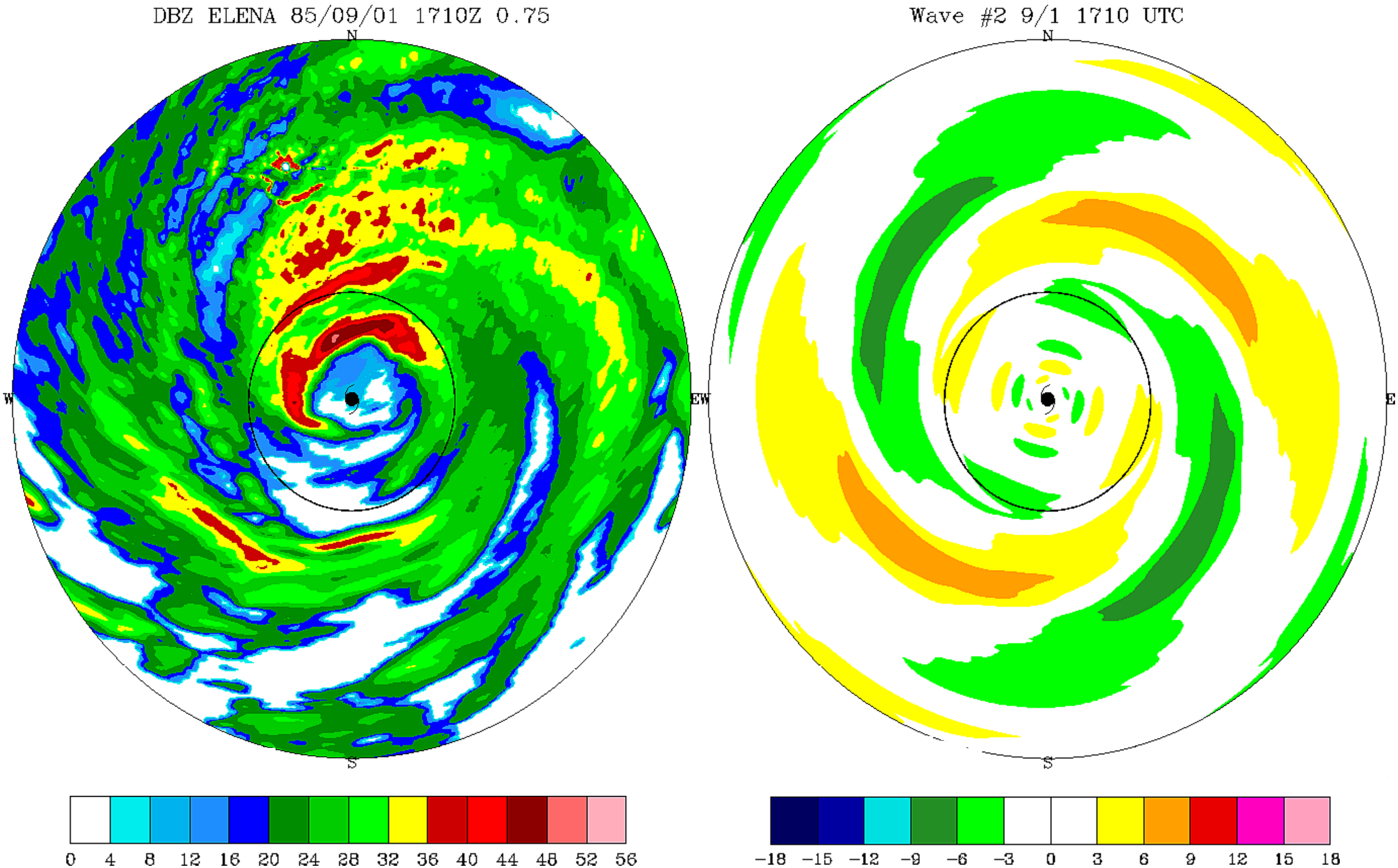
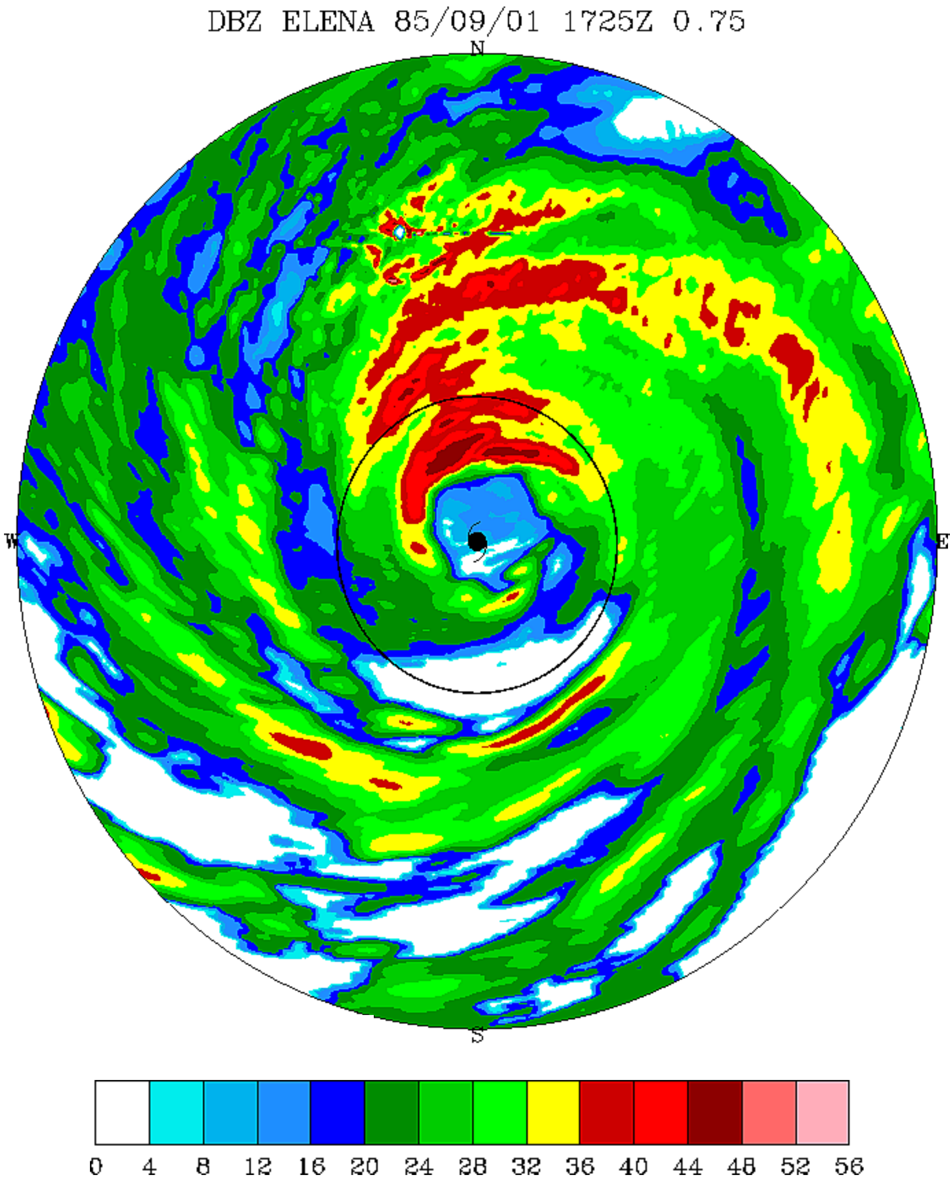
W
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18

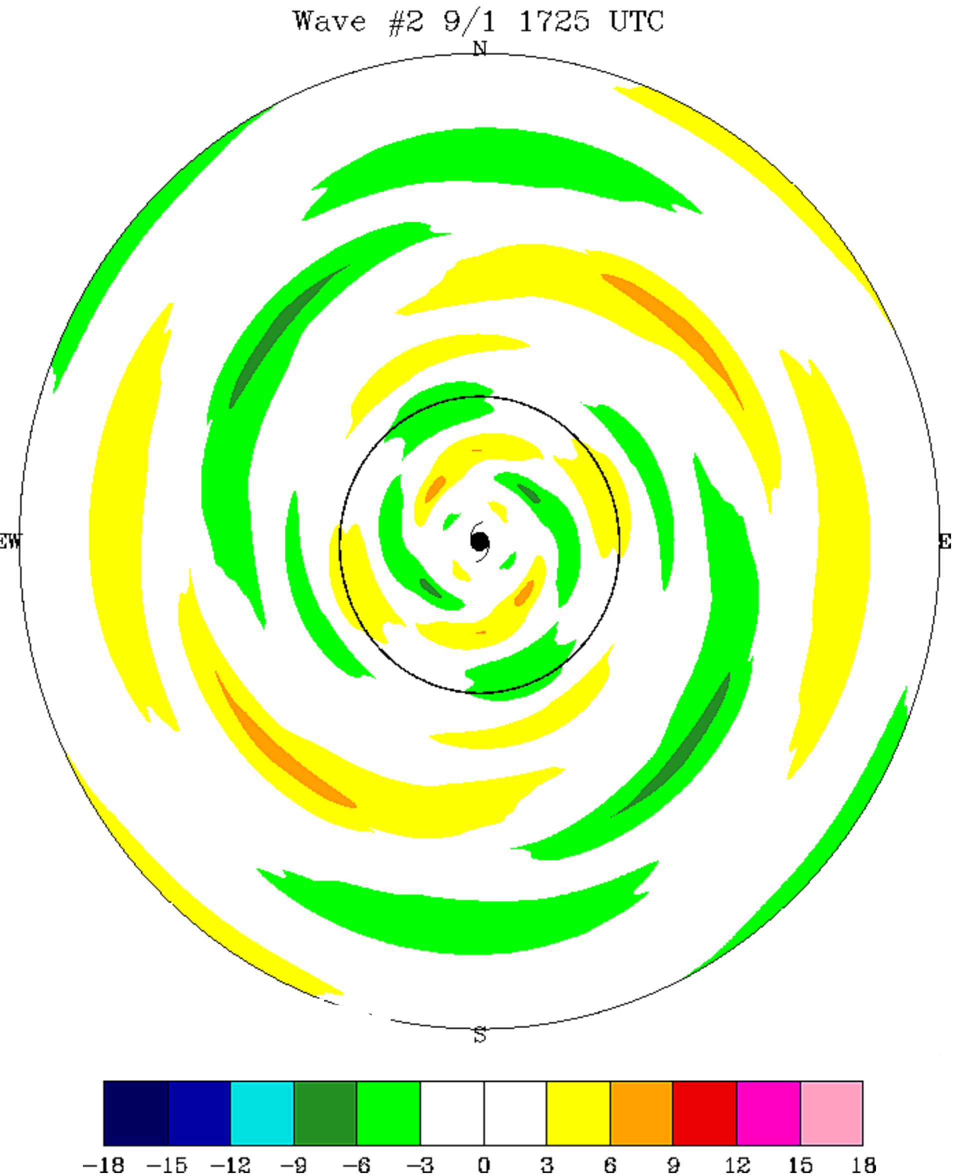


DBZ ELENA 85/09/01 1640Z 0.75
N
W
E
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
Wave #2 9/1 1640 UTC
N
W
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18


DBZ ELENA 85/09/01 1655Z 0.75
N
W
EW
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
Wave #2 9/1 1655 UTC
N
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18

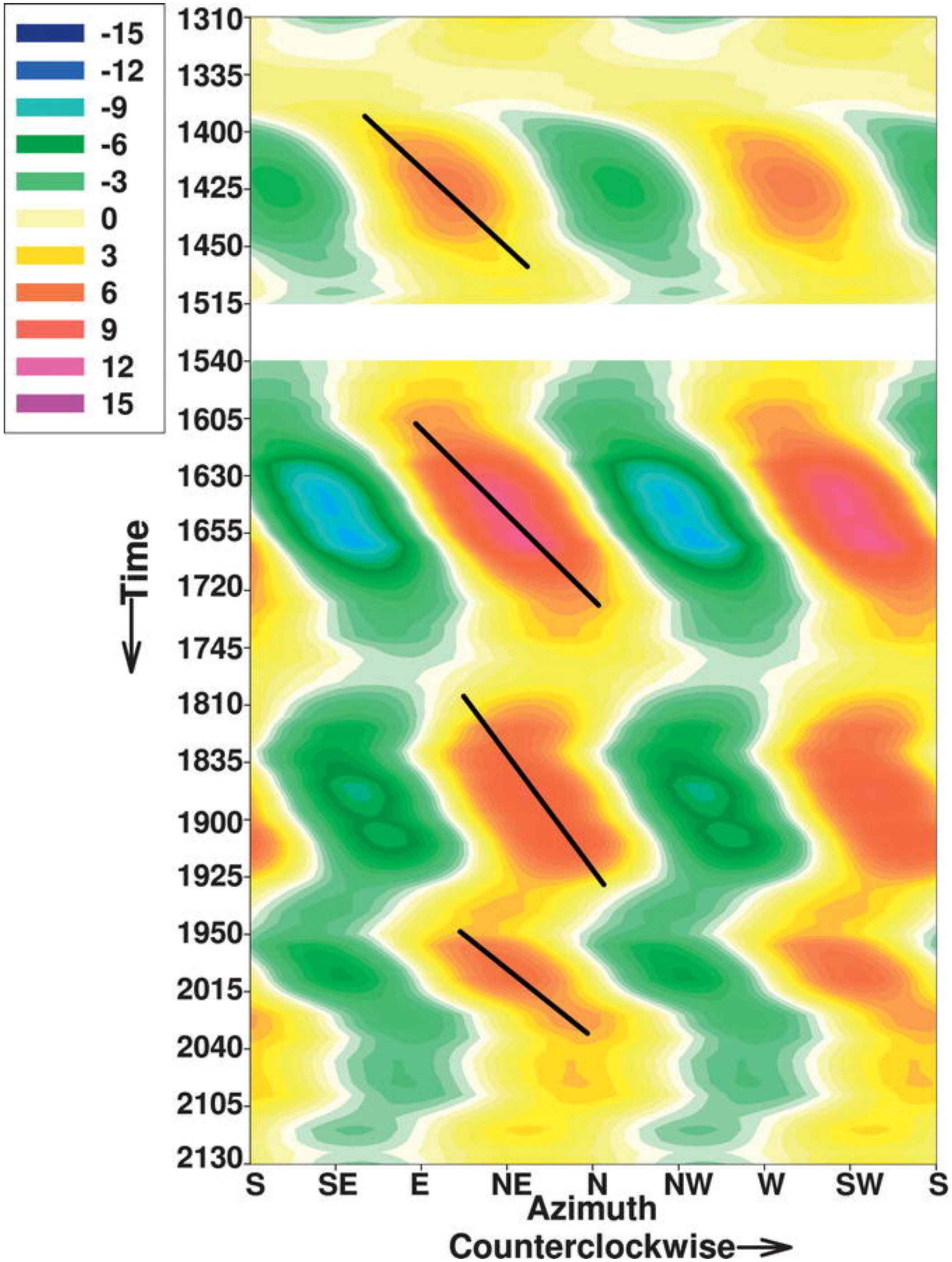

DBZ ELENA 85/09/01 1710Z 0.75
N
W
E
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
Wave #2 9/1 1710 UTC
N
W
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18

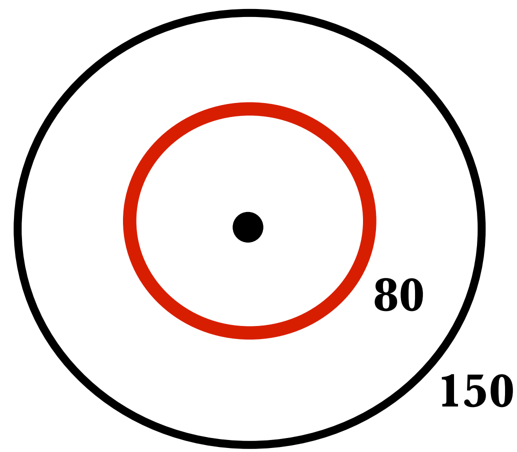

DBZ ELENA 85/09/01 1725Z 0.75
N
W
E
S
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56


Wave #2 9/1 1725 UTC
N
W
E
S
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18

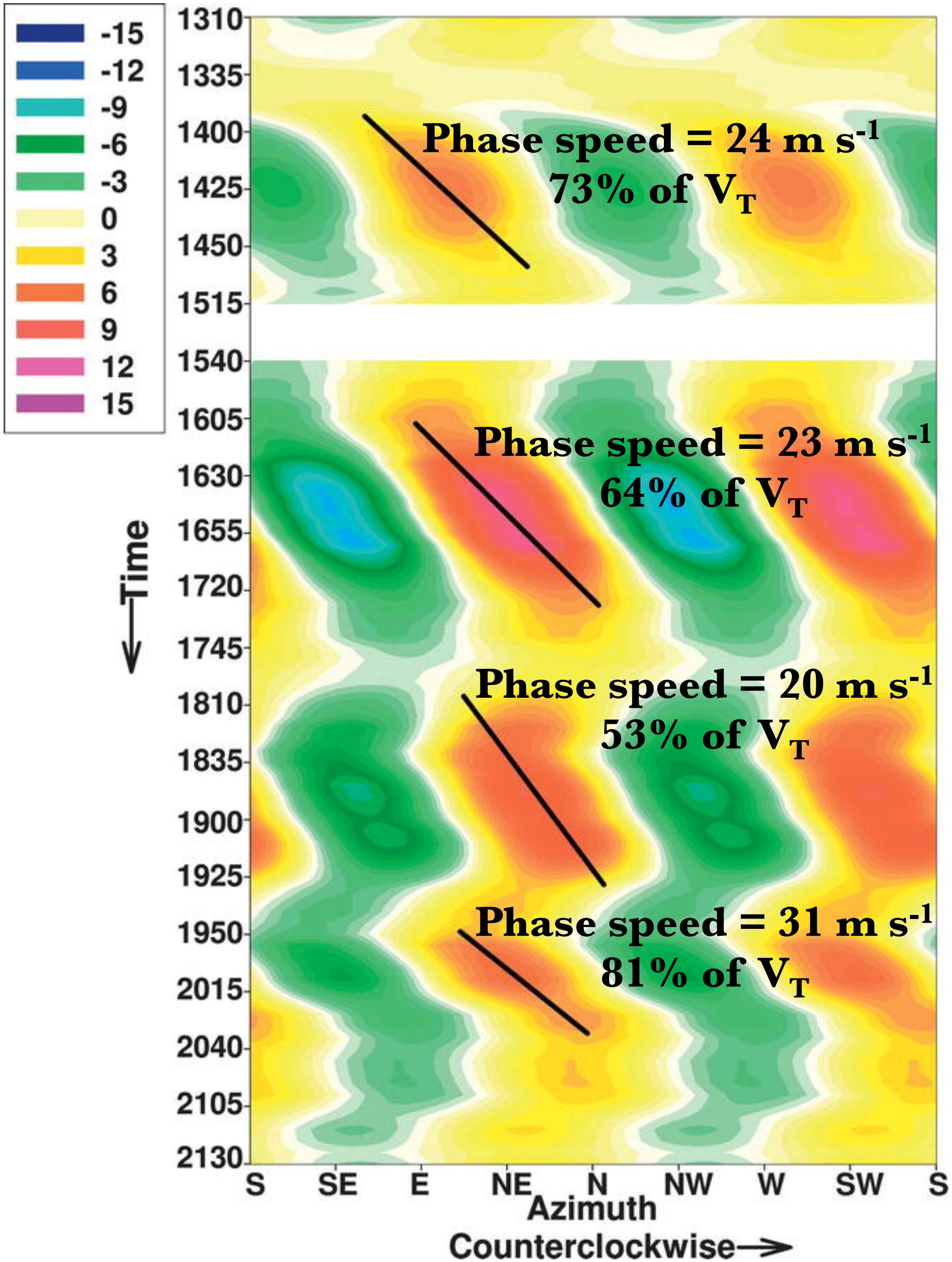
Elena (1985)

Azimuth-time Hovmöller Wavenumber 2 Reflectivity



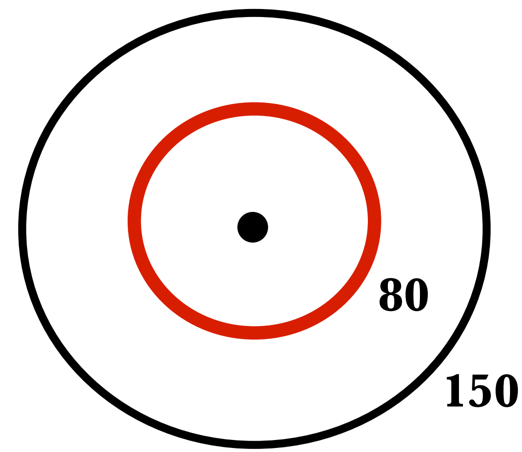


Corbosiero et al. (2006)



Elena (1985)

Azimuth-time Hovmöller Wavenumber 2 Reflectivity



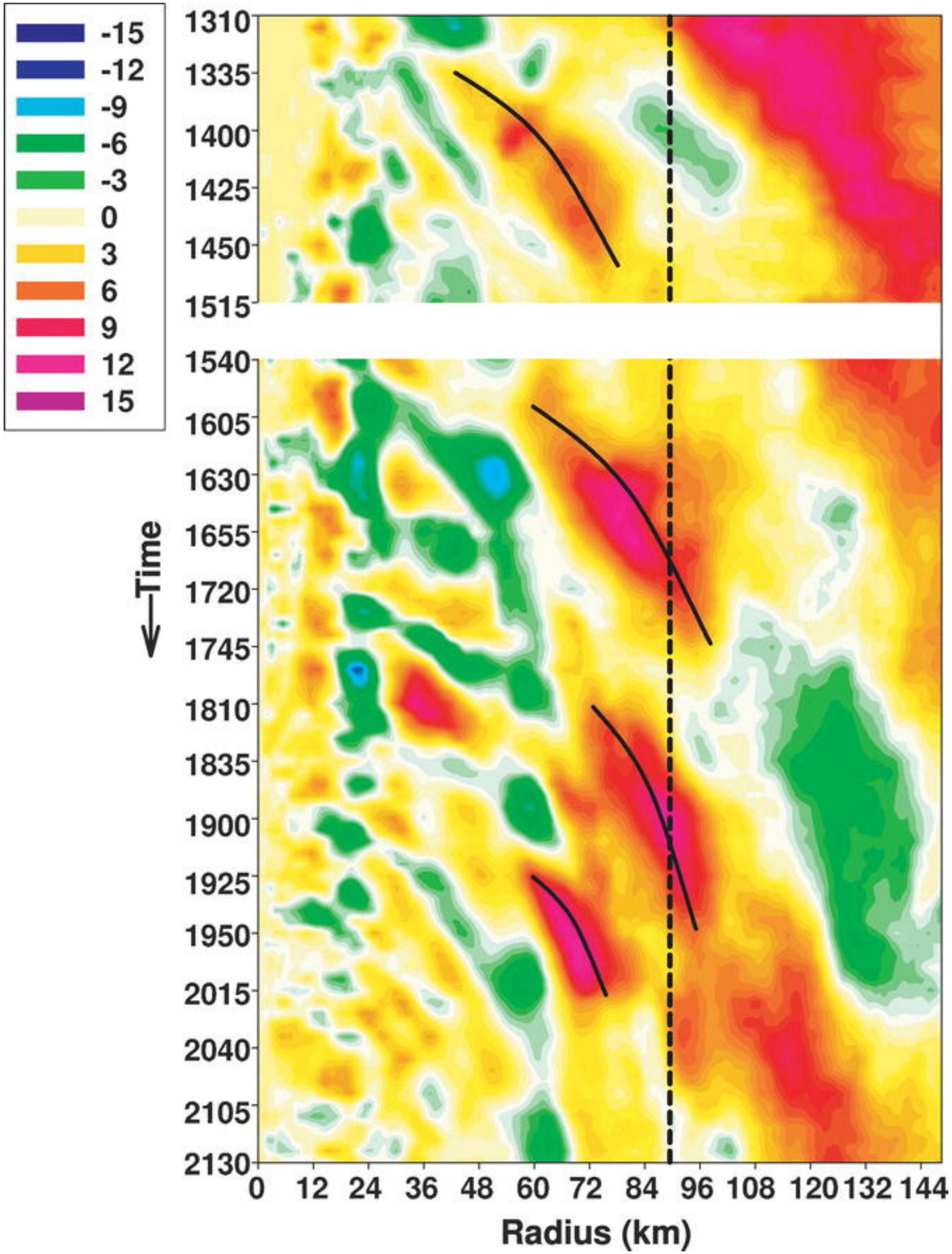
Corbosiero et al. (2006)

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

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

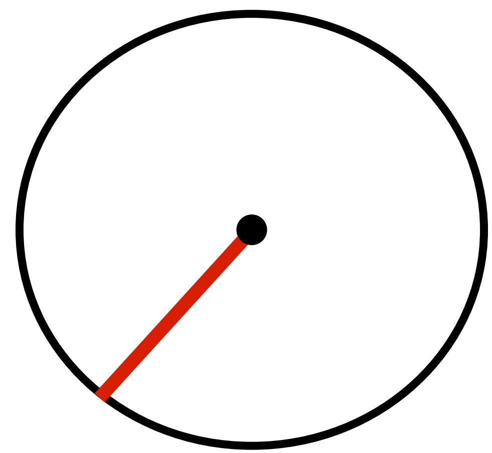
Rossby waves on the outer, negative vorticity gradient propagate cyclonically around the storm, slower than the local mean tangential wind.

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

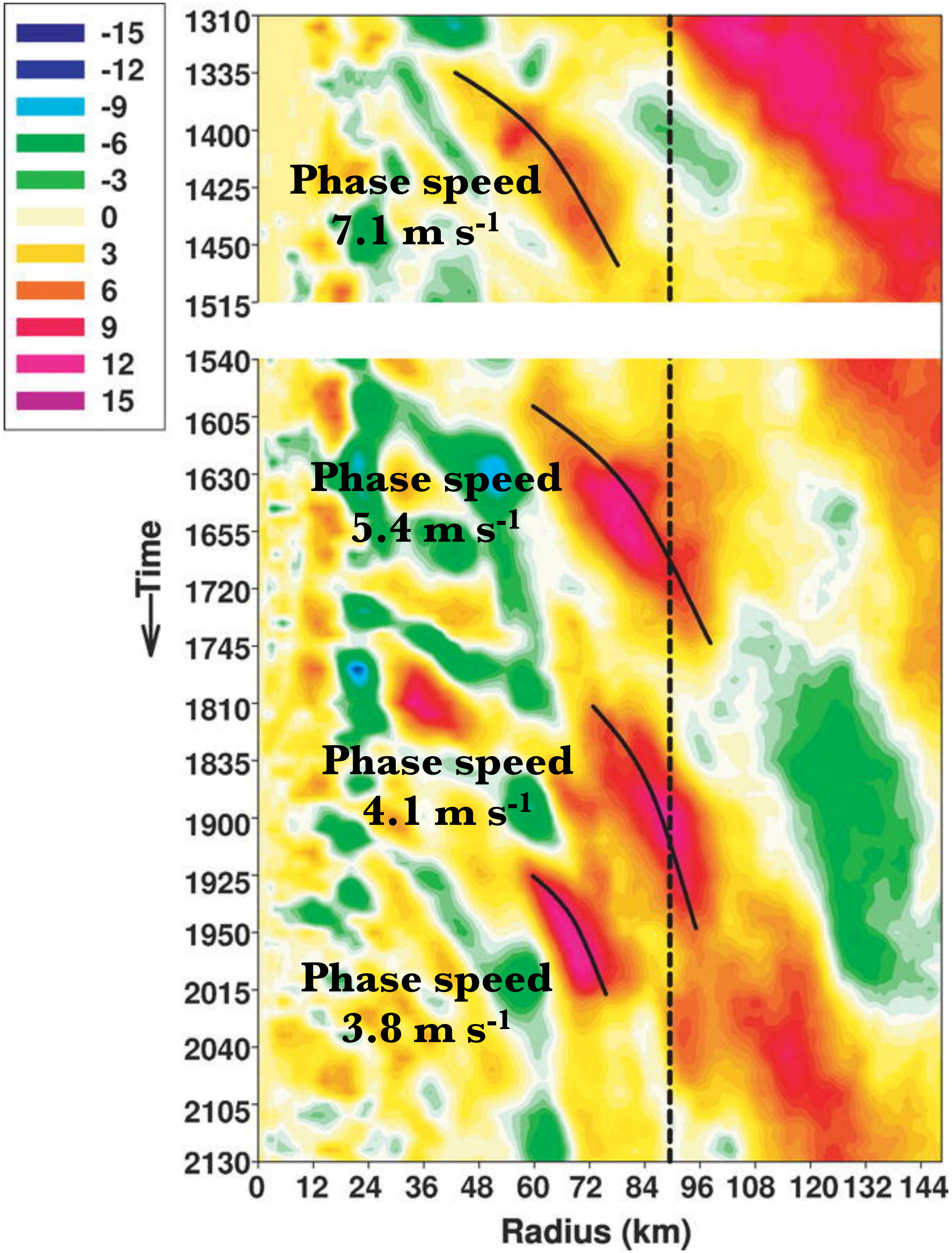


Elena (1985)

Radius-time Hovmöller Wavenumber 2 Reflectivity



Corbosiero et al. (2006)



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

The radial group velocity is O(k^{-3})

Evidence of a radius beyond which the bands no longer propagate

Corbosiero et al. (2006)

The Advanced Hurricane WRF (AHW)

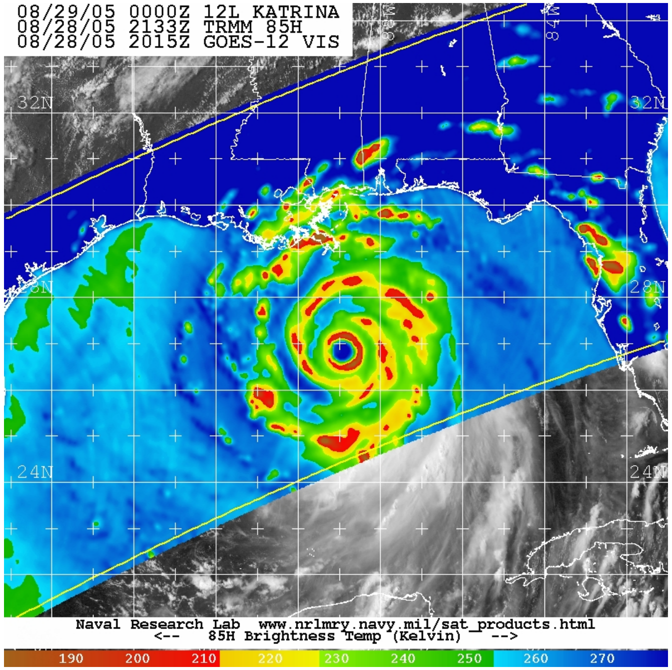
- **Run in real-time at NCAR since 2004 and available at http://www.wrf-model.org/plots/realtime_main.php**

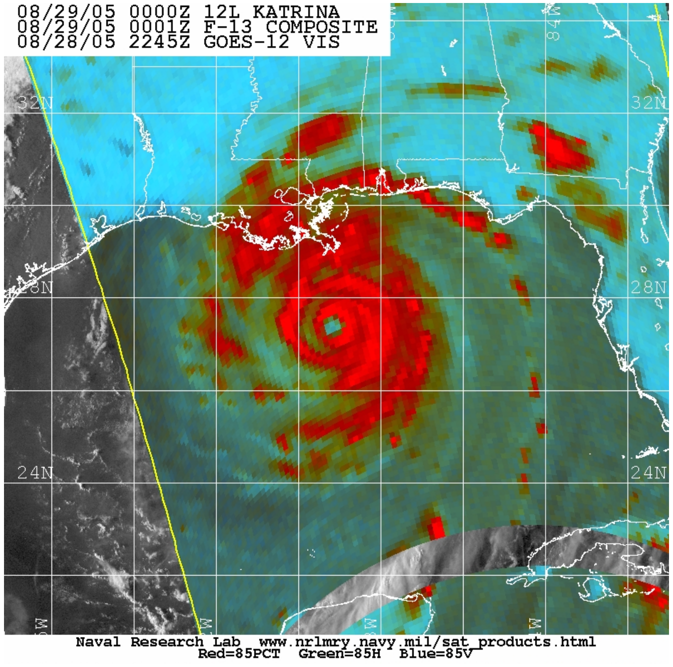
- **Three domains (12, 4, 1.33 km) with two-way moveable nests that follow the hurricane center**

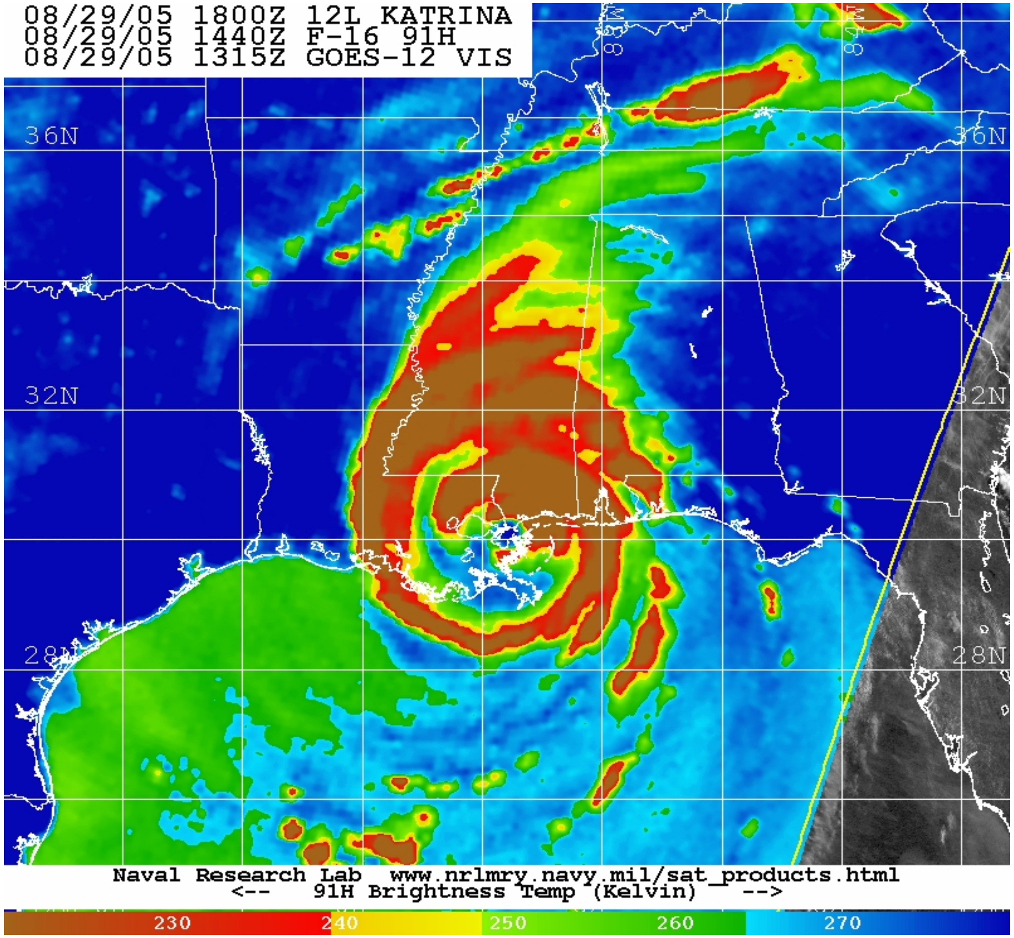
- **WRF version 2.1.2 with Kain-Fritsch cumulus parametrization (12 km only), WSM3 microphysics, YSU PBL scheme, drag (Donelan) and surface enthalpy coefficients (Carlson-Boland) for TCs {see *Davis et al.* (2008)}**

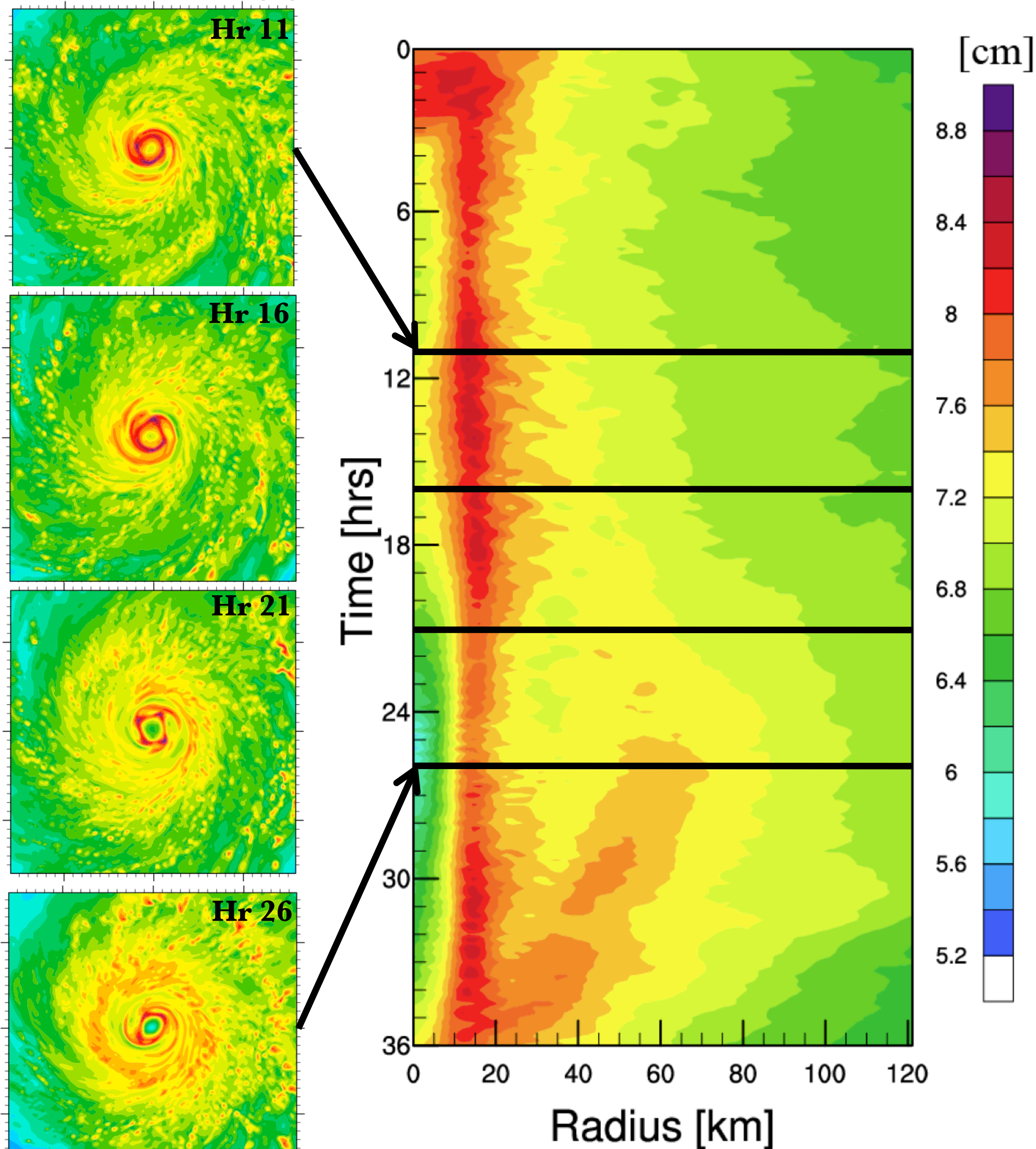
- **Initialized from the GFDL model at 0000 UTC 27 August 2005**

Hurricane Katrina (2005): No in situ observations of a secondary eyewall, but convincing satellite evidence









Katrina (2005)

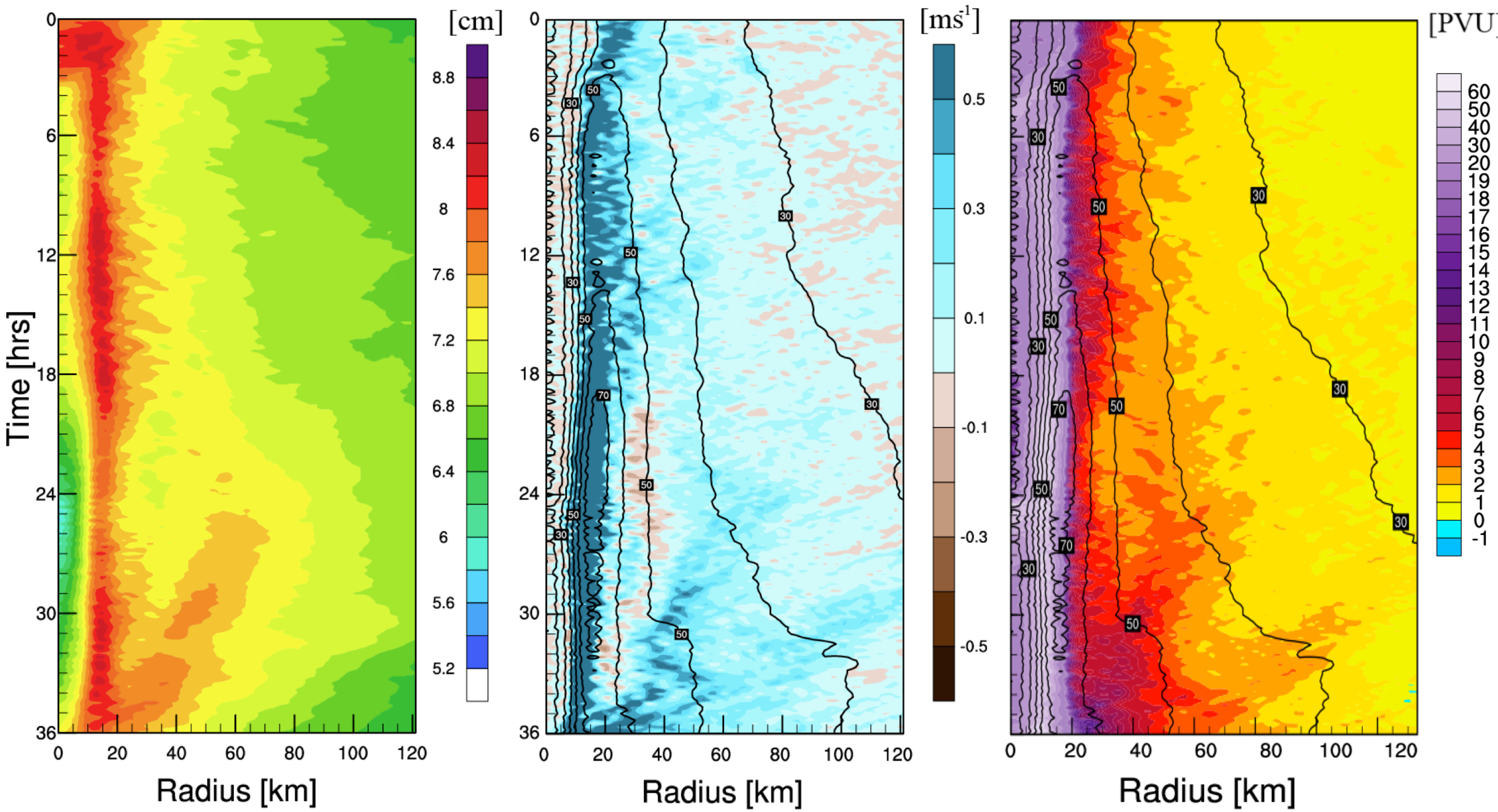
10 min time resolution from 00 UTC 28 August (0 h)

Precipitable Water

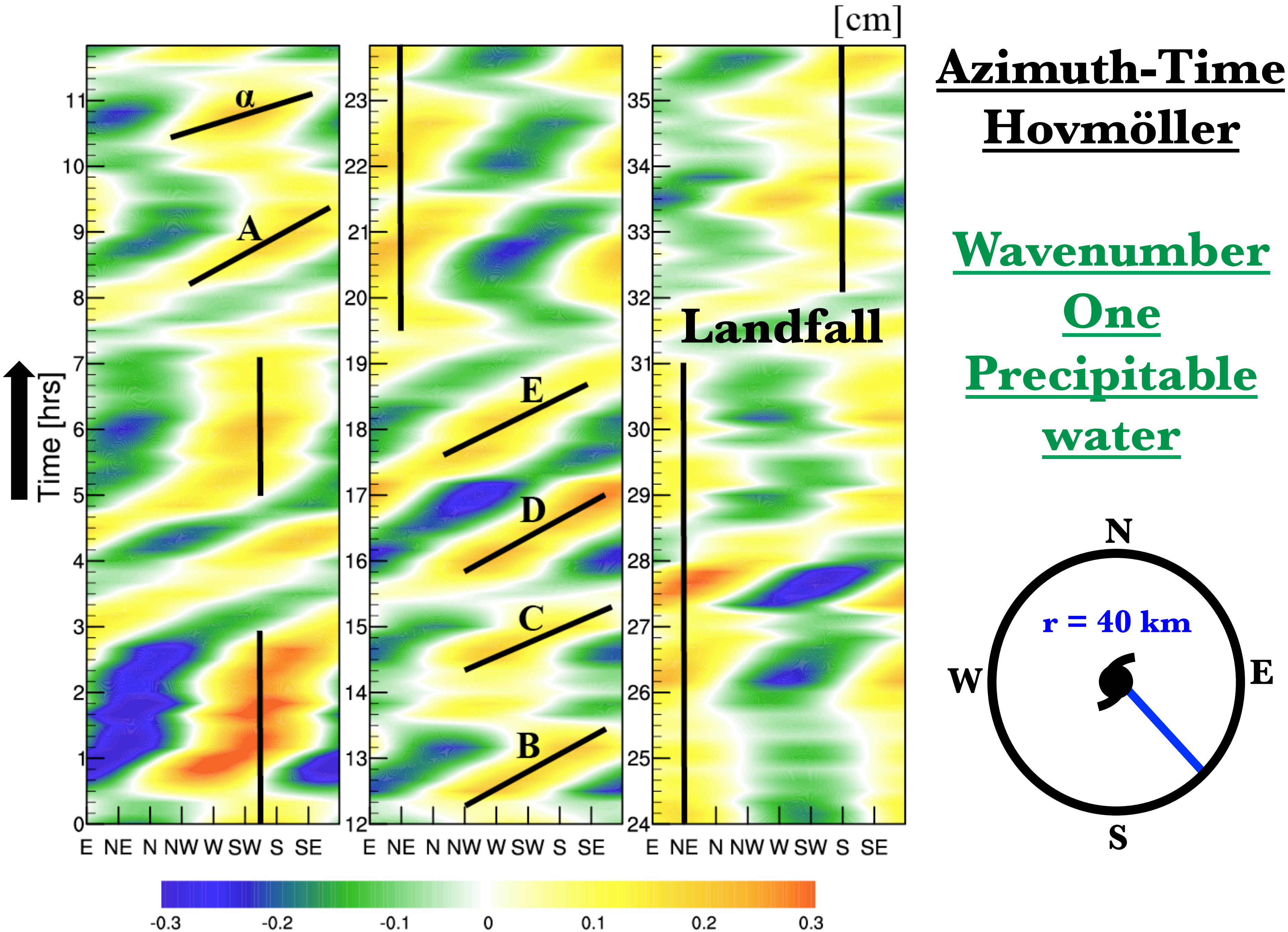
Secondary eyewall first distinguishable at hour 25

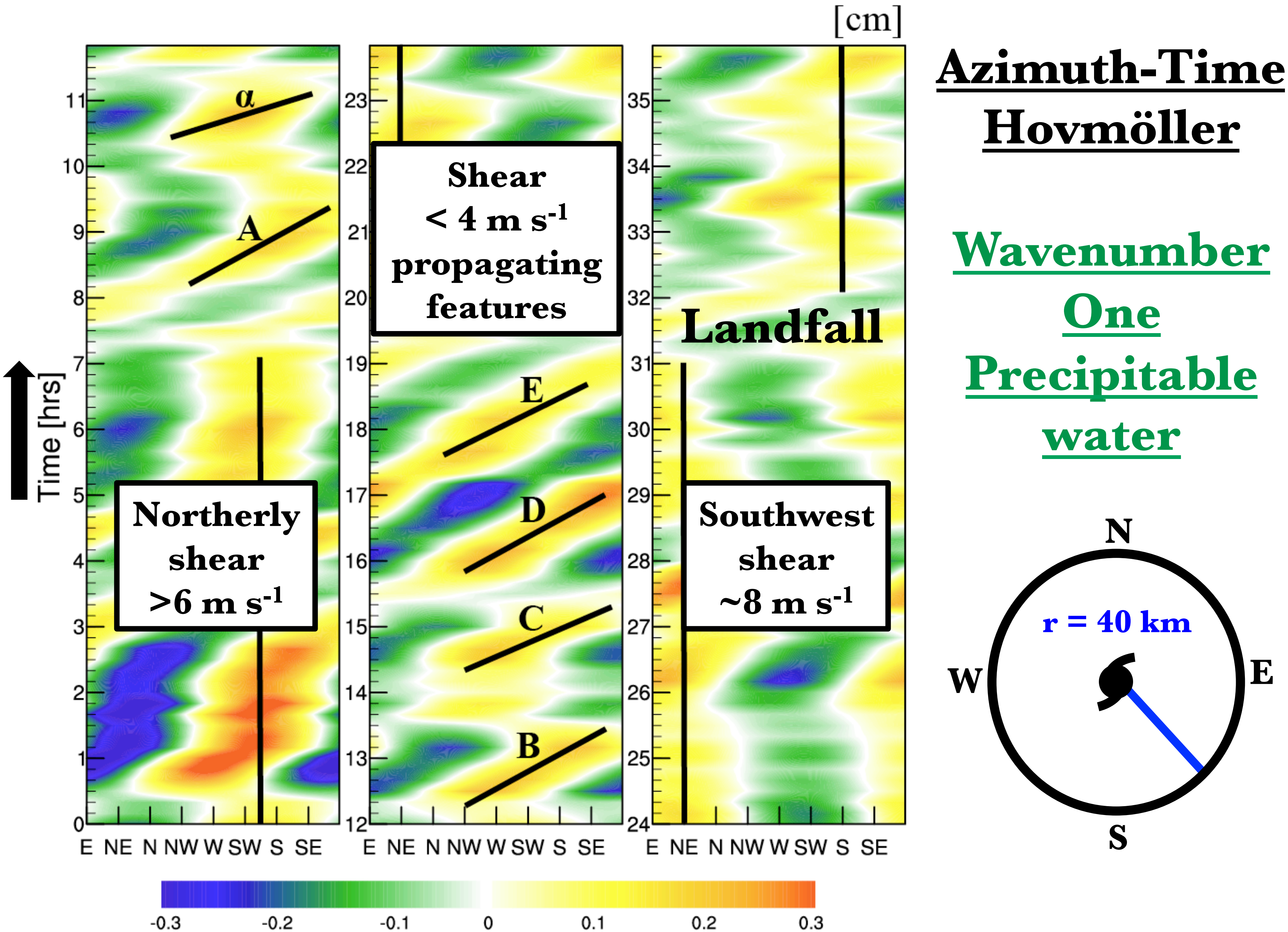
Katrina (2005)

Azimuthally averaged radius-time Hovmöllers

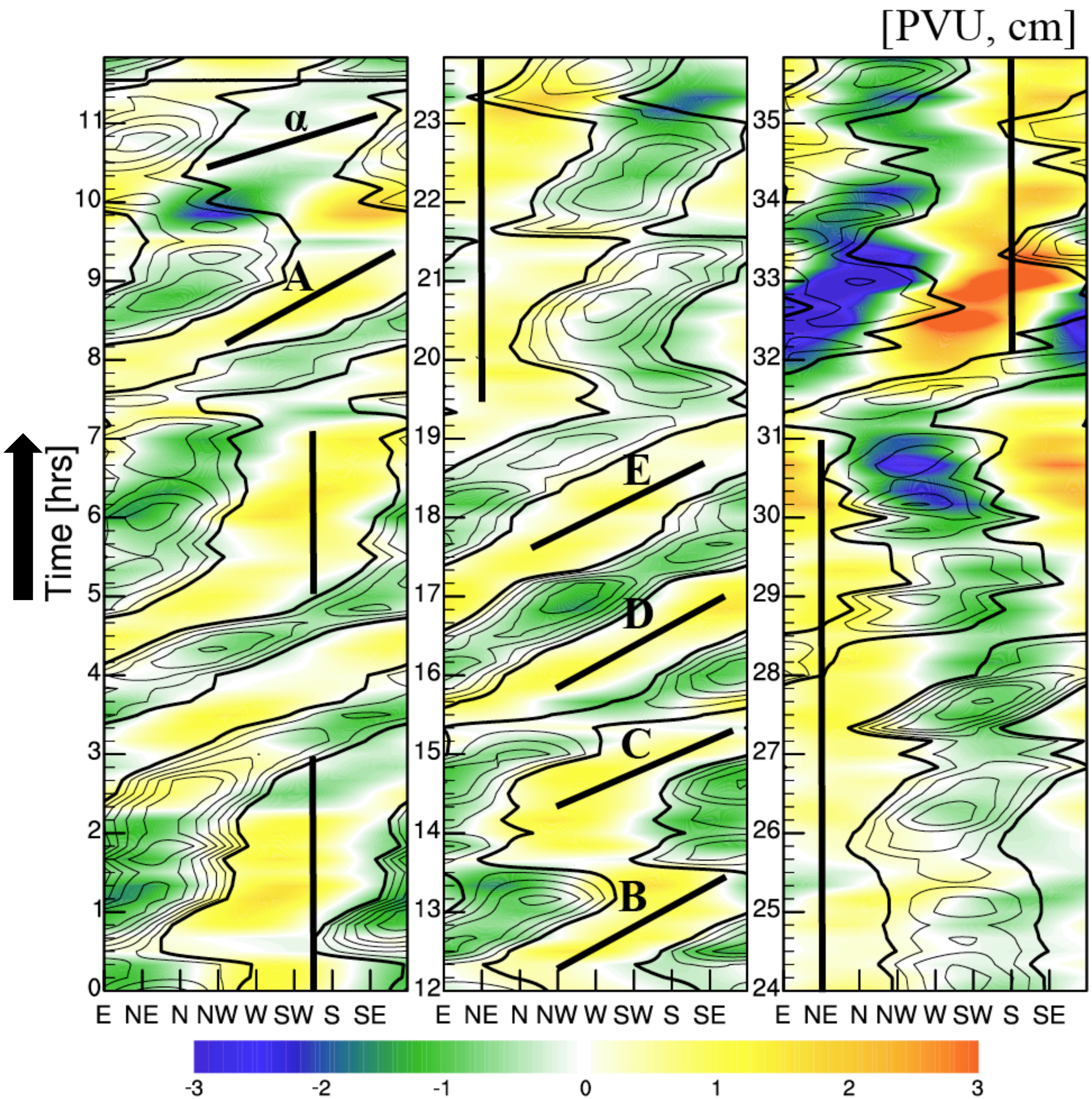


Precipitable water | **Vertical and horizontal winds** | **Potential vorticity**


[cm]
Azimuth-Time Hovmöller
Wavenumber One Precipitable water
Time [hrs]
α
A
B
C
D
E
Landfall
E NE N NW W SW S SE
-0.3 -0.2 -0.1 0 0.1 0.2 0.3
N
S
W
E
r = 40 km

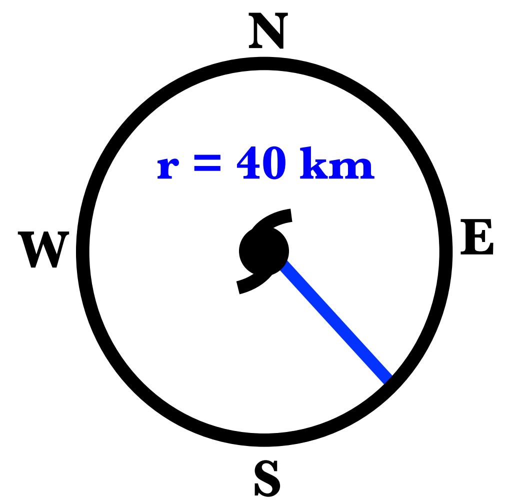


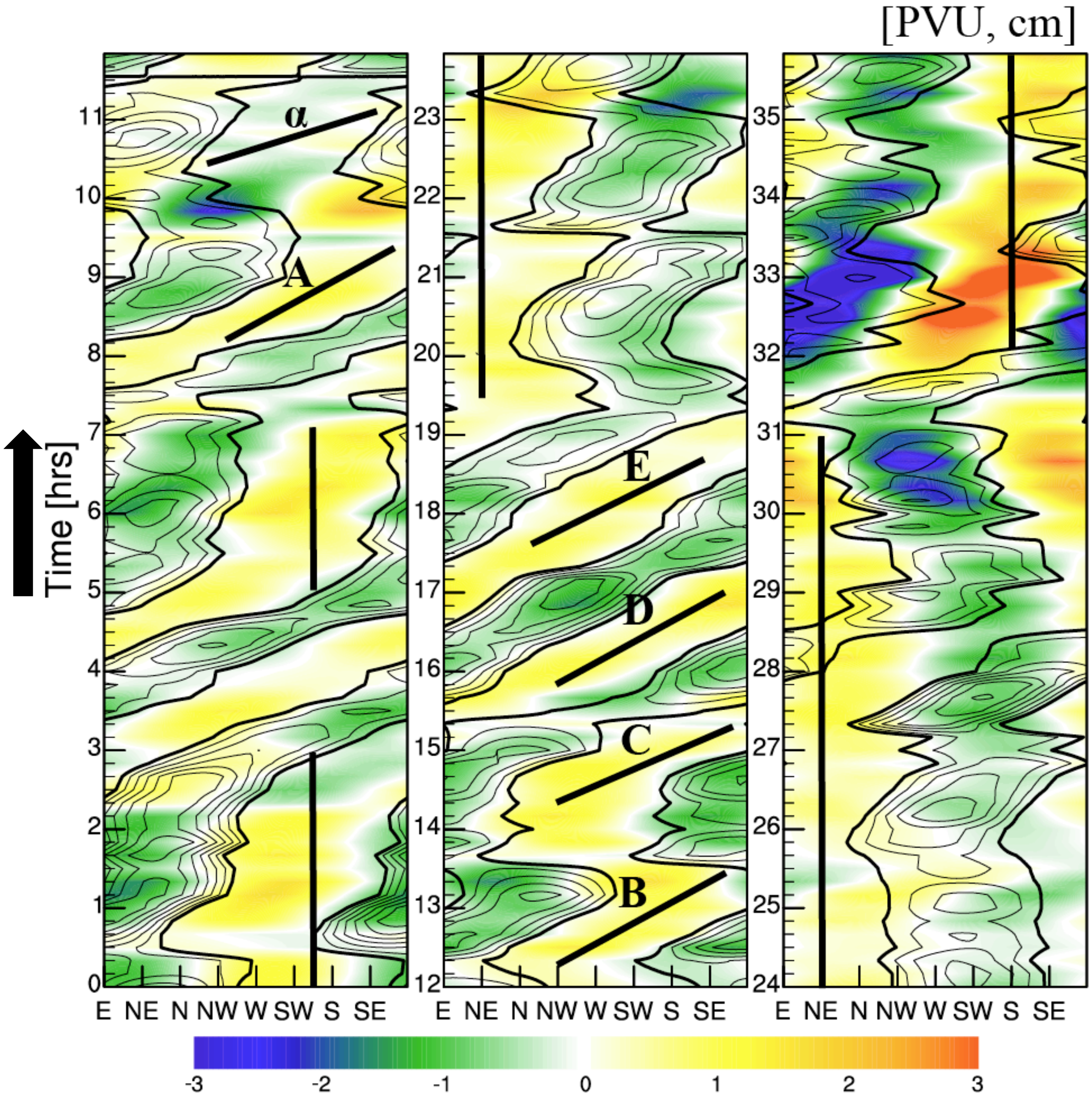
[cm]
Azimuth-Time Hovmöller
Wavenumber One Precipitable water
Time [hrs]
α
A
Northerly shear >6 m s-1
Shear < 4 m s-1 propagating features
E
D
C
B
Landfall
Southwest shear ~8 m s-1
E NE N NW W SW S SE
-0.3 -0.2 -0.1 0 0.1 0.2 0.3
N
W
E
S
r = 40 km



Azimuth-Time Hovmöller

Wavenumber One PV (shaded) and PW (contours)



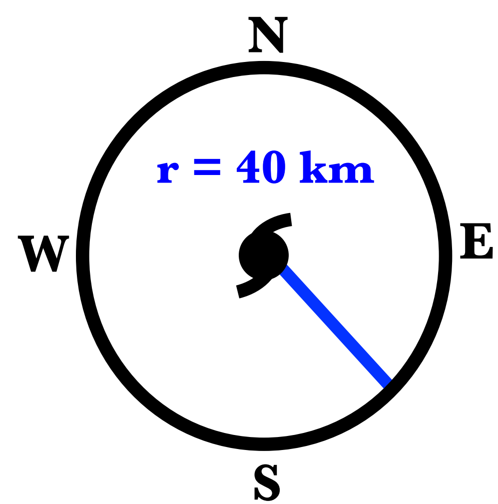


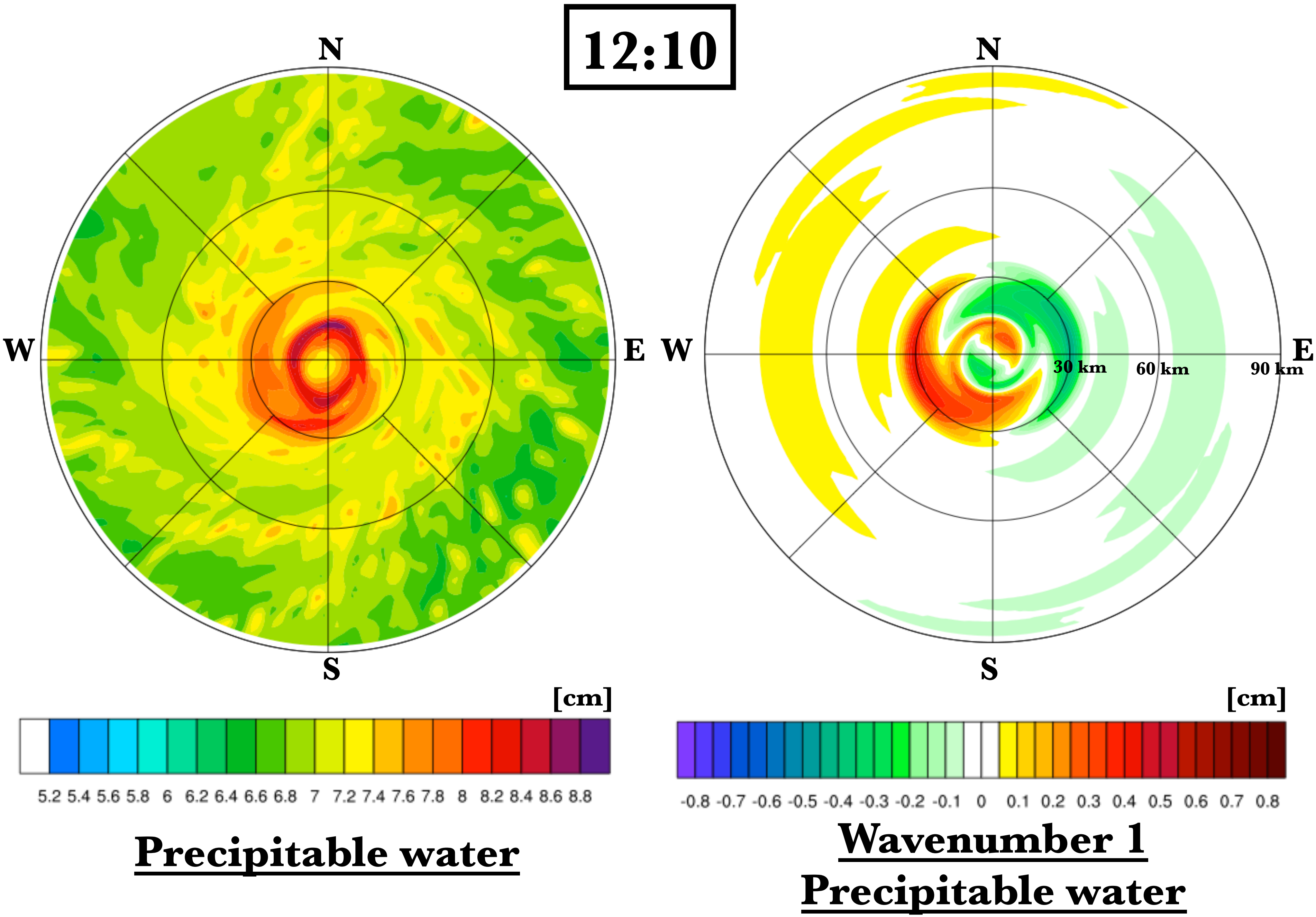
Convectively coupled PV features

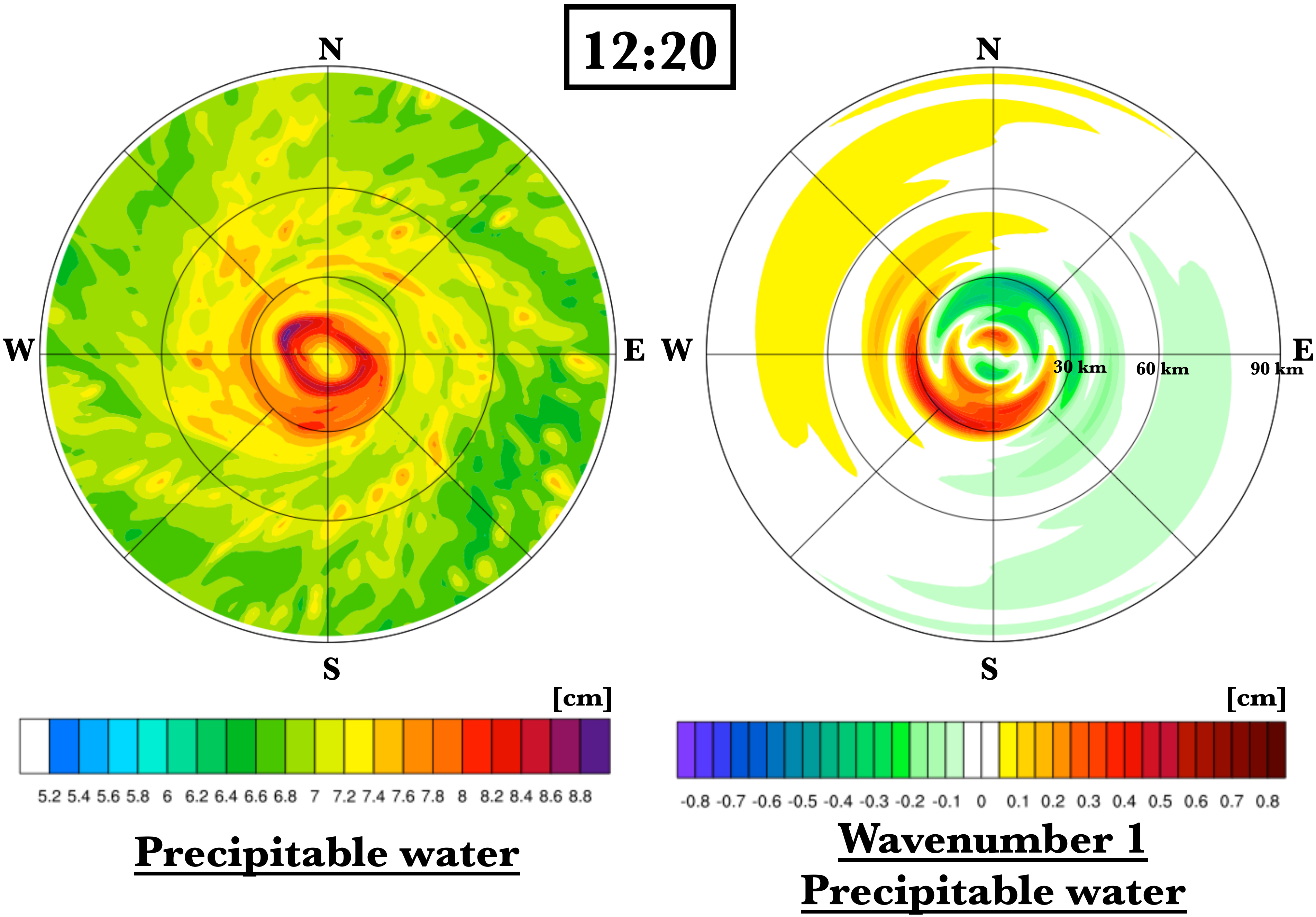
Azimuthal phase speeds:

32 – 38 m s^{-1}

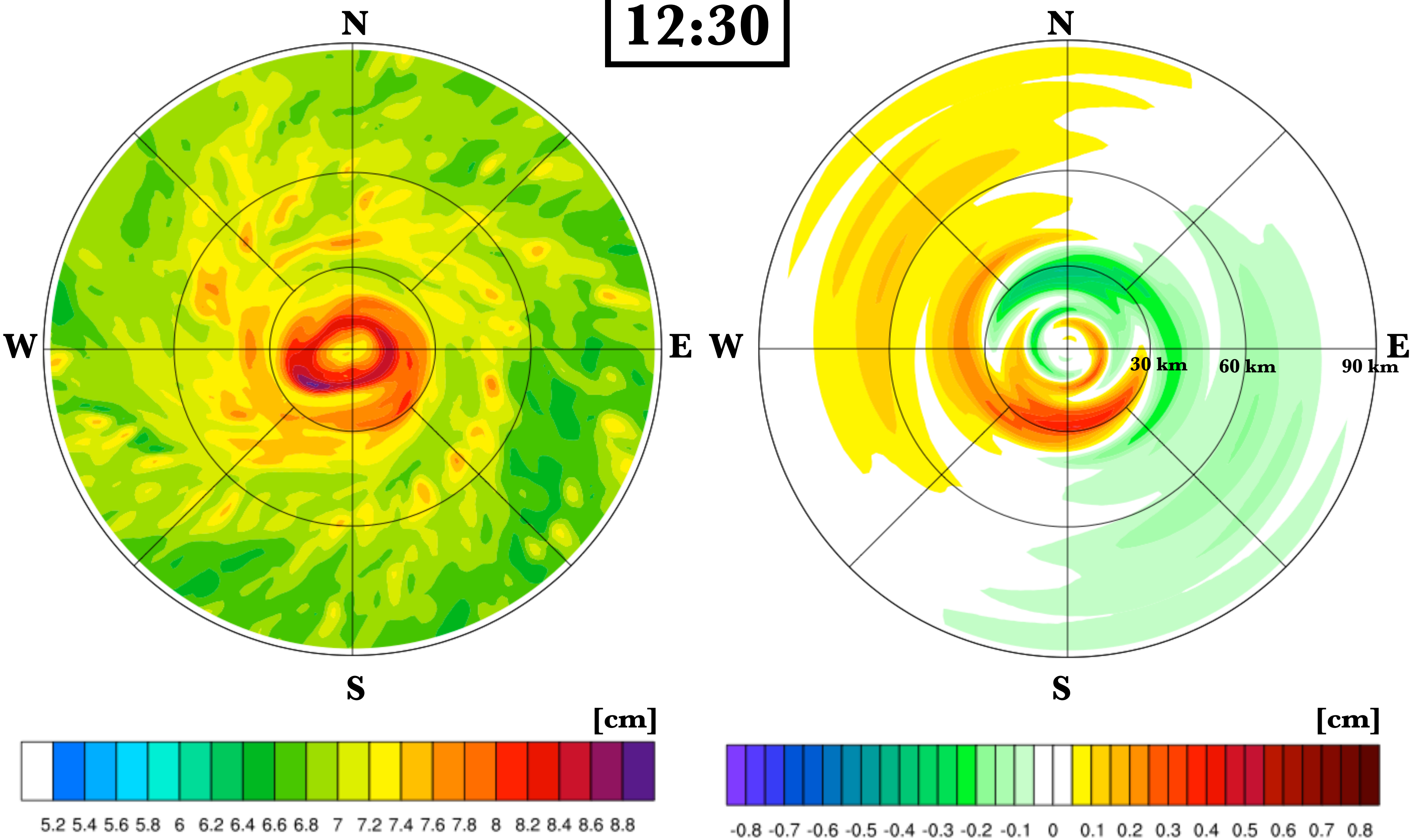
74 – 84% of V_T




12:10
N
W
E
S
N
W
E
S
30 km
60 km
90 km
[cm]
5.2 5.4 5.6 5.8 6 6.2 6.4 6.6 6.8 7 7.2 7.4 7.6 7.8 8 8.2 8.4 8.6 8.8
[cm]
-0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Precipitable water
Wavenumber 1
Precipitable water

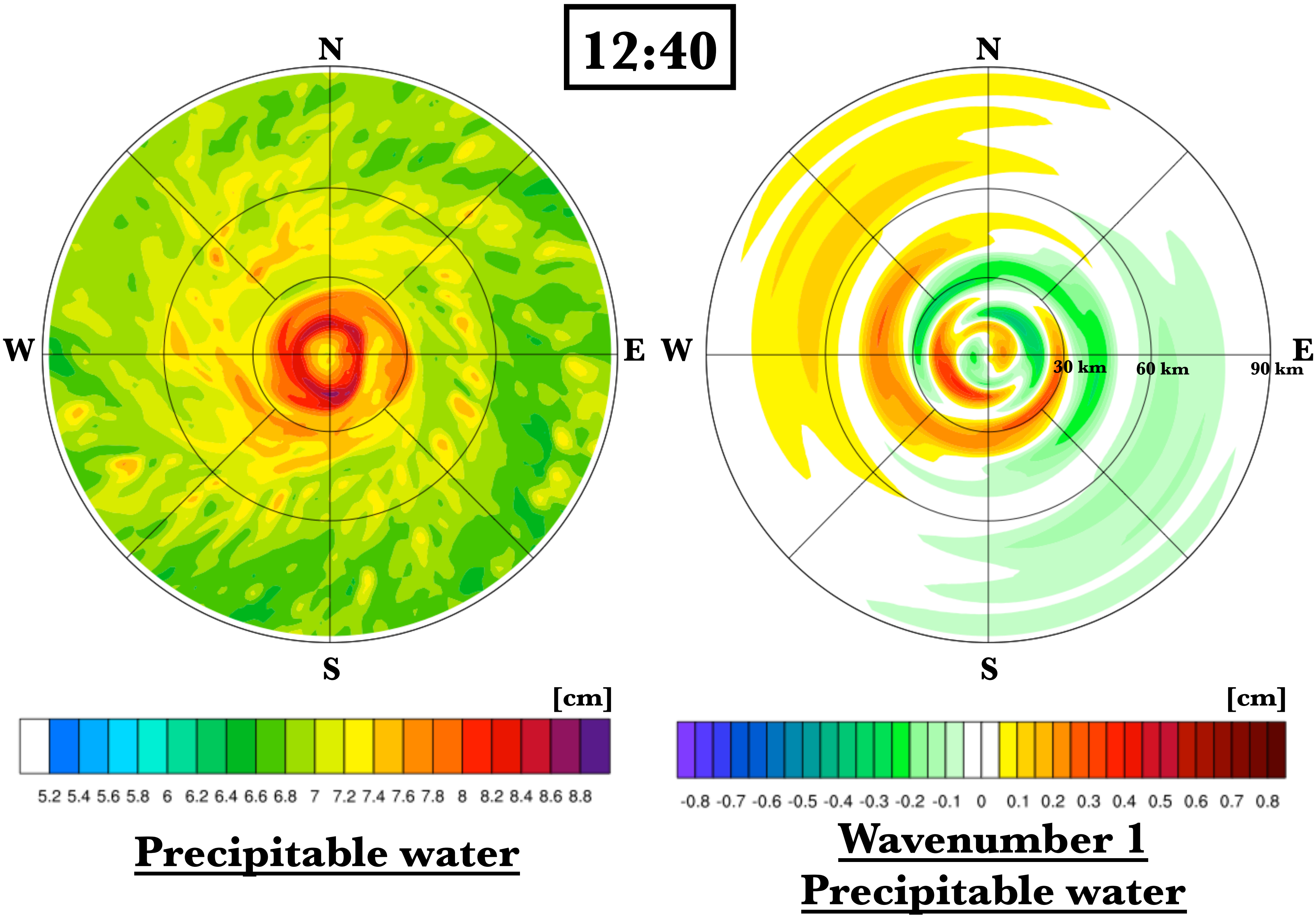

12:20
N
W
E
S
[cm]
5.2 5.4 5.6 5.8 6 6.2 6.4 6.6 6.8 7 7.2 7.4 7.6 7.8 8 8.2 8.4 8.6 8.8
Precipitable water
N
W
E
S
30 km
60 km
90 km
[cm]
-0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Wavenumber 1
Precipitable water

12:30

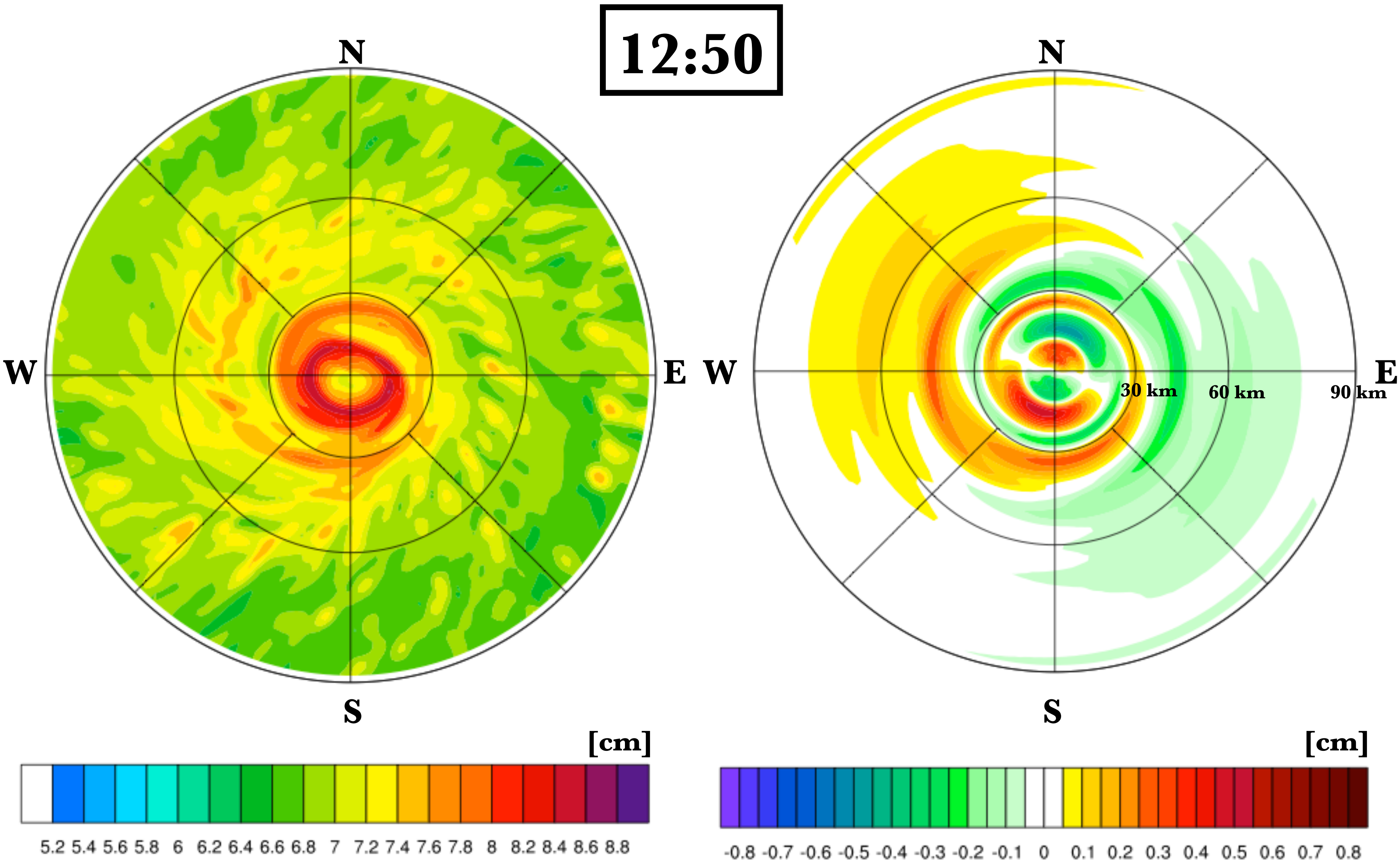


Precipitable water

Wavenumber 1 Precipitable water



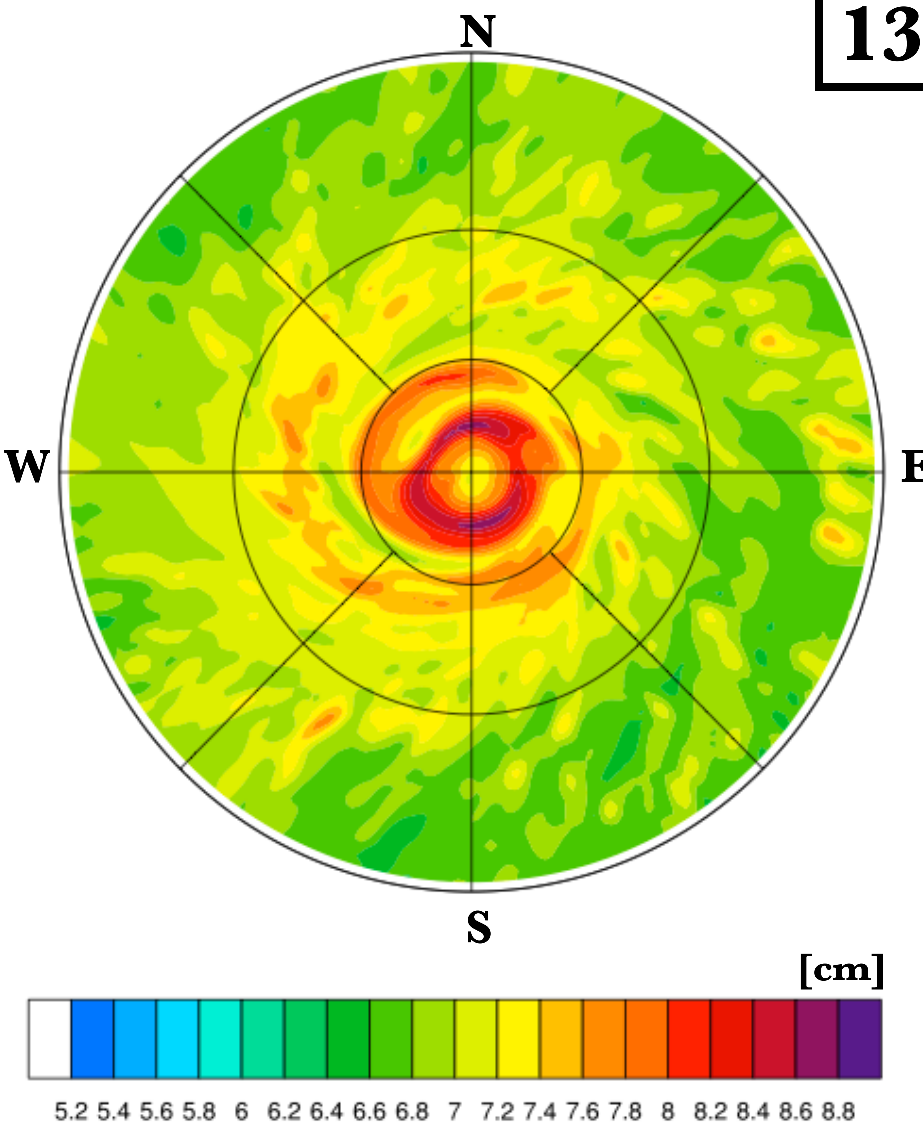
12:40
N
W
E
S
[cm]
5.2 5.4 5.6 5.8 6 6.2 6.4 6.6 6.8 7 7.2 7.4 7.6 7.8 8 8.2 8.4 8.6 8.8
Precipitable water
N
W
E
S
30 km
60 km
90 km
[cm]
-0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Wavenumber 1
Precipitable water



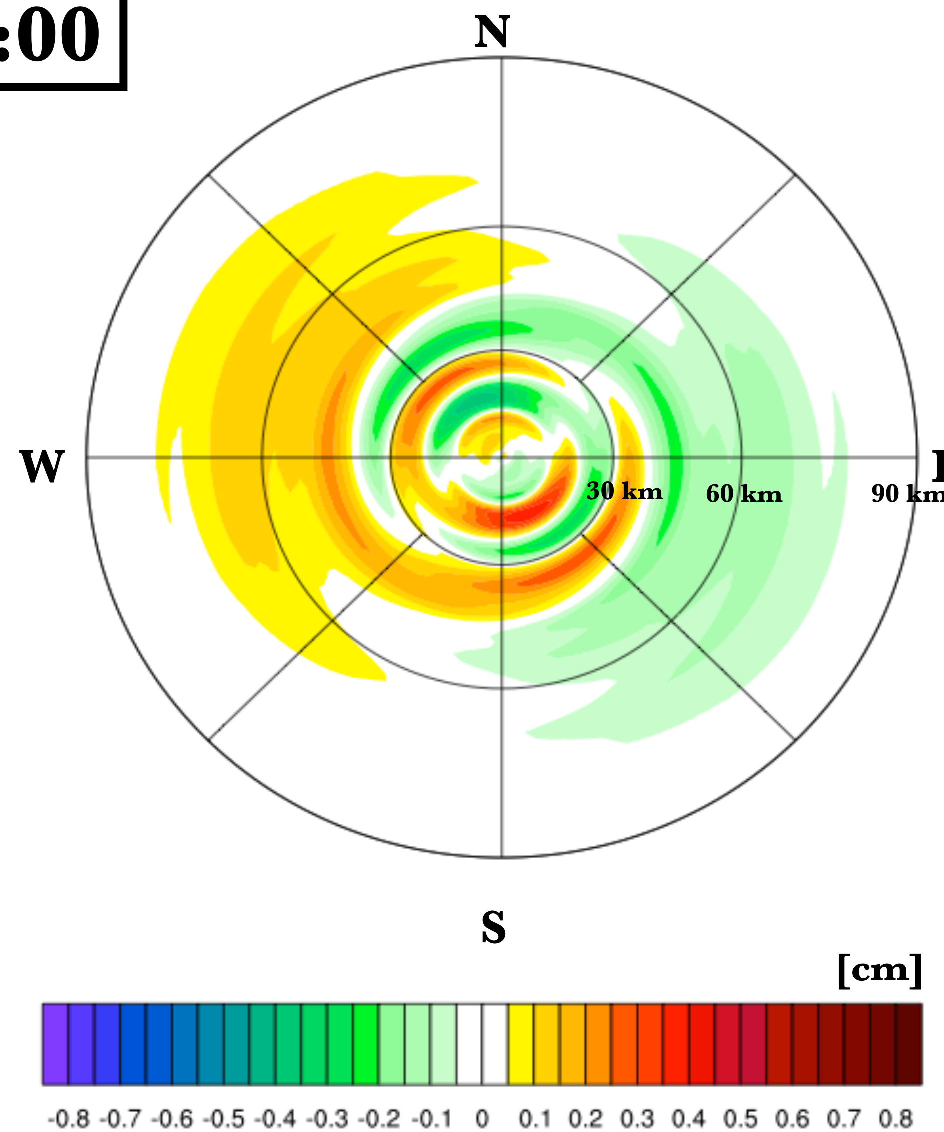
Precipitable water

Wavenumber 1
Precipitable water

13:00

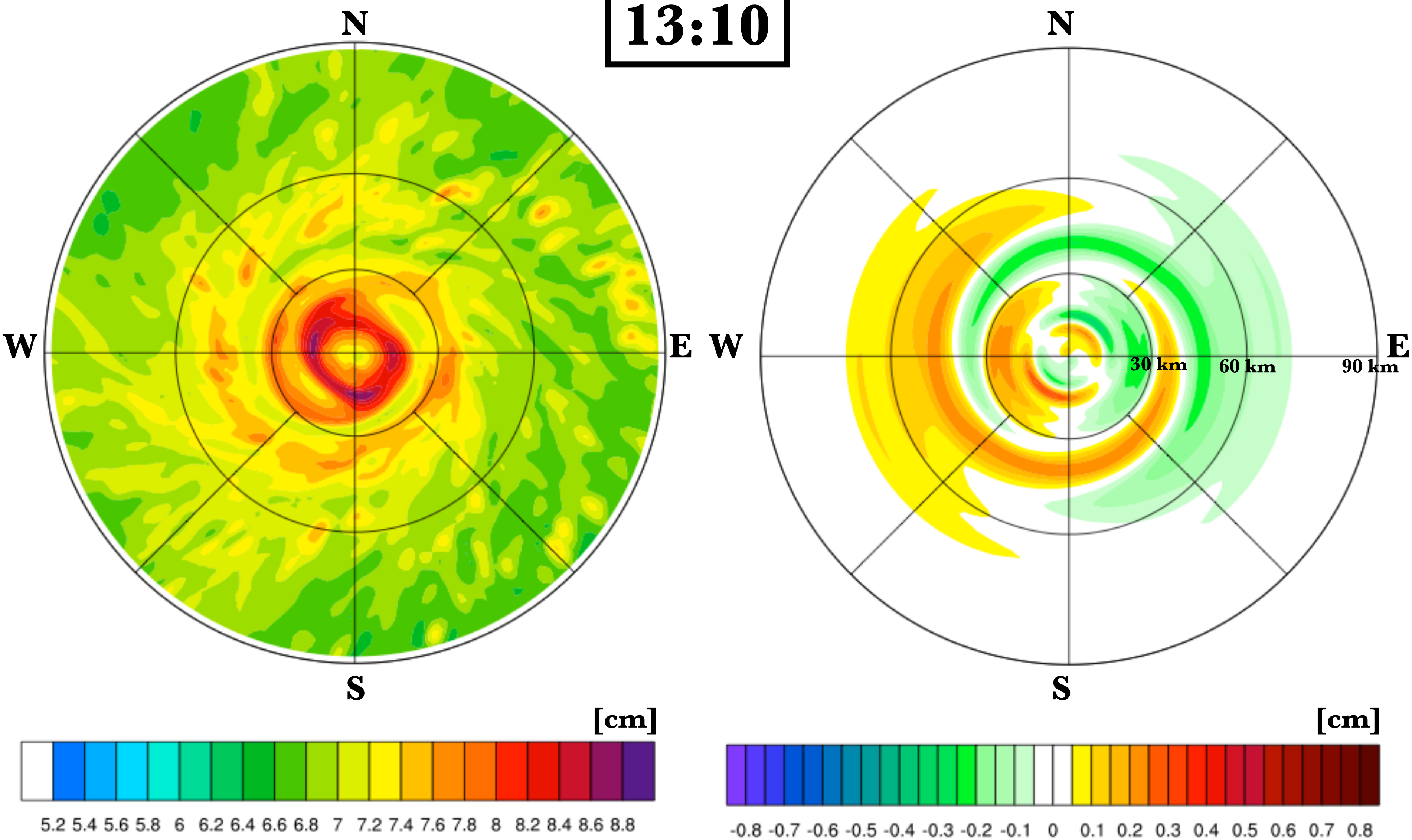


Precipitable water



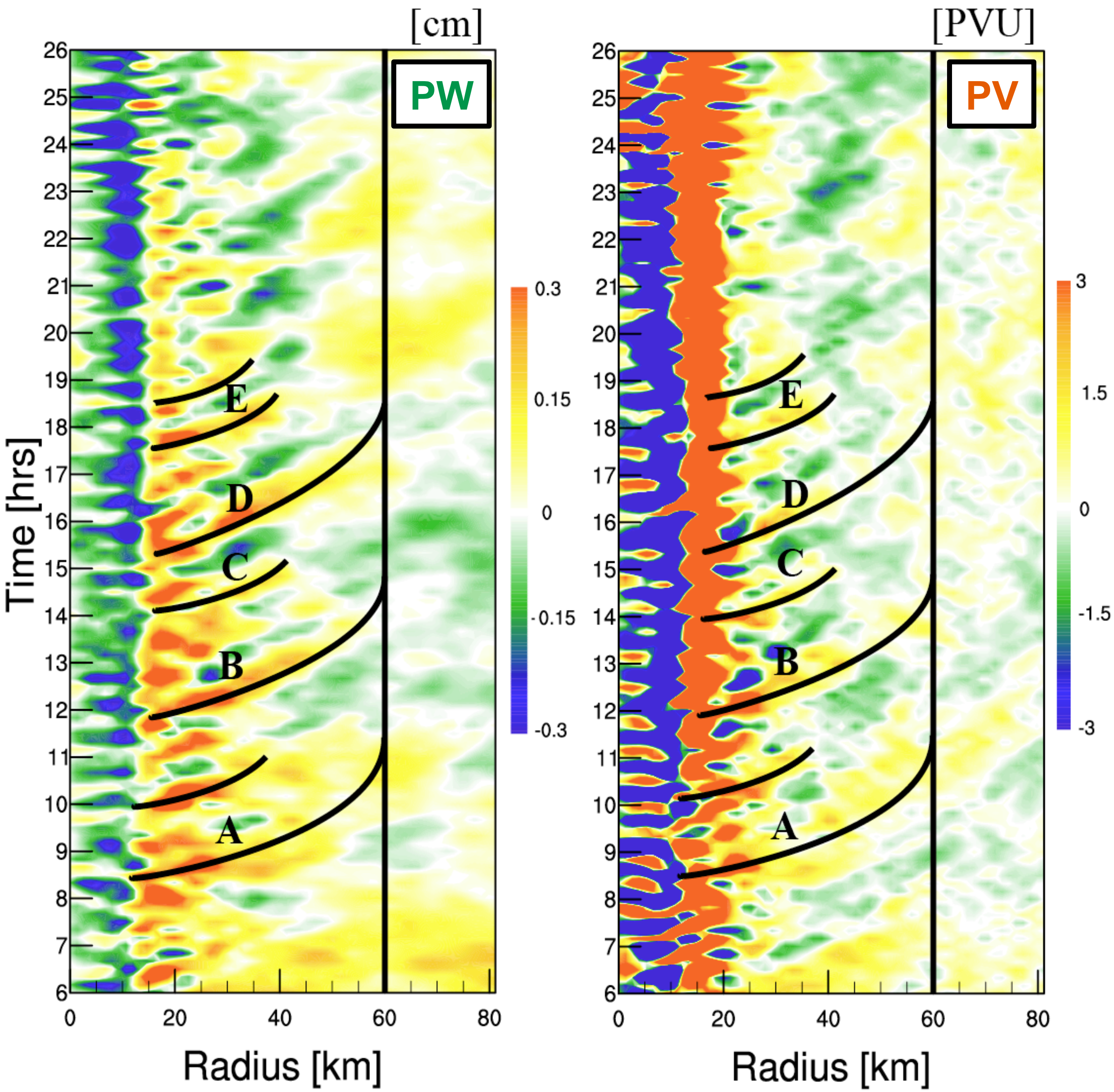
Wavenumber 1
Precipitable water

13:10



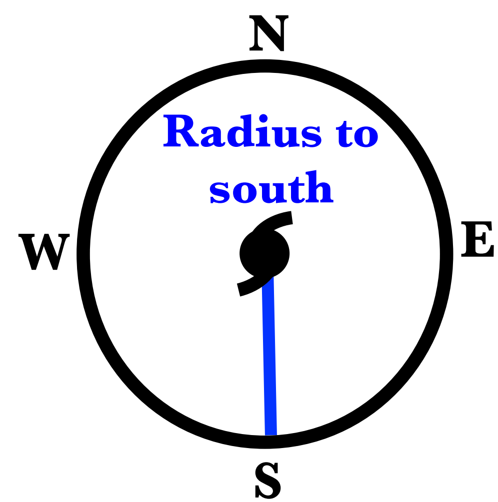
Precipitable water

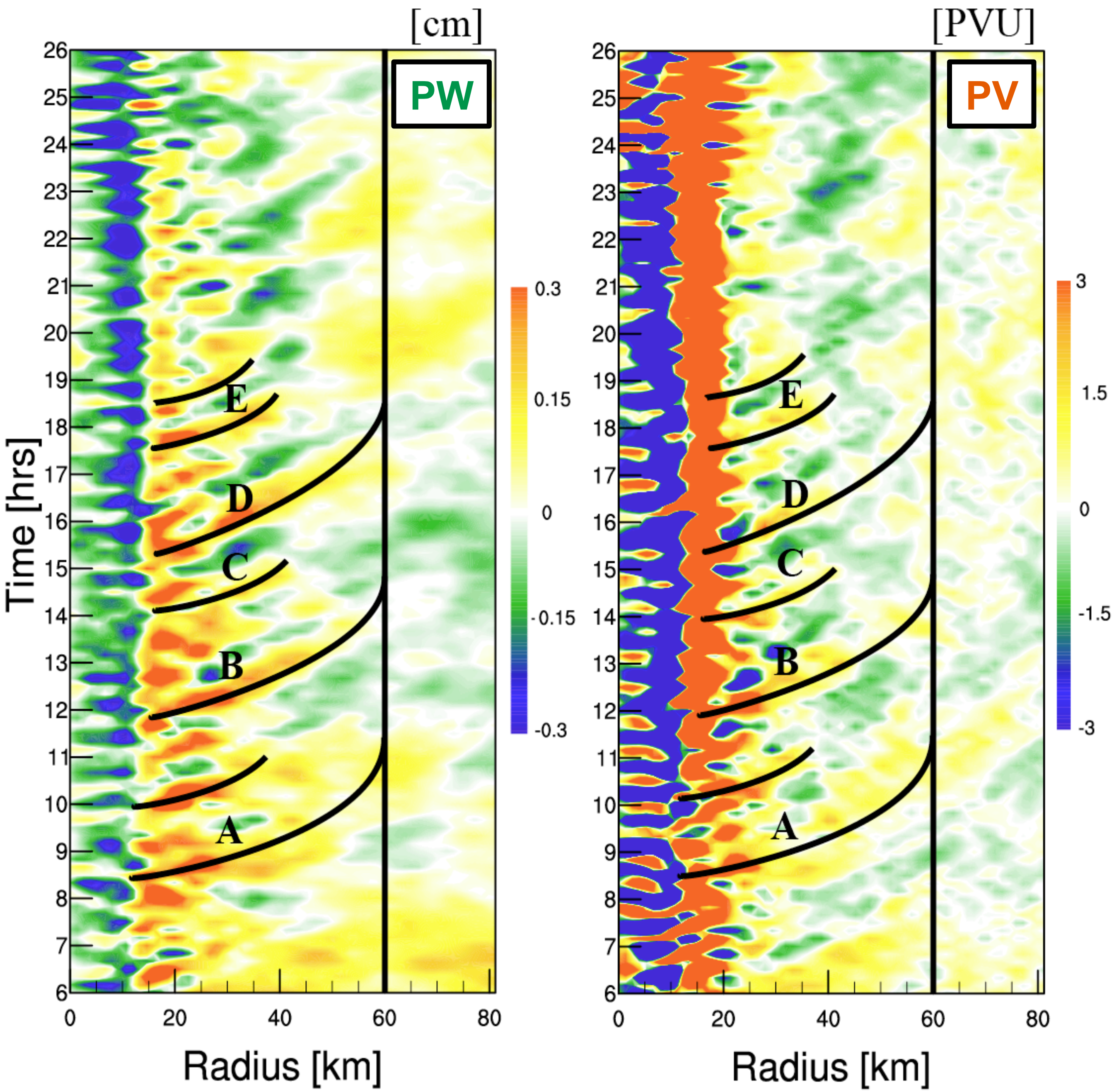
Wavenumber 1 Precipitable water



Radius-Time Hovmöller

Wavenumber One
PW (left) and PV (right)





Features propagate

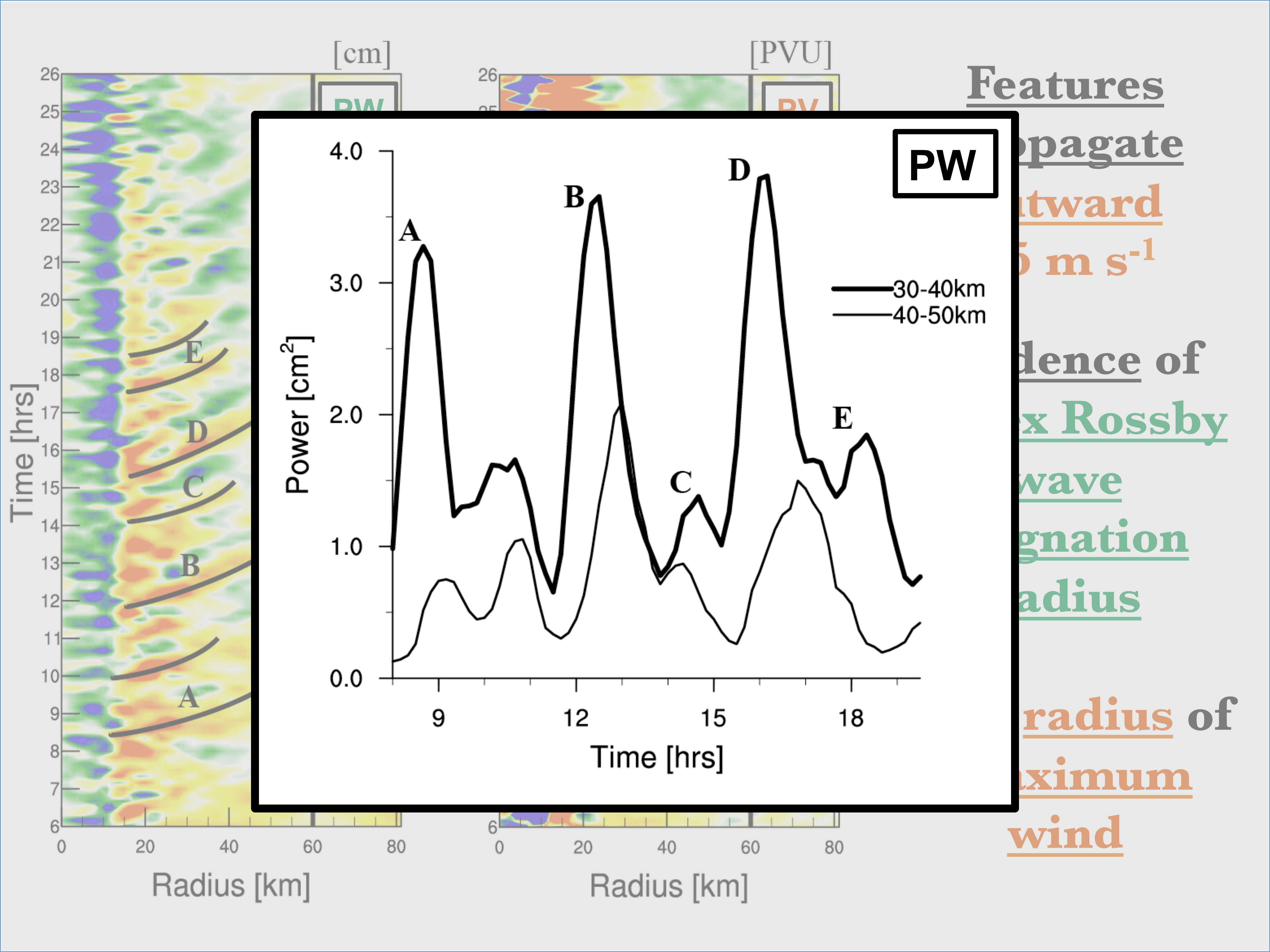
outward

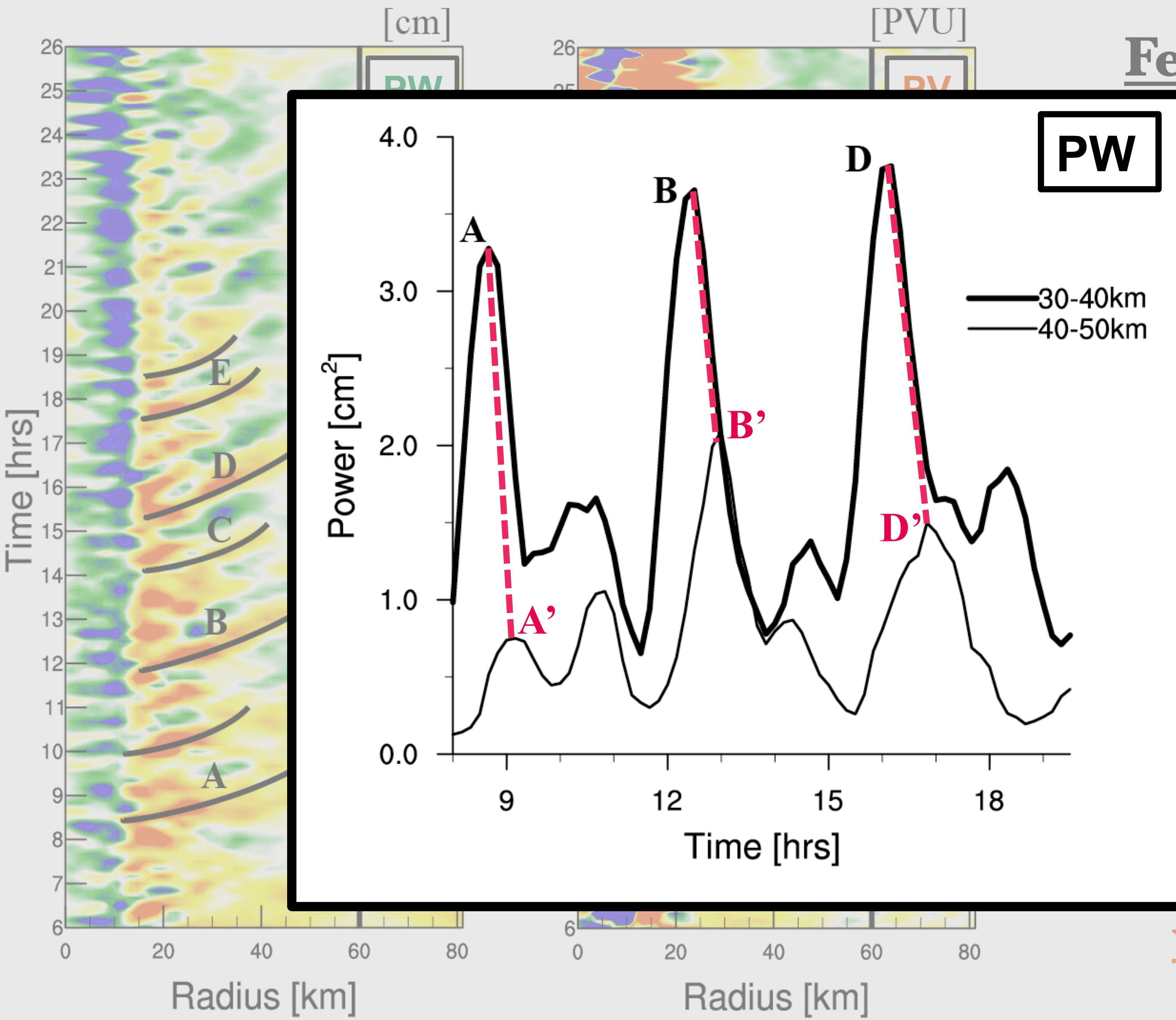
~5 m s^{-1}

Evidence of

vortex Rossby wave stagnation radius

~ 3 x radius of maximum wind


[cm]
PW
Time [hrs]
Radius [km]
A
B
C
D
E
[PVU]
PV
Radius [km]
PW
Power [cm^2]
Time [hrs]
30-40km
40-50km
4.0
3.0
2.0
1.0
0.0
9
12
15
18
Features
opagate
tward
5 m s^{-1}
dence of
x Rossby
wave
gnation
adius
radius of
ximum
wind



Features
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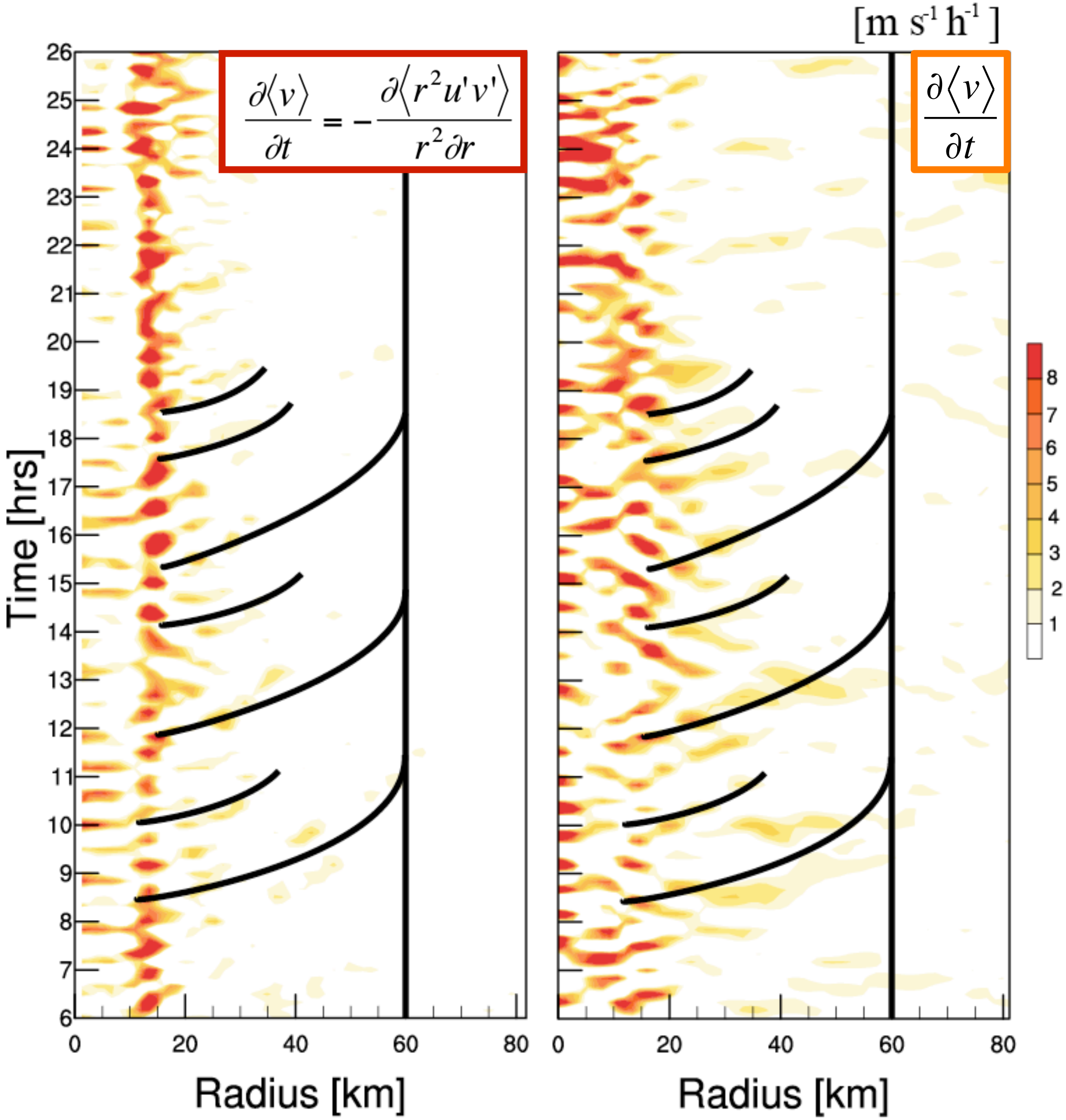
5 m s^{-1}

dence of
x Rossby
wave
gnation
adius

radius of
aximum
wind

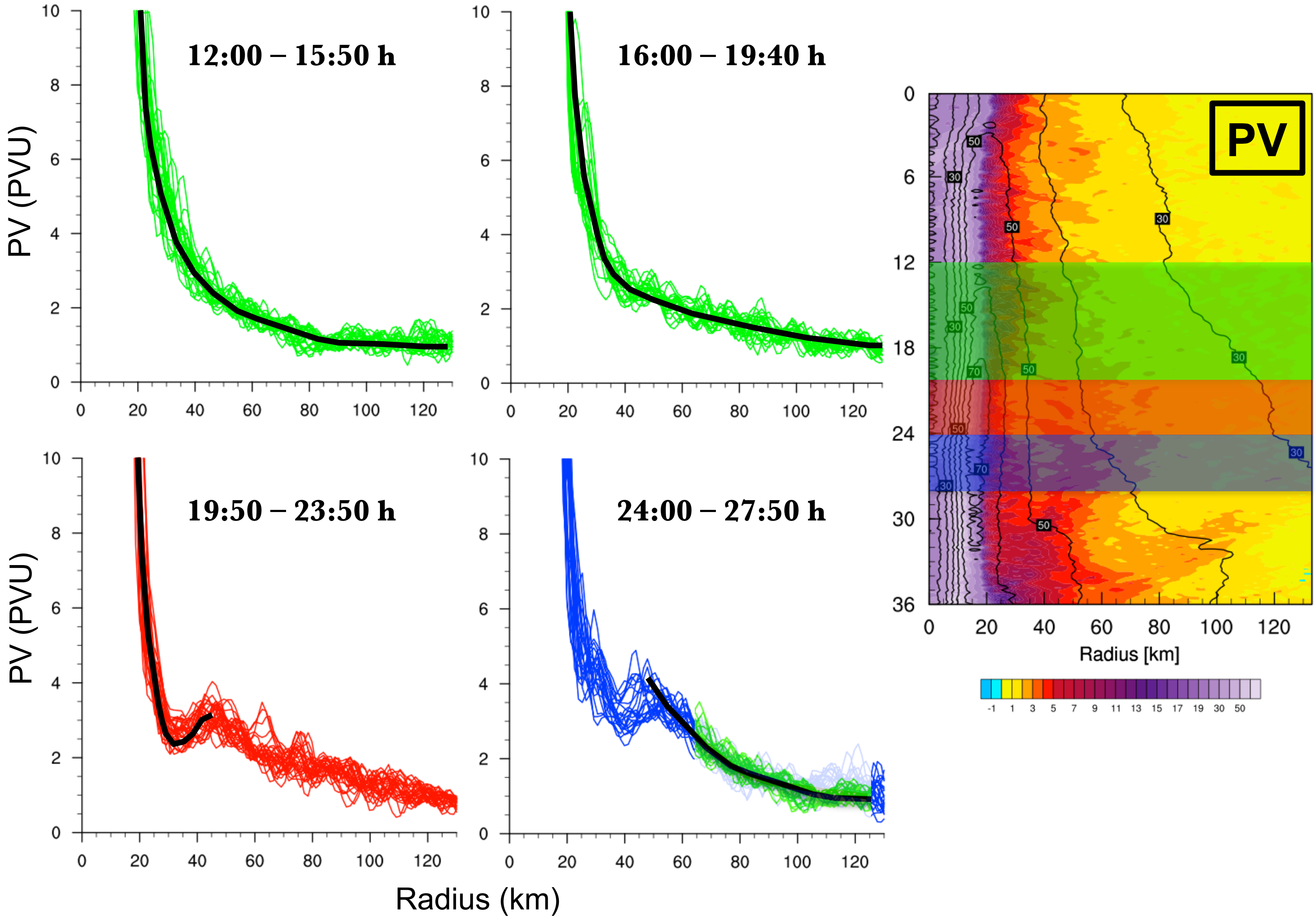


Radius-Time Hovmöller

Azimuthally averaged 850 hPa

Eddy momentum flux divergence (left)

Tangential wind acceleration (right)



12:00 – 15:50 h
16:00 – 19:40 h
19:50 – 23:50 h
24:00 – 27:50 h
PV (PVU)
Radius (km)
PV
Radius [km]

Summary, Conclusions and Future Work

- Advanced Hurricane WRF simulation of Katrina (2005) underwent secondary eyewall formation (SEF) with (some) characteristics observed in nature

- SEF is related to the axisymmetrization of inner spiral rainbands that propagate outward and stagnate at a radius ~3 times the RMW

- Inner spiral rainbands are vortex Rossby waves generated through barotropic instability

- Examine null cases with high VRW activity and no SEF; explore environmental factors with the AHW EnKF system