HEDAS: The HWRF Ensemble Data Assimilation System

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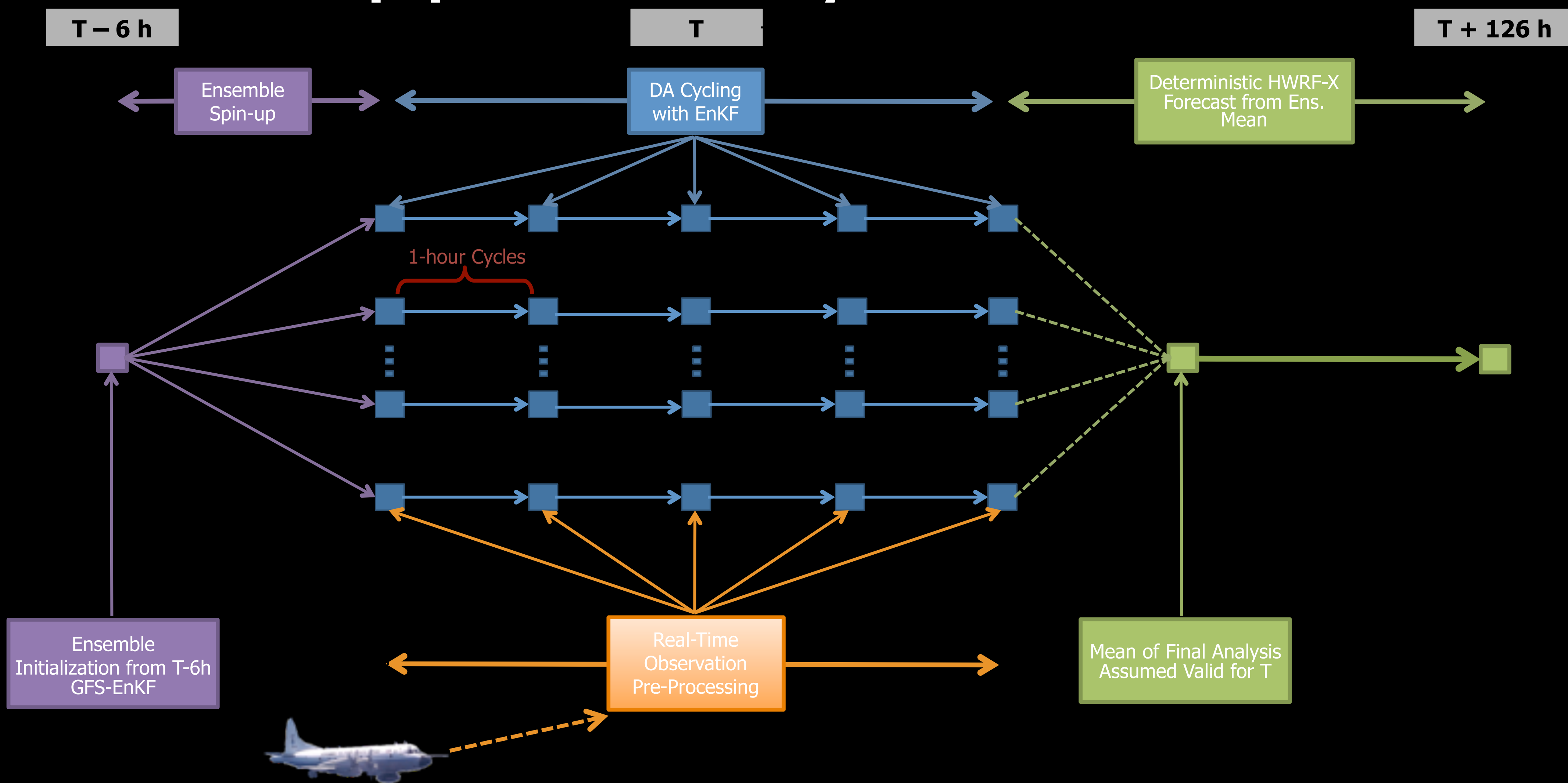
HFIP Conference Call
07 December 2011

HEDAS Cycling Workflow

- Run for cases (2008–2011) when NOAA Airborne Doppler Radar data were available (84 cases)
- Uses 1452 processors on NOAA's t-jet cluster (supported by HFIP)



- **Forecast model:**
  - HRD's Experimental HWRF (HWRF-X)
  - 2 nested domains (9/3 km horizontal resolution, 42 vertical levels)
  - Static inner nest to accommodate covariance computations
    - ➔ Inner nest size: ~10x10 degrees
  - Ferrier microphysics, explicit convection on inner nest

- **Ensemble system:**
  - Initialized from GFS-EnKF (NOAA/ESRL) ensemble
  - Initial ensemble is spun up for 3-4 h before assimilation begins
  - 30 ensemble members

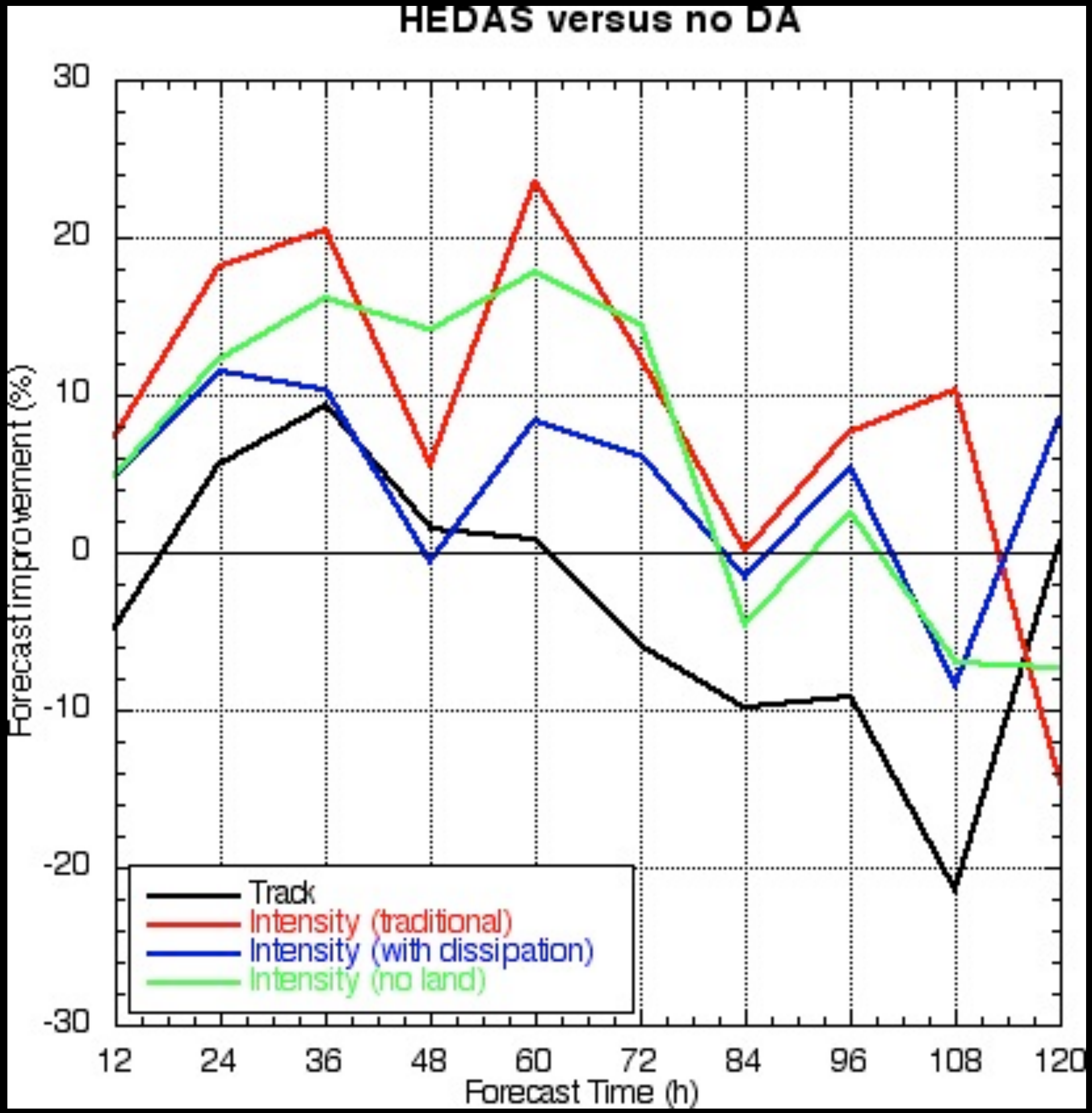
- **Data assimilation:**
  - Square-root ensemble Kalman filter, EnKF (Whitaker and Hamill 2002)
  - Assimilates all realtime aircraft data on the inner nest
    - ➔ NOAA P-3, NOAA G-IV, USAF C-130
  - Covariance localization (Gaspari and Cohn 1999)

Intensity verification techniques

1. Traditional - mean of the absolute values of the differences between the forecast and the best track when both exist.

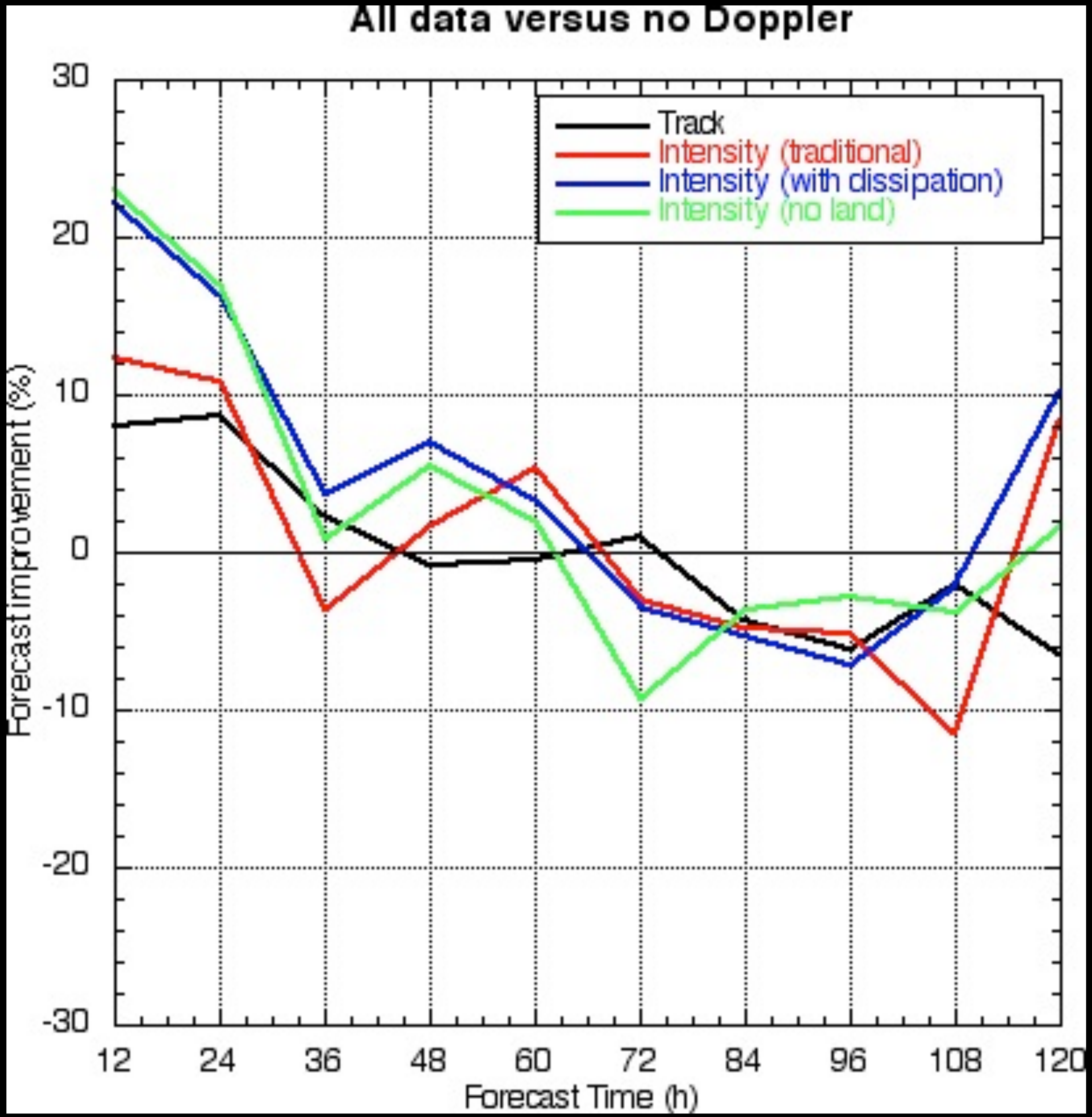
2. Including cases in which either the real storm or the model storm dissipated. Because the model forecasts intensities as low as 12 kt, I chose to make the forecast or best track intensities of dissipated systems 10 kt instead of 15 kt as James Franklin uses.

3. Only including cases in which both the model and real storms were over water. This eliminated cases in which large intensity differences were due to differences in track, not due to changes in the initial conditions.



The Data Assimilation improves track forecasts by up to 10% at 24-36 h versus no DA. [The poor result at 108 is due to a very few Ike forecasts. The majority of the forecasts at 108 h are improved.]

The Doppler data improves intensity forecasts by 5-25% during the first three days versus no DA.



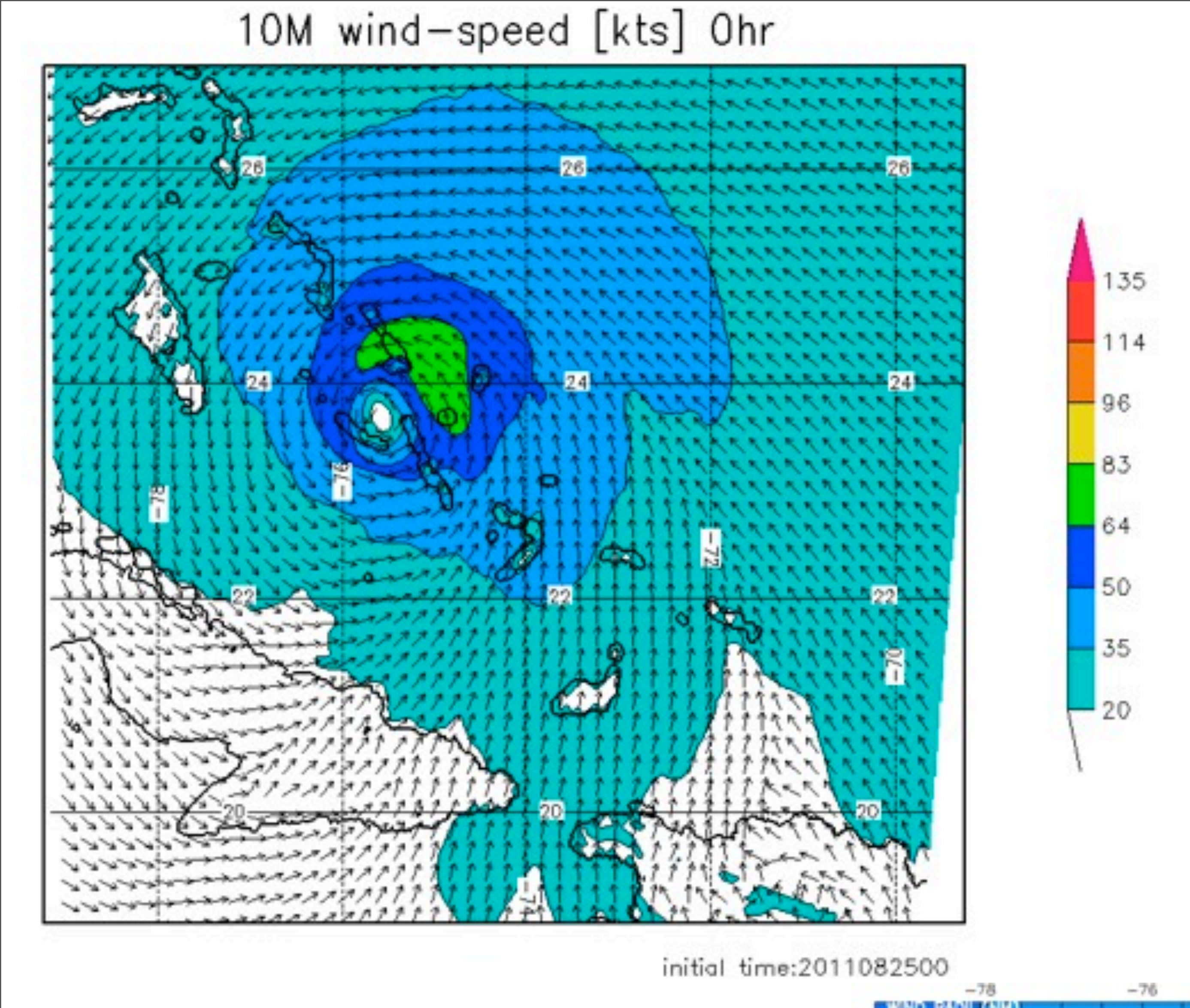
The Doppler data improves track forecasts by up to 10% in the first 24 h versus using only HDOBS and dropwindsonde data.

The Doppler data improves intensity forecasts by 5-25% during the first 24-36 h versus using only HDOBS and dropwindsonde data.

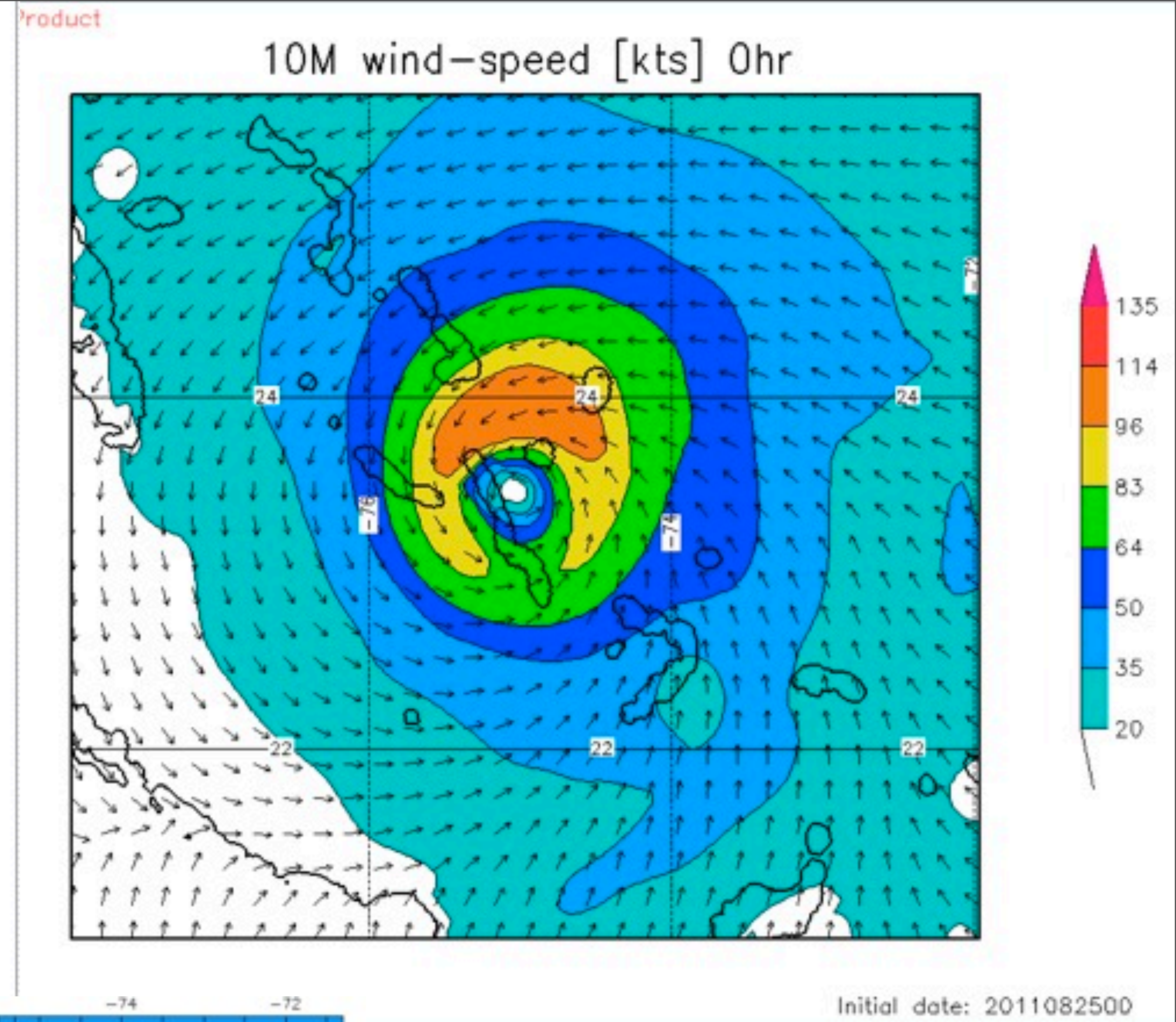
Conclusion from retro runs

The data assimilation itself and the Doppler data are both important tools to improve short-range track and intensity forecasts in regional models.

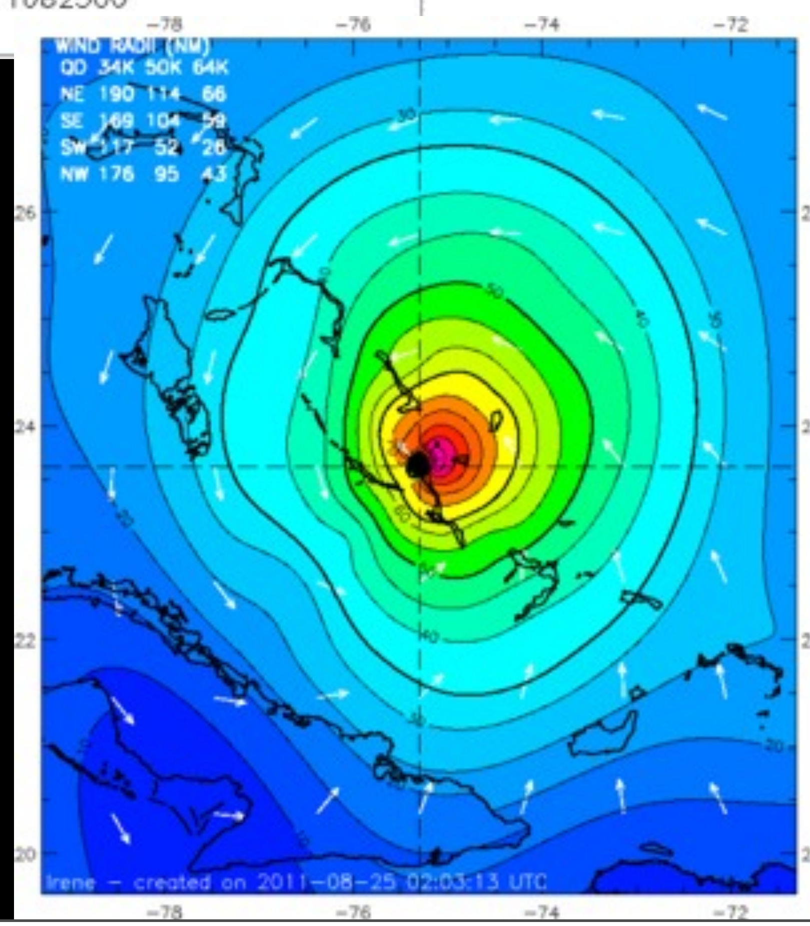
Most of the improvement at early times comes from the assimilation of the Doppler data. By 48 h, the impact of the Doppler itself wanes, but the improved conditions by that time in the model keeps the improvements for a longer time period.



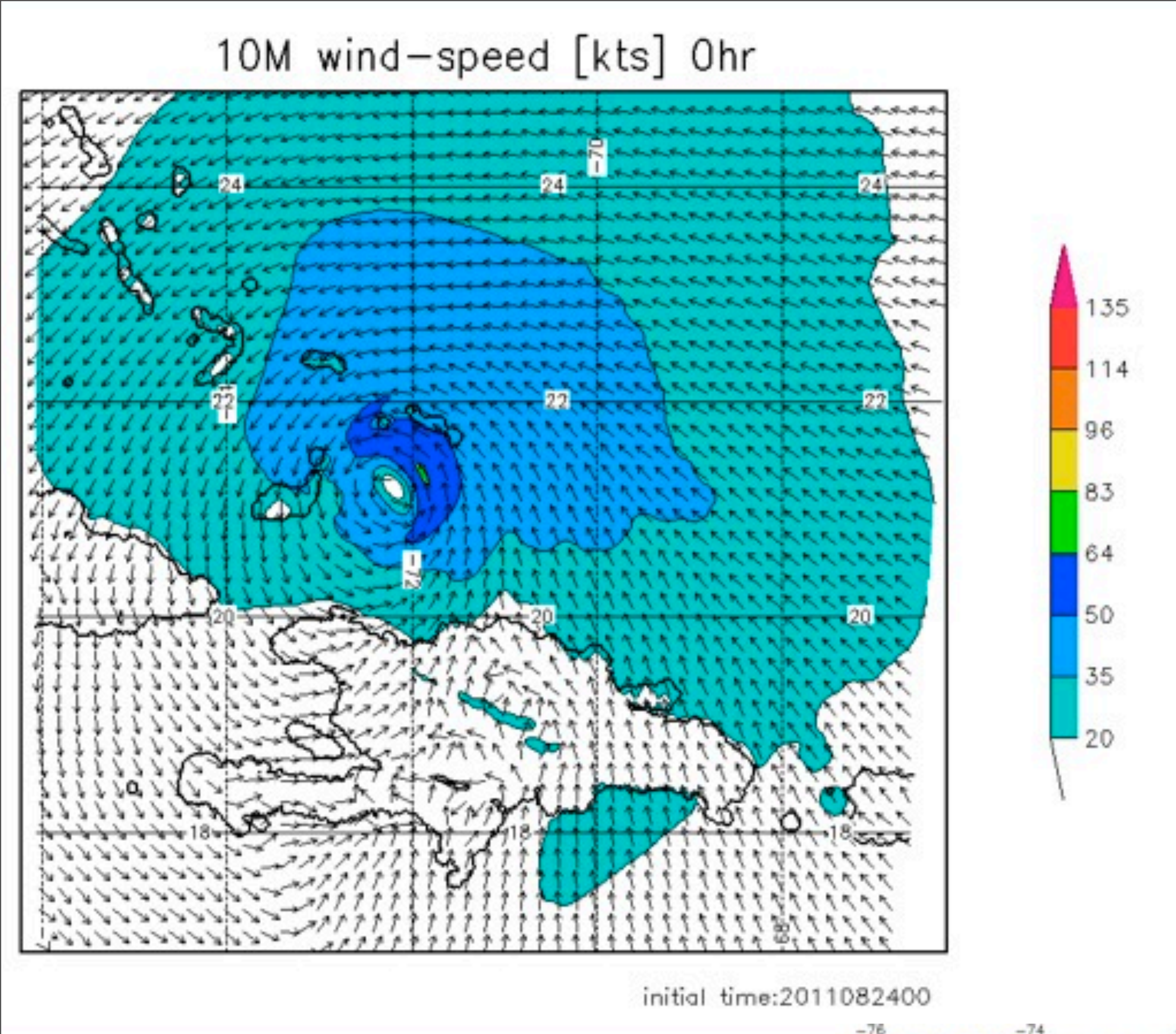
HEDAS

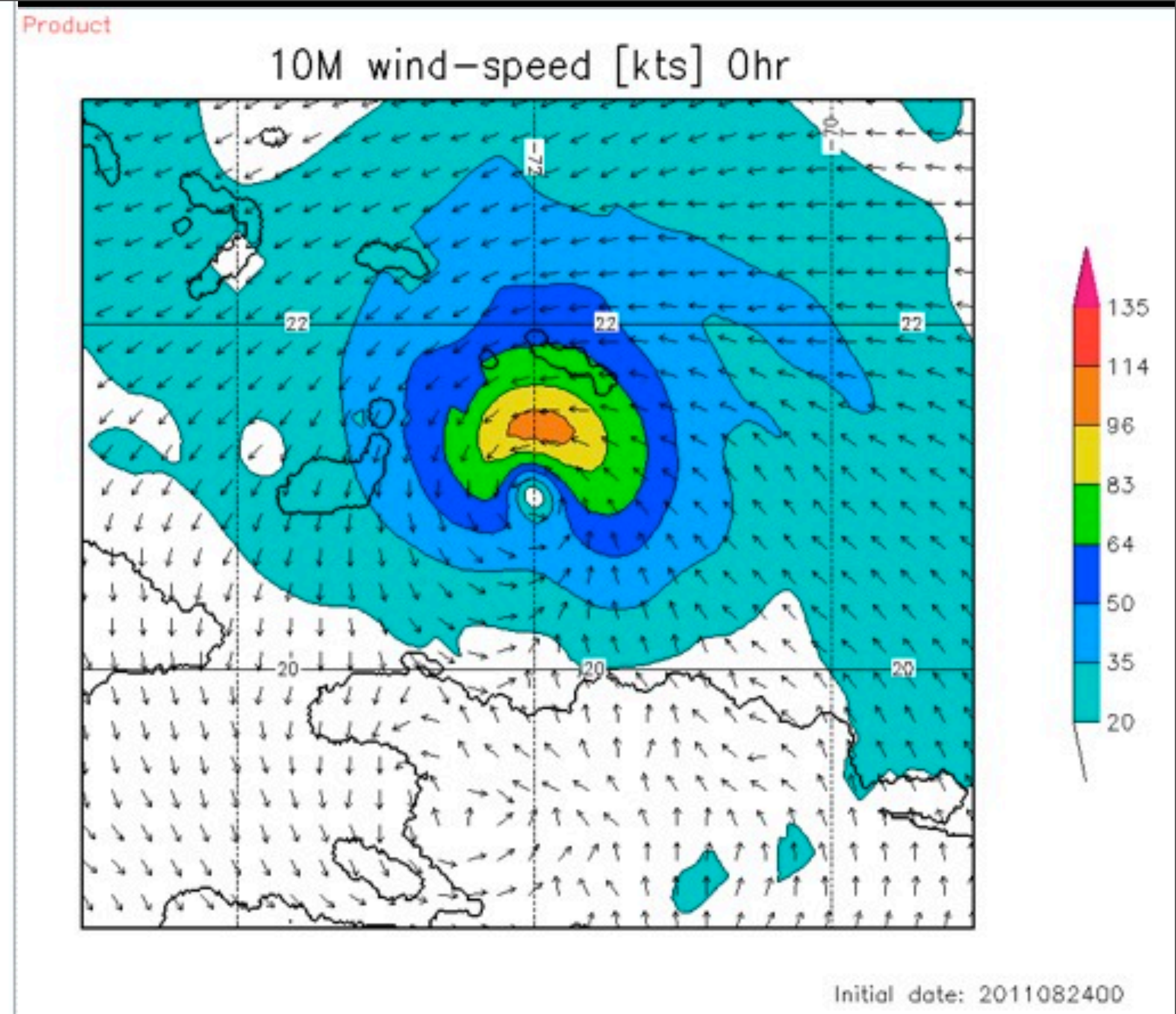


hwrf-noaahfip (3km)

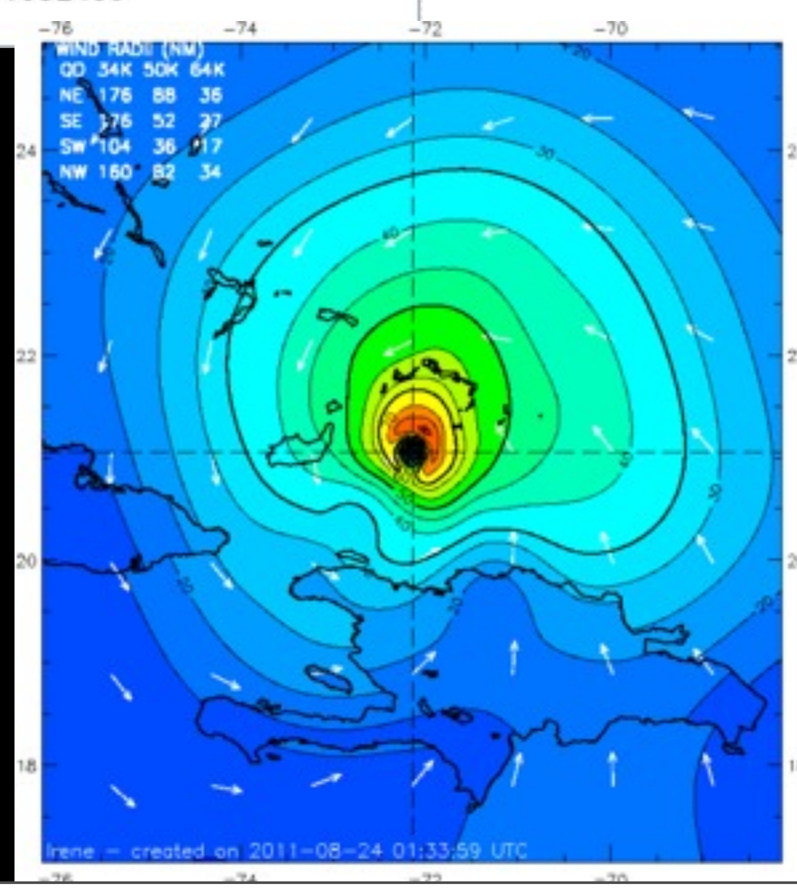


H*Wind



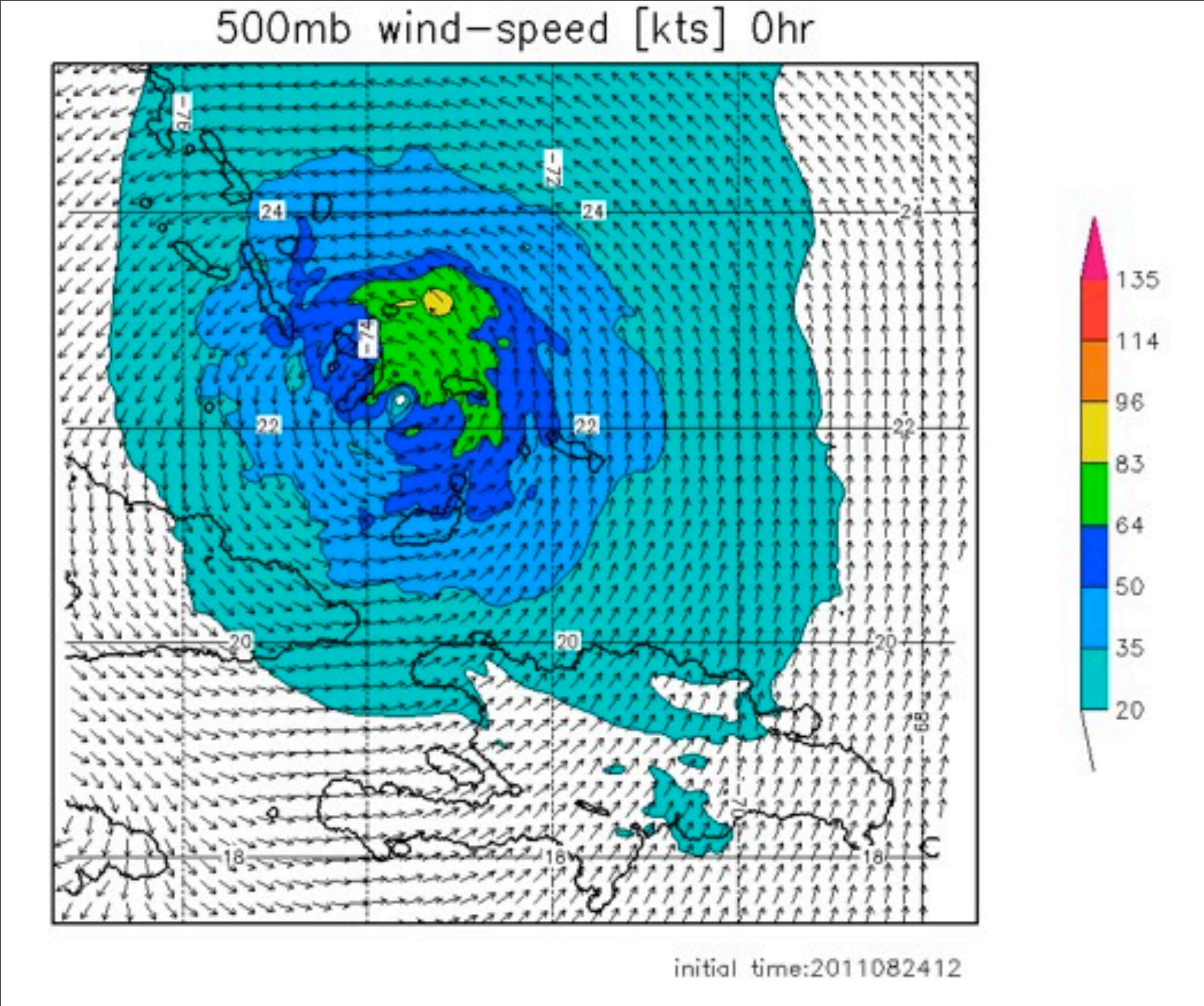


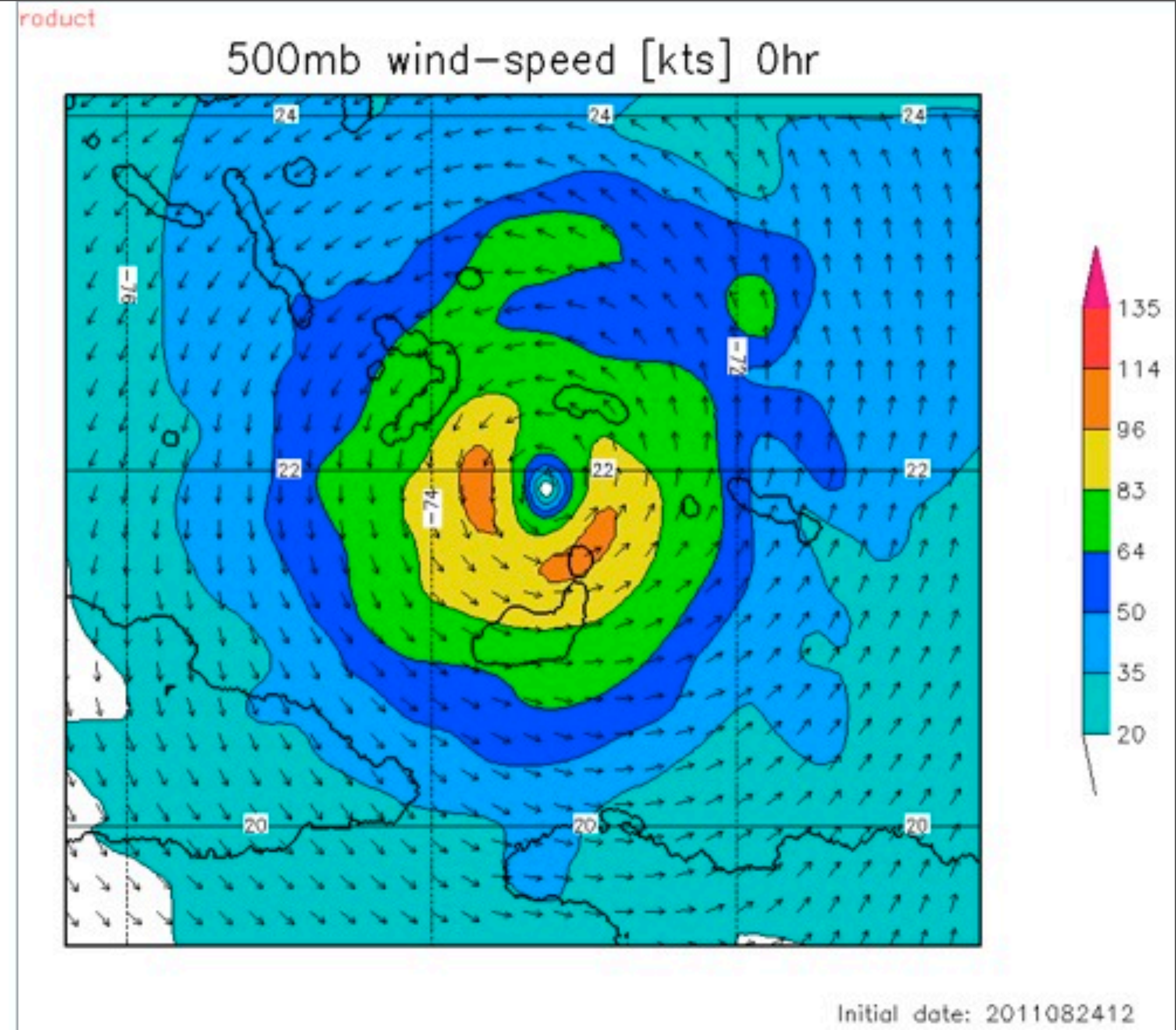
HEDAS



hwrf-noaahfip (3km)

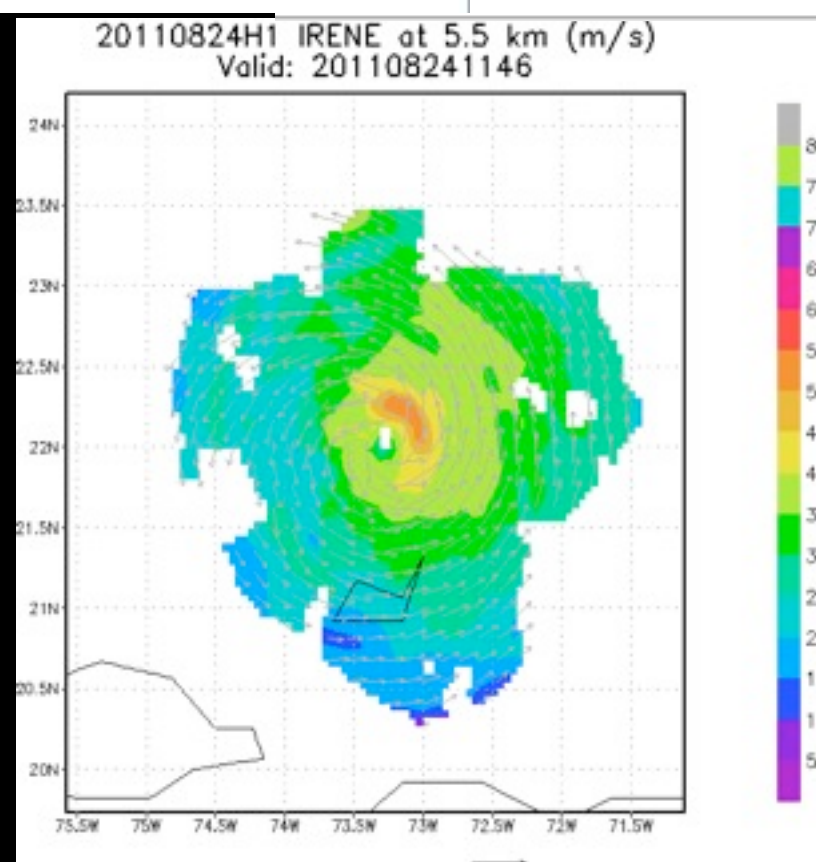
H*Wind



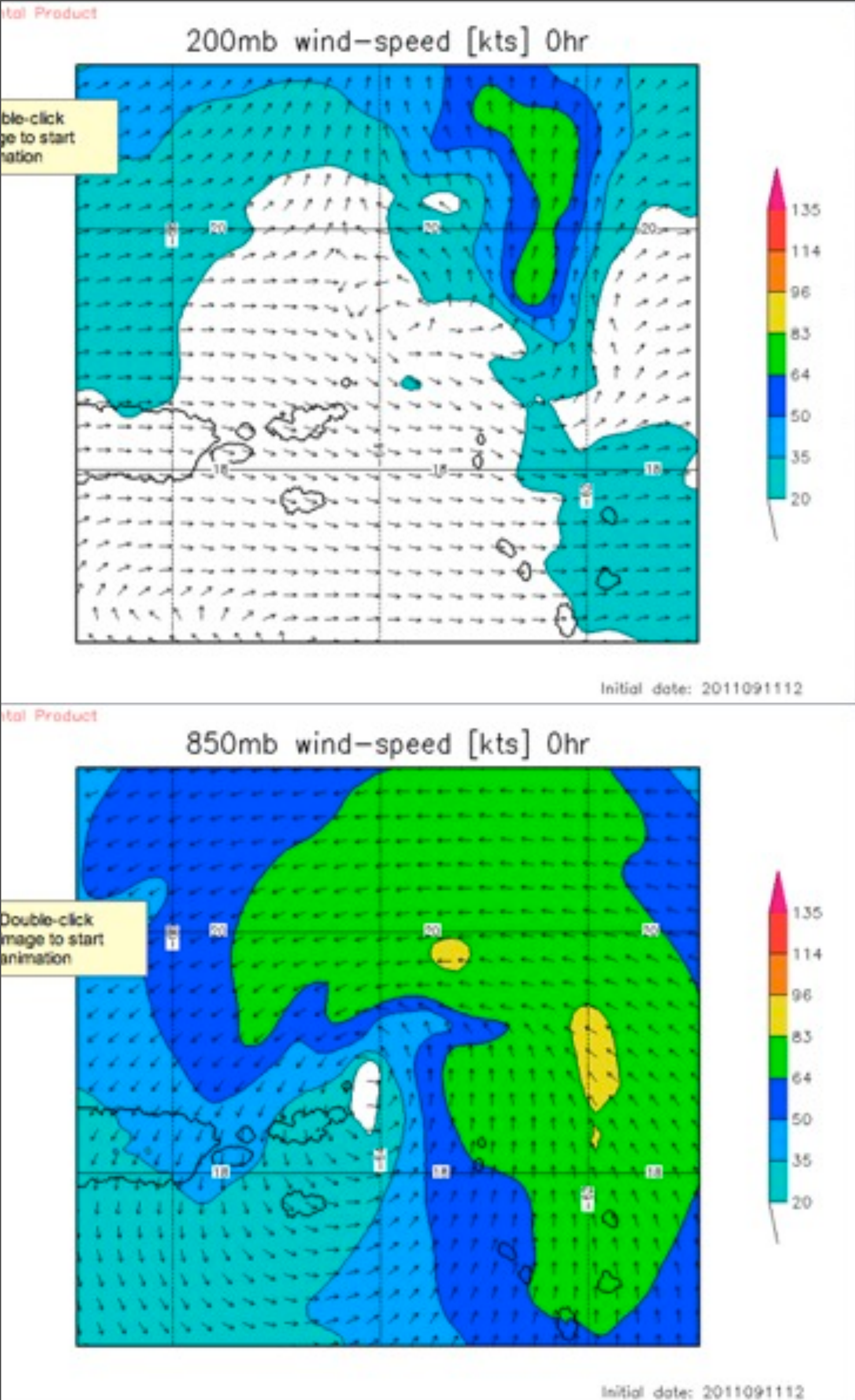


HEDAS

hwrf-noaahfip (3km)



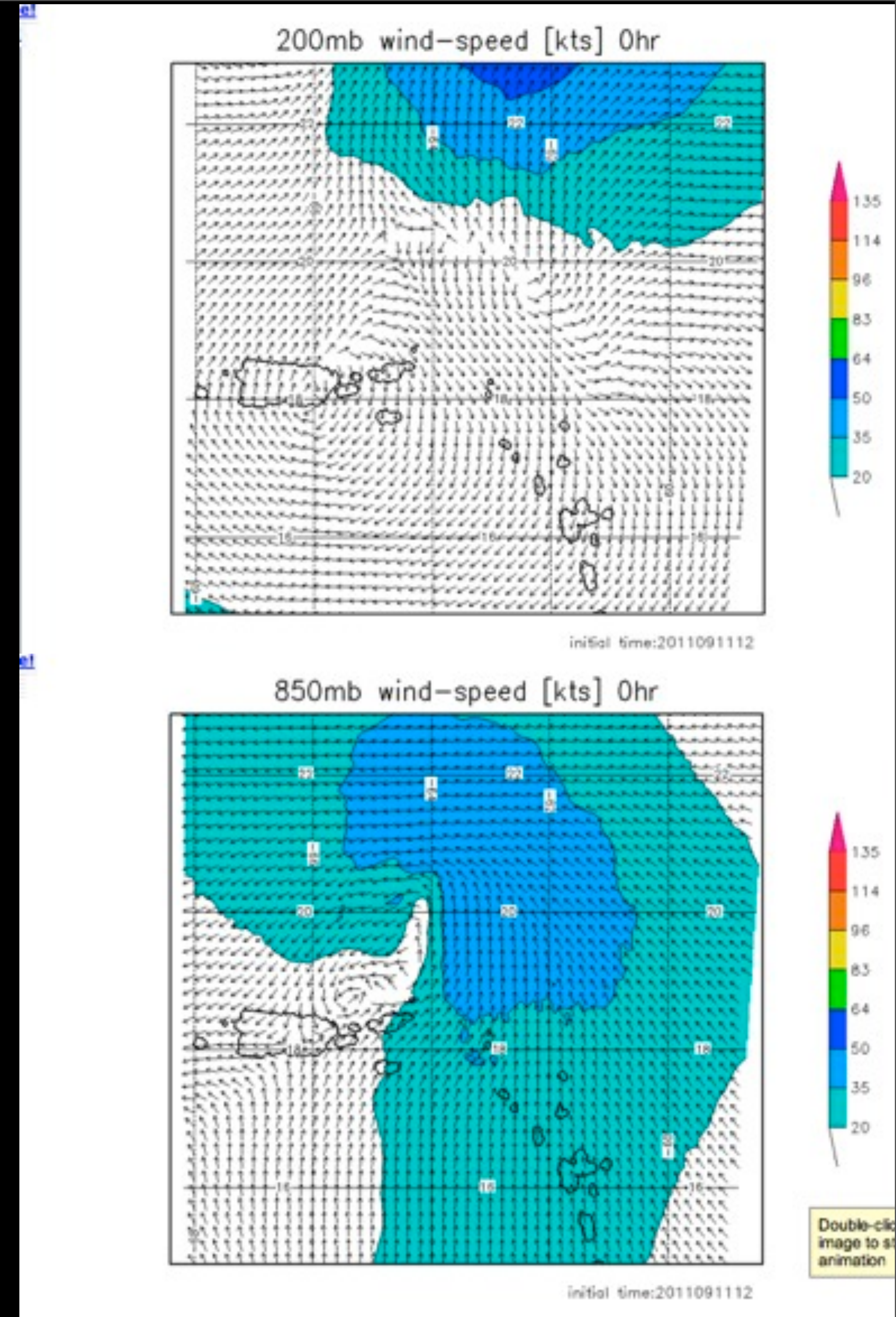
Radar composite



HWRF Stream1.5

Tropical Storm Maria was a difficult case for 2011

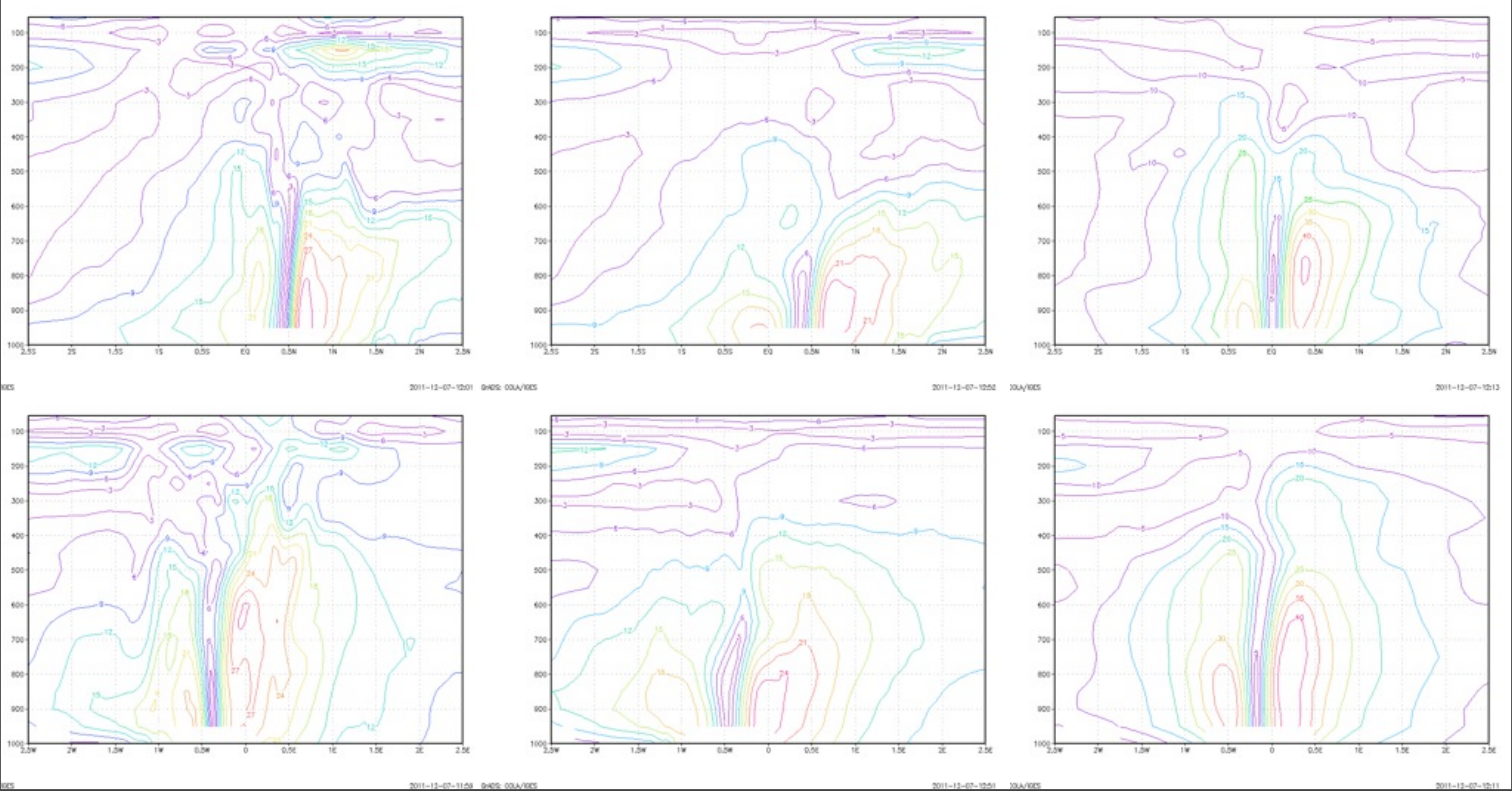
Only Air Force flight-level (850 hPa) data in HEDAS. Very different initial conditions, very different forecast.



HEDAS

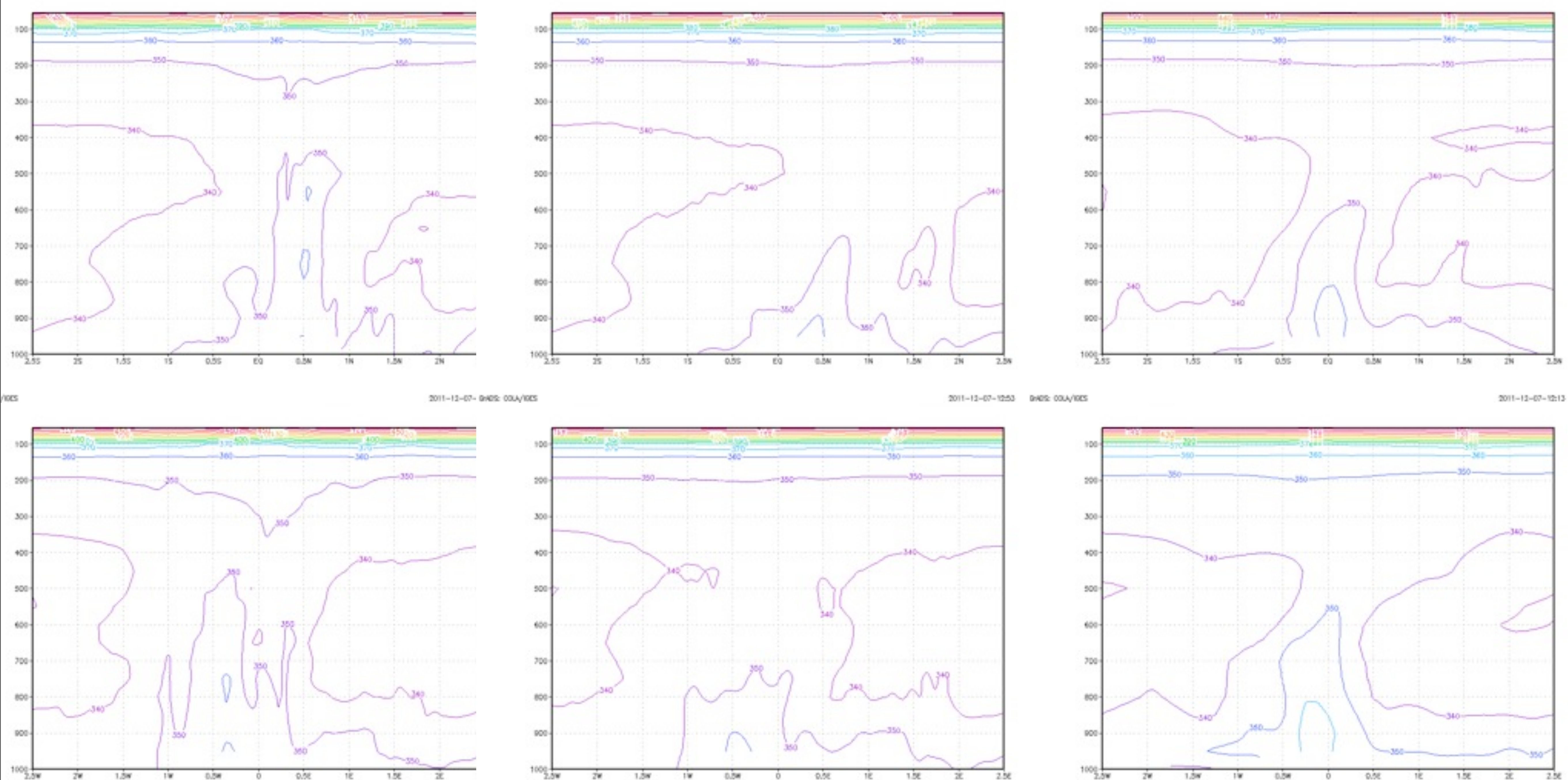
Rina 2011102712
wind speed cross sections

HEDAS all data | HEDAS no Doppler | No DA



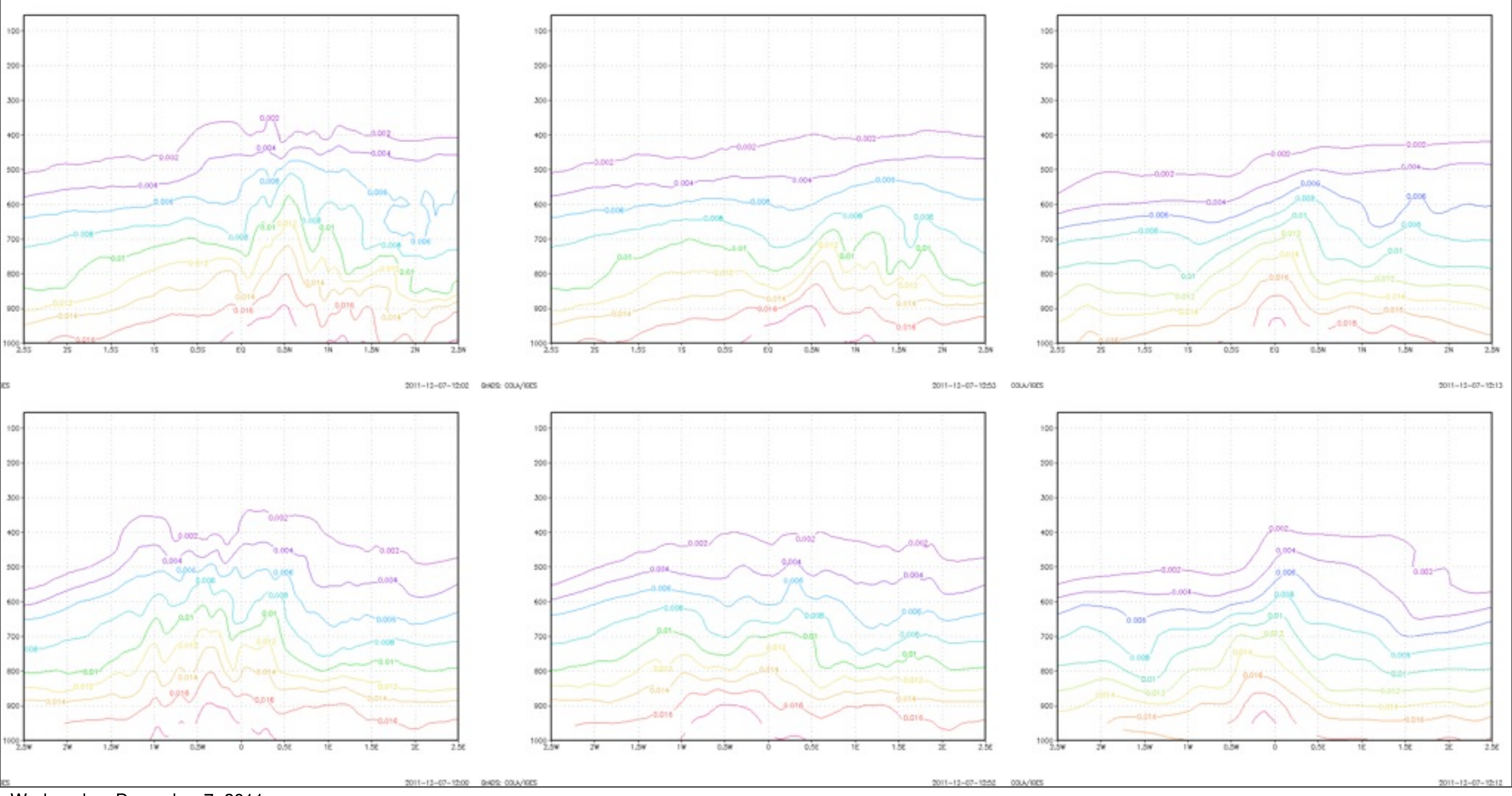
Rina 2011102712
θ_e cross sections

HEDAS all data | HEDAS no Doppler | No DA



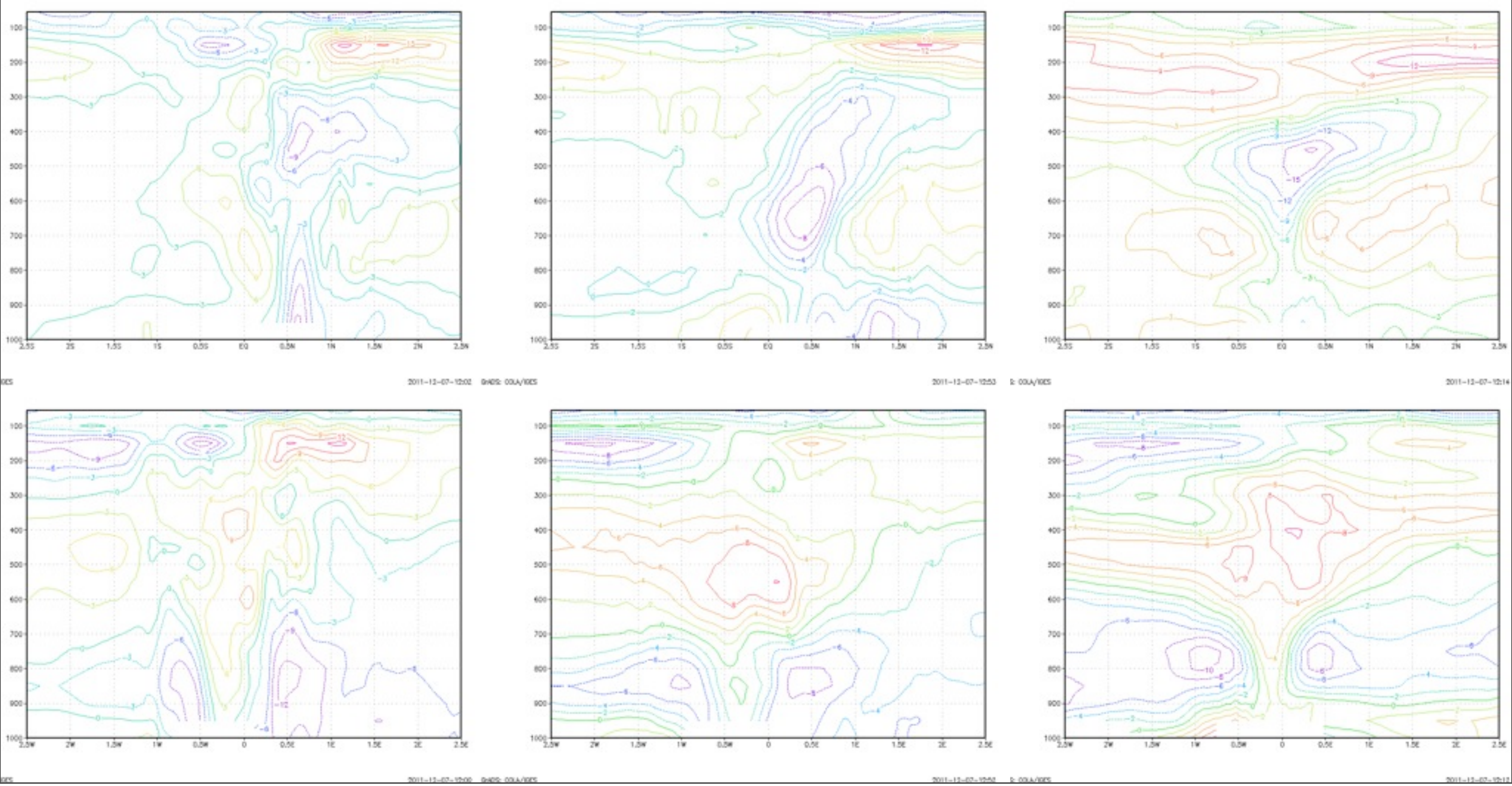
Rina 2011102712
specific humidity cross sections

HEDAS all data | HEDAS no Doppler | No DA



Rina 2011102712 radial wind cross sections

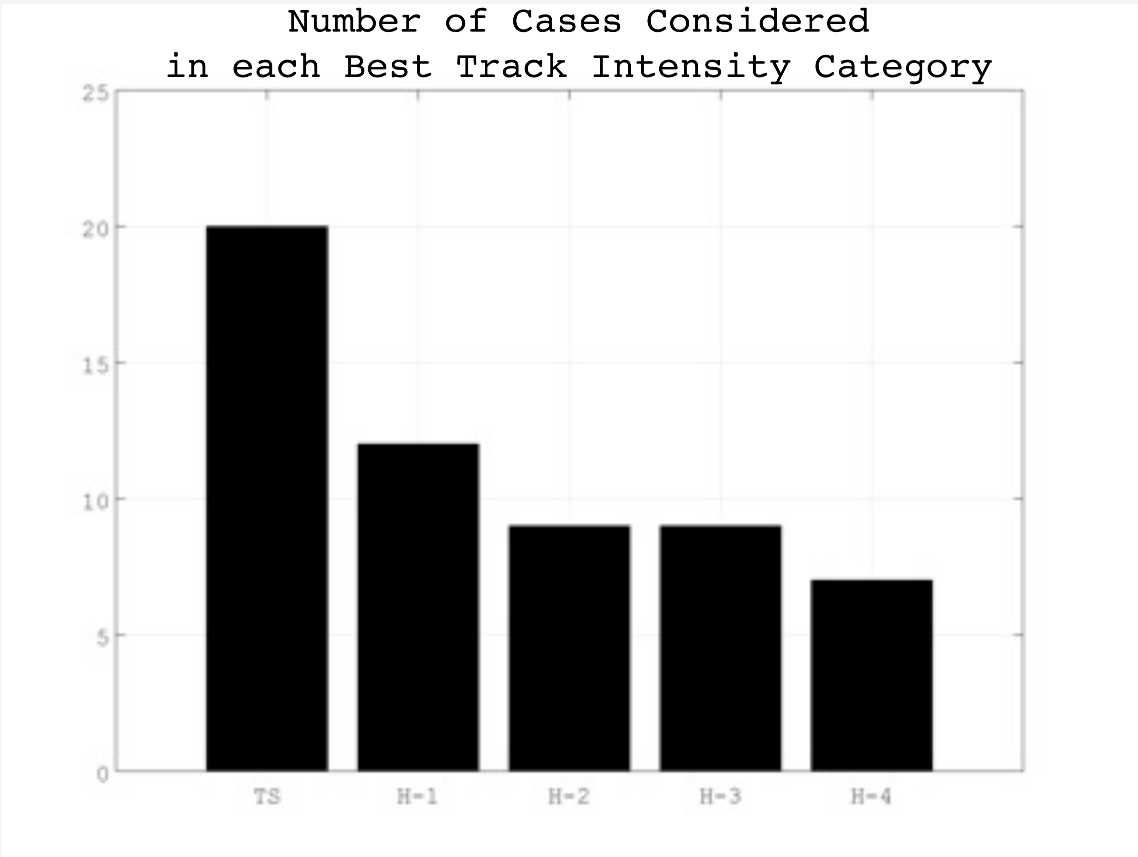
HEDAS all data | HEDAS no Doppler | No DA



HEDAS ANALYSIS STATISTICS (2008-2011)

by Altug Aksoy (NOAA/AOML/HRD)

- HEDAS retrospective/real-time analyses have been performed for 2008-2011
- Only cases that were at least tropical storm intensity in the best track are considered: 52 total cases (so far)
- HEDAS assimilated Doppler wind speed, flight-level, SFMR, and dropwindsonde data
- 30 ensemble members
- HWRF 3.1 at 9/3-km resolution
- Caveat: Observation error for specific humidity observations was set too high, which effectively led to these observations to not have much impact on analyses

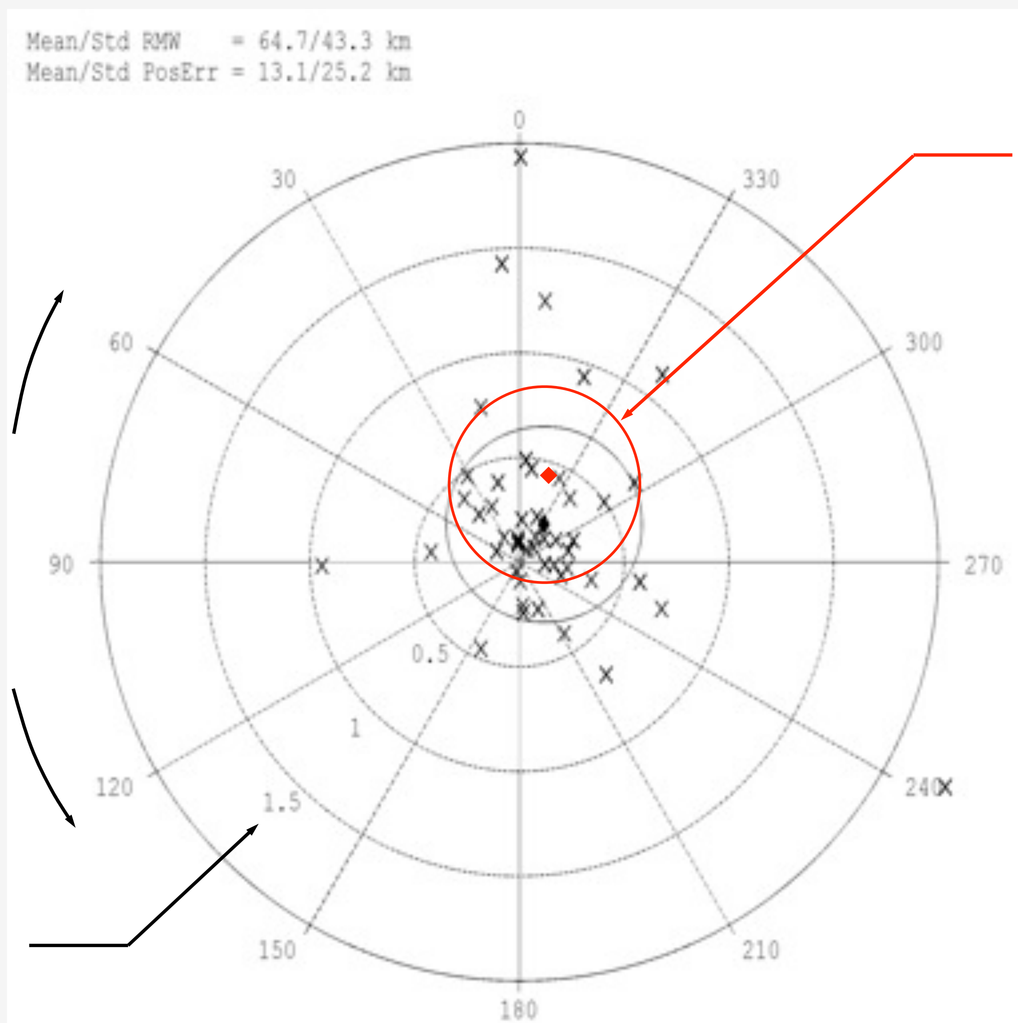


POSITION ERROR STATISTICS for HEDAS FINAL MEAN ANALYSIS

- Position error is computed with respect to HRD's high-resolution center fixes database
- Position error is computed relative to best track storm motion direction

X = Position error in each case

Degrees relative to storm motion



RMW-relative distance from observed center

Mean and standard deviation of the position error in RMW-relative terms is:

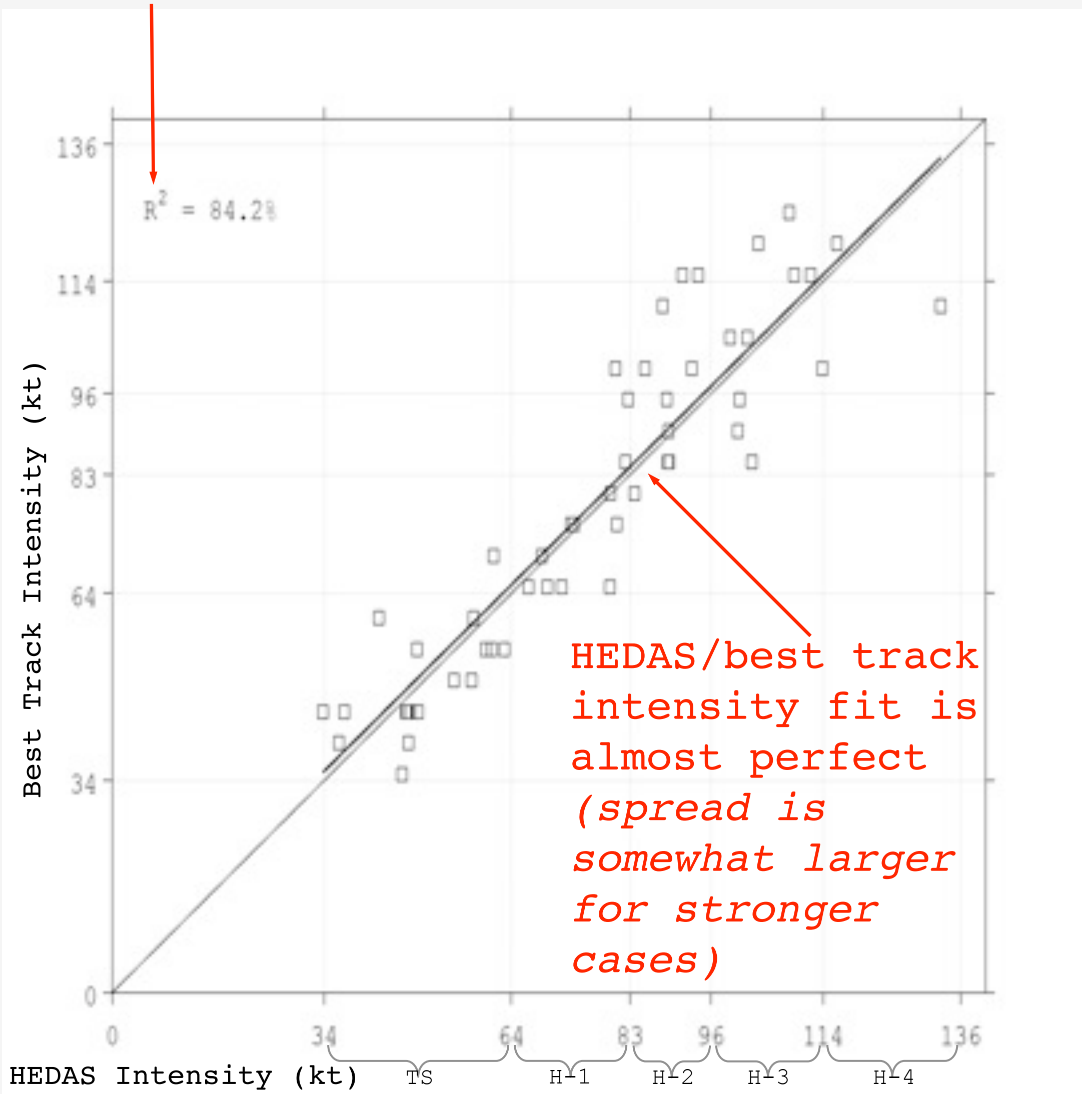
Mean error = 0.2 RMW
Std. dev = 0.5 RMW

(0° = direction of storm motion) and relative to RMW (r=1 corresponds to 1 RMW)

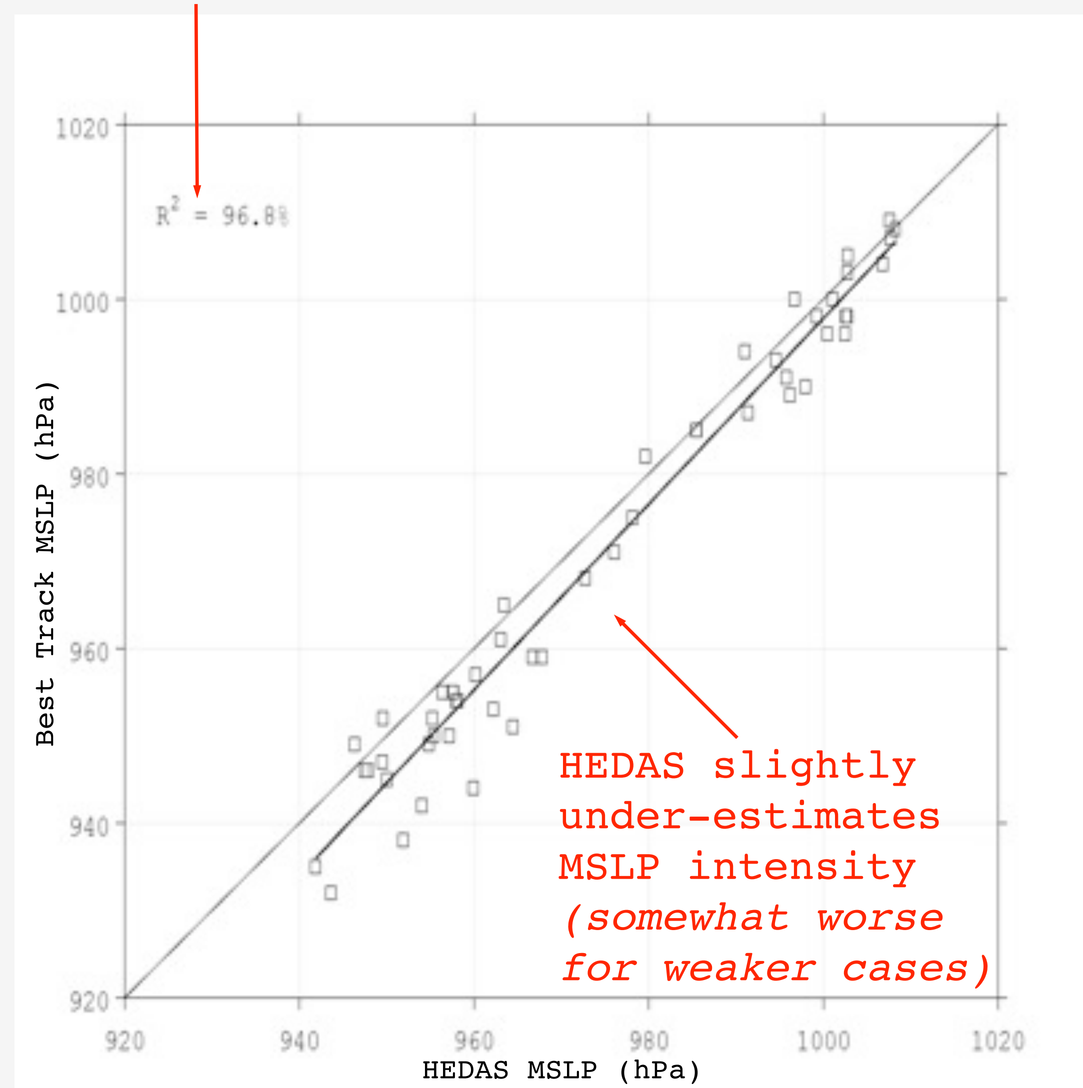
INTENSITY ERROR STATISTICS for HEDAS FINAL MEAN ANALYSIS

- HEDAS intensities (max. 10-m wind speed and min. sea-level pressure) versus **best track intensities** for each case

HEDAS intensity explains **84%** of the variance of best track intensity



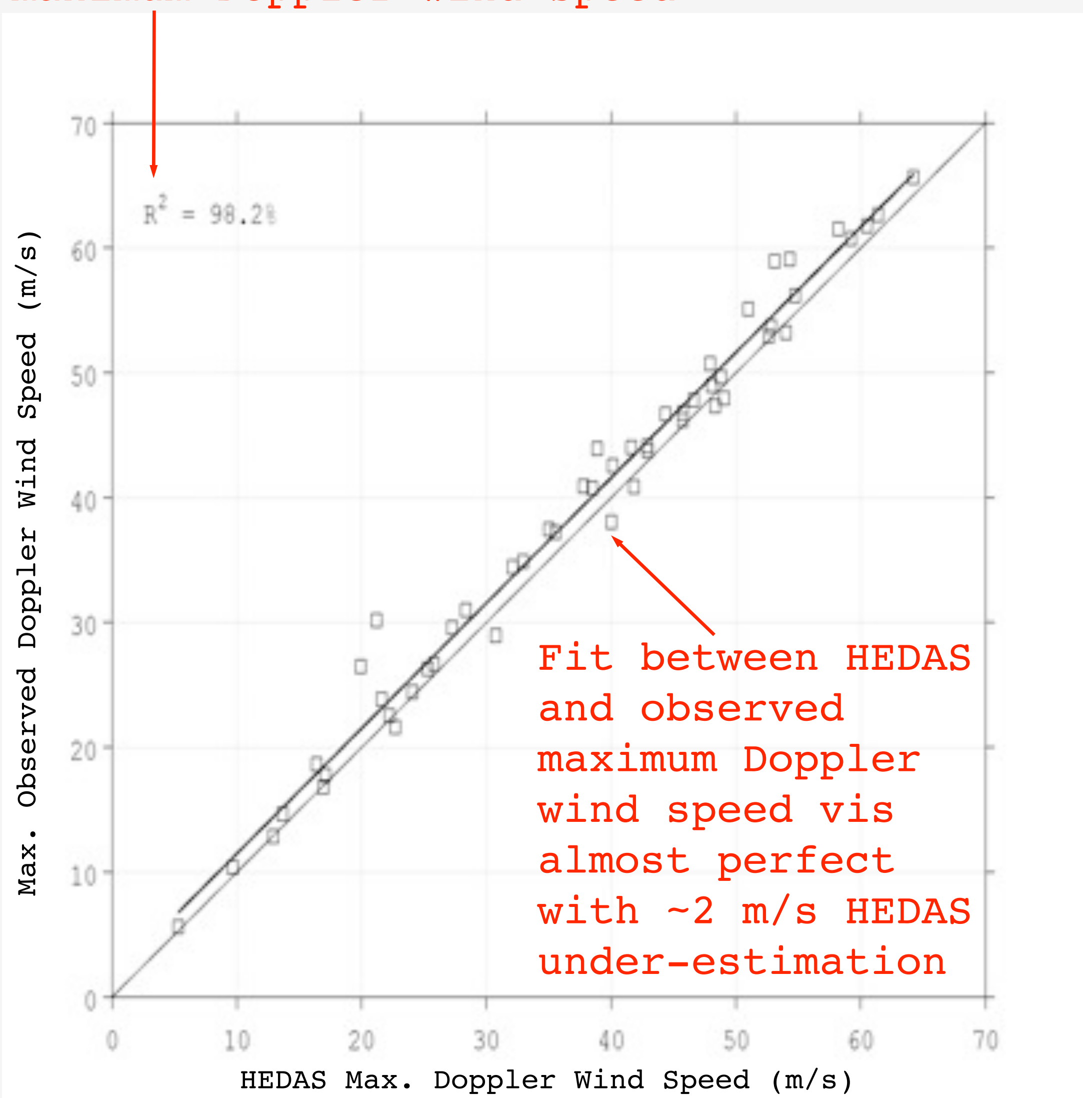
HEDAS MSLP explains **97%** of variance of best track MSLP



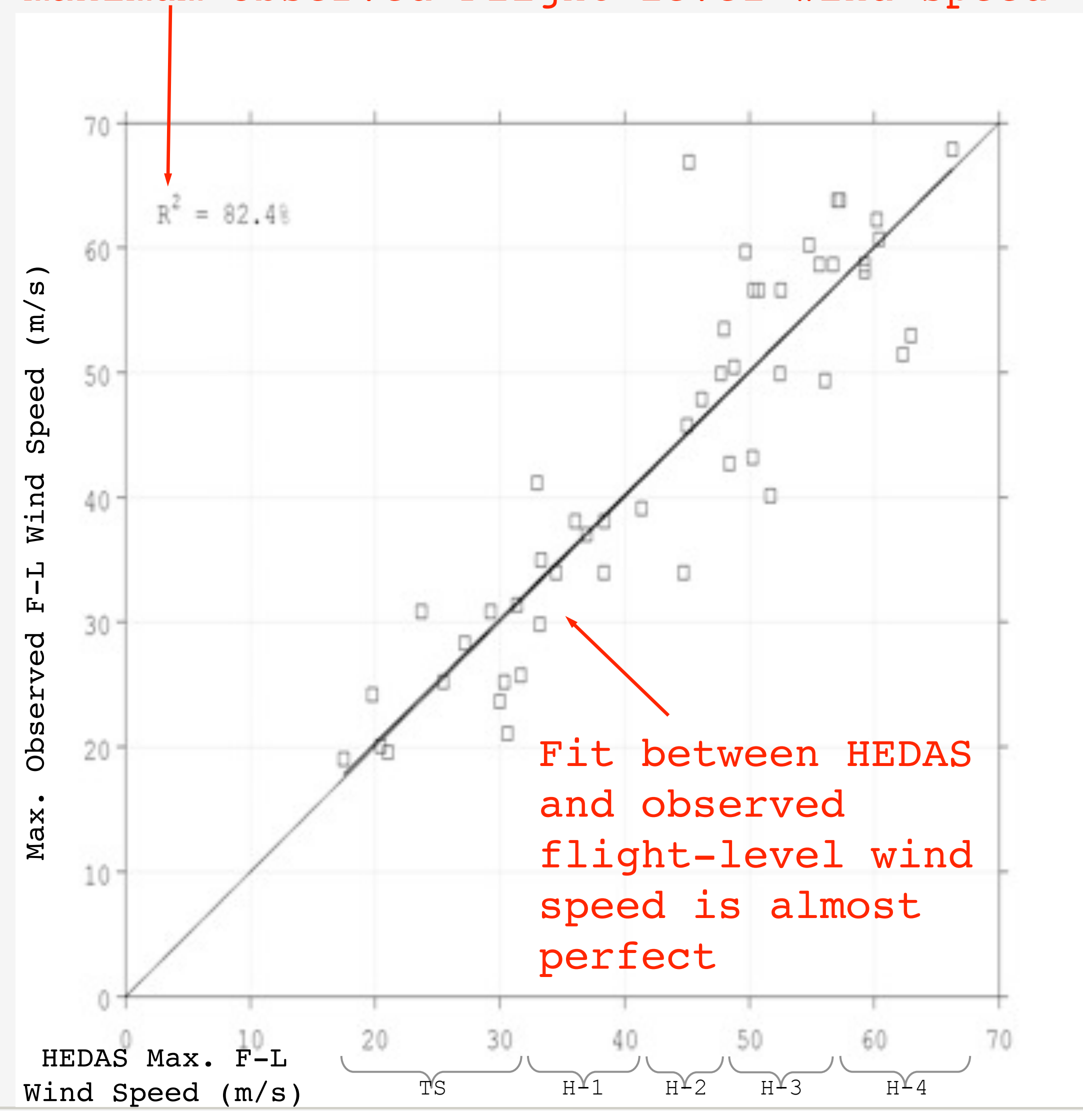
INTENSITY ERROR STATISTICS for HEDAS FINAL MEAN ANALYSIS

- **Observed** maximum Doppler and flight-level wind speeds versus **HEDAS analyzed values** for each case

HEDAS maximum Doppler wind speed explains **98%** of the variance of the observed maximum Doppler wind speed

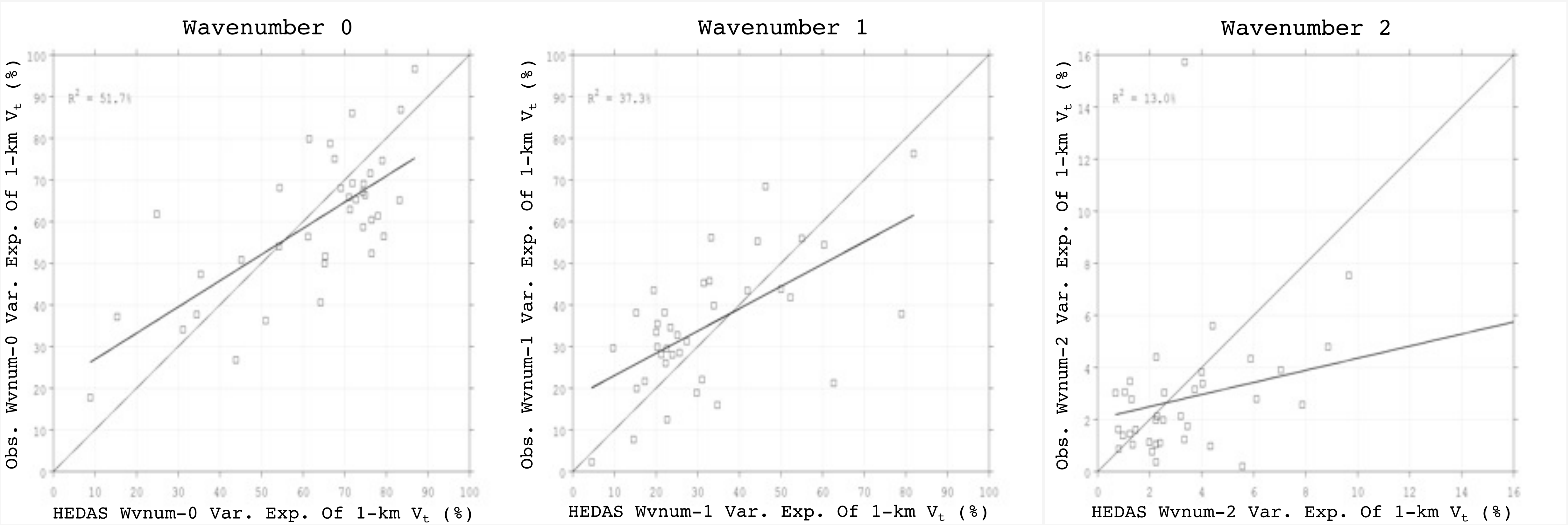


HEDAS maximum flight-level wind speed explains **82%** of the variance of the maximum observed Flight-level wind speed



STORM STRUCTURE STATISTICS for HEDAS FINAL MEAN ANALYSIS

- **Variance explained by wavenumber 0-2 components of the azimuthally-averaged tangential wind** for HEDAS final mean analyses versus corresponding Doppler radar observations

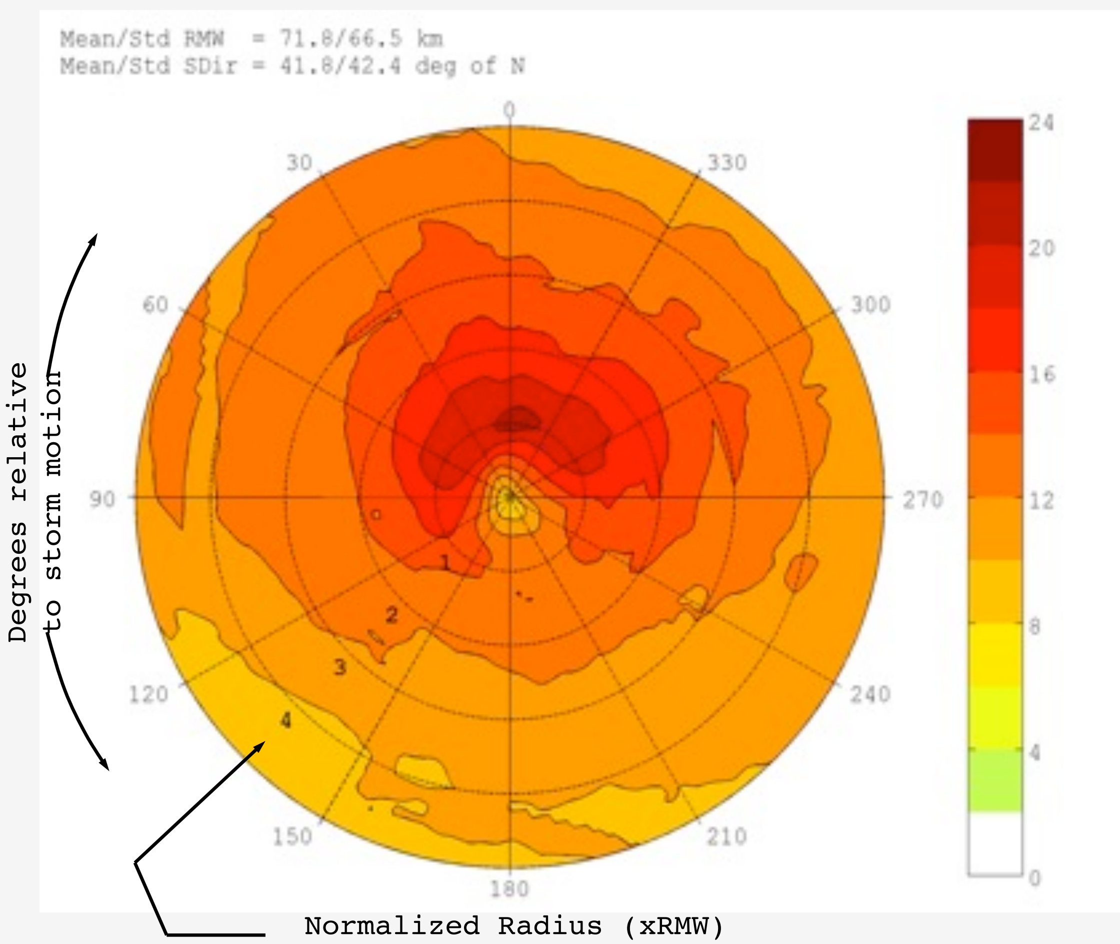


Variance of V_t explained by HEDAS gradually diminishes with wavenumber. HEDAS generally appears to be within the observed range.

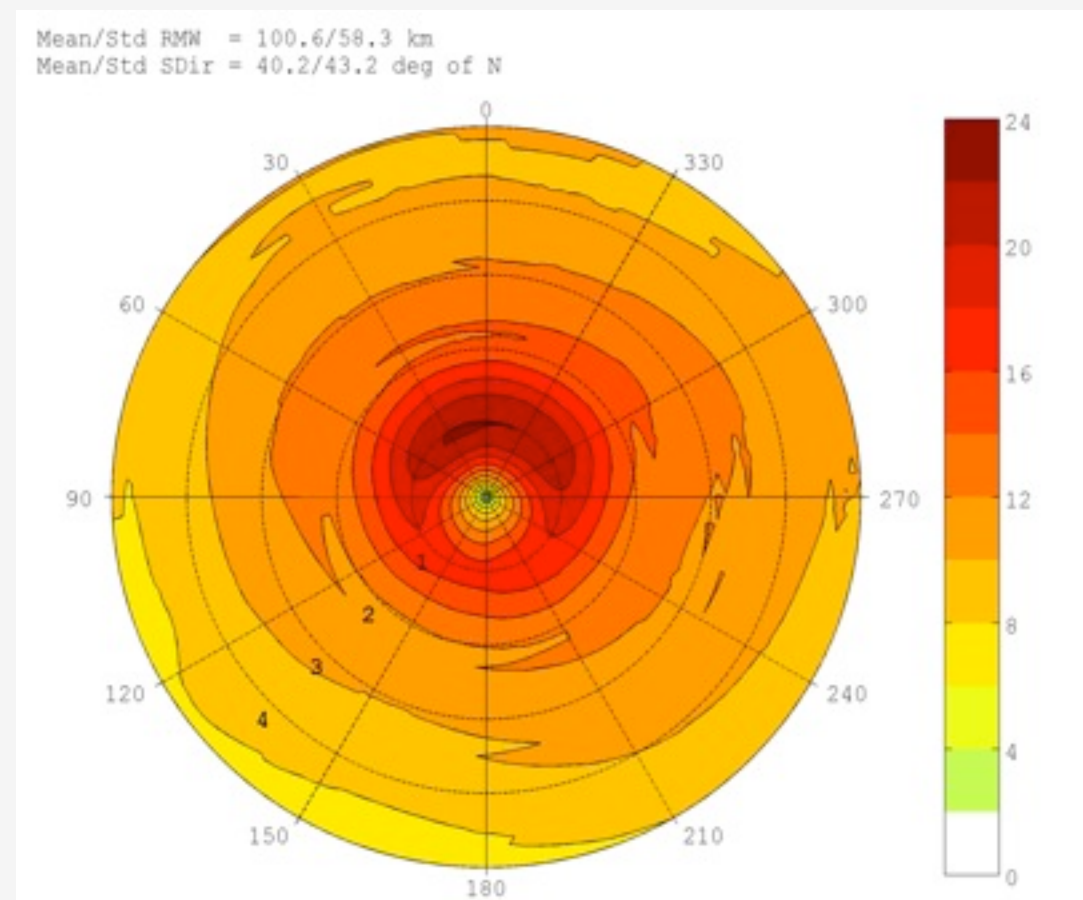
STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite of 10-m surface wind** versus H*Wind (m/s) – tropical storms only

HEDAS



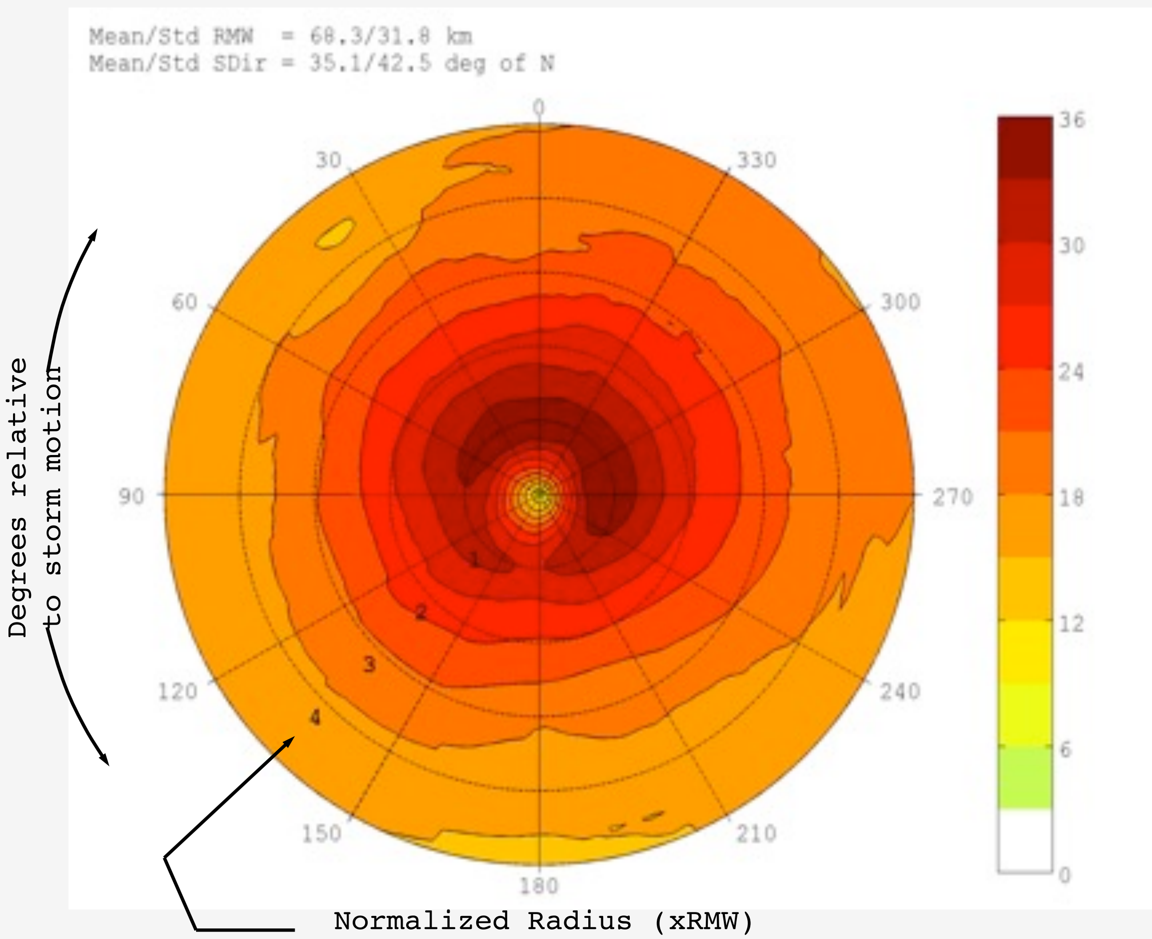
H*Wind



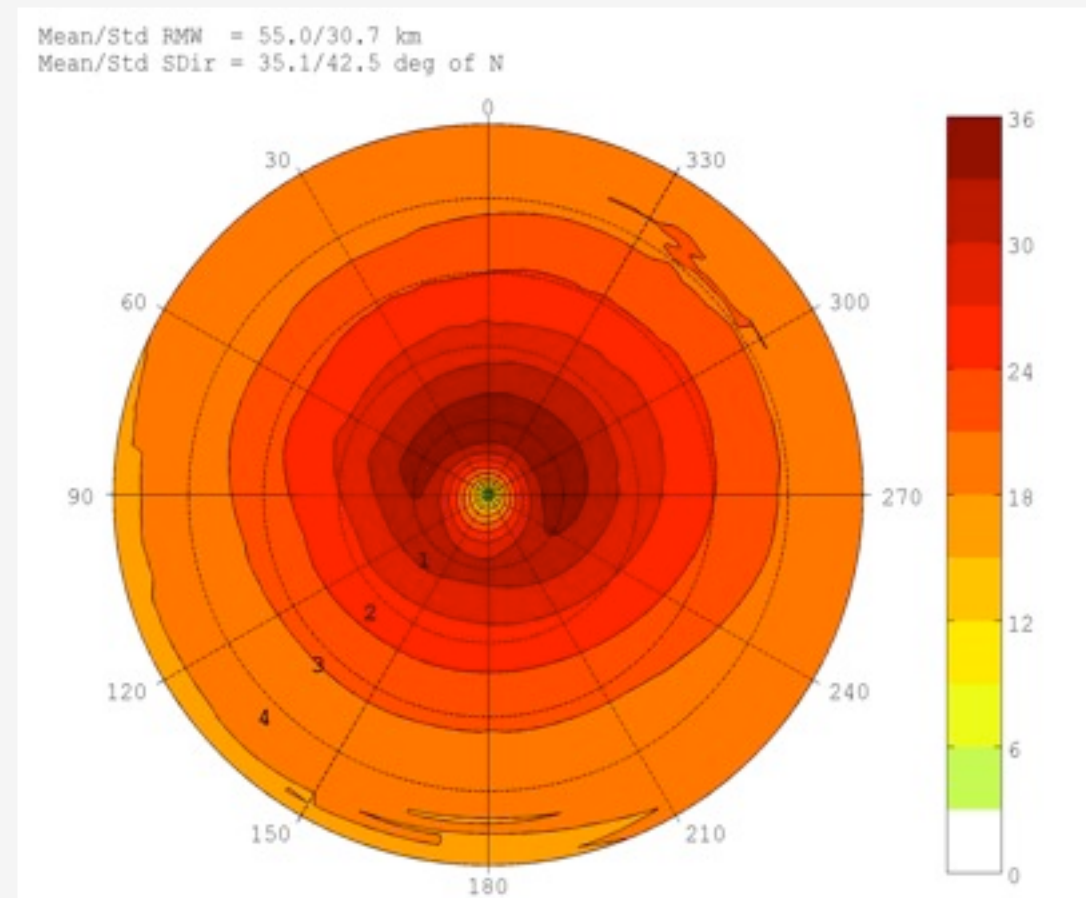
STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite 10-m surface wind speed** (m/s) versus H*Wind - Categories 1-2 only

HEDAS



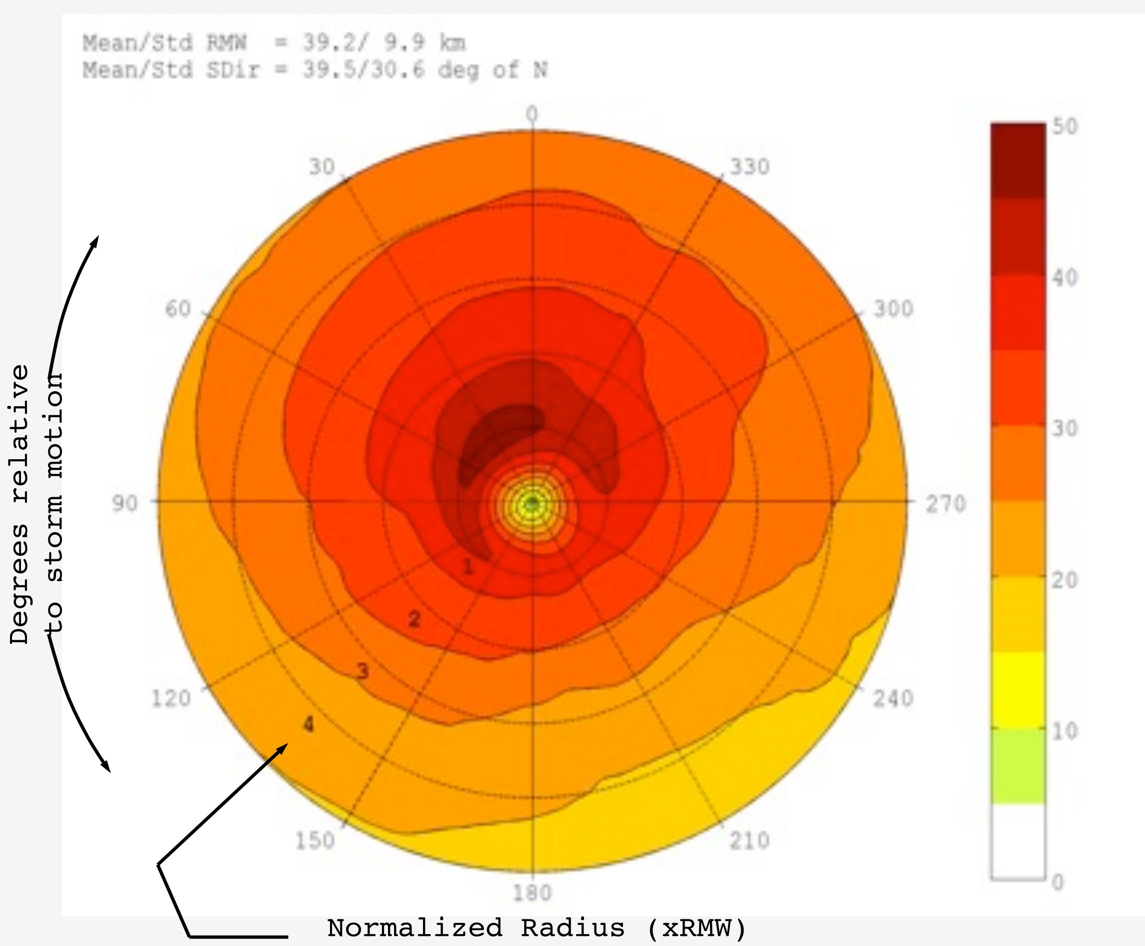
H*Wind



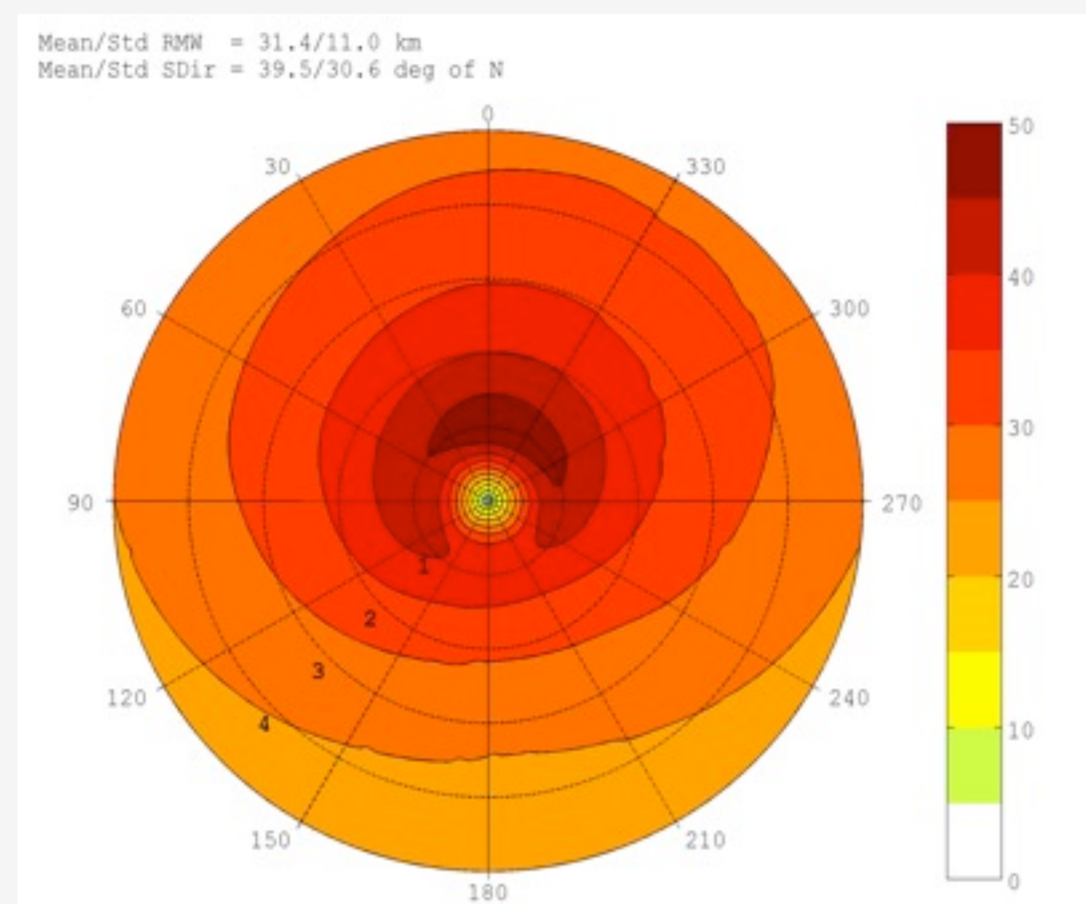
STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite 10-m surface wind speed** (m/s) versus H*Wind - major hurricanes only

HEDAS

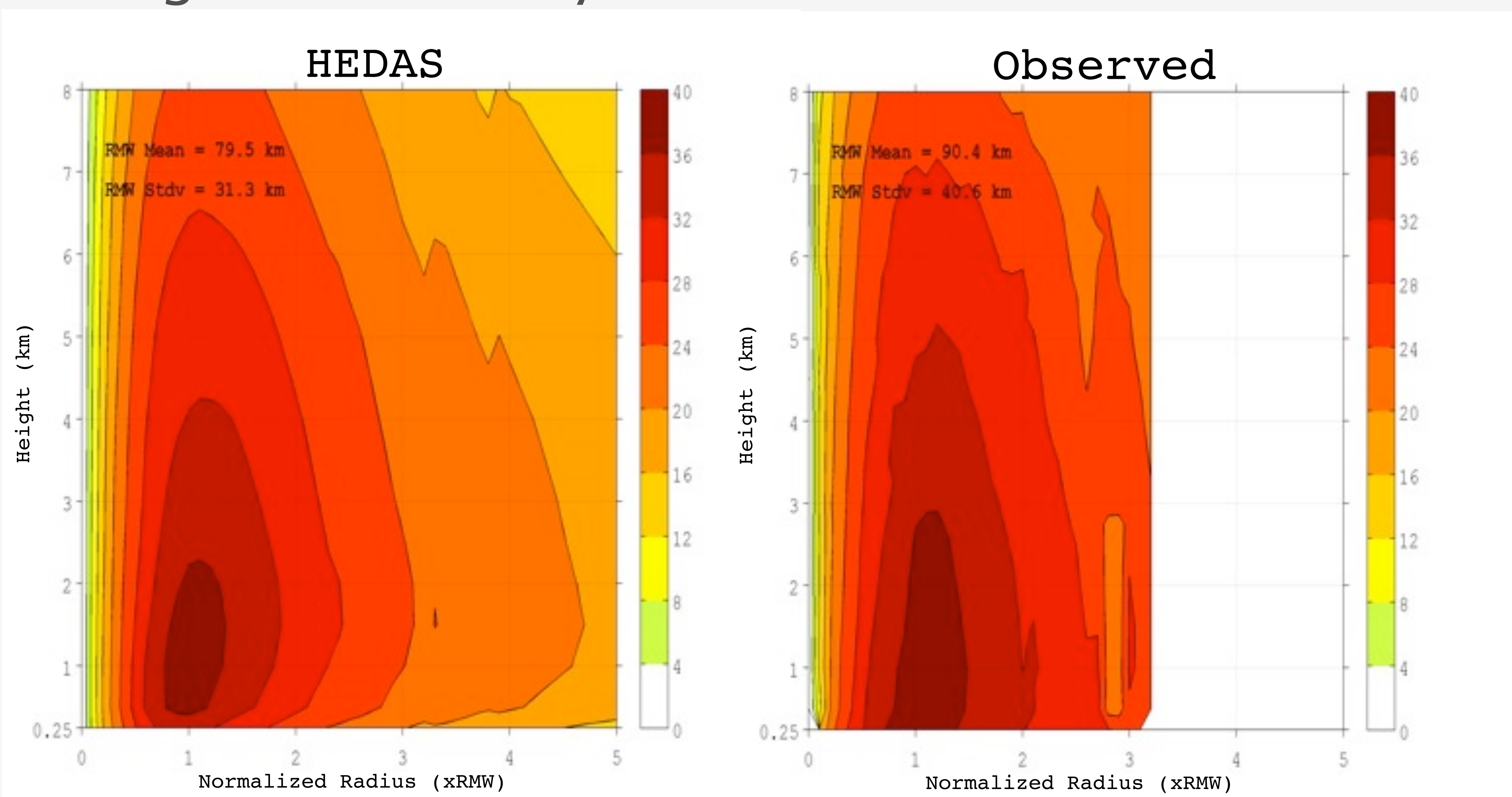


H*Wind



STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

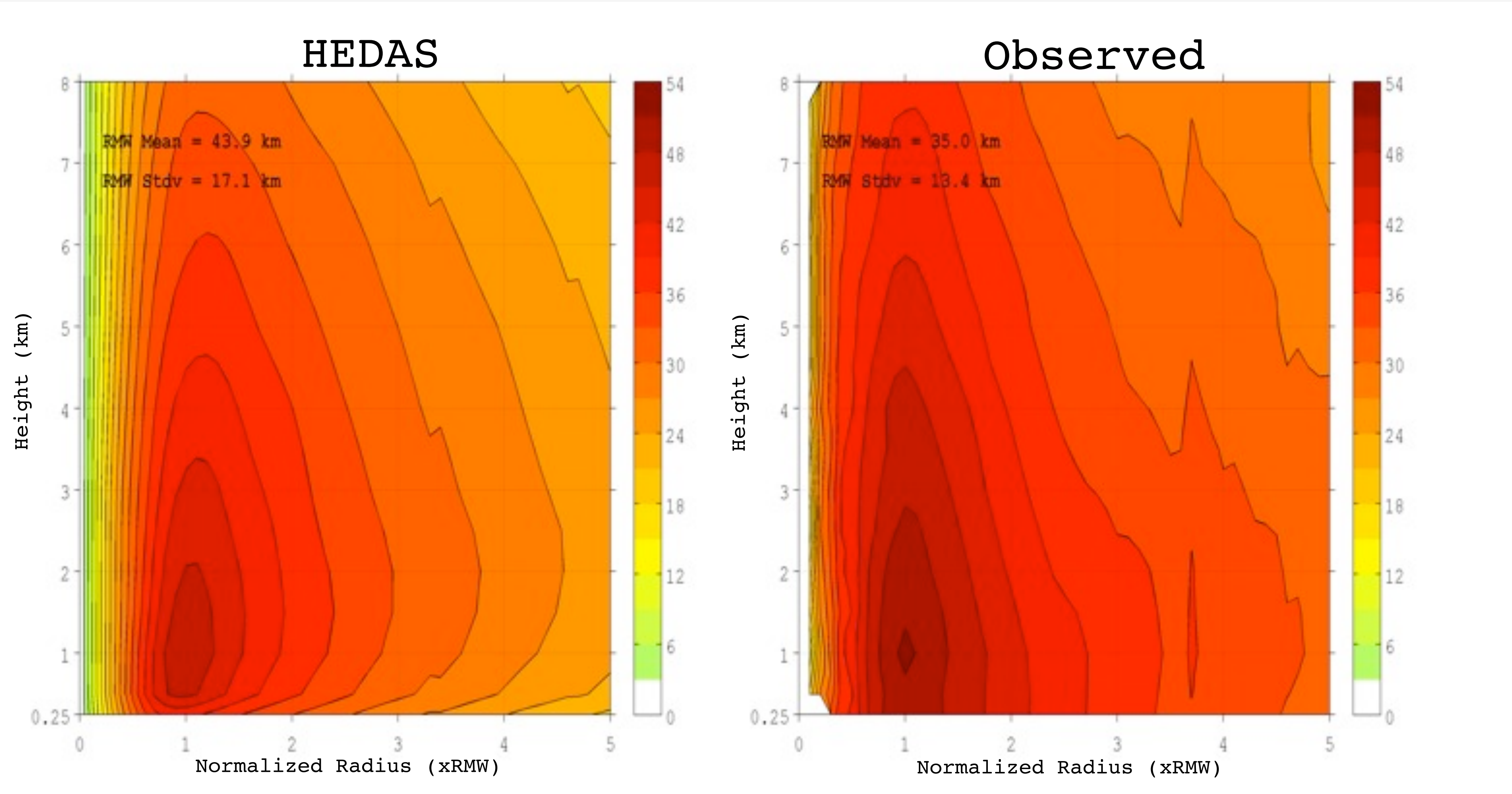
- HEDAS **composite of primary circulation** (azimuthally-averaged tangential wind speed) versus radar observations – categories 1-2 only



HEDAS captures well the observed primary circulation. Mean RMW is within 10 km of observed.

STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

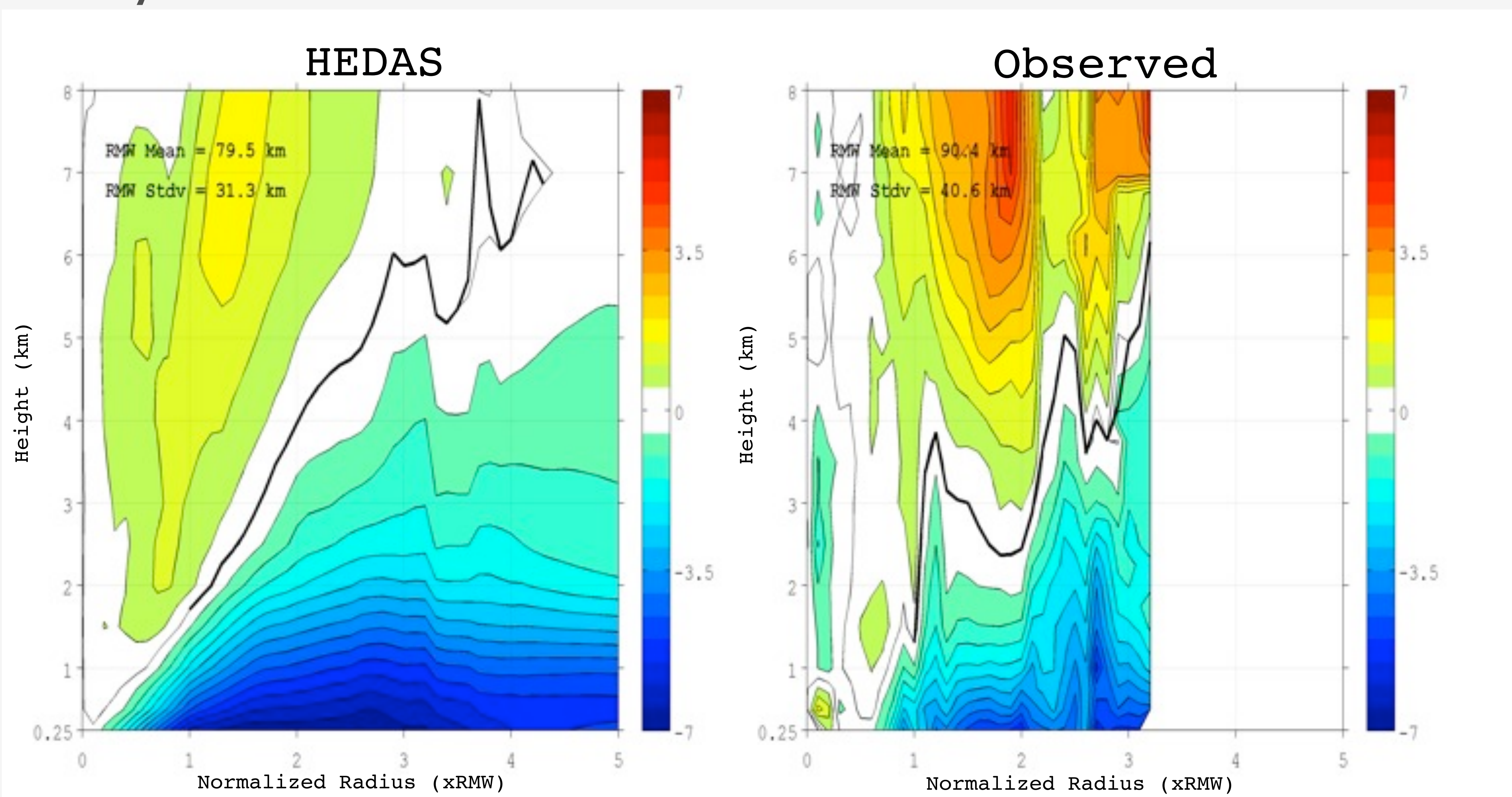
- HEDAS **composite of the primary circulation** (azimuthally-averaged tangential wind speed) versus observed – major hurricanes only



HEDAS captures well the observed structure of the primary circulation as obtained from radar data. There appears to be a low bias in HEDAS intensities in strong storms. RMW is also somewhat over-estimated by HEDAS.

STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

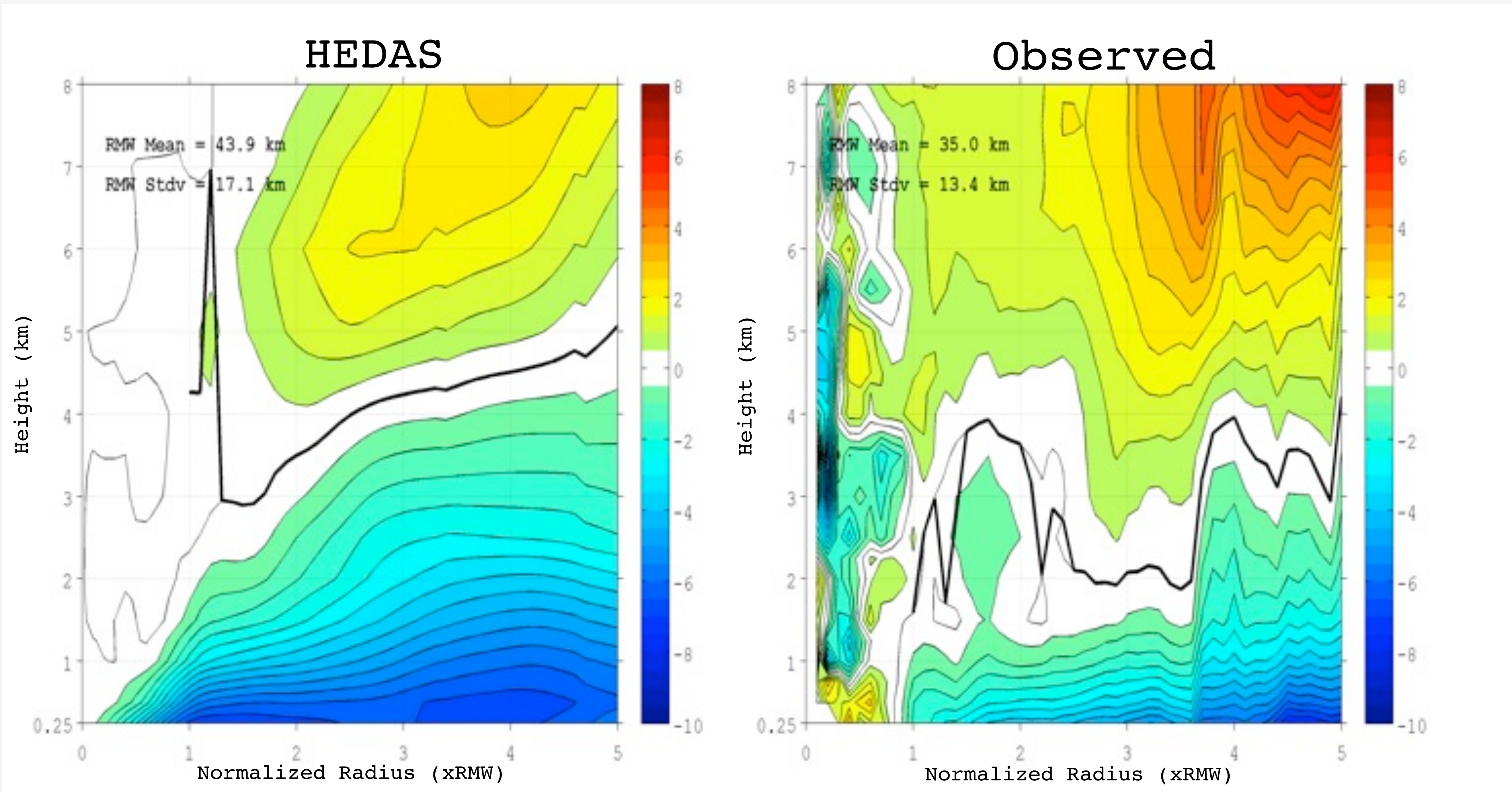
- HEDAS **composite of secondary circulation** (azimuthally-averaged radial wind speed) versus observed – categories 1-2 only



HEDAS has difficulty in capturing the secondary circulation. The depth of the inflow layer has distinct positive bias in HEDAS versus observations. This may be due to noisiness in the radar observations of the secondary circulation.

STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

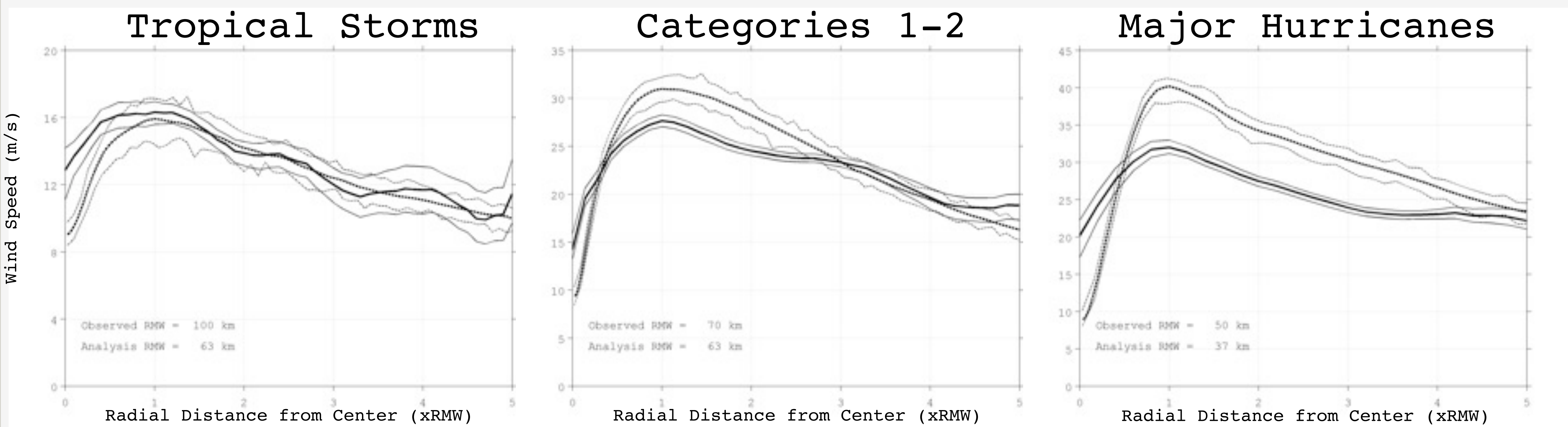
- HEDAS **composite of secondary circulation** (azimuthally-averaged radial wind speed) versus observed - major hurricanes only



These results are very similar to those for categories 1-2 sample.

STORM STRUCTURE STATISTICS for HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite radial profile of 10-m wind speed** versus **composite radial profile of SFMR observations**



———————— Observed

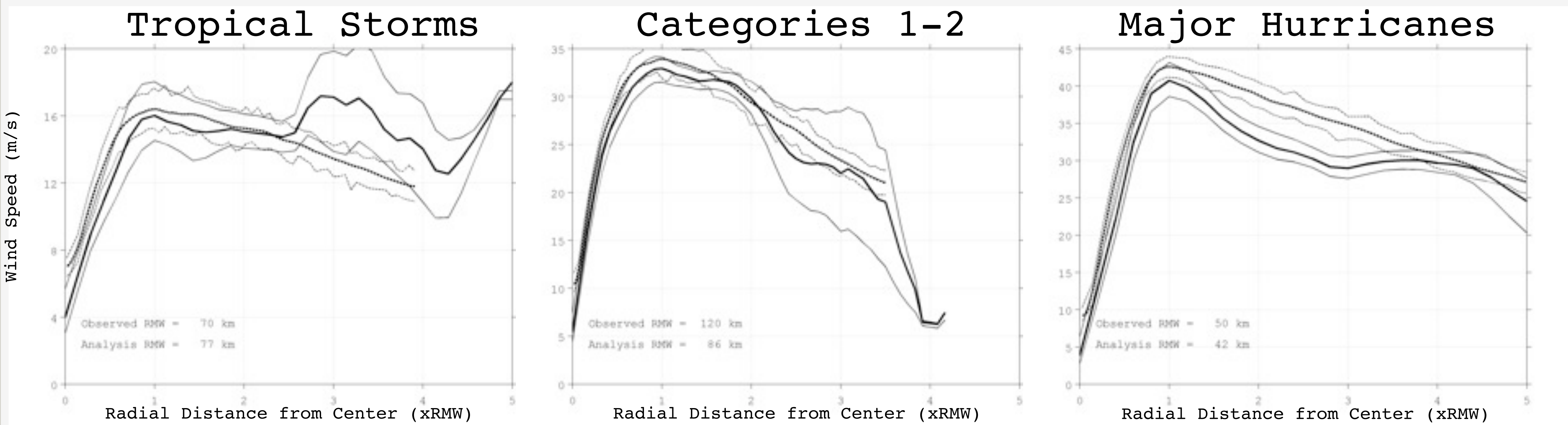
- - - - - - - - - - - HEDAS

Thin lines: 95% confidence interval

HEDAS captures well the structure of weak storms, but over-estimates wind speed for strong systems. RMW also appears to be somewhat under-estimated in HEDAS.

STORM STRUCTURE STATISTICS for HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite radial profile of flight-level wind speed** versus **composite radial profile of flight-level observations**



———— Observed

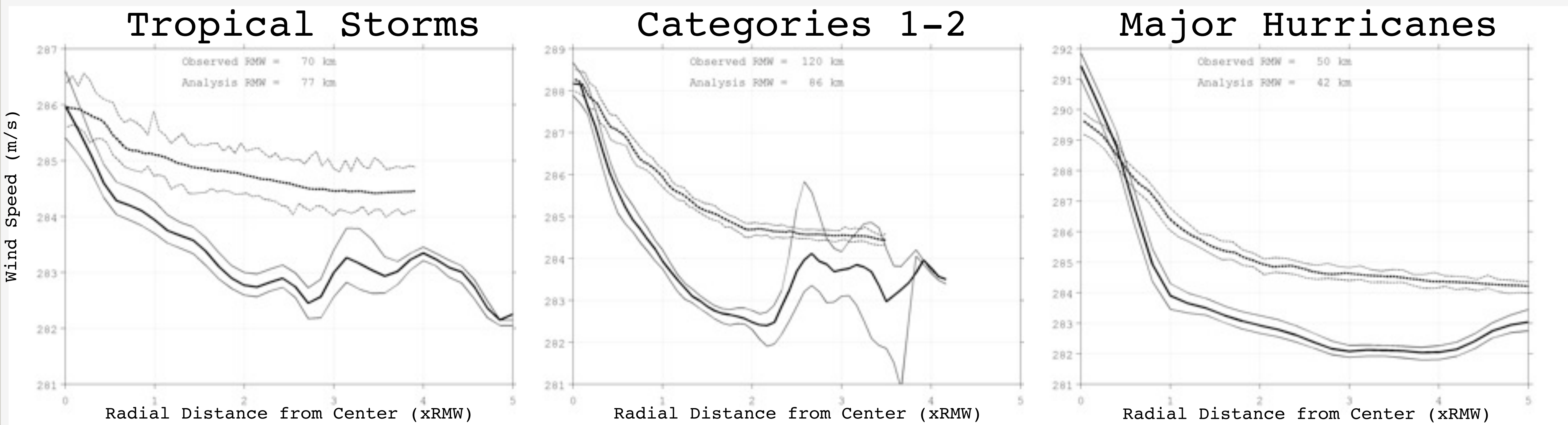
- - - - - HEDAS

Thin lines: 95% confidence interval

HEDAS captures very well the wind speed structure at flight level.

STORM STRUCTURE STATISTICS for HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite radial profile of flight-level temperature** versus **composite radial profile of flight-level observations**



____________ Observed

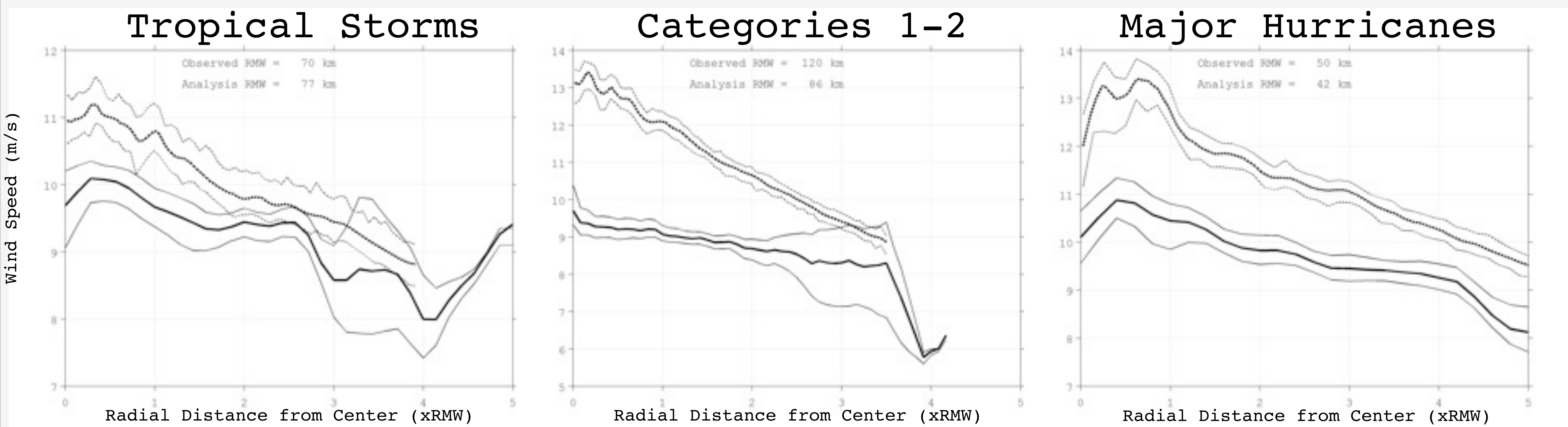
------------ HEDAS

Thin lines: 95% confidence interval

HEDAS captures the warm-core structure of weaker systems. Temperature is generally over-estimated in HEDAS outside the RMW.

STORM STRUCTURE STATISTICS for HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite radial profile of flight-level (3 km) spec. humidity** versus **composite radial profile of flight-level observations**



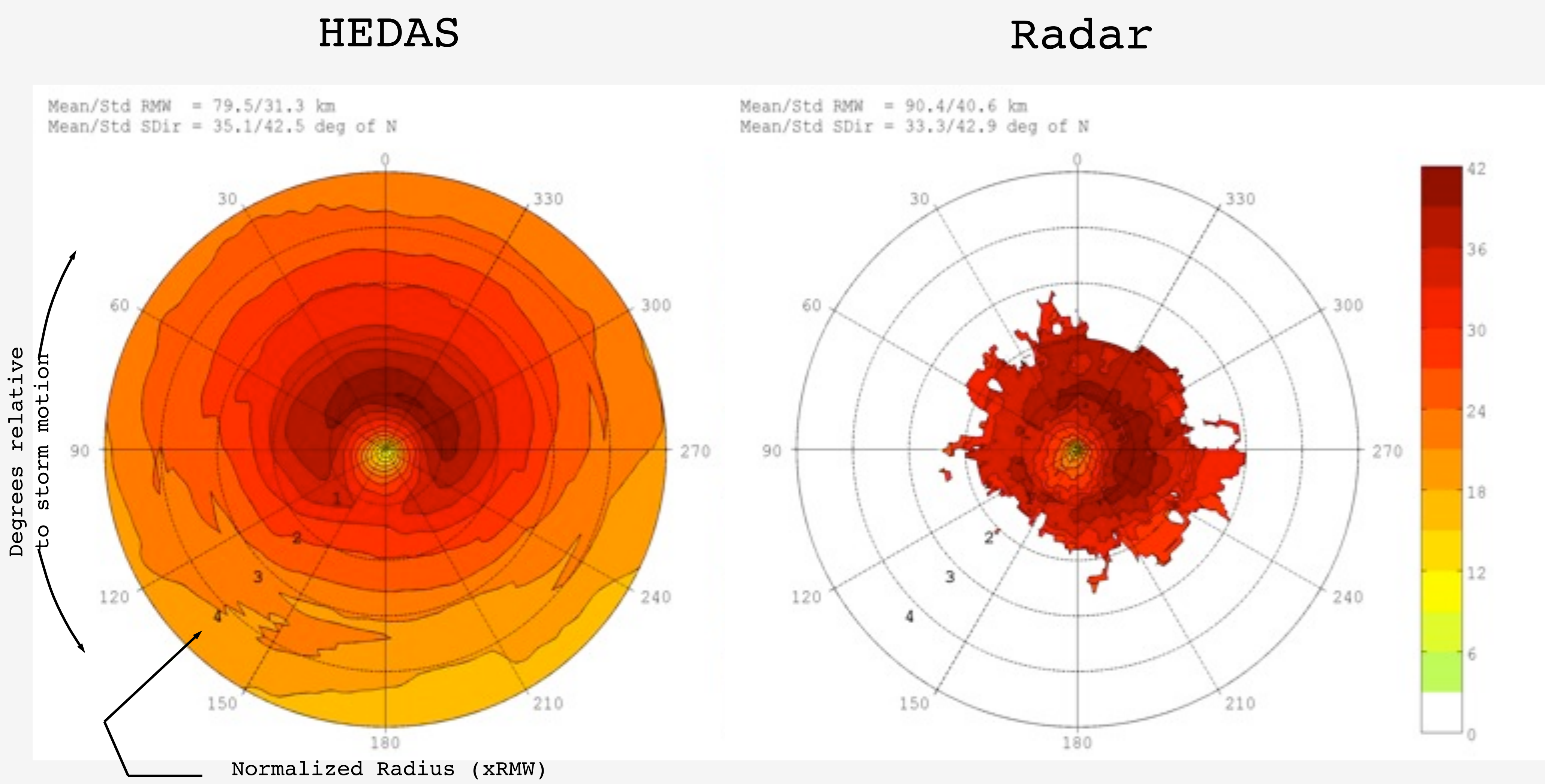
________________	Observed
----------------	HEDAS

Thin lines: 95% confidence interval

HEDAS generally appears to be more moist then observations at flight level. This may be due to the deep boundary layer in the HEDAS analyses.

STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite of 2-km wind speed** (m/s) versus Doppler radar data - Categories 1-2 only

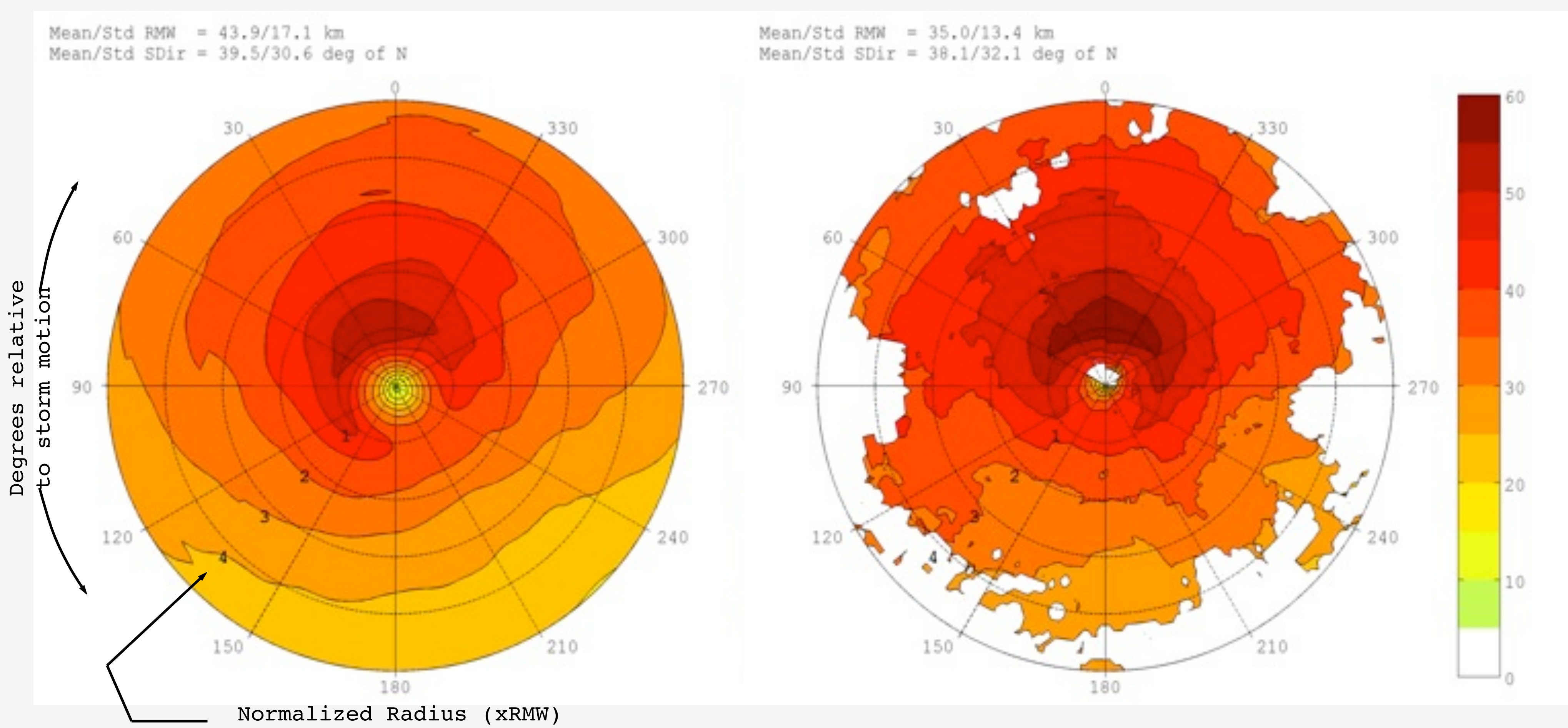


STORM COMPOSITE STRUCTURE in HEDAS FINAL MEAN ANALYSIS

- HEDAS **composite of 2-km wind speed (m/s)** versus Doppler radar data – major hurricanes only

HEDAS

Radar



CONCLUSIONS (1)

- A dataset of 2008–2011 cases is obtained with a good distribution of cases across intensity categories (tropical storm to category-4 hurricane)
- All cases assimilated airborne Doppler, flight-level, dropwindsonde, and SFMR 10-m wind speed observations
- Average position error in the final mean analysis is ~11 km (0.2 RMW), comparable to the best track uncertainty (0.1°) – no explicit position information is assimilated
- No bias in HEDAS analysis intensity is observed, though a small under-estimation occurs in HEDAS MSLP analysis – HEDAS does not assimilate pressure information

CONCLUSIONS (2)

- HEDAS appears to over-estimate intensity compared to H*Wind and maximum observed SFMR data; however, HEDAS fits to observed maximum Doppler wind and observed maximum flight-level wind speed suggest that the intensity is heavily influenced by the relatively large volume of Doppler wind data – the surface analysis is indirect through model correlations between levels above the surface and the surface itself
- In terms of storm structure, HEDAS captures well the wavenumber-0 and wavenumber-1 components of the tangential wind, with more difficulties apparent in capturing the wavenumber-2 structure. HEDAS analyses demonstrate a realistic range of variance explained values for wavenumbers 0-2 when compared to observed

CONCLUSIONS (3)

- In a composite sense:
  - HEDAS captures well the flight-level wind speed radial distribution.
  - Flight-level temperature is represented well within the inner core but is over-estimated outside.
  - Maximum 10-m wind speed is over-estimated compared to SFMR.
  - Vertical structure of the primary circulation is realistic when compared to radar observations, but the maximum wind speed is under-estimated for strong storms.
  - Vertical structure of the secondary circulation is problematic, with exaggerated inflow-layer depth and under-estimated inflow magnitude; this could also be partially due to the relatively noisy representation of the secondary circulation by the radar data.
  - Good agreement between the horizontal 10-m wind speed structure and SFMR data is obtained.
  - At 2-km altitude, relatively good agreement between the horizontal wind speed structure and the radar data, although magnitudes are somewhat under-estimated for strong storms.

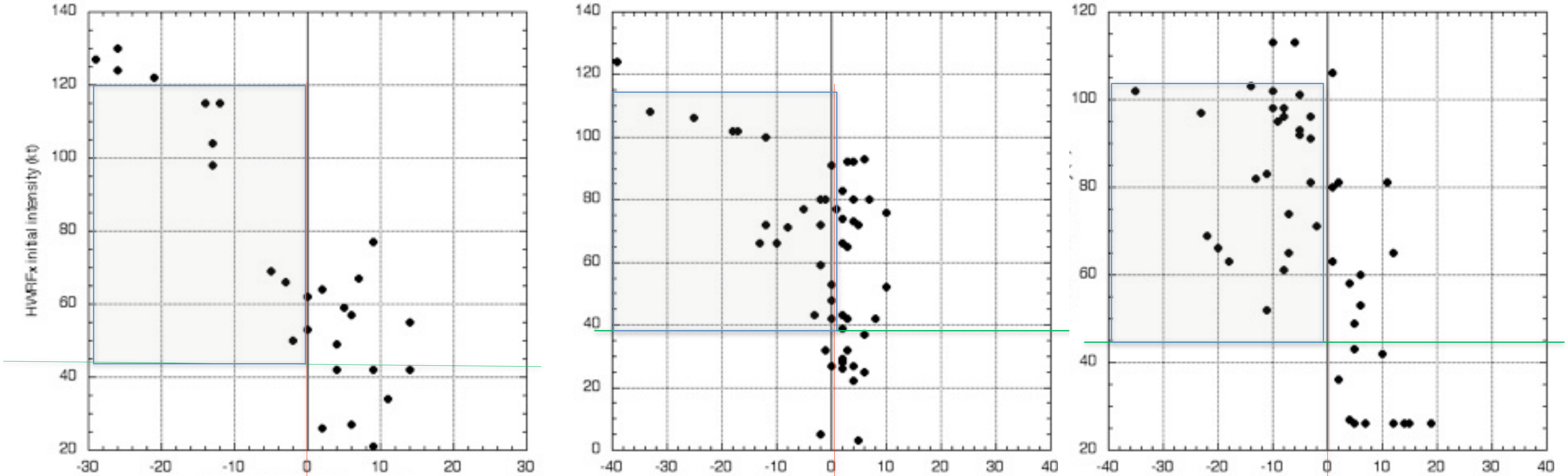
Short-term forecast bias

- The high-resolution forecasts from HWRF and WRF-ARW show a significant negative intensity bias through 36 h
  - Maximum bias occurs at 6-24 h, depending on the system and initialization method (and frequency of output)
  - The bias seems to account for a large portion of the forecast error at short-ranges

Tomislava Vukicevic
NOAA/AOML Hurricane Research Division

Identifying the source of bias in HWRF

HWRFx with initialization | HWRFx with HEDAS IC | HWRF_3.2 with initialization



3-h change | 1-h change | 6-h change

Samples are not uniform among panels, for illustration only

- **Vortex spin-down for cases with hurricane initial intensity**
- **The spin-down is present regardless of the method of initialization or model version**

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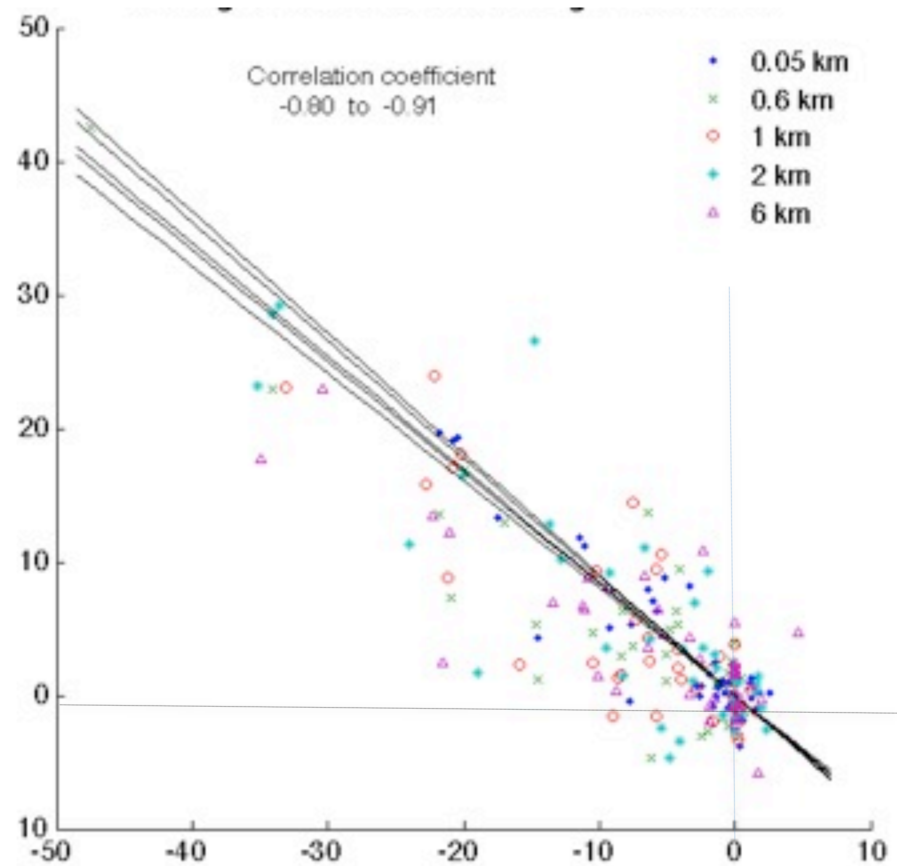
NOAA/AOML Hurricane Research Division

Impact of short-term spin-down on data assimilation in HEDAS

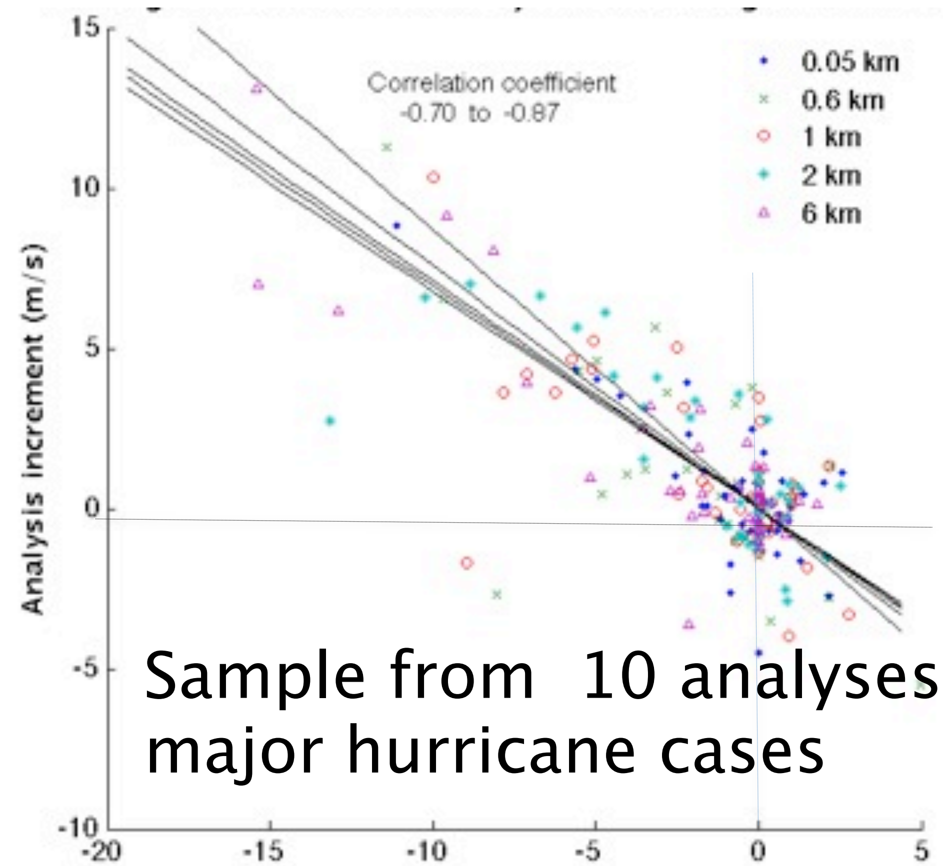
Maximum tangential velocity (Vt)

Maximum axisymmetric Vt

Analysis increment



m/s
Change in subsequent forecast



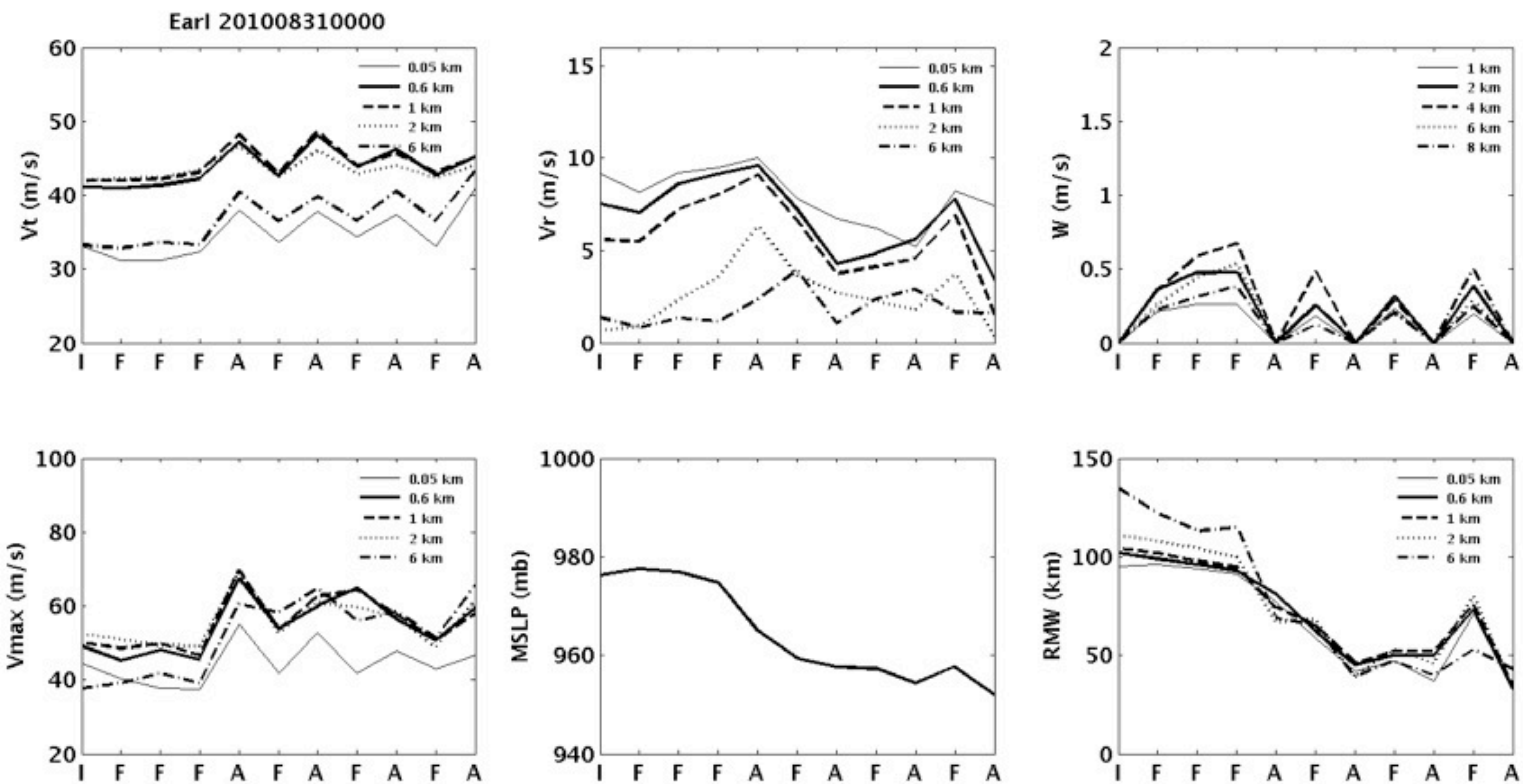
Sample from 10 analyses of major hurricane cases

m/s
Change in subsequent forecast

- **In each cycle, the core spins down during the first hour, after the DA spins it up**

Vortex dynamics in HEDAS cycling

➢All wind components show the opposite tendency from the analysis update, whereas MSLP and RMW tendencies are consistent: Possible cause is impact of friction when convection is initially weak



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Future plans

Upgrade from HWRFx to HWRF3.X (latest version) and start using restart capability so all variables are initialized.

Parallelize the HEDAS code for efficiency.

Investigate assimilating satellite wind data such as scatterometry and cloud-motion winds.

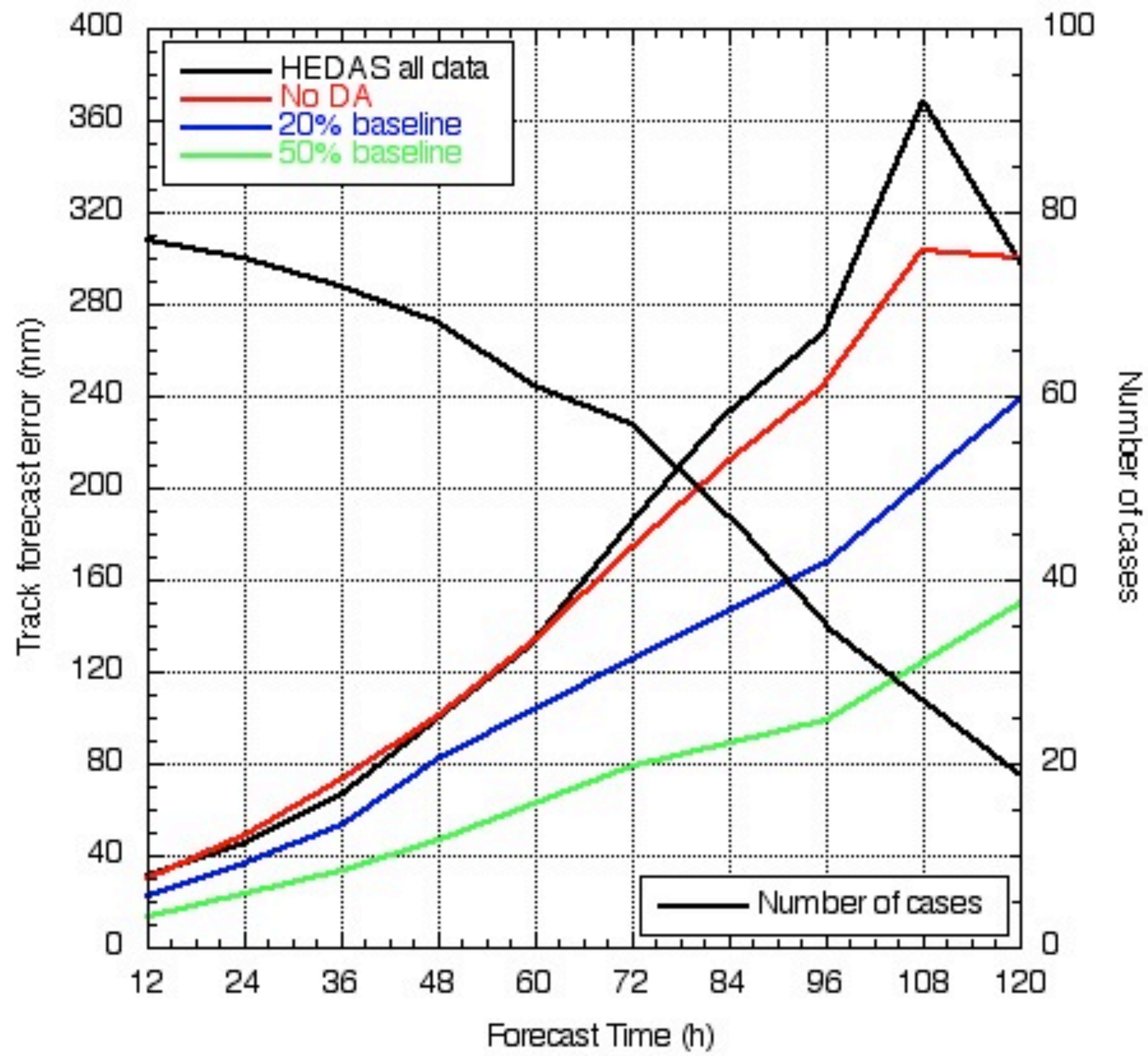
Start assimilating G-IV HDOBS.

Convert from NOAA-flight-specific analysis times to regular synoptic-based times.

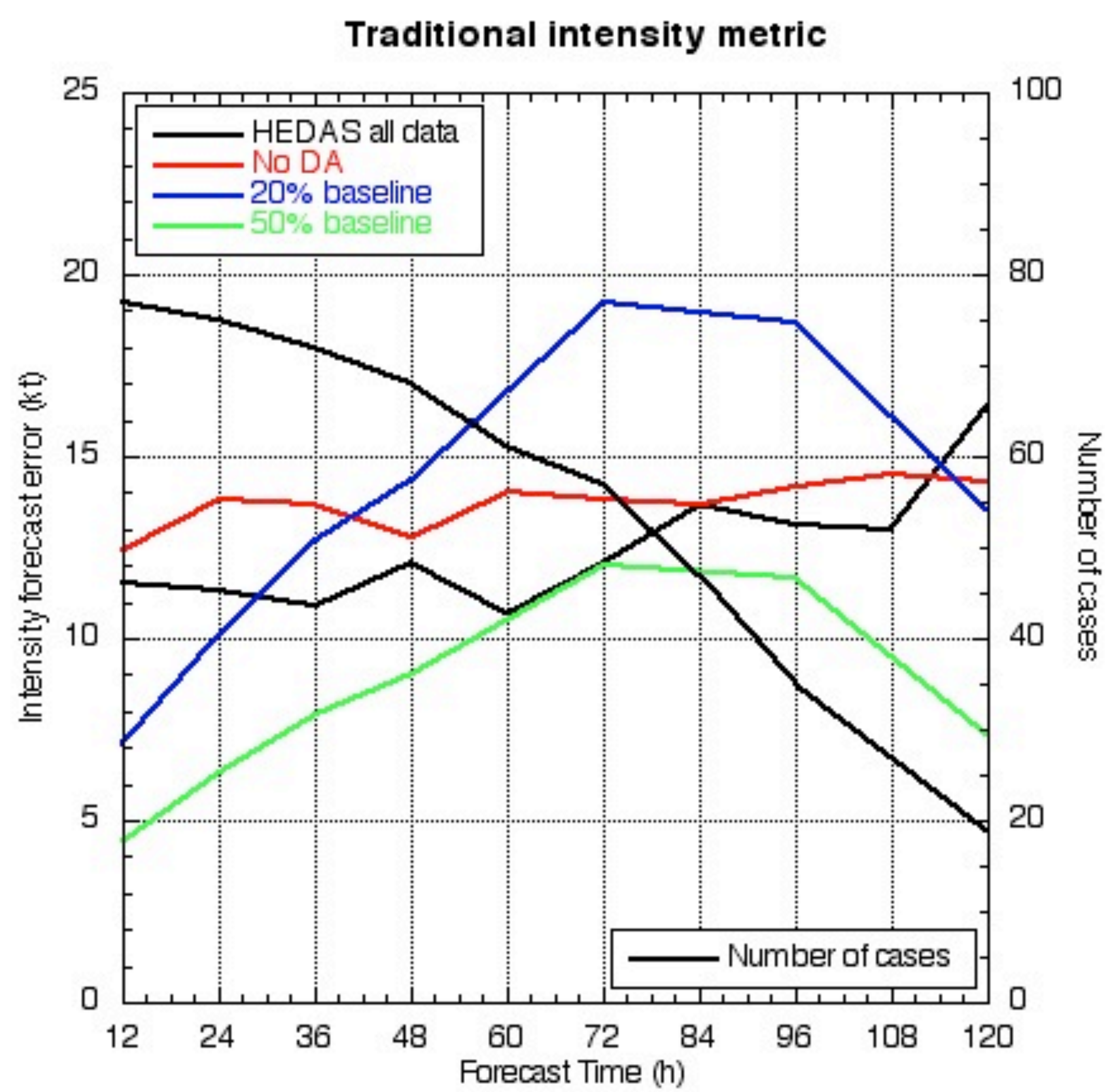
Possible improvement to superobs code to get more data in boundary layer.

Investigate running Stream1.5 for all cases with aircraft data, not just NOAA Airborne Doppler observations.

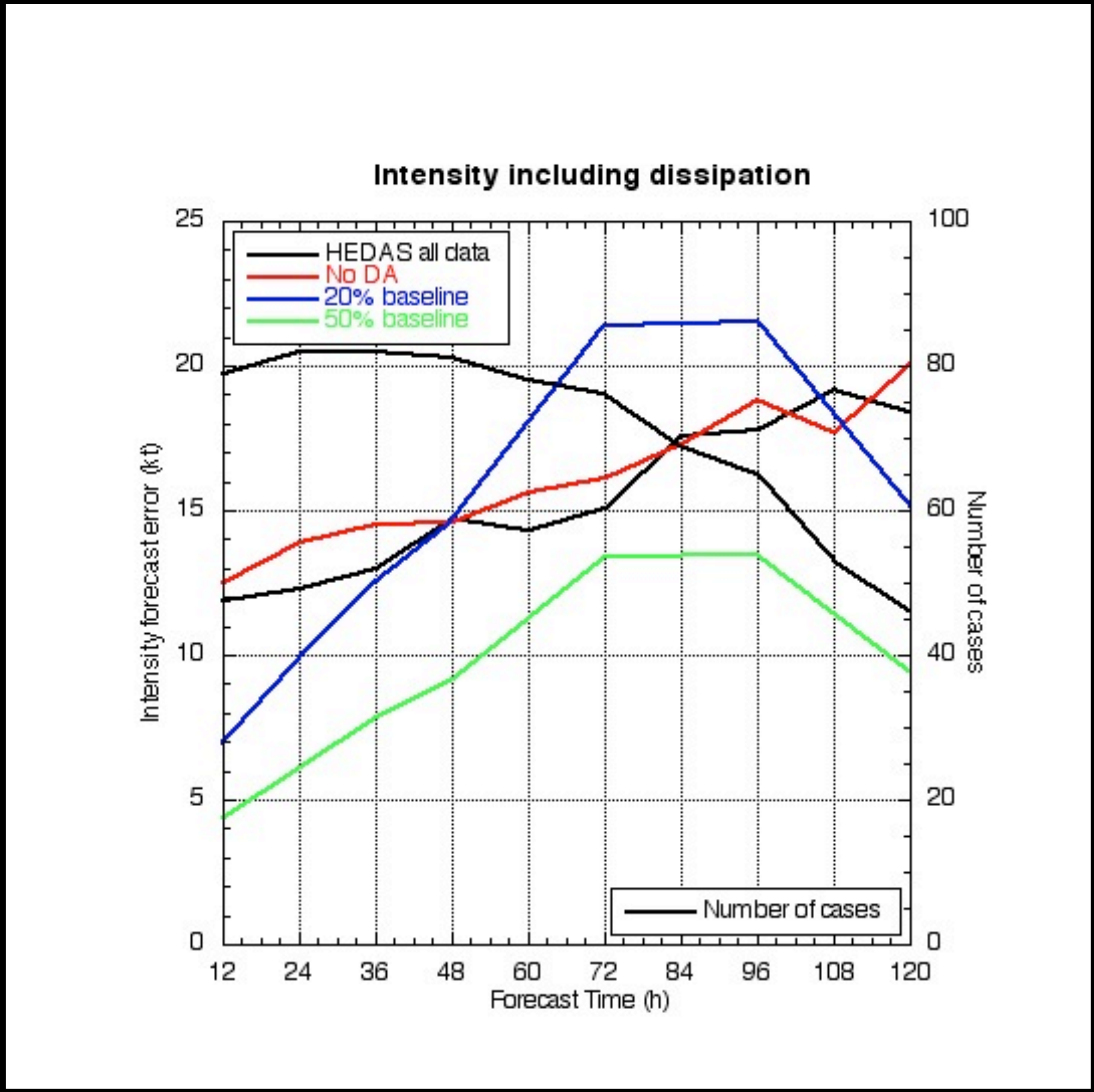
Supplemental Figures



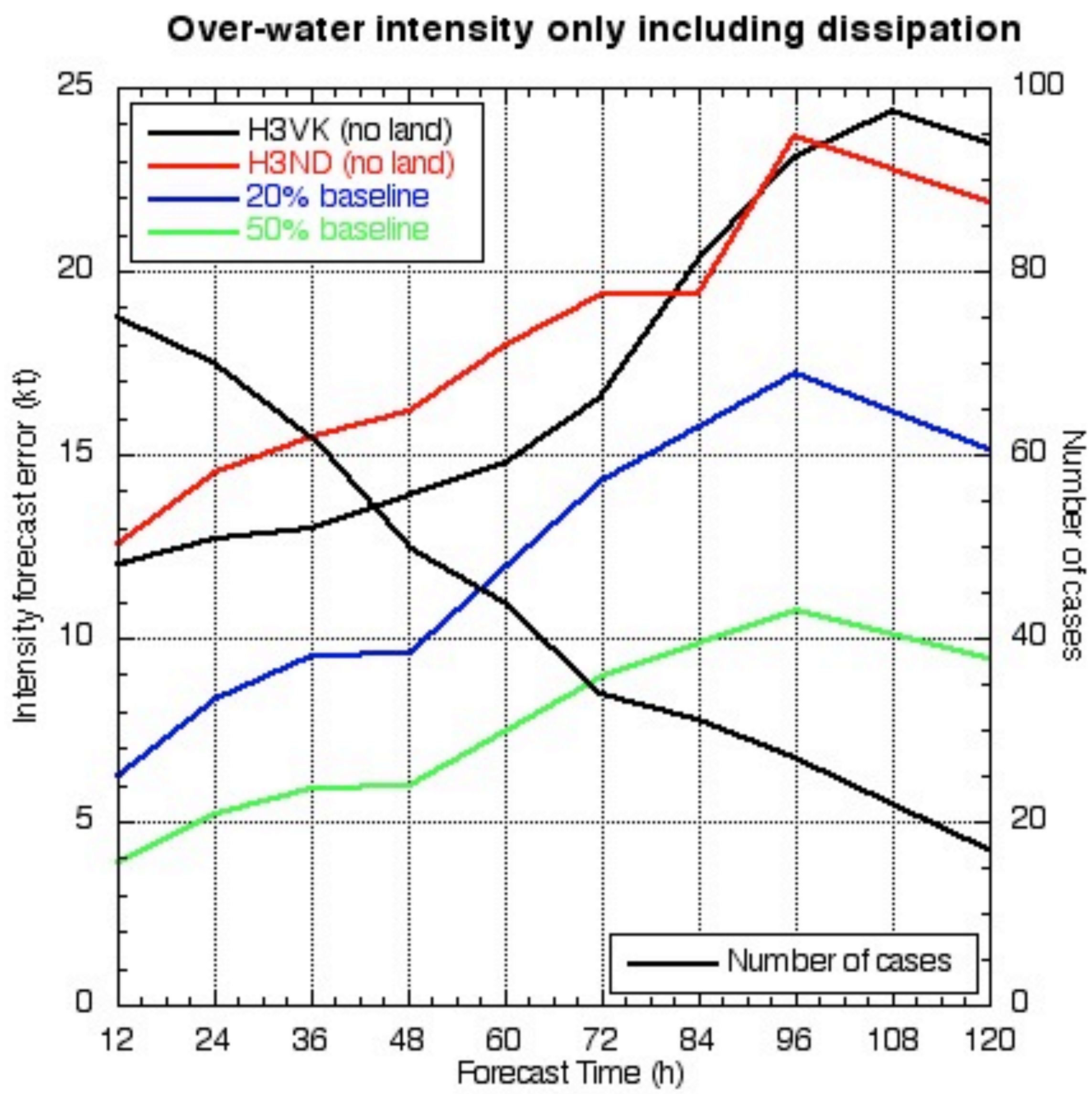
HEDAS all data
No DA
20% baseline
50% baseline
Number of cases
Track forecast error (nm)
Number of cases
Forecast Time (h)
0
40
80
120
160
200
240
280
320
360
400
0
20
40
60
80
100
12
24
36
48
60
72
84
96
108
120

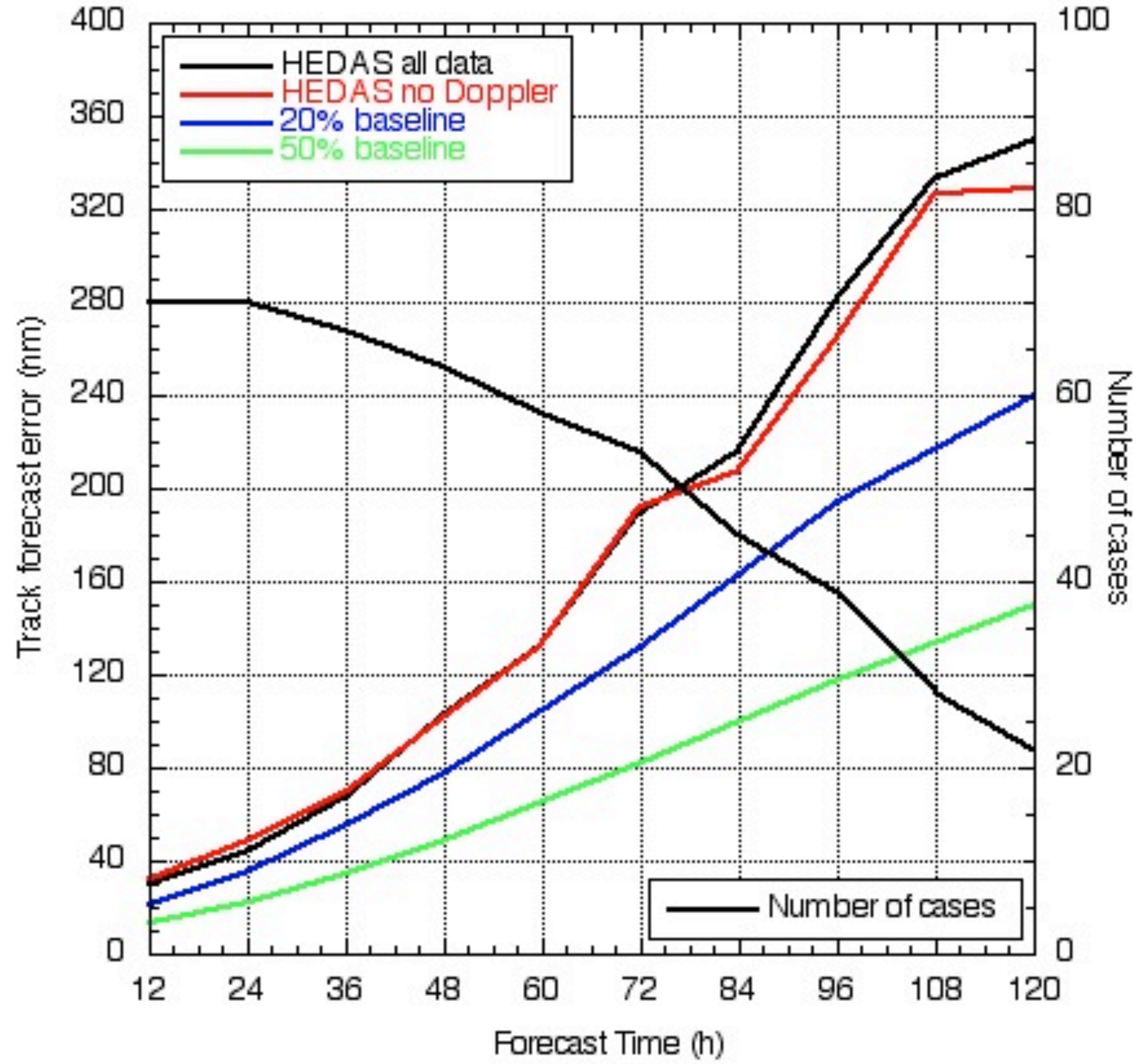


Traditional intensity metric
HEDAS all data
No DA
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
0
5
10
15
20
25
0
20
40
60
80
100
12
24
36
48
60
72
84
96
108
120

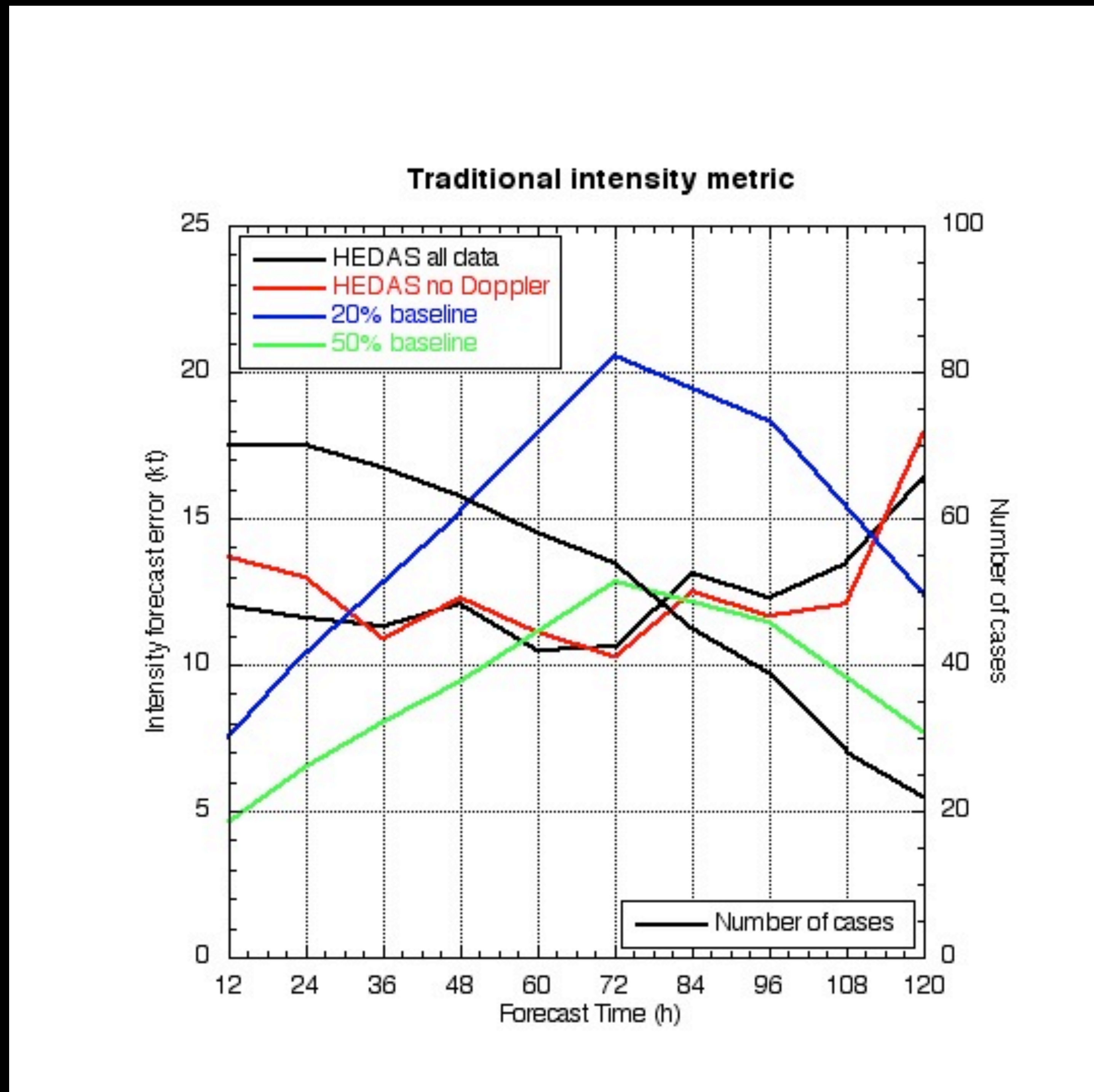


Intensity including dissipation
HEDAS all data
No DA
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
0
5
10
15
20
25
0
20
40
60
80
100
12
24
36
48
60
72
84
96
108
120


Over-water intensity only including dissipation
H3VK (no land)
H3ND (no land)
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
25
20
15
10
5
0
100
80
60
40
20
0
12
24
36
48
60
72
84
96
108
120



HEDAS all data
HEDAS no Doppler
20% baseline
50% baseline
Number of cases
Track forecast error (nm)
Number of cases
Forecast Time (h)
400
360
320
280
240
200
160
120
80
40
0
100
80
60
40
20
0
12
24
36
48
60
72
84
96
108
120


Traditional intensity metric
HEDAS all data
HEDAS no Doppler
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
25
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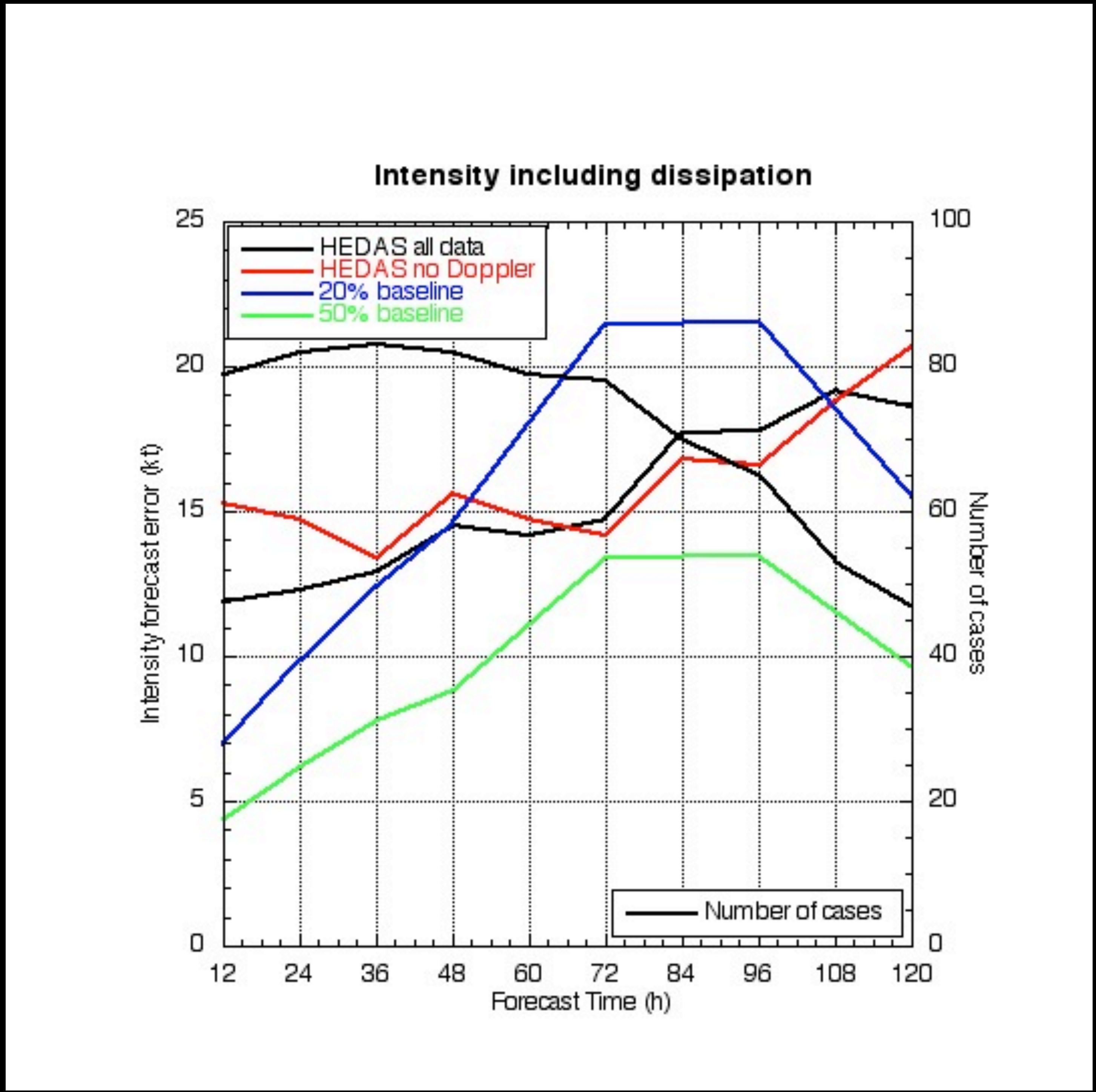
Intensity including dissipation
HEDAS all data
HEDAS no Doppler
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
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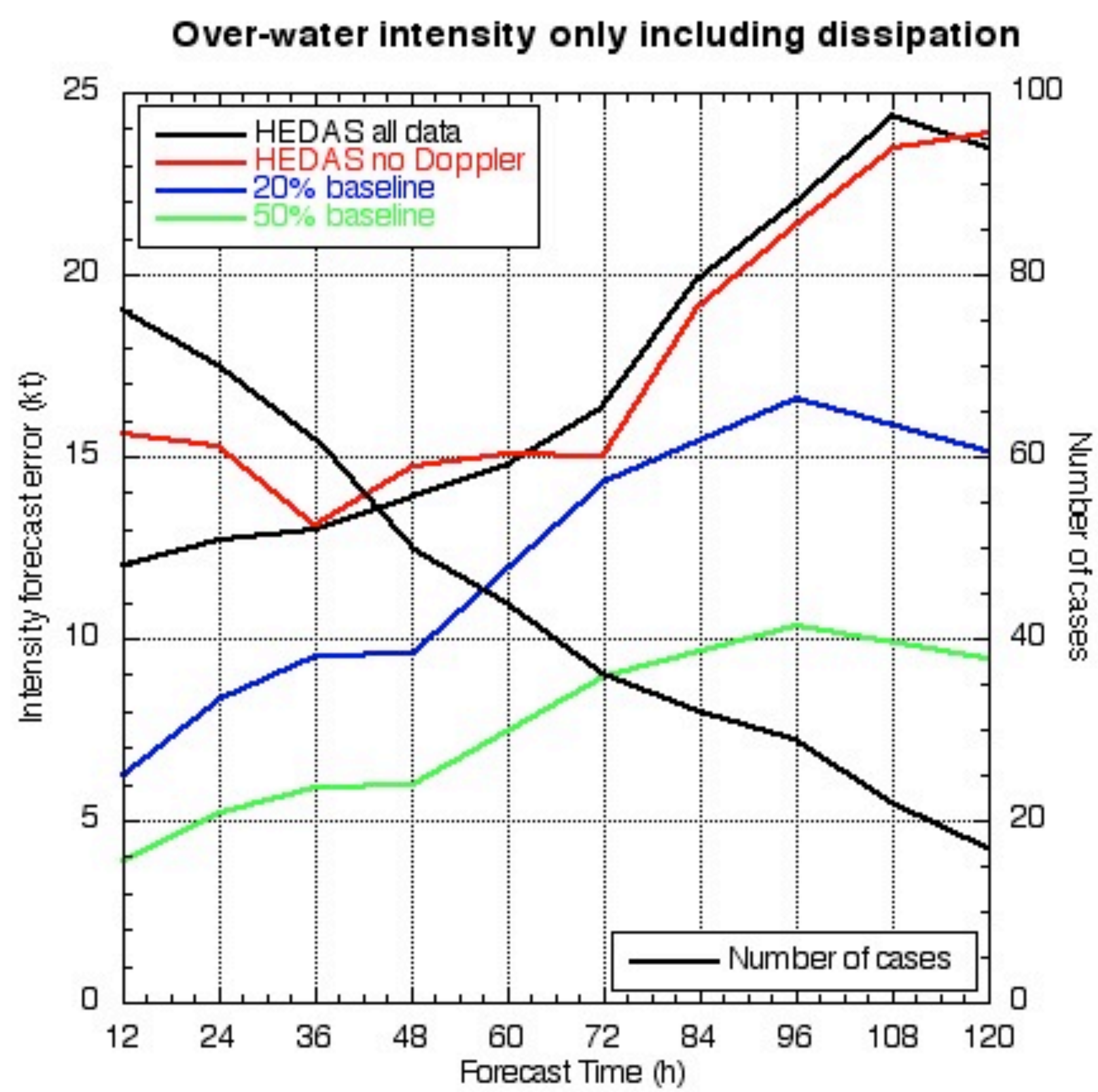
Over-water intensity only including dissipation
HEDAS all data
HEDAS no Doppler
20% baseline
50% baseline
Number of cases
Intensity forecast error (kt)
Number of cases
Forecast Time (h)
25
20
15
10
5
0
100
80
60
40
20
0
12
24
36
48
60
72
84
96
108
120