Assimilation of Fine-scale Observations for Tropical Cyclones

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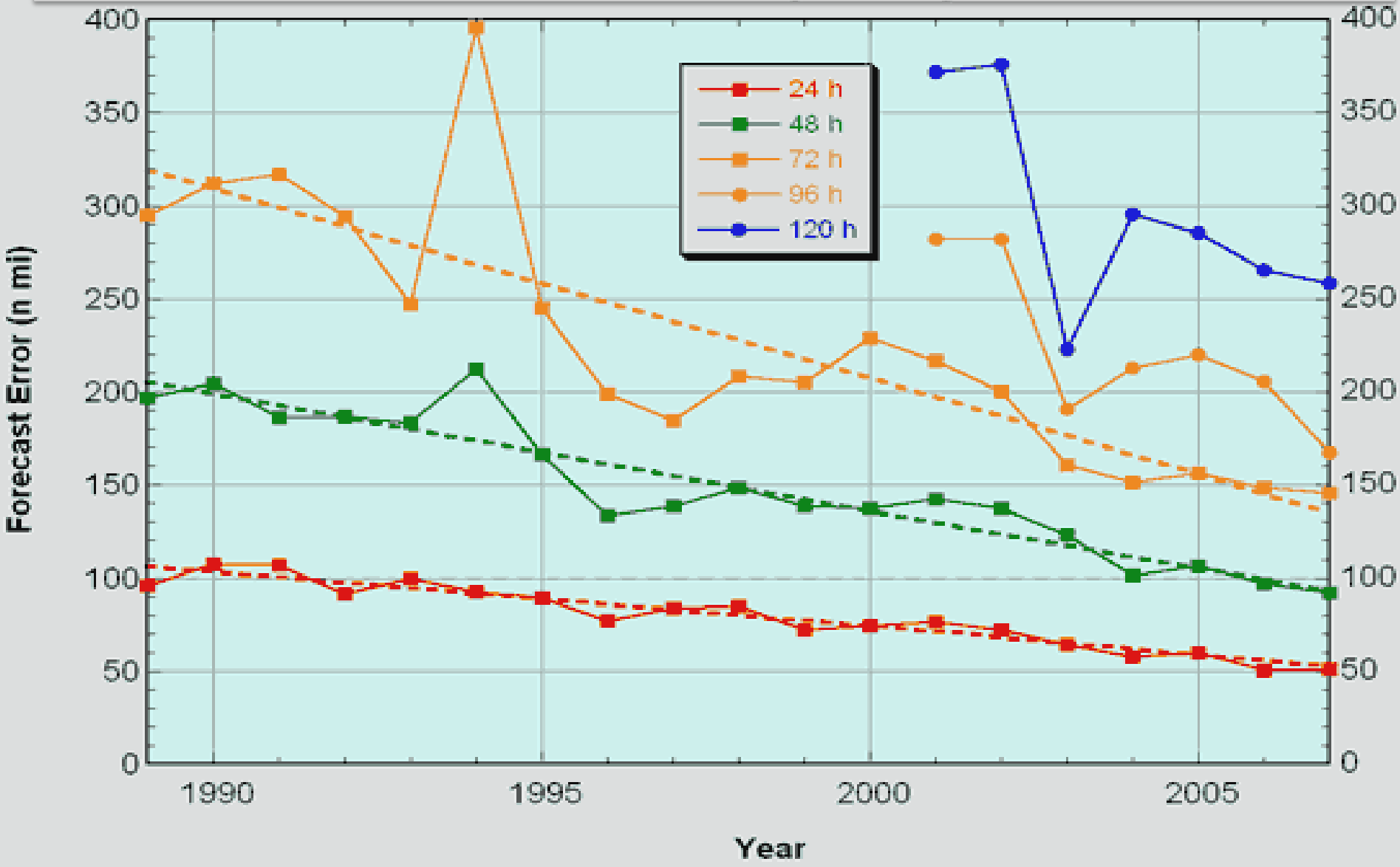
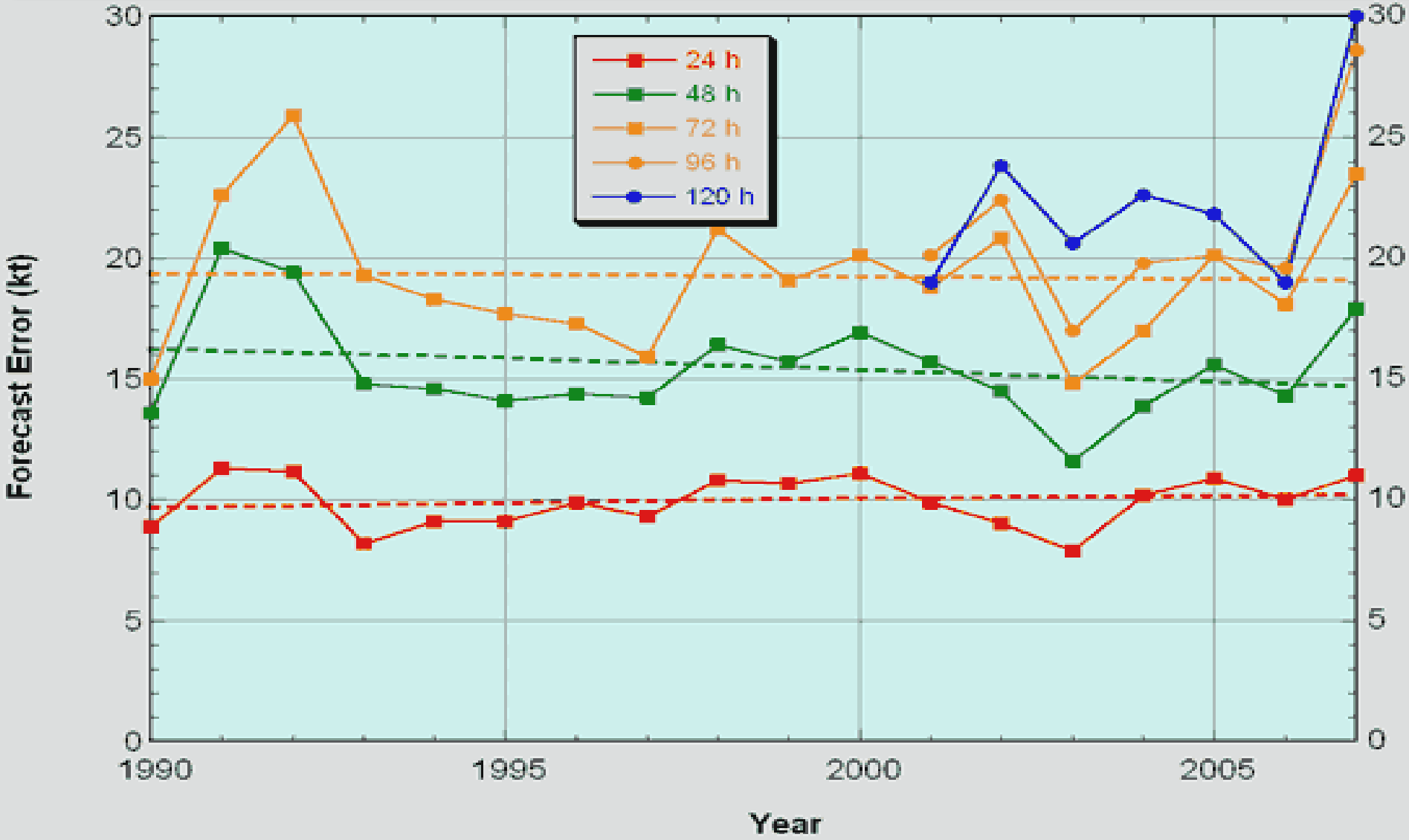
National Hurricane Center Official Track Errors



Tropical cyclone track is mostly determined by larger-scale environment whose forecast improves with better observations, better models, higher resolution (T80->T382) and 100,000 times faster computers

National Hurricane Center Official Intensity Errors



Tropical cyclone intensity is strongly dependent on internal dynamics and moist convection which are smaller in scales, more chaotic, less understood, under-observed, under-resolved, and/or intrinsically less predictable?

Vortex Initialization in Operational Models

NOGAPS: (1) Vortex generation based on balanced hurricane vortex of Kurihara; (2) Fully-developed vortex is inserted in HPC-analyzed position

GFS: (1) Vortex removal is made using multiple filter passes; (2) Hurricane component moved to HPC-analyzed position

UKMO: (1) Manual intervention when satellite or in-situ data is significantly different from first guess field; (2) Synthetic wind observations are added; (3) Analysis cycle balances mass field to produce a realistic vortex

ECMWF: Regular 4DVAR global analysis, no bogussing or relocation

GFDL: (1) Vortex in GFS initial fields is removed using filters and optimal interpolation; (2) New vortex is grown in model; (3) Full treatment of SST evolution and interaction; (4) Strong, well-balanced vortex in initial fields

HWRF: (1) GFS analysis + modified 6-h HWRF forecasted TC vortex (merged through GSI); (2) Adjustment of the initial HWRF forecasted TC vortex: RMW, Vmax, Psfc and 3D T, moisture (hydrometeor), and storm depth

Overview of DA for TC Initialization

0. Business as usual: from global analysis ("NoDA") or from own DA (ECWMF)

1. Vortex bogussing through insertion of a balanced TC-type vortex (GFDL, COAMPS)

2. Vortex relocation or surgery (GFS)

3. Combination of vortex bogussing with variational data assimilation:

   - HWRF (Liu et al. 2008); BDA (Xiao and Zou 2001); UKMO

4. Balance inversion often with high-resolution radar/sat observations:

   - Vorticity method (Lee et al. 2003); 3.5-DVAR (Zhao and Jin 2008)

5. Vortex initialization with advanced DA methods: EnKF and 4DVAR

   - EnKF assimilation of TC location/intensity (Chen&Snyder 2006; Torn&Hakim 2010)

   - EnKF assimilation of WSR88D or airborne radar observations

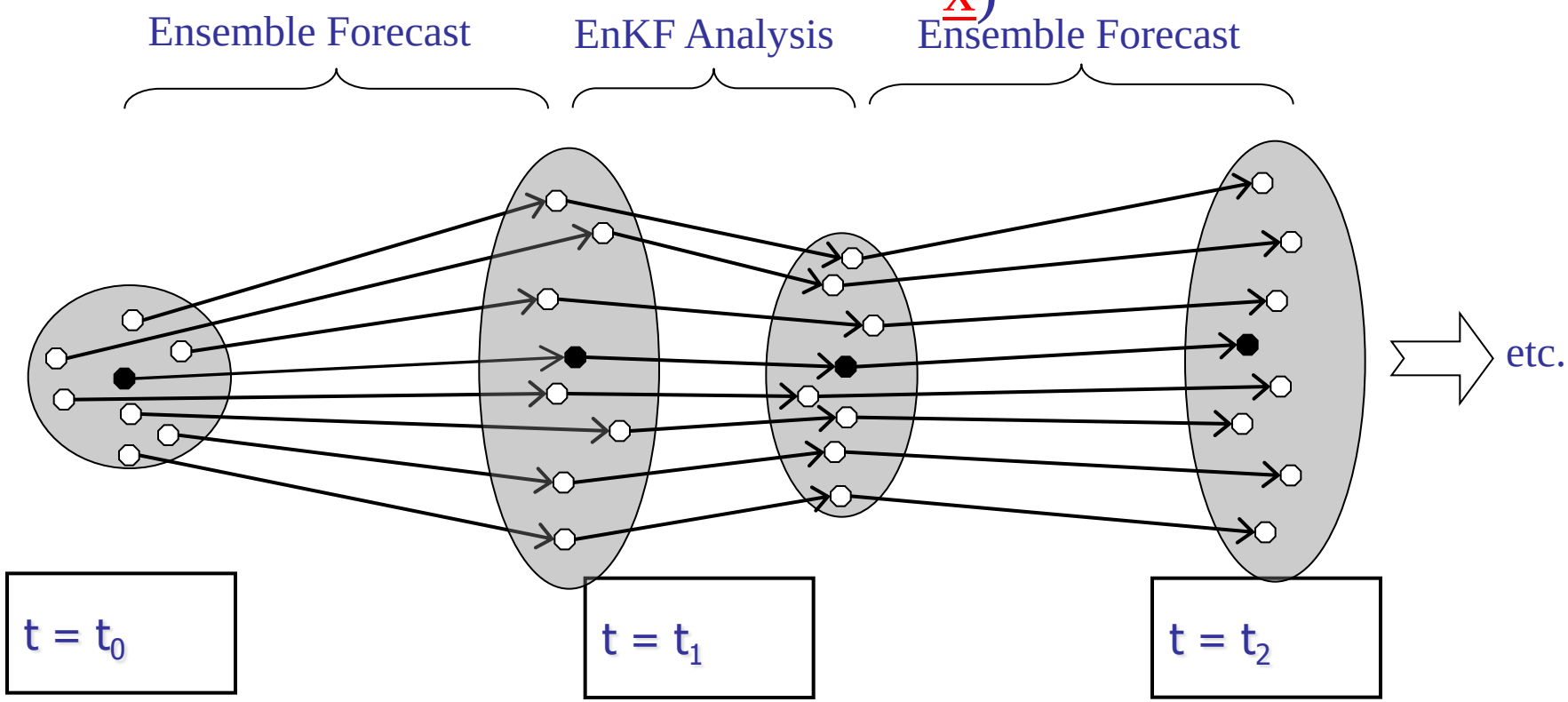
   - PEDA: pseudo-ensemble hybrid data assimilation with a TC vortex tape library

EnKF: flow-dependent sample covariance from ensemble

(Evensen 1994; Snyder and Zhang 2003)

$$x^a = x^f + BH^T(HBH^T+R)^{-1}(y-Hx^f)$$

$$B = N_e^{-1}\Sigma\,(x_i^f-\underline{x})(x_i^f-\underline{x})^T$$



Equivalence to 4Dvar in linear systems; no adjoint or TLM; fully coupled with ensemble forecast; nonlinear dynamics included; adaptable to be coupled/hybrid with 3D/4DVar

Flow-Dependent Error Covariance in Hurricanes

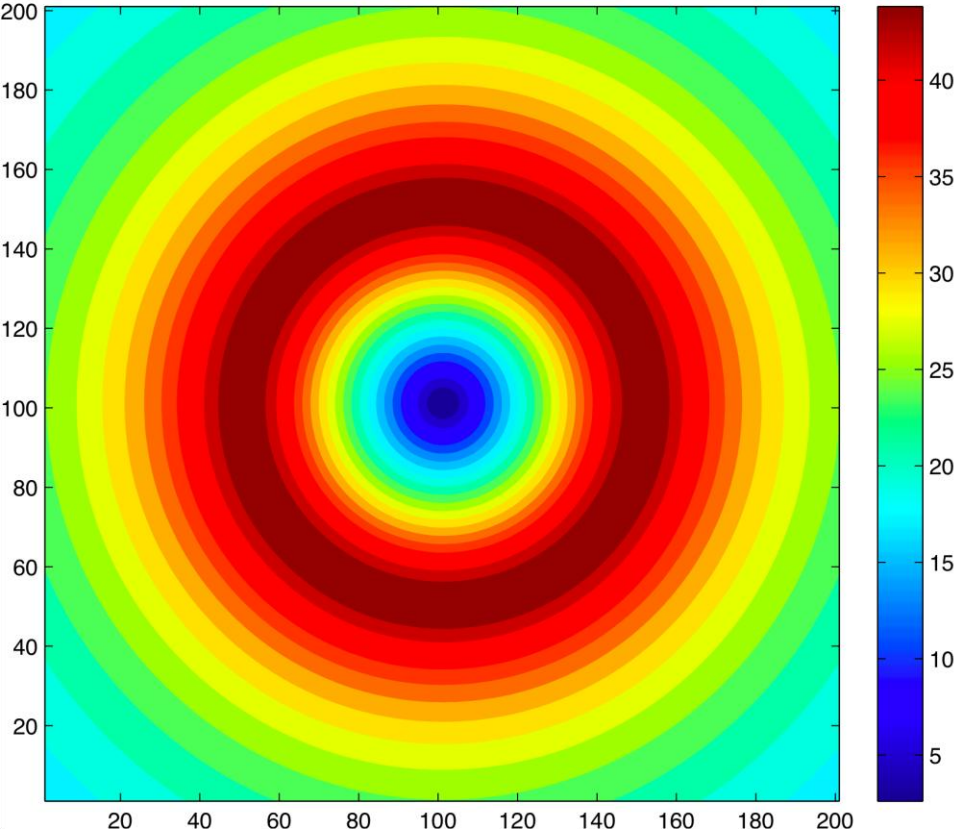
Rankine Vortex: V(r)=(V0/R0)*r for r<R0

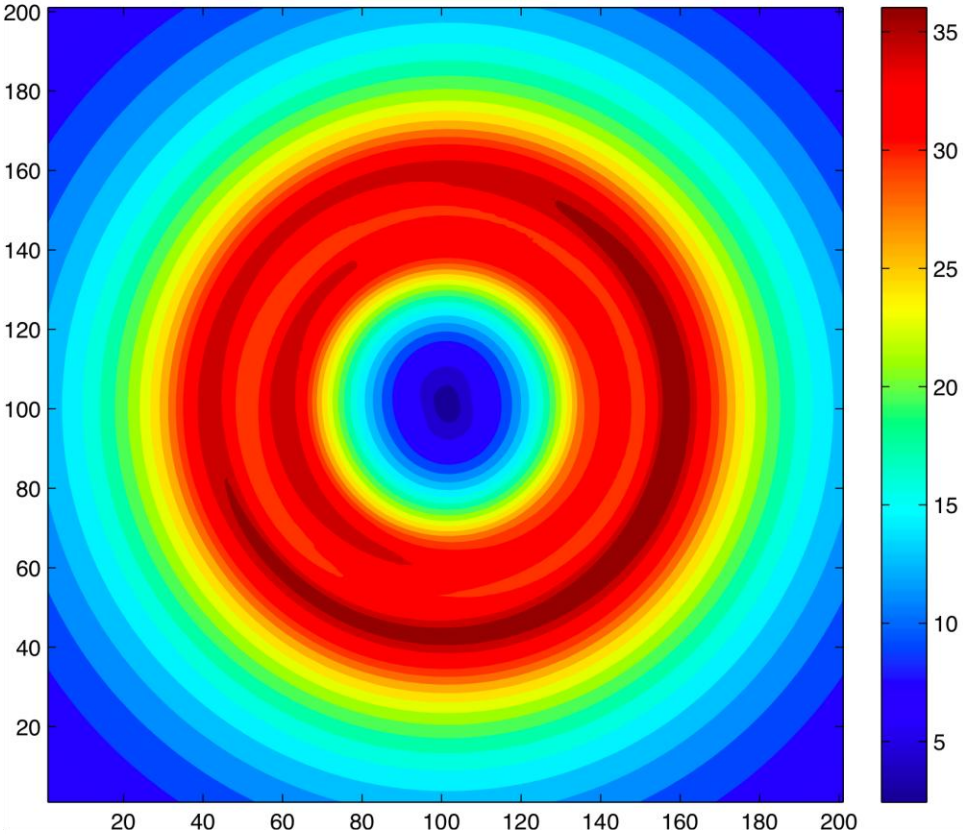
V(r)=(V0*R0)/r for r>R0

Intensity: V0={50m/s, ±5m/s},

Radius: R0={50km, ±5km},

Position: X0={101, ±2}, y0={101, ±2} km

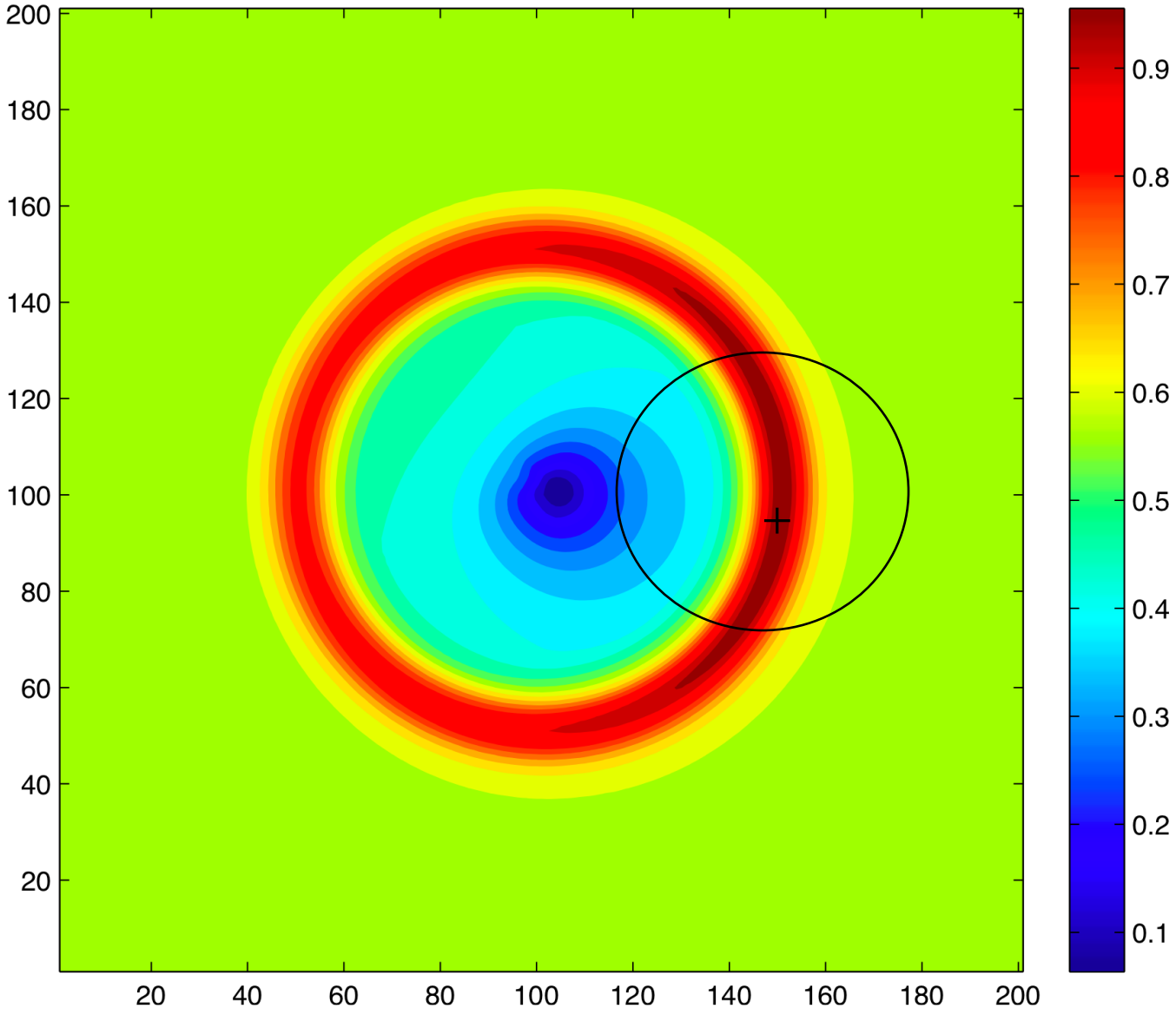




Ensemble mean (left) and Variance (top) estimated from 300 ensemble members

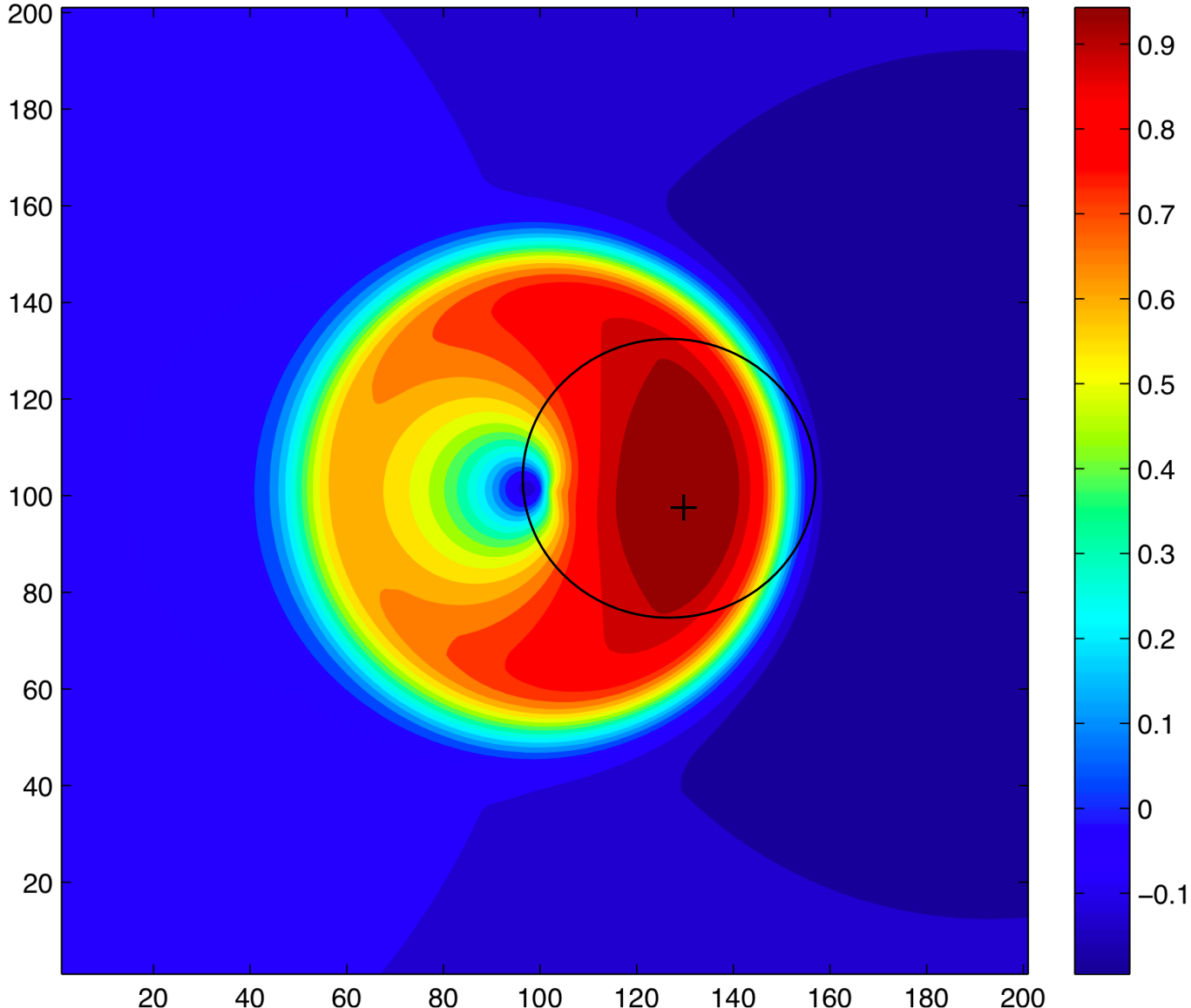
Flow-Dependent Error Covariances in Hurricanes

Correlation to Velocity observations on radius of Maximum Wind



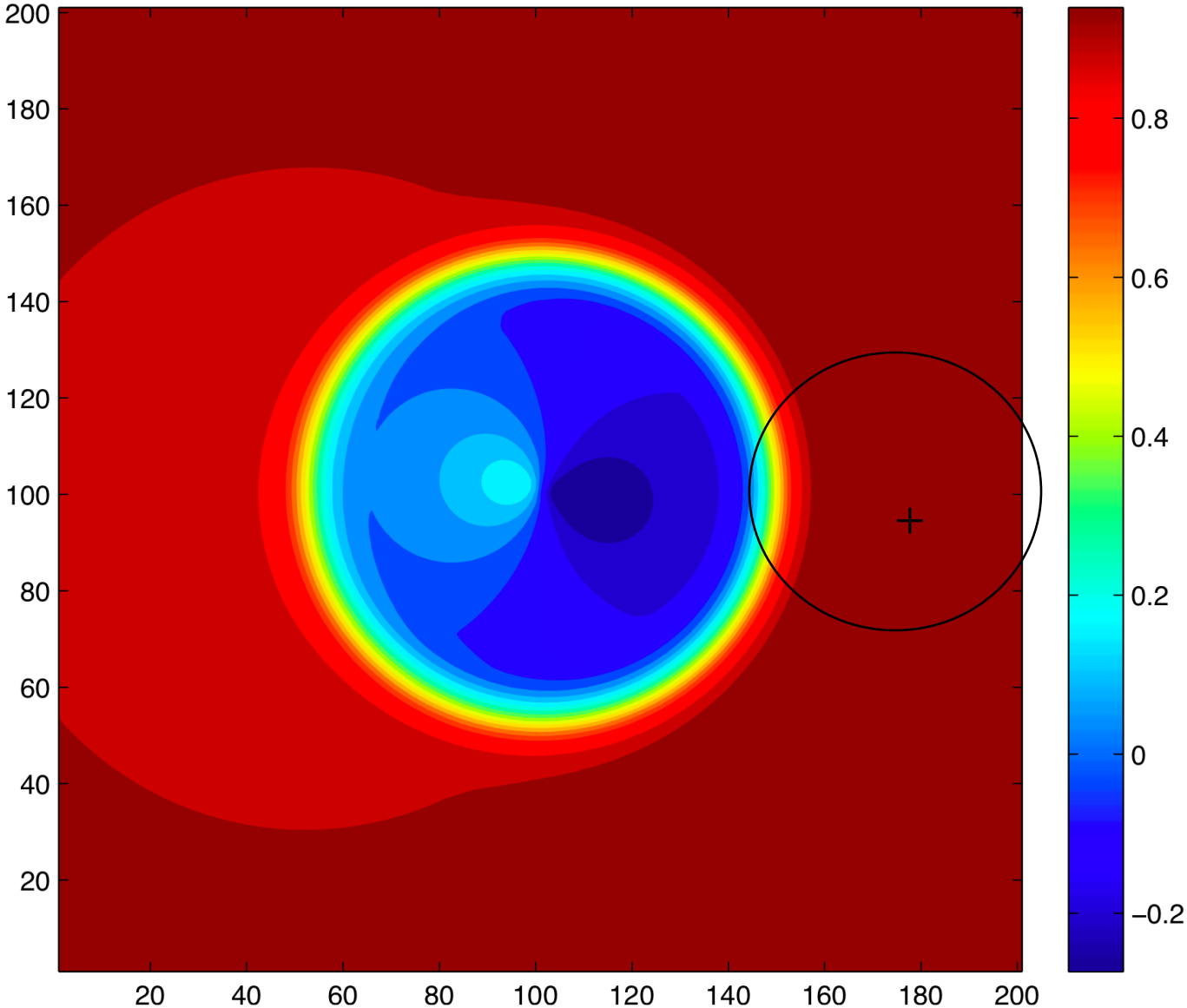
Flow-Dependent Error Correlations in Hurricanes

Correlation to Velocity observations inside radius of Maximum Wind



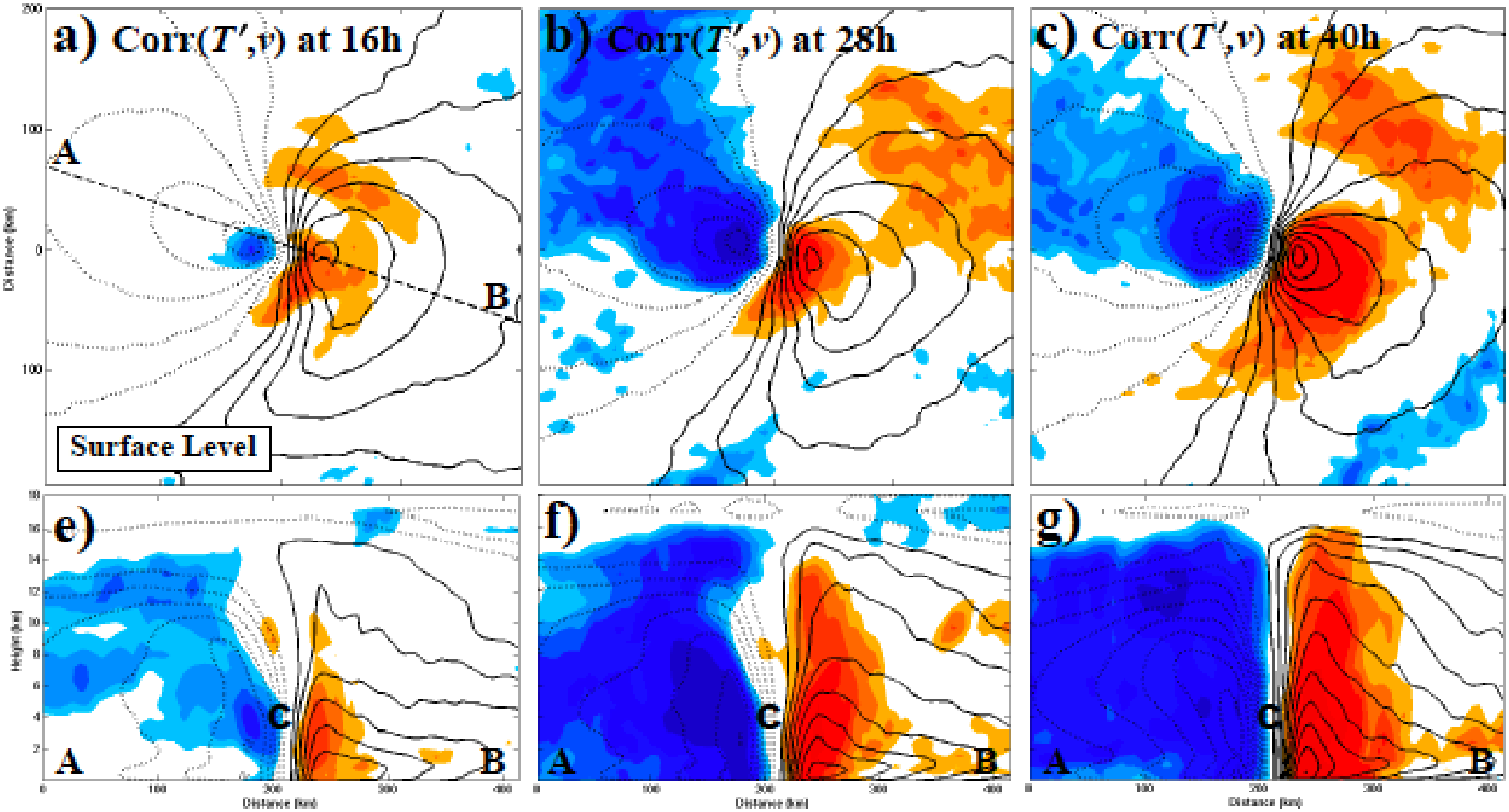
Flow-Dependent Error Correlations in Hurricanes

Correlation to Velocity observations outside of radius of Maximum Wind



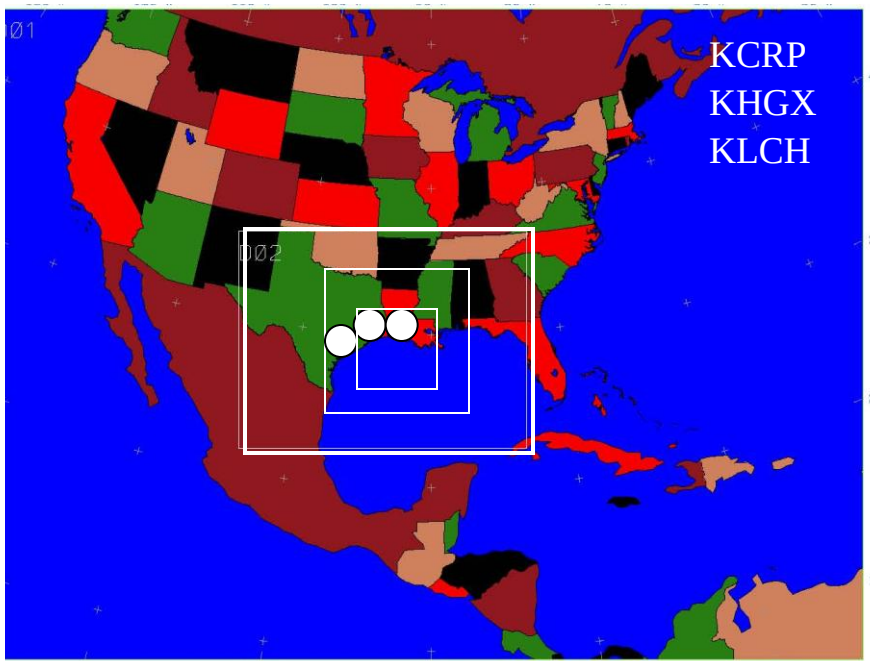
Dynamics and Structure of Error Covariances

Cross-spatioal correlation of 4-km T at point C with v



(Poterjoy and Zhang 2011 JAS, in press)

Cloud-Resolving Hurricane Initialization: Assimilation of Radar Observations with EnKF



W88D Vr for Humberto (2007)

- EnKF (Meng & Zhang 2008a,b): - 30-member ensemble

  - Initialized at 00Z 12 using 3DVar background uncertainty with FNL analysis; GFS forecast used for boundary condition in forecasts

  - Advantage: flow-dependent background error covariance from ensemble; flow dependent analysis uncertainty for ensemble forecasting

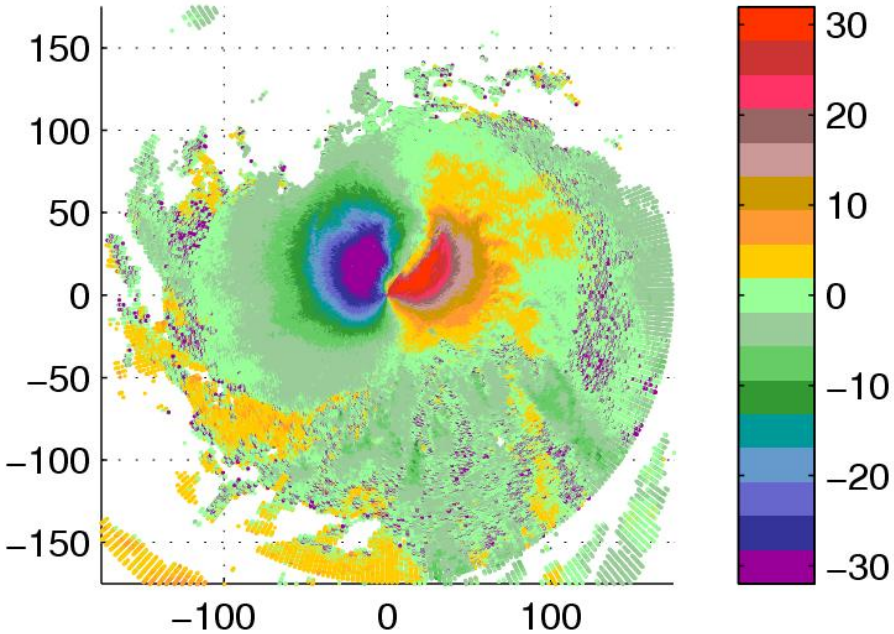
- WRF domains: D1-D2-D3-D4 grid sizes---40.5, 13.5, 4.5, 1.5km (movable)
  - Physics: WSM 6-class microphysics; YSU PBL; Grell-Devenyi CPS

- Data assimilated: WSR88D at KCRP, KHGX and KLCH radar radial velocity (Vr) Super-obs hourly from 09Z 12 September 2007

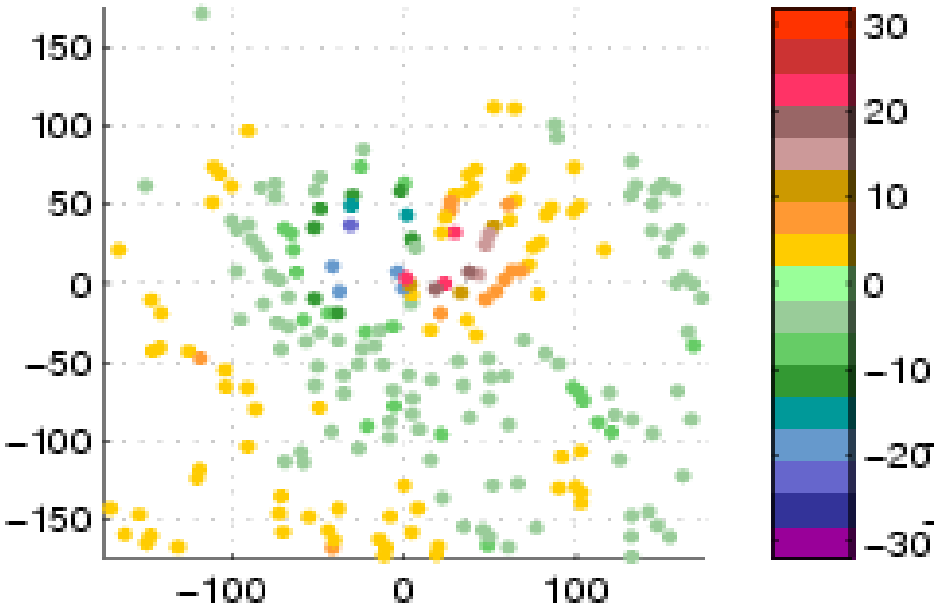
(Zhang et al. 2009 MWR)

Super-Obs: QC and Thinning of WSR-88D Vr Obs

0.5degree RAW data

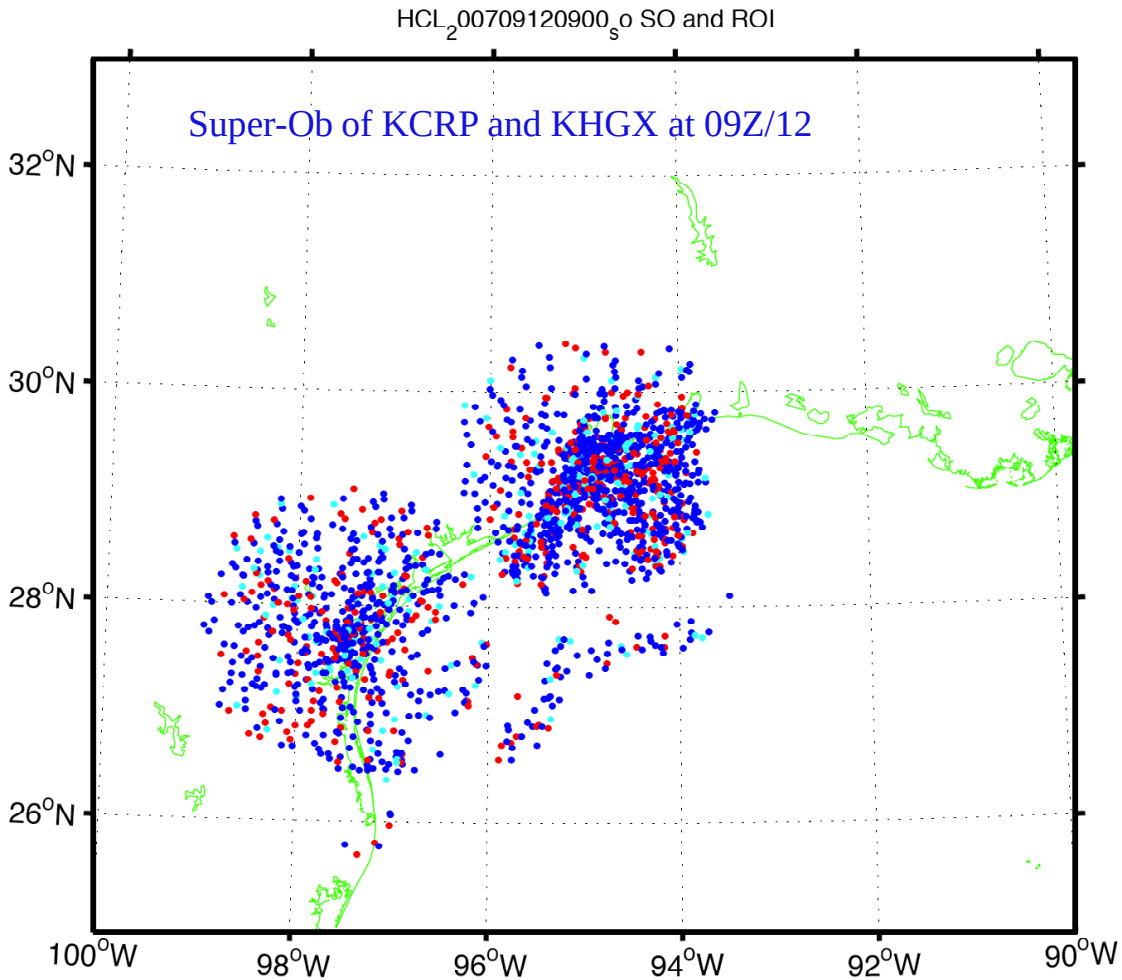


0.5degree SO



- Define SO position depended on the radial distance
- Average10 nearest data points in the raw polar scan to create a SO
- Averaging bin is 5km max radial range and 5° max azimuthally resolution
- There are at least 4 valid velocity data within an averaging bin.
- The standard deviation checking of the velocities.

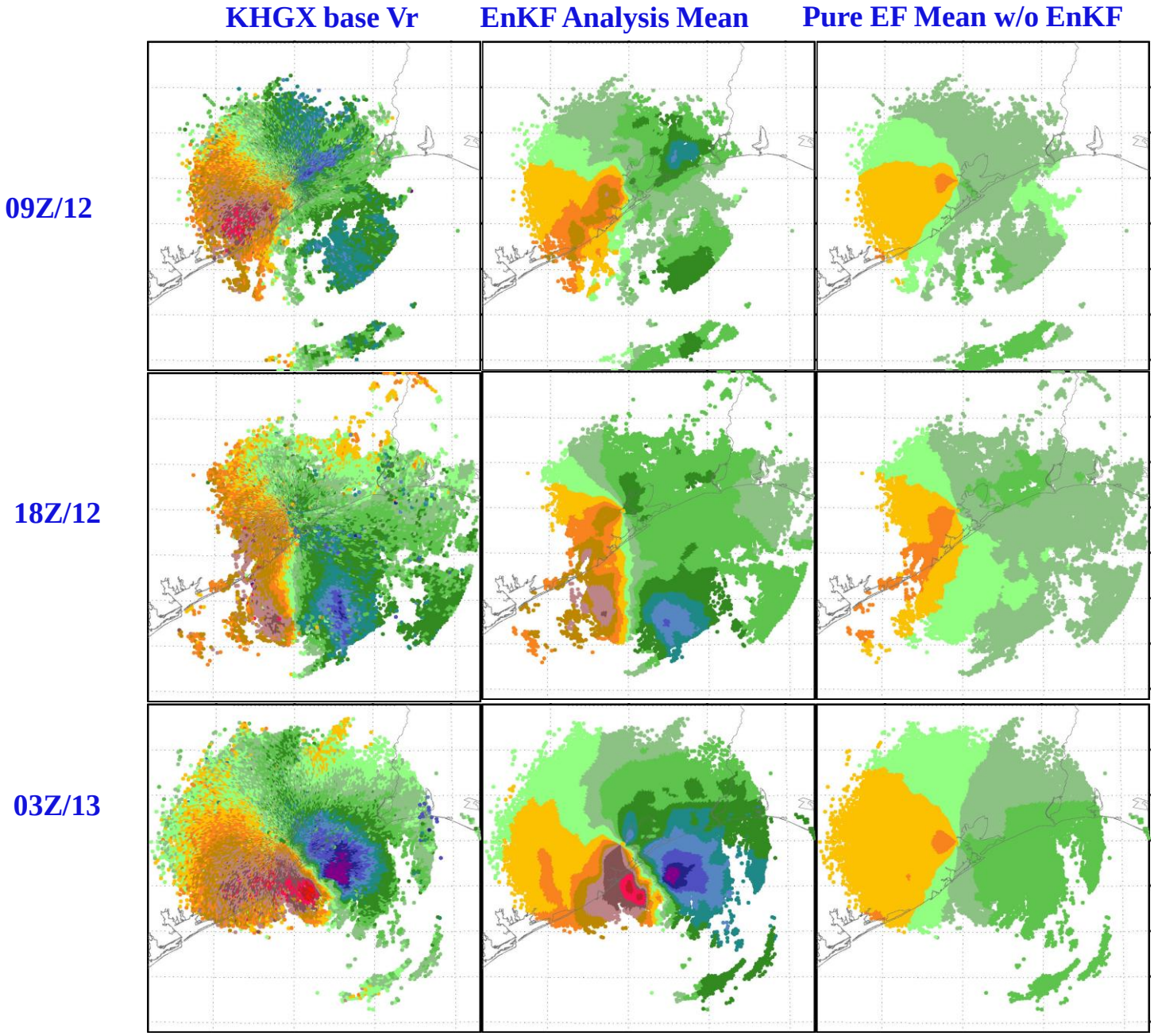
Humberto'07: Super-Observations at 09Z/12



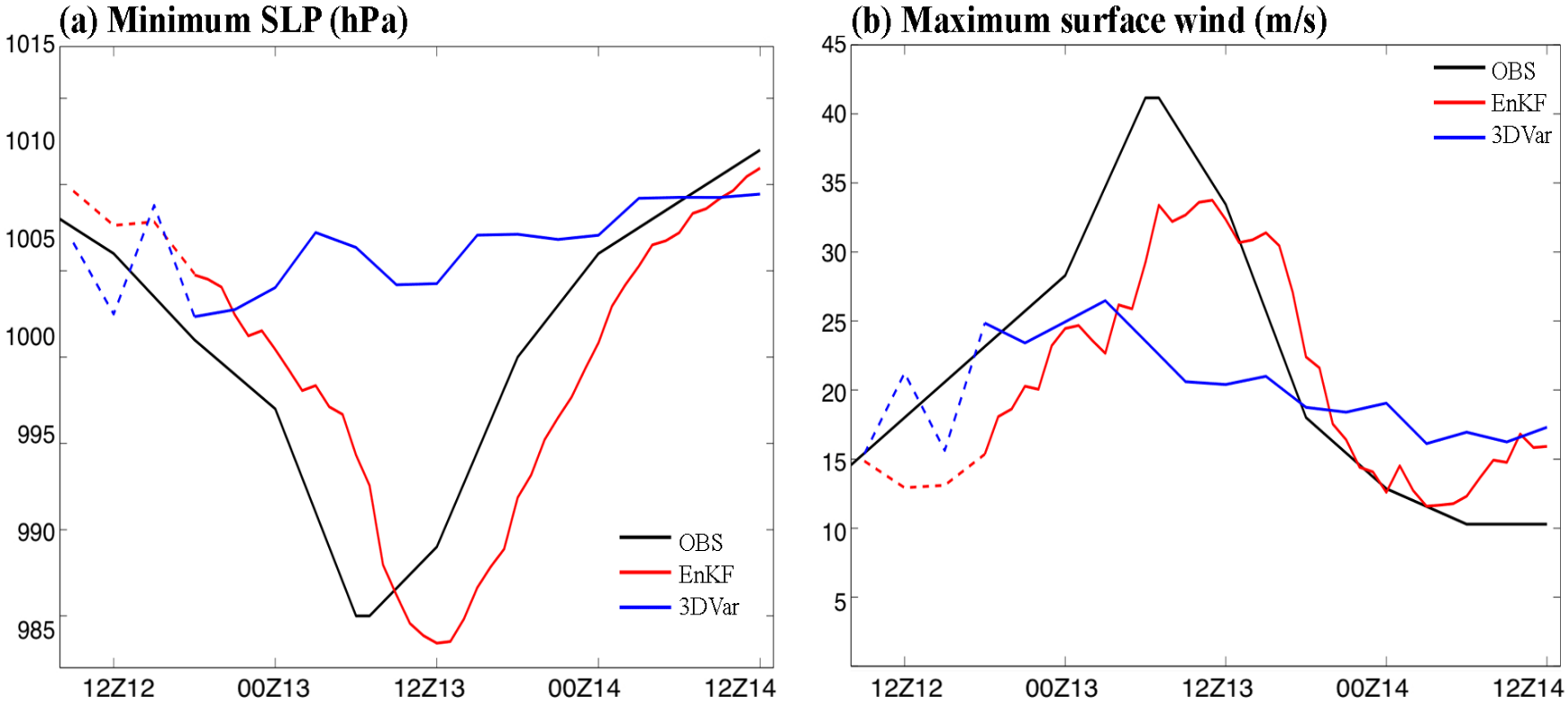
-WRF/EnKF starts assimilating hourly Vr obs of CRP, HGX and LCH WSR88D radars from 09Z/12 to 21Z/12 after a 9-h ensemble forecast from GFS/FNL analysis

-Successive covariance localization with different ROIs for different subset of SOs

WRF/EnKF Analysis vs. Observations vs. NoDA



WRF/EnKF Forecast vs. Observations vs. 3DVAR

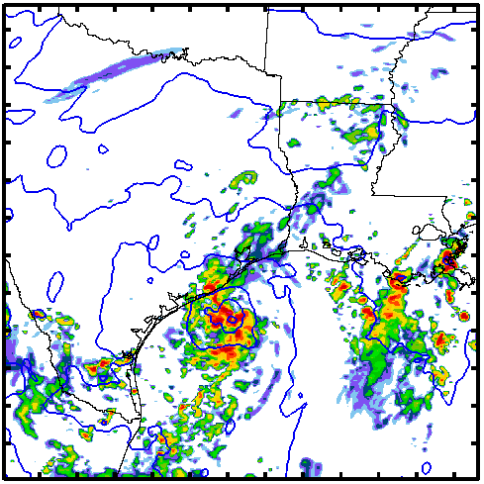


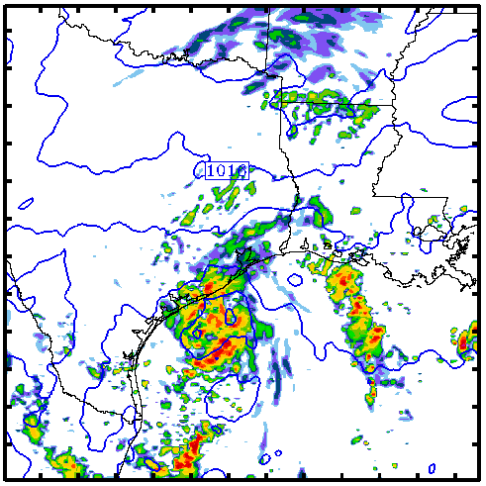
The WRF/3DVAR (as a surrogate of operational algorithm) assimilates the same radar data but without flow-dependent background error covariance, its forecast failed to develop the storm despite fit to the best-track observation better initially

(Zhang et al. 2009 MWR)

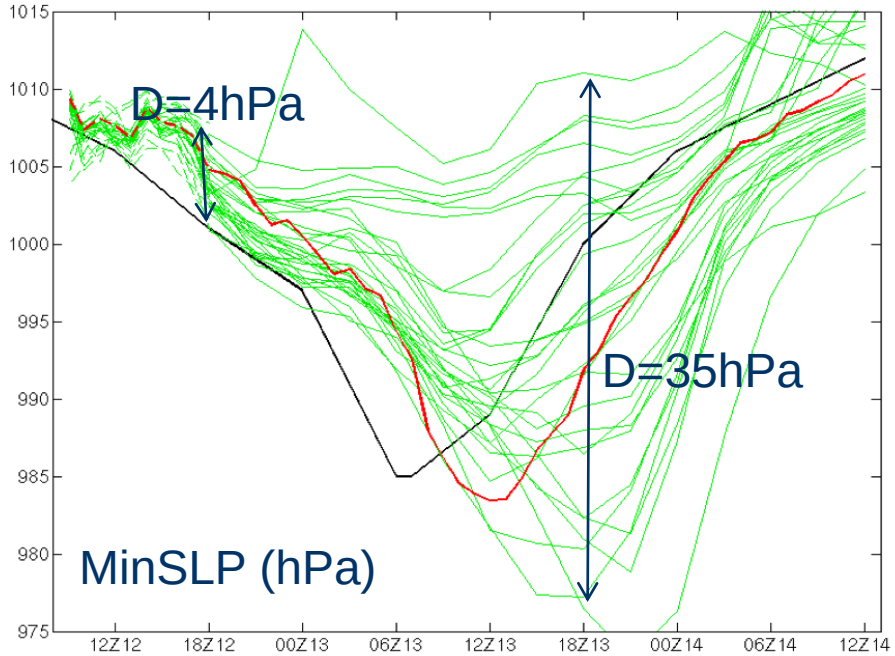
Ensemble Forecast and Predictability of Intensity

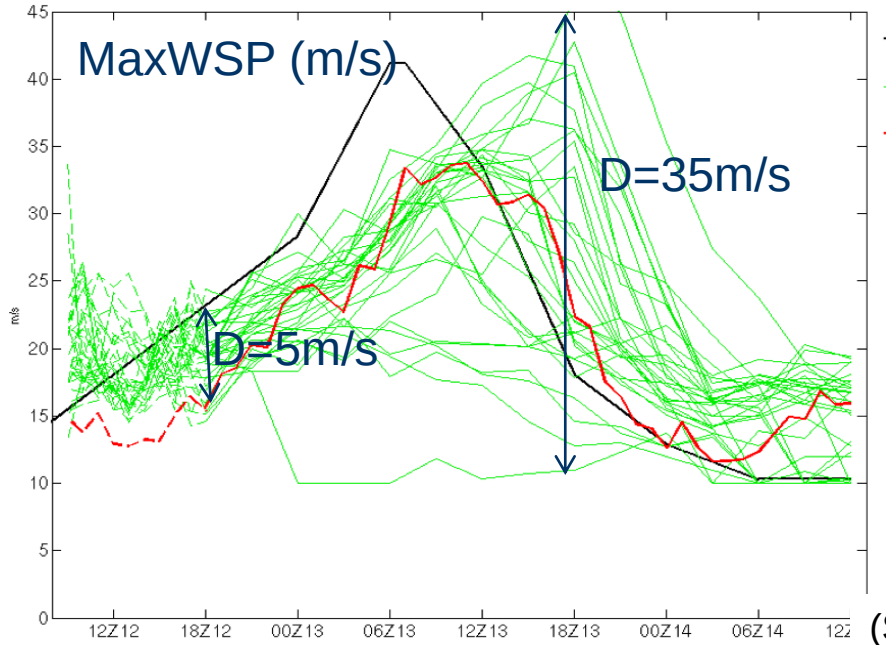
Strong member



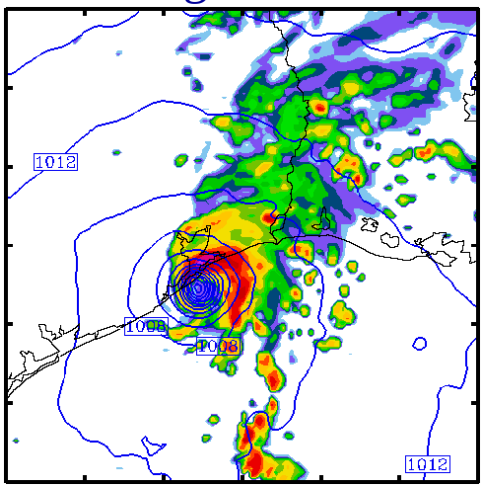


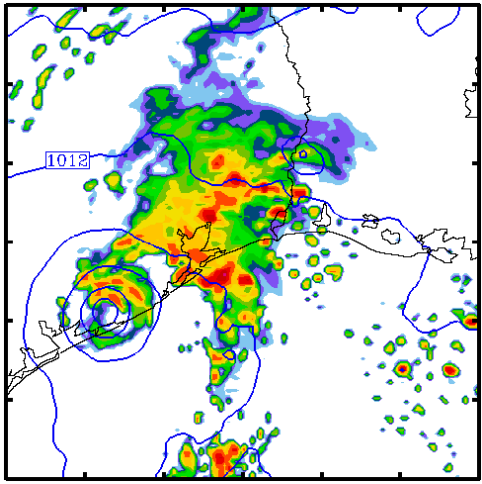
Weak member





Strong member



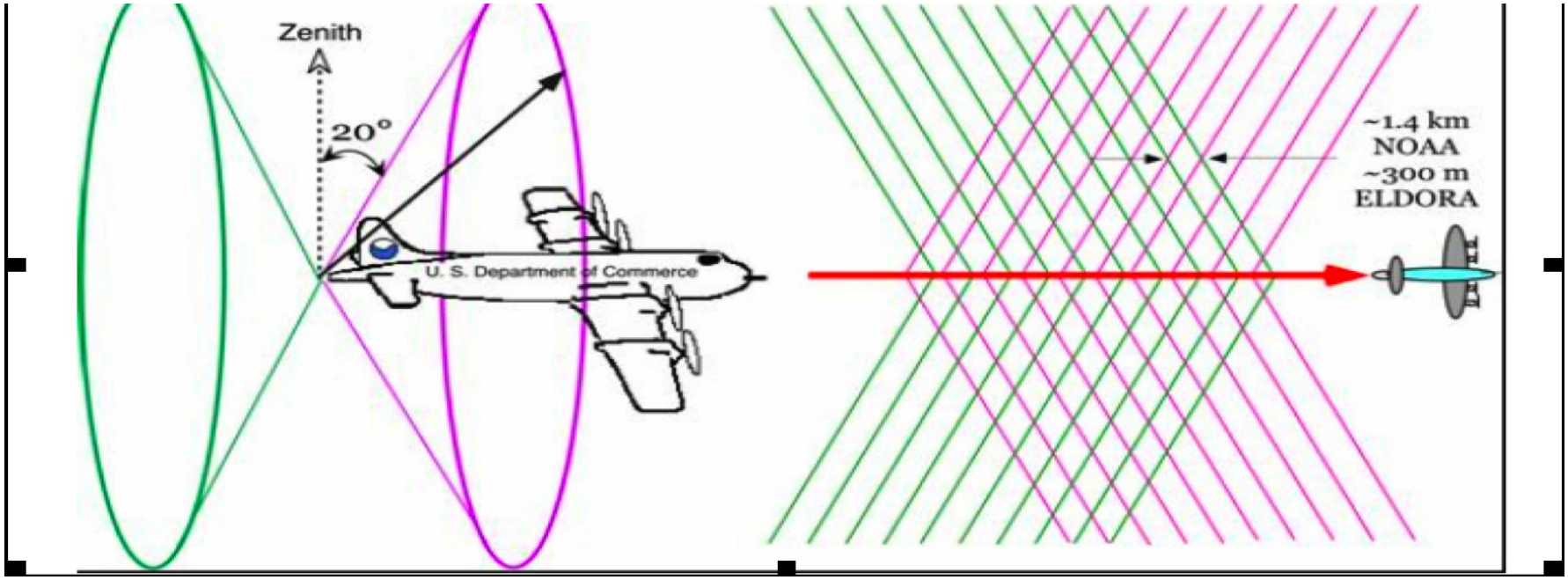


Weak member

(Sippel and Zhang 2010 JAS)

Assimilate Airborne Doppler Winds with WRF-EnKF

Available for 20+ years but never used in operational models due to the lack of resolution and/or the lack of efficient data assimilation methods



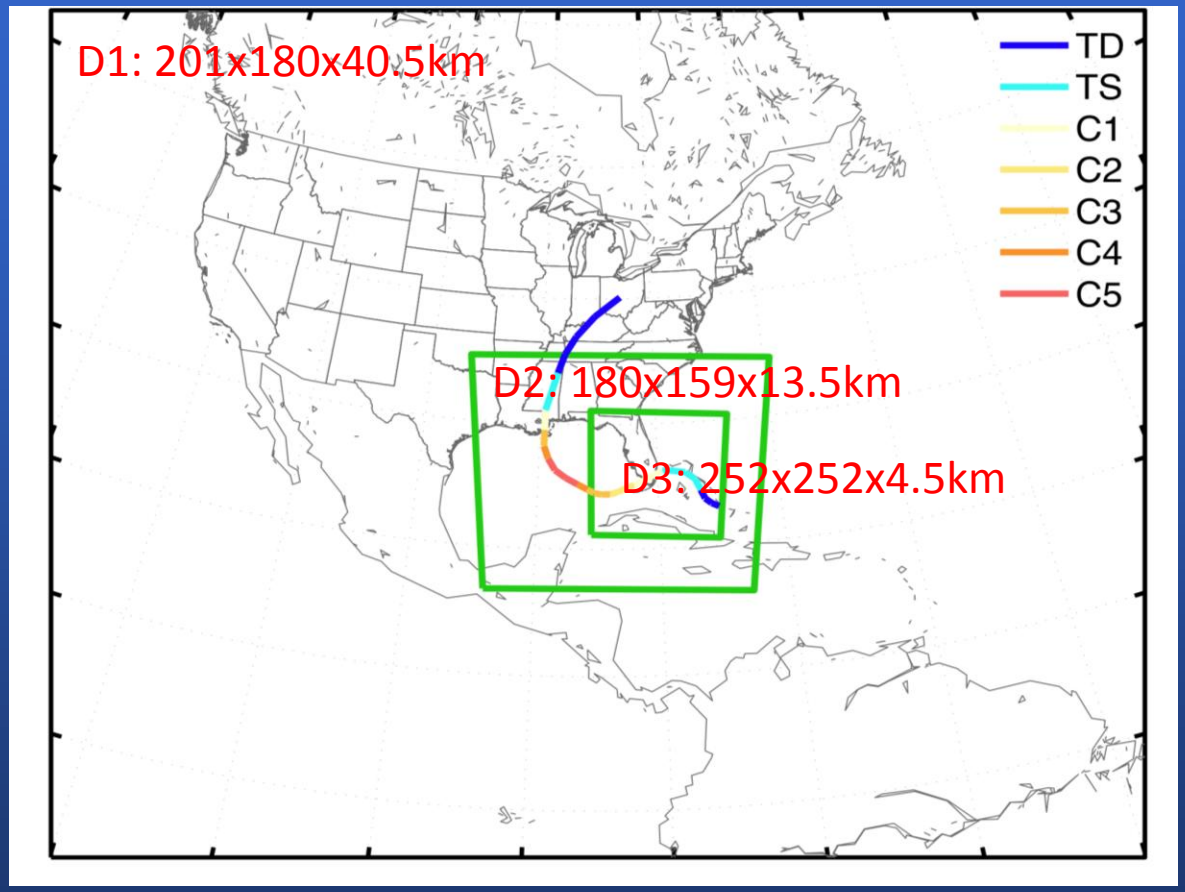
Superobservations: 1. Separate forward and backward scans; 2. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 3. thinning ---one bin for 2 km in radial distance and 3 degree in scanning angle; 4. use medium as SO after additional QC checking

These SOs are generated on flight of NOAA P3's; transmitted to ground in real-time

WRF-EnKF: 3 domains (40.5, 13.5&4.5km), 60-member ensemble

(Weng and Zhang 2011, MWR, in revision)

Experimental design



Katrina Best Track and model domain configuration at 2005082500, the inner domains will be auto-moving by vortex center after 12hr integration.

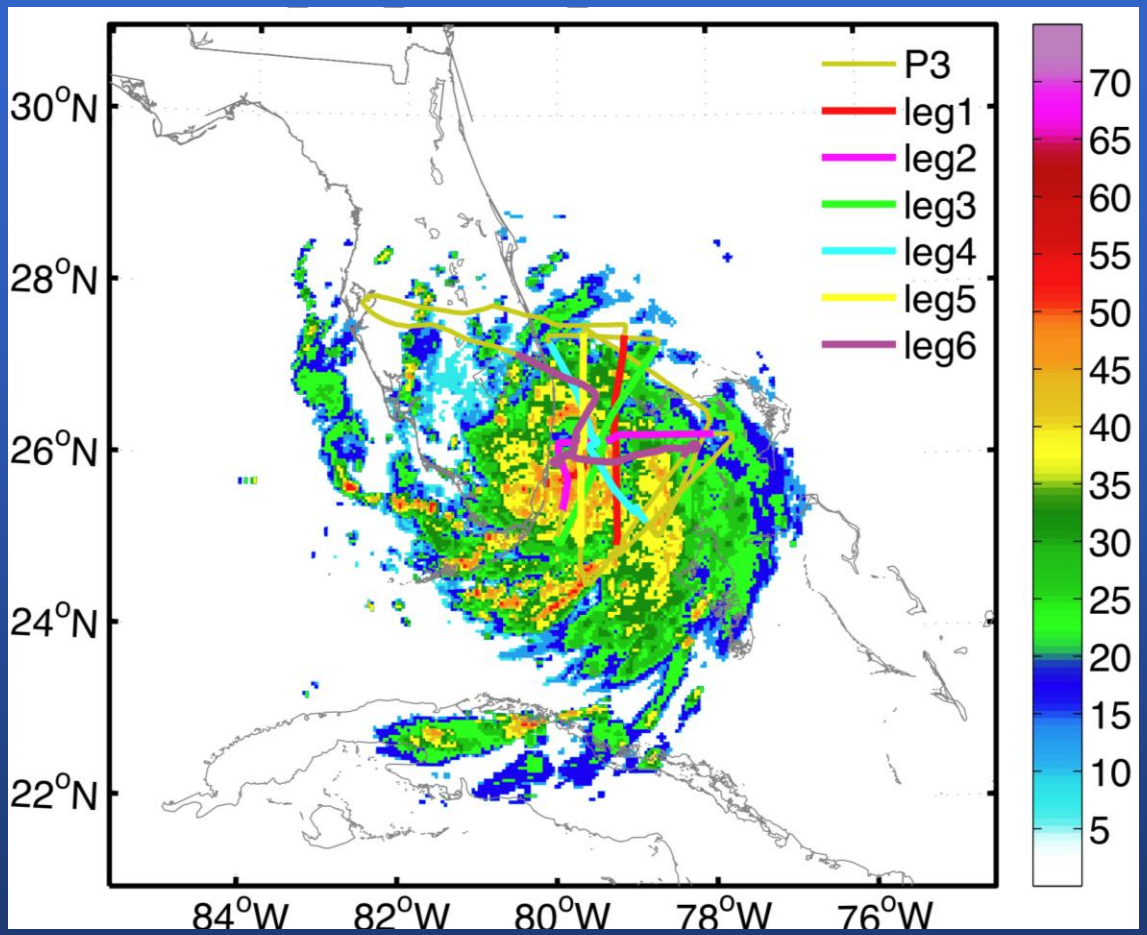
- WRF ARW V3.1
- 35 vertical levels
- 2-way nested
- vortex-following movable

- microphysics: WSM 6
- PBL: YSU scheme

- ICs: GFS analysis
- BCs: GFS forecast

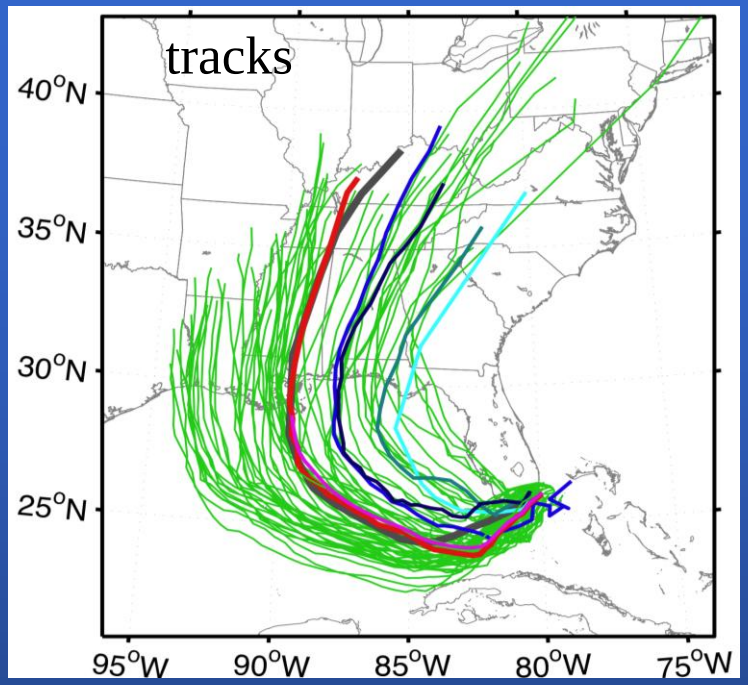
- Perturbation: WRFDA V3
- Ensemble members: 60

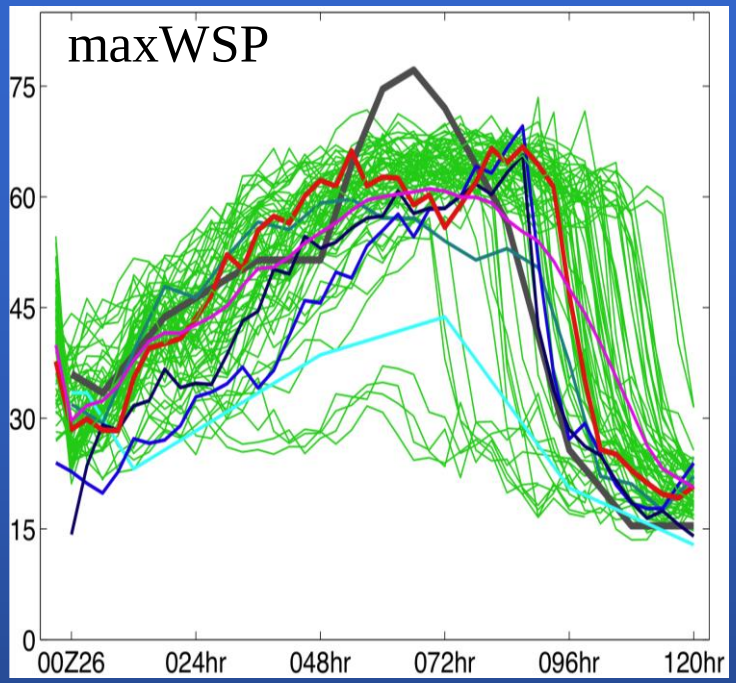
Radar Observation

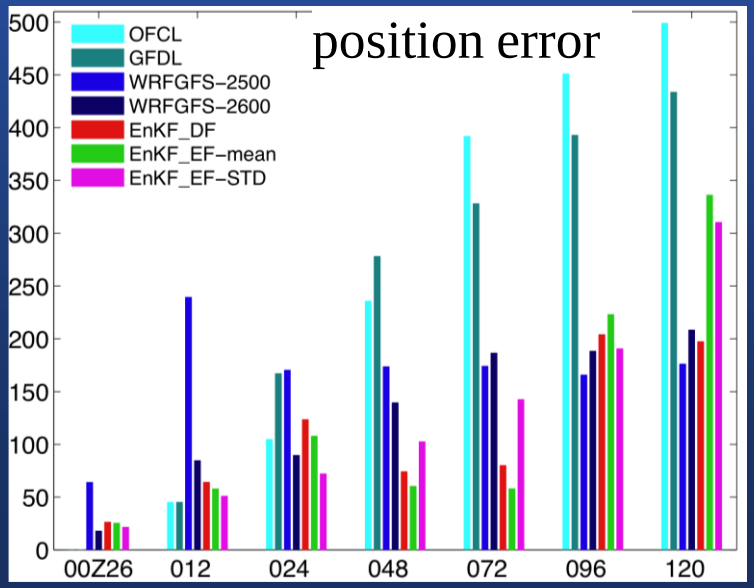


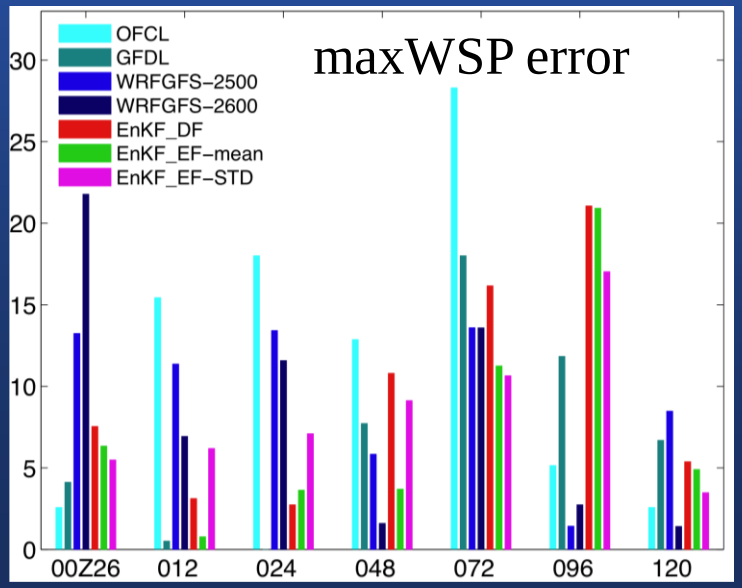
KAMX composite reflectivity at 2000 UTC 25 Aug 2005 (the center time of the last leg of P3 050825I1 mission) and P3 flight track for the 050825I1 mission over the 4.5 km horizontal resolution model domain.

Hurricane track forecast and forecast error



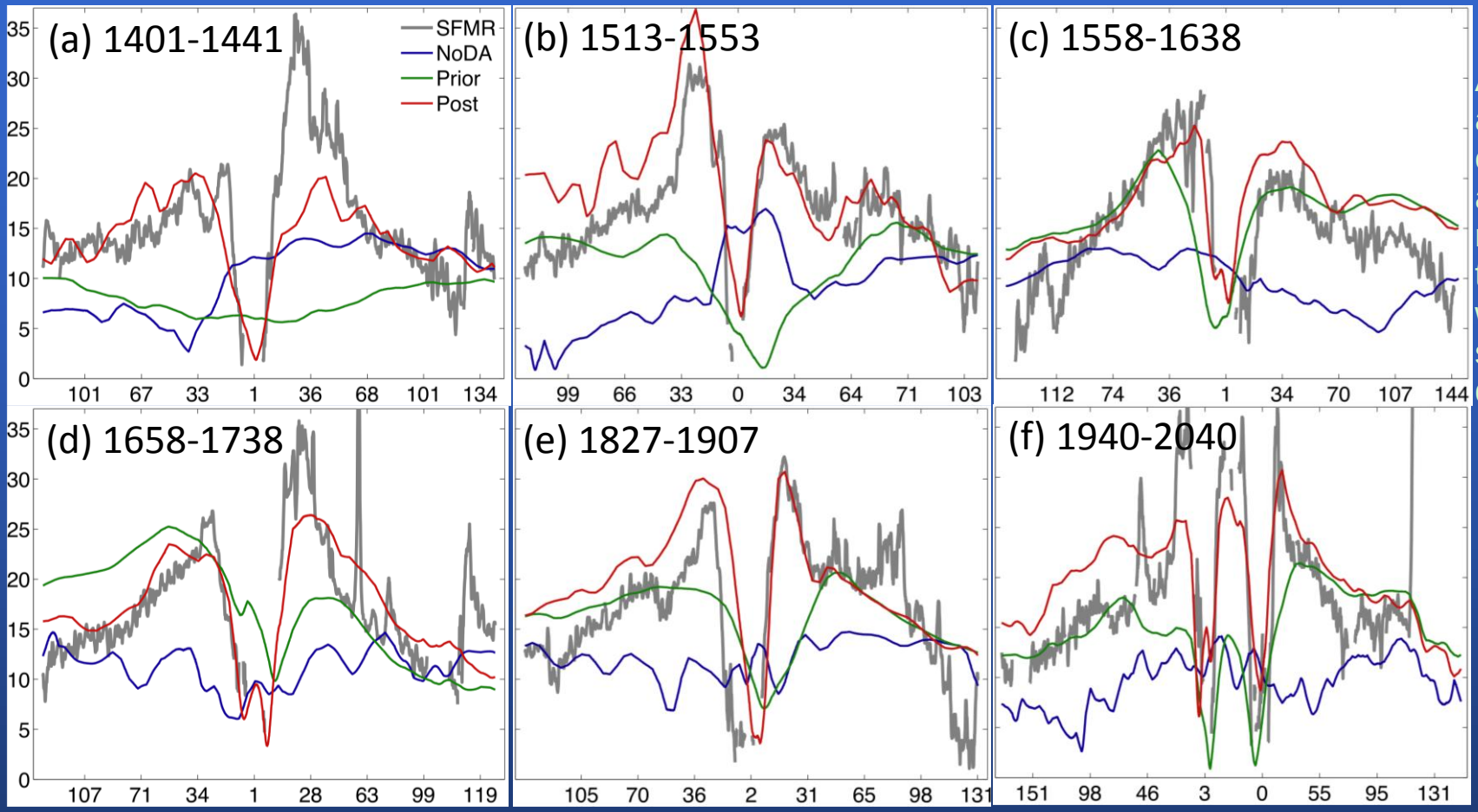






- EnKF_DF closely followed the best track except 6h delay;
- EnKF_DF were much closer to the best track observations than NODA and operational forecast;
- Ensemble mean has the similar result of EnKF_DF;
- large ensemble forecast spread indicates the high amount of uncertainty

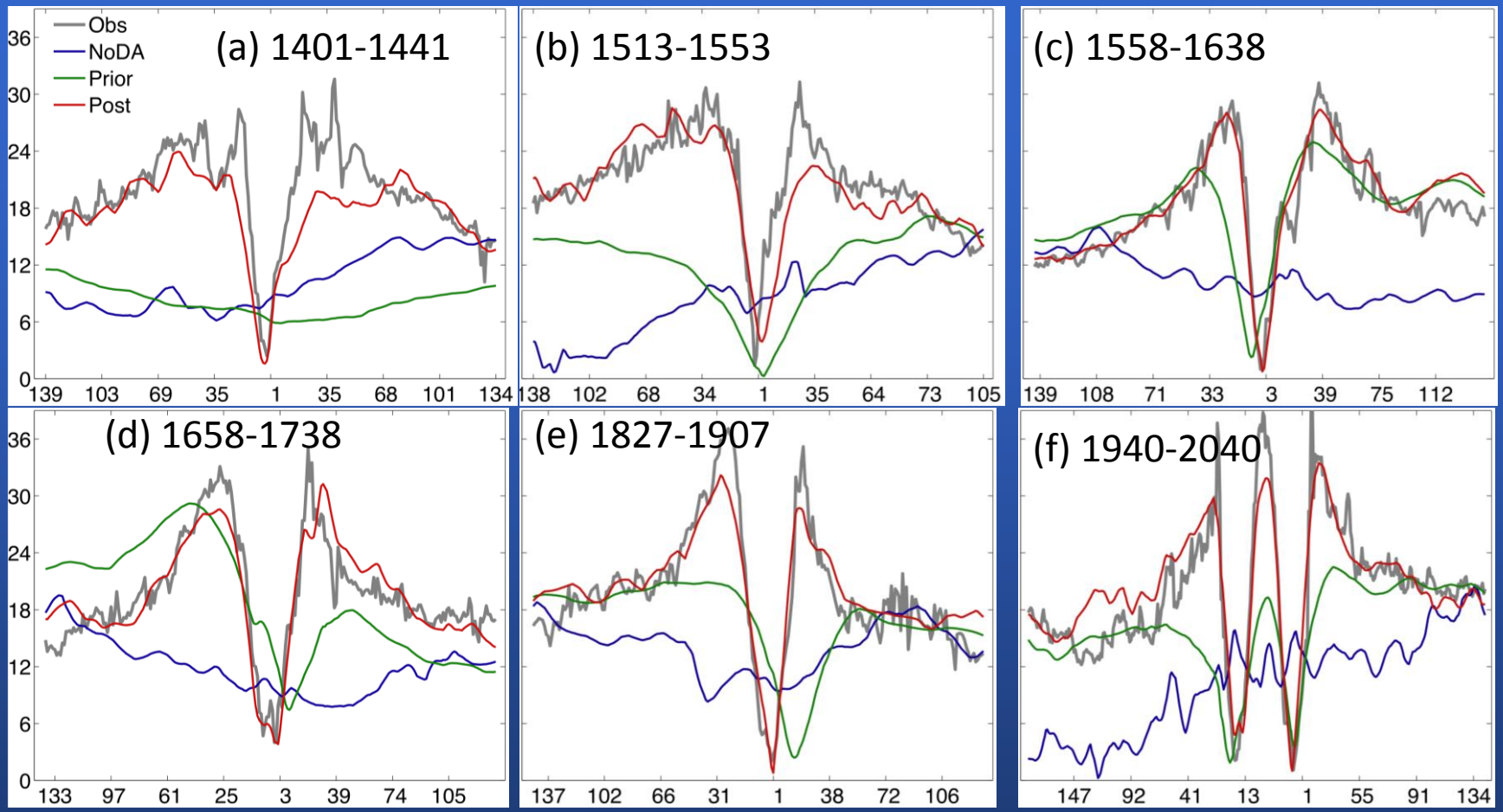
SFMR surface wind speed along the leg tracks



After the 2nd assimilation cycle, EnKF analyses reproduces the observed wind structure quite well.

Surface wind speed retrieved by Stepped Frequency Microwave Radiometer (SFMR) (grey). The x-axis is the horizontal distance between the flight and the storm center of the NHC operational analyses.

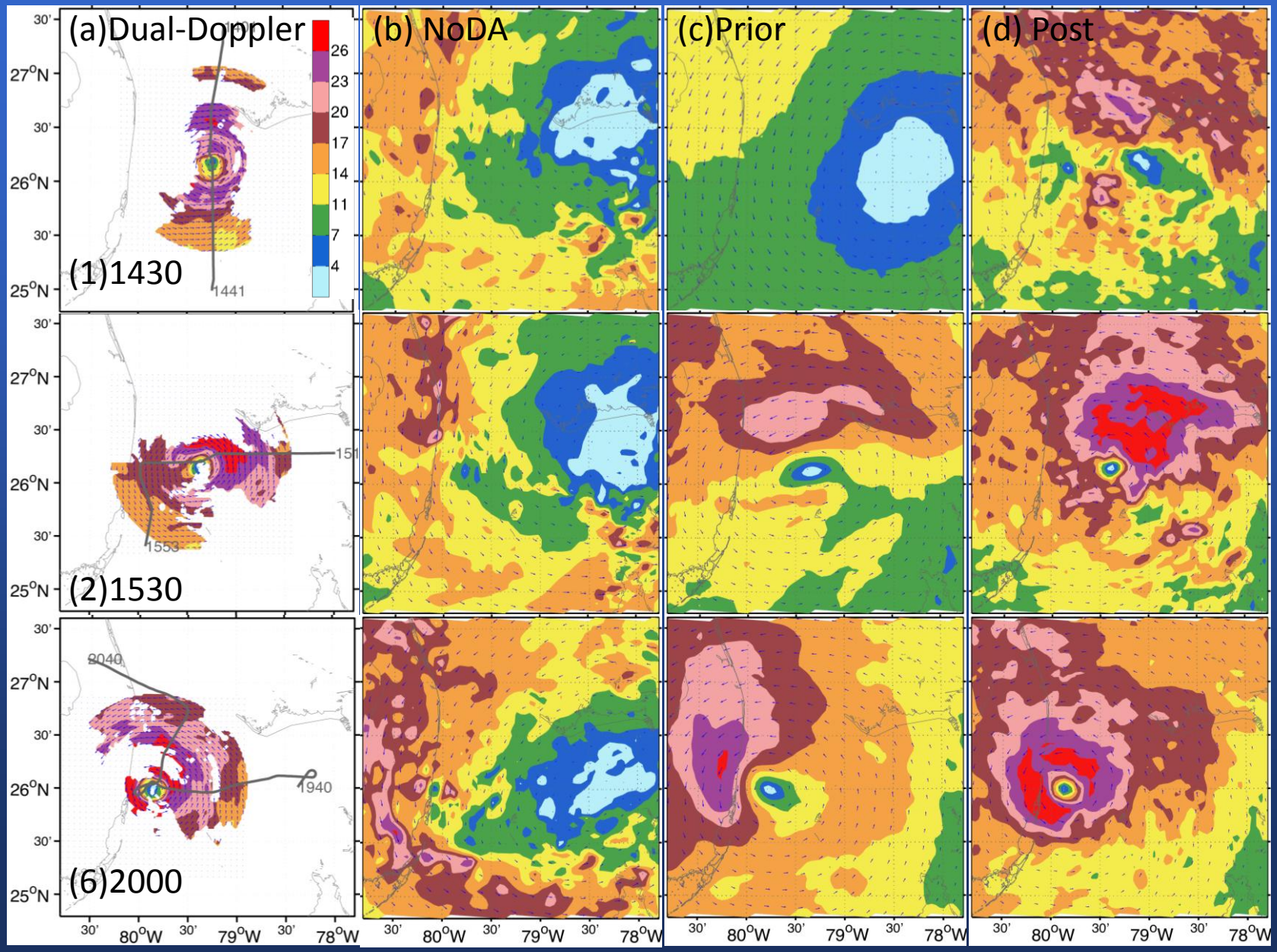
Flight-level wind speed along the leg tracks



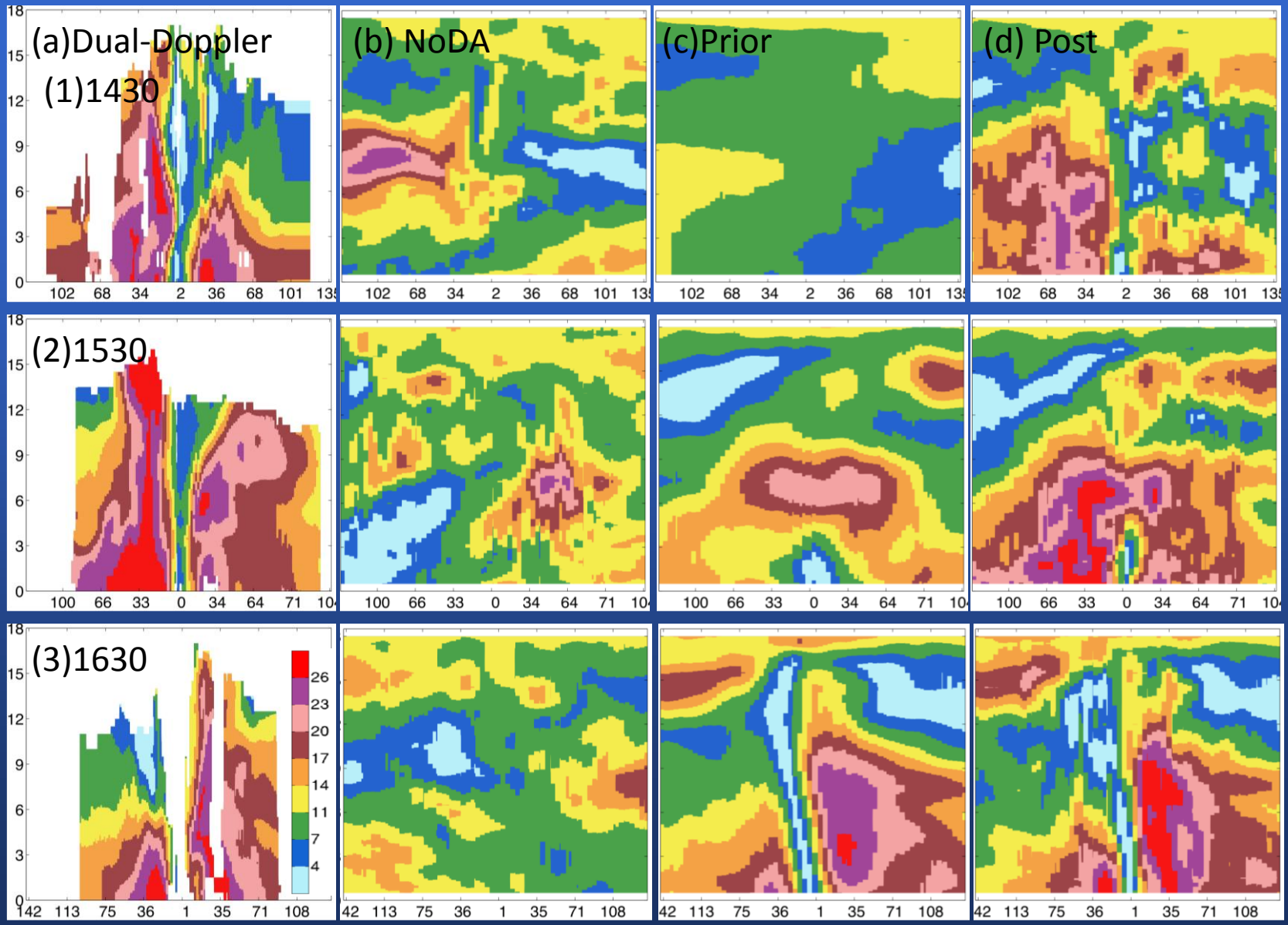
Flight-level wind speed observed by NOAA P3 mission (grey)

After the 2nd assimilation cycle, EnKF analyses reproduces the observed wind structure quite well.

Winds at 3km height

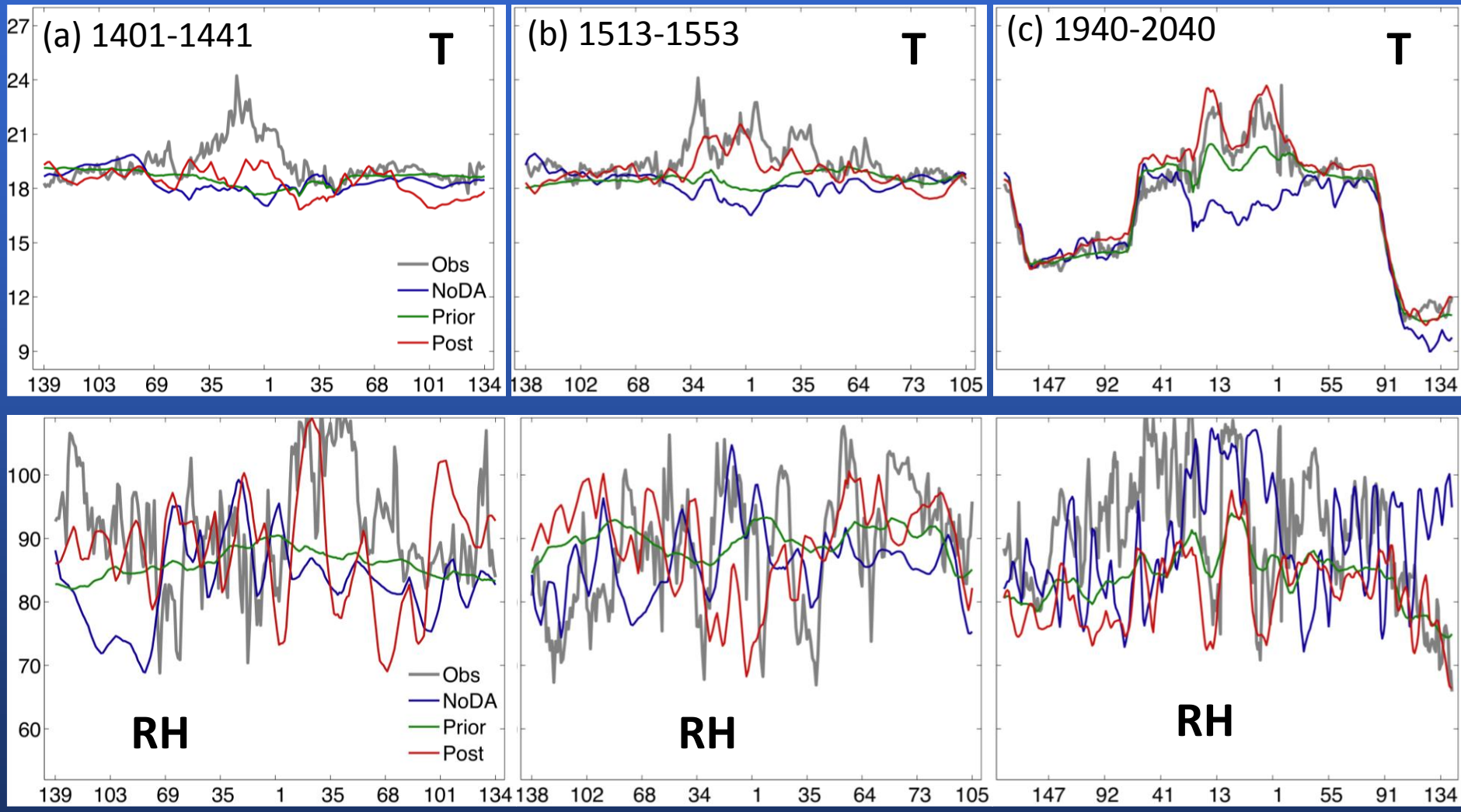


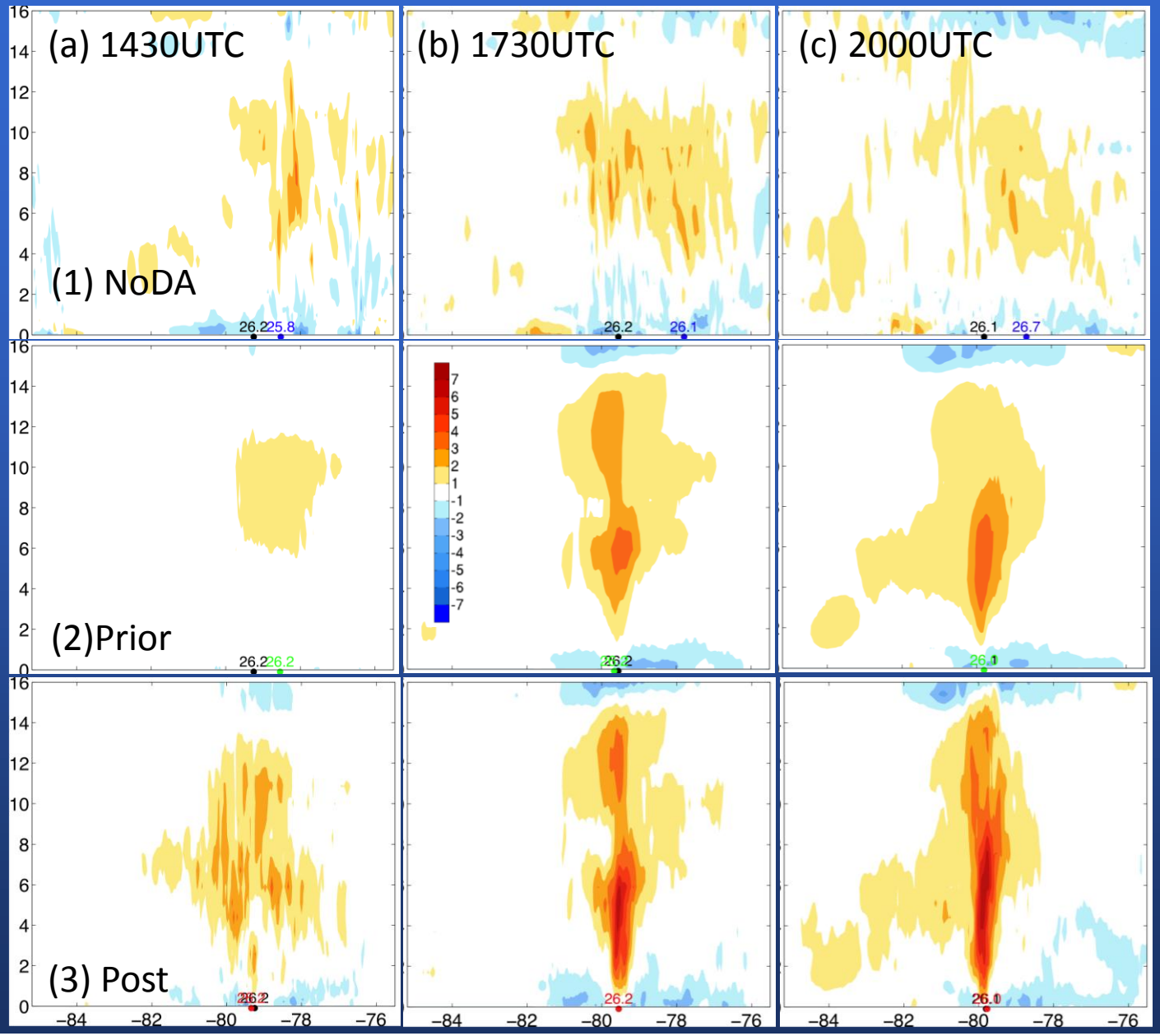
Track-height wind speed sections along the leg tracks



EnKF analyses strengthens the storm and makes the storm vortex up to 6 km which is much lower than the dual-Doppler radar analyses.

Verification for thermodynamics fields



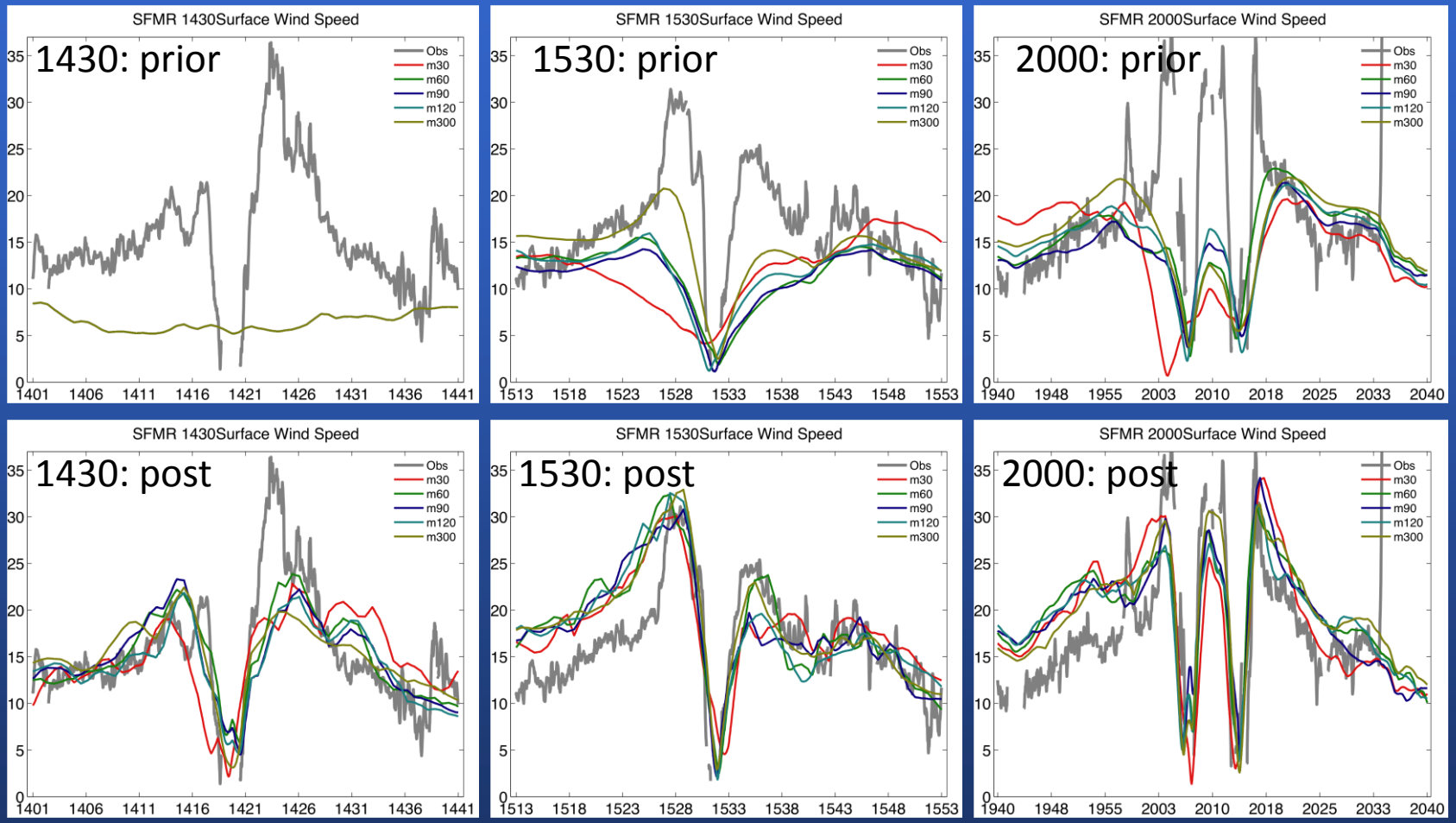


- The EnKF assimilation continually warms the hurricane core while the vortex develops;
- The warm core is up to 15 km, which is higher than the 9-km height of vortex center from the wind analyses.

Anomaly temperature longitude-height section across the model forecast/analyses storm center along the latitude. The anomaly temperature is the bias from the averaged temperature over the same model level.

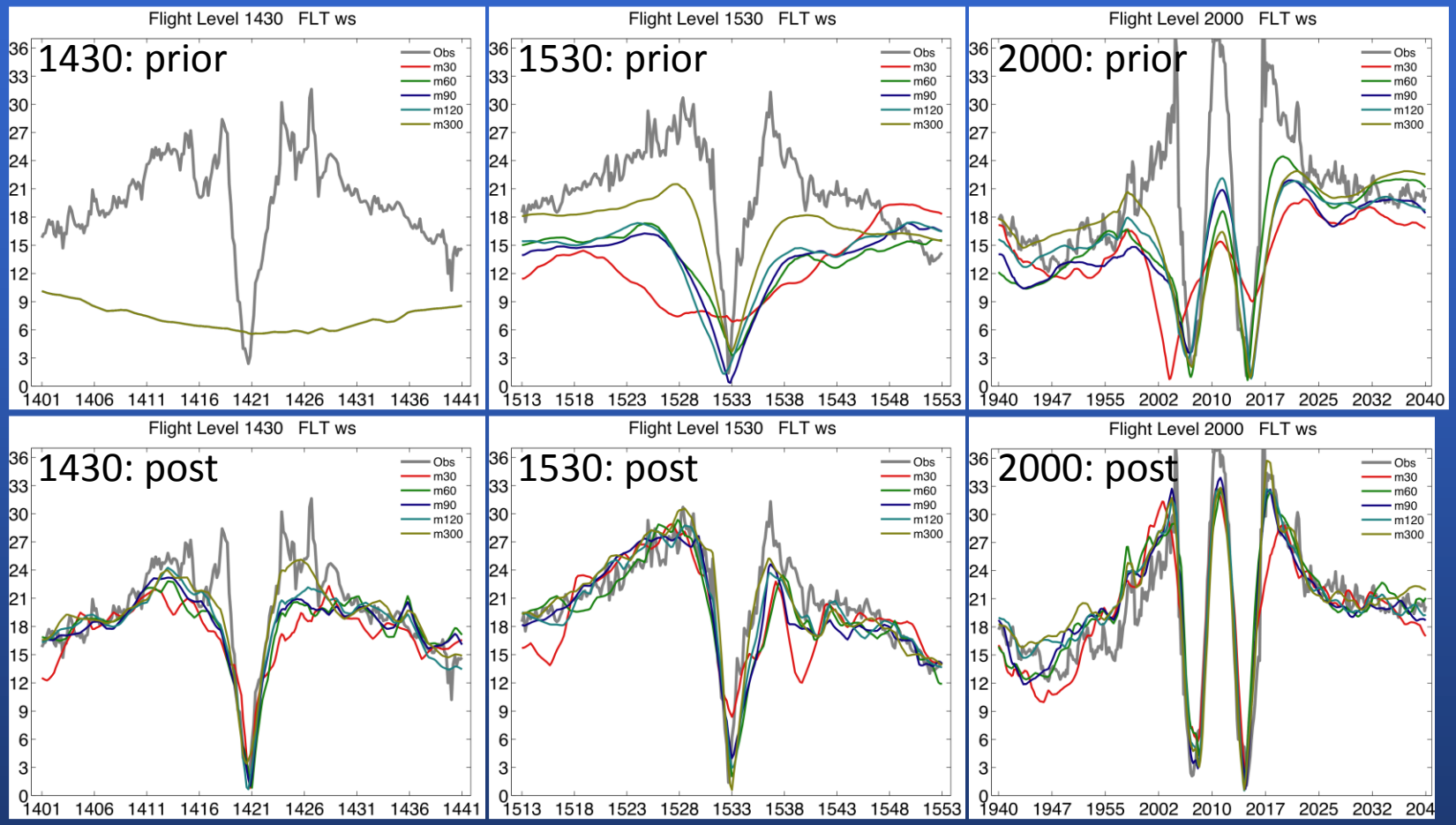
How many members are acceptable?

SFMR surface wind speed



- More members are closer to the observation in vortex position, size and intensity;
- The differences are small with more than 60 members.

Flight level wind speed



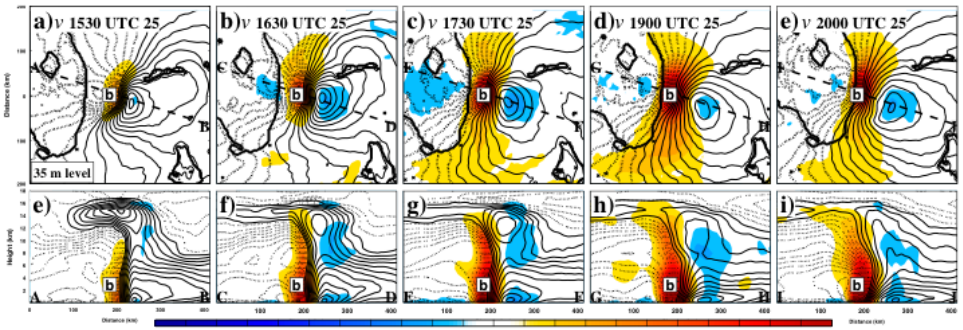
- More members are closer to the observation in vortex position, size and intensity;
- The differences are small with more than 60 members.

Covariance between v_b and the v *field*

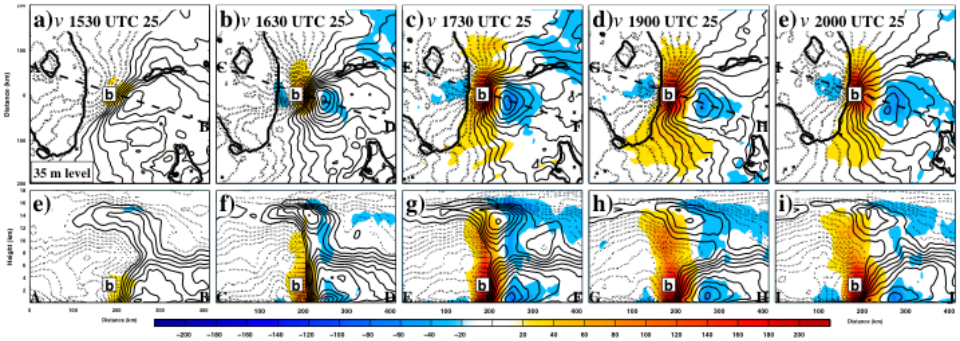
300-m ensemble mean and covariance

60-m mean and covariance

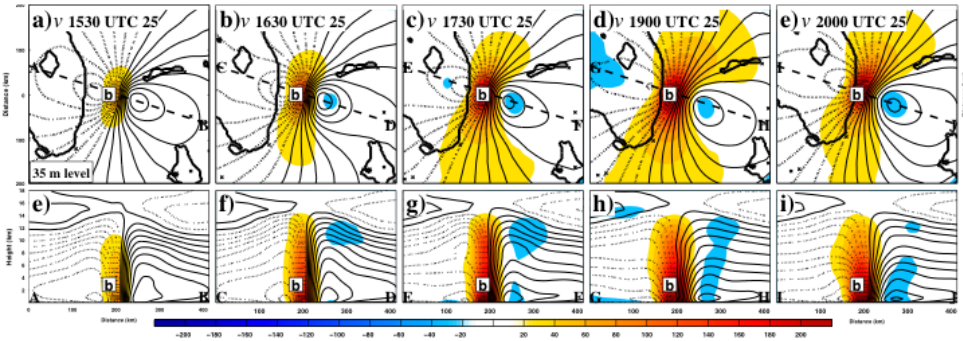
Cov(v_b,v)



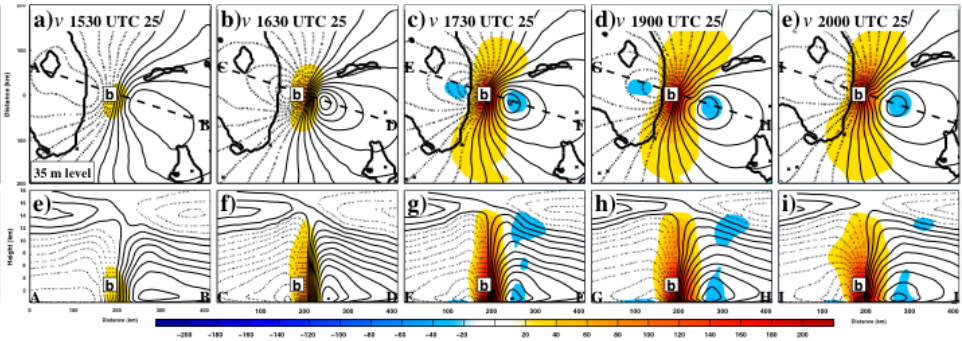
Cov(v_a,v)



Cov(v_b,$v_{n=0}$)



Cov(v_b,$v_{n=0}$)



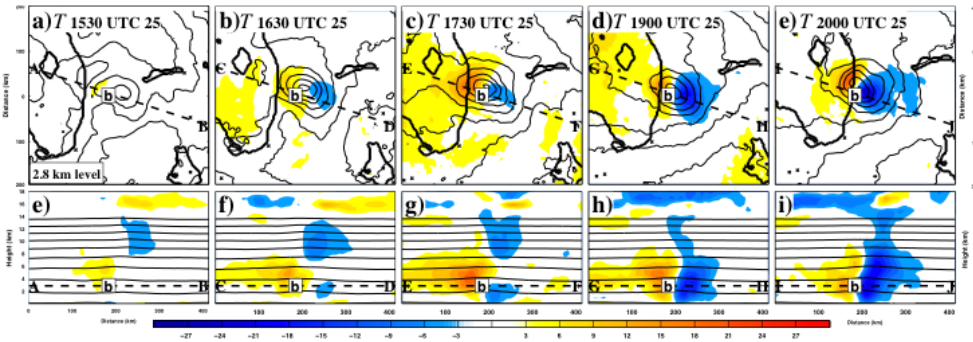
Above is a second example to show the similarity between the two ensembles' representation of cov(v,$v_{n=0}$). For the wavenumber 1-2 example in the previous slide, the magnitudes of covariance are similar, but in different locations. Some of the differences may also be due to the fact that each ensemble is updated using slightly different samples. After several assimilation cycles, the covariance matrix for the two cases will probably evolve in slightly different ways.

Covariance between v_a and the T *field*

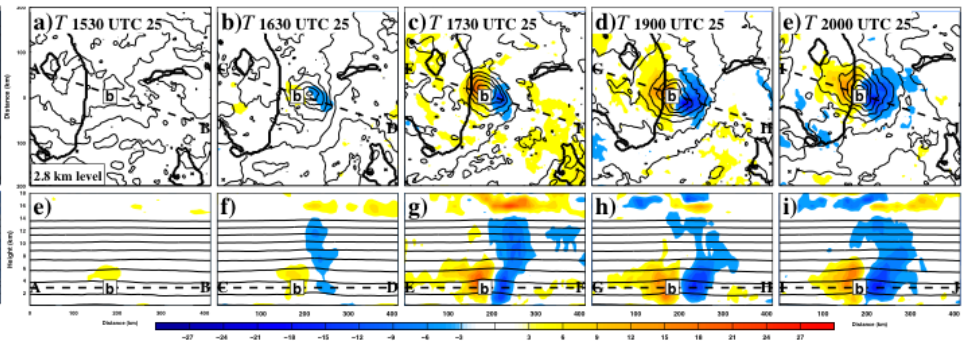
300-m ensemble mean and covariance

60-m mean and covariance

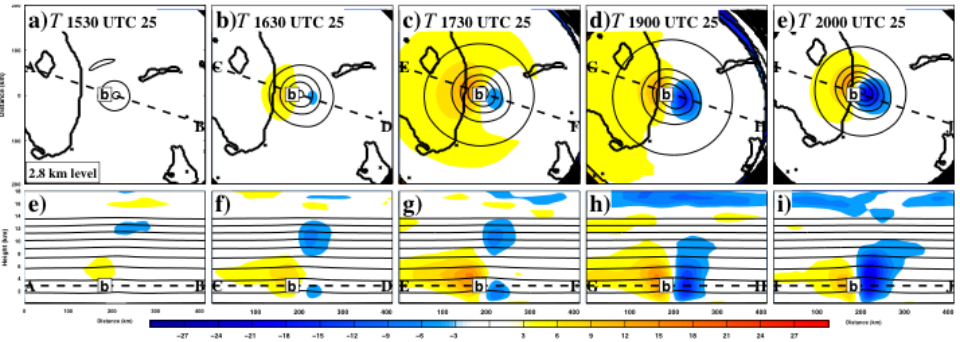
Cov(v_b,T)



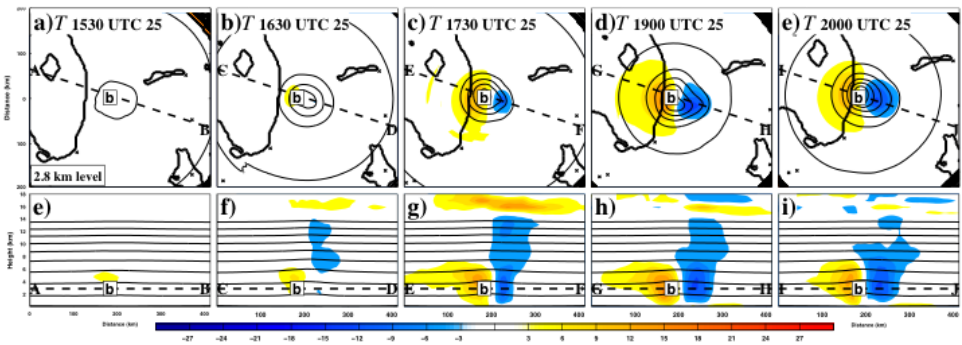
Cov(v_b,T)



Cov(v_b,$T_{n=0}$)



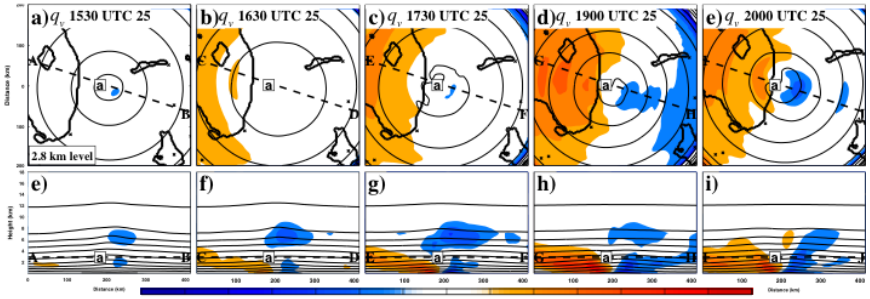
Cov(v_b,$T_{n=0}$)



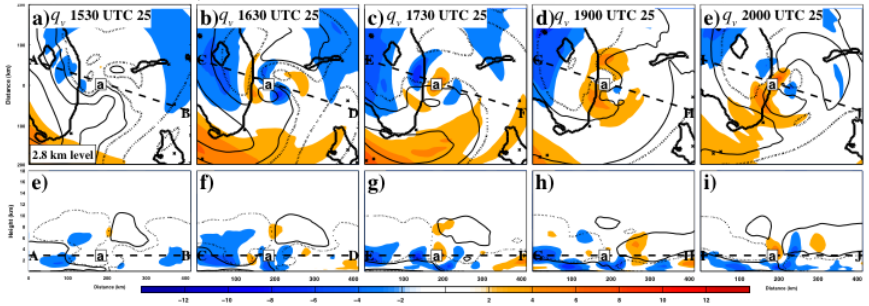
Spatial covariance is similar for the two ensembles, with the exception of being larger in magnitude for the wavenumber 0 300-m ensemble. This trend continues for most other variables.

300-m ensemble mean and covariance

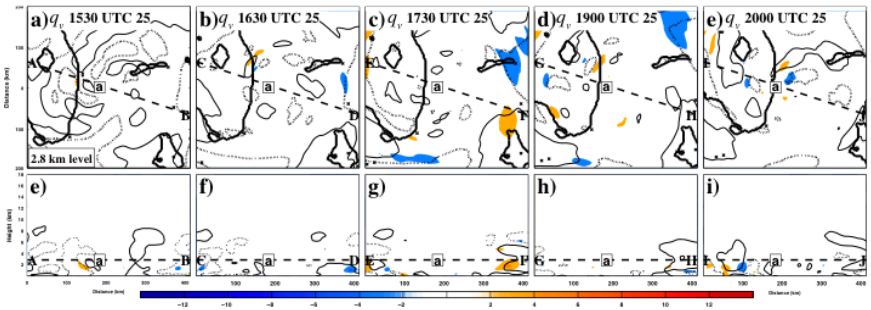
Cov(v_a,$q_{n=0}$)



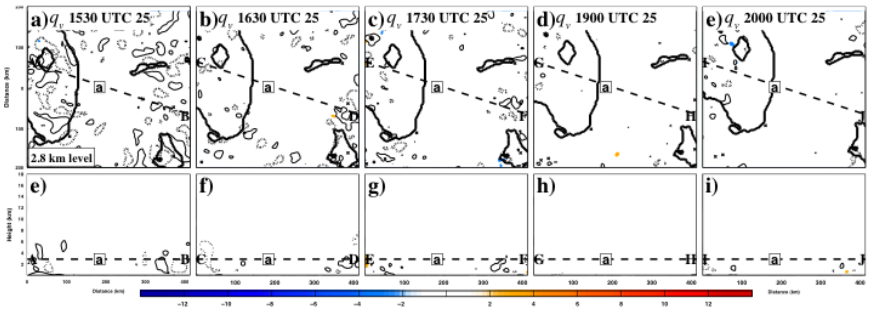
Cov(v_a,$q_{n=1,2}$)



Cov(v_a,$q_{n=3\text{-}7}$)

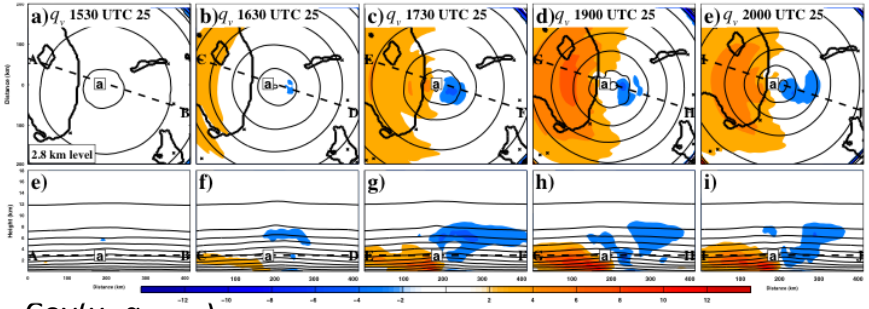


Cov(v_a,$q_{n>7}$)

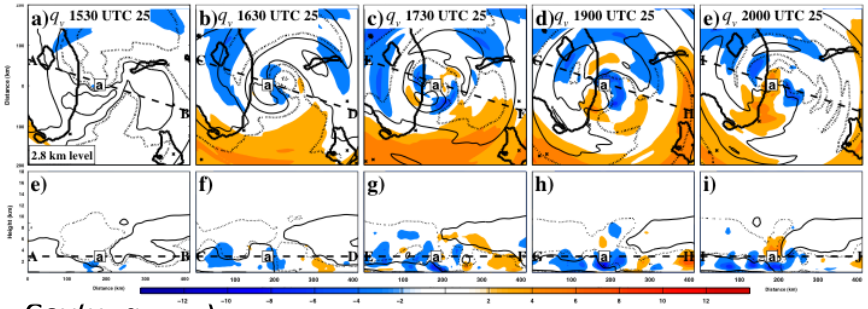


60-m mean and covariance

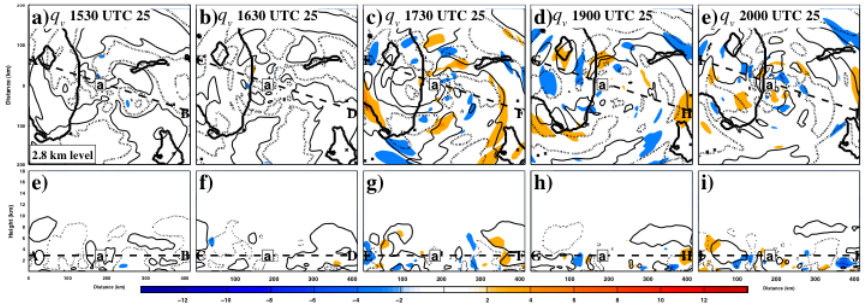
Cov(v_a,$q_{n=0}$)



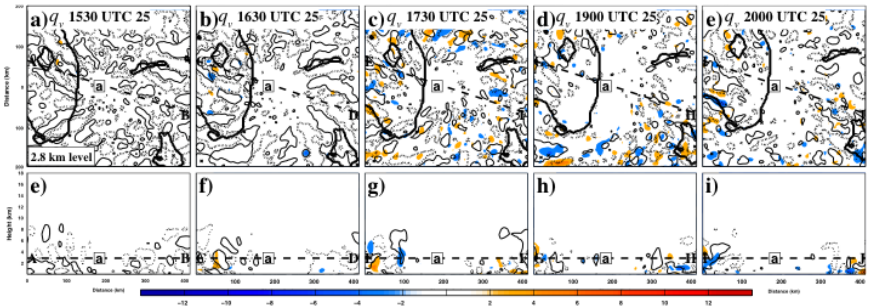
Cov(v_a,$q_{n=1,2}$)



Cov(v_a,$q_{n=3\text{-}7}$)



Cov(v_a,$q_{n>7}$)

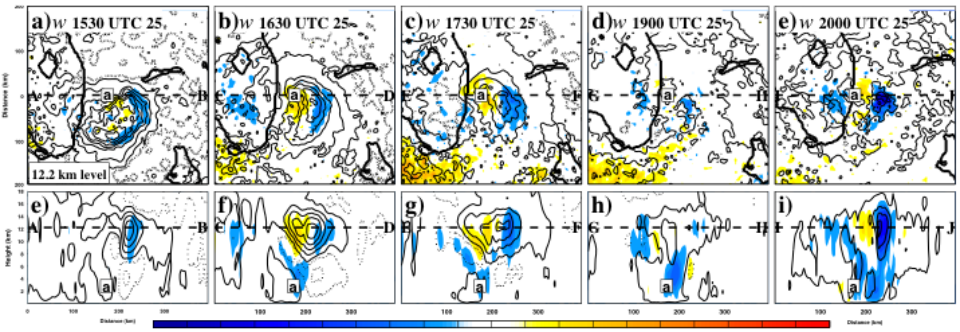


Covariance between v_a and the w *field*

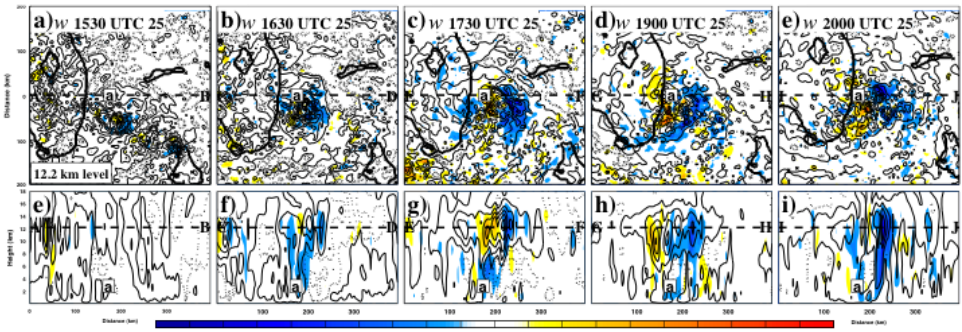
300-m ensemble mean and covariance

60-m mean and covariance

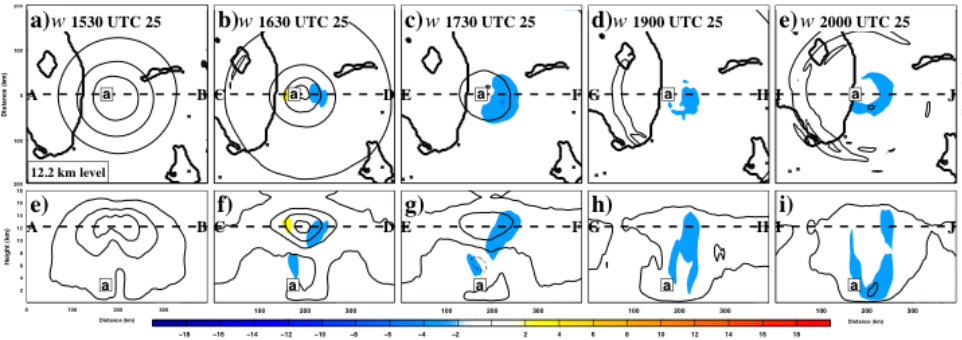
Cov(v_a,w)



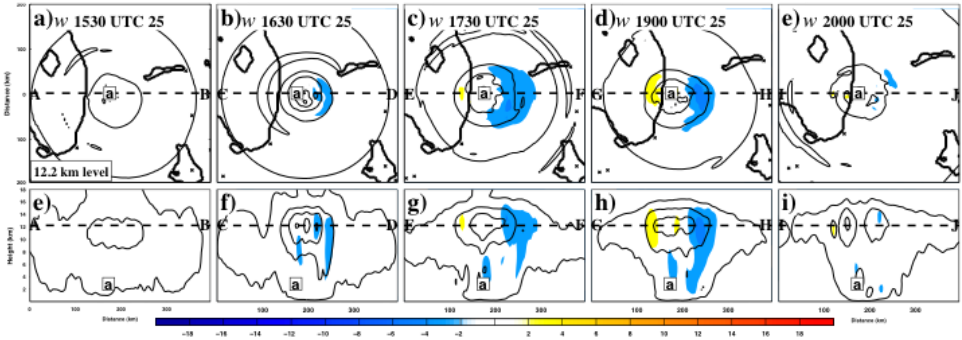
Cov(v_a,w)



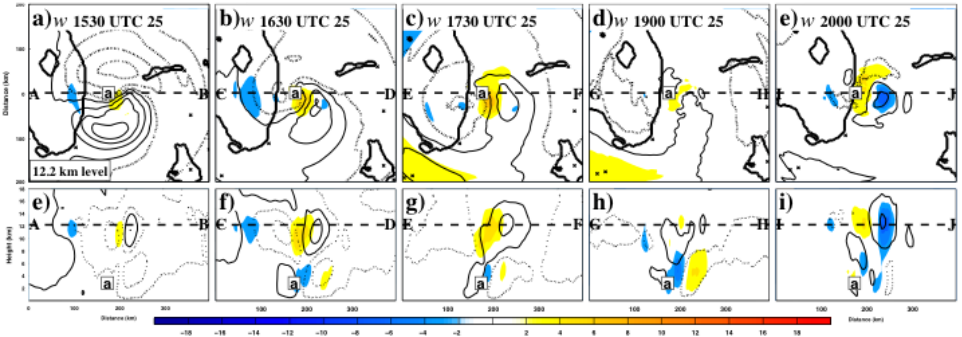
Cov(v_a,$w_{n=0}$)



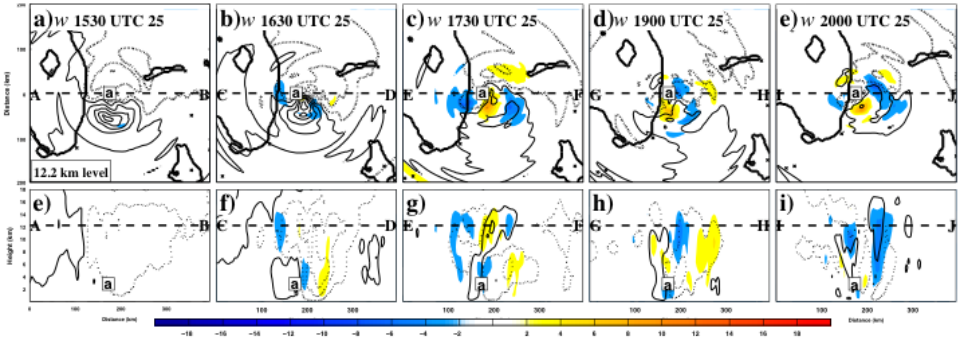
Cov(v_a,$w_{n=0}$)



Cov(v_a,$w_{n=1,2}$)



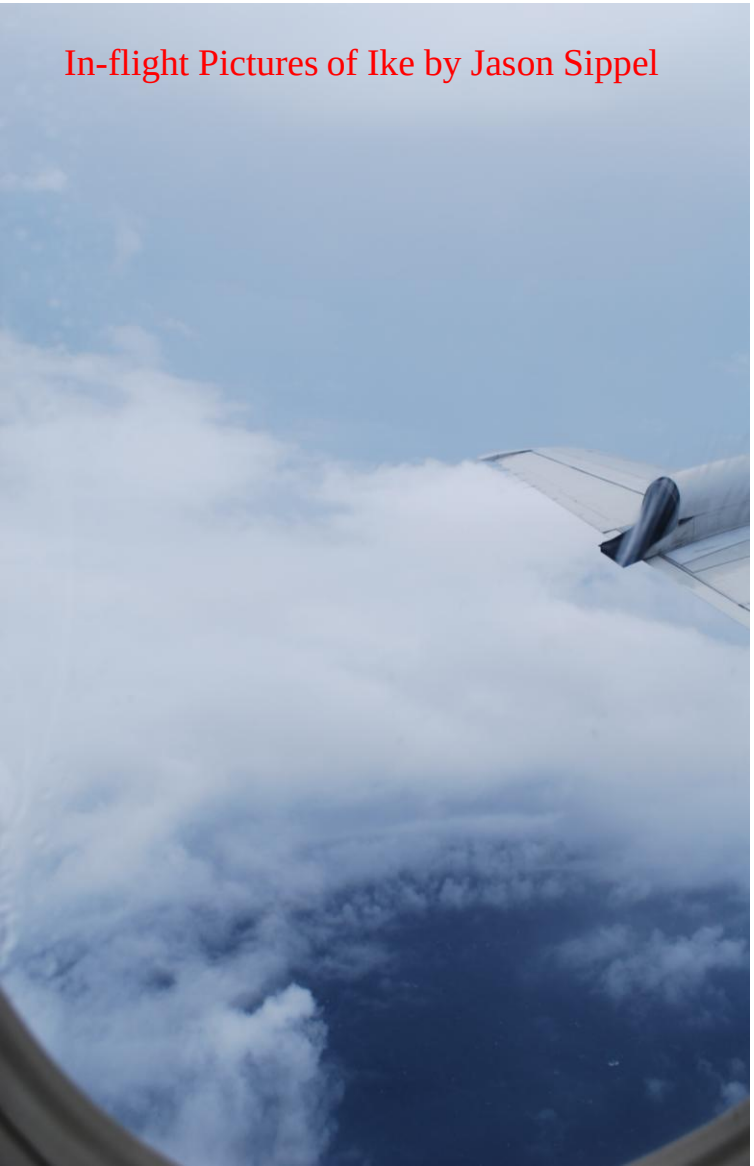
Cov(v_a,$w_{n=1,2}$)



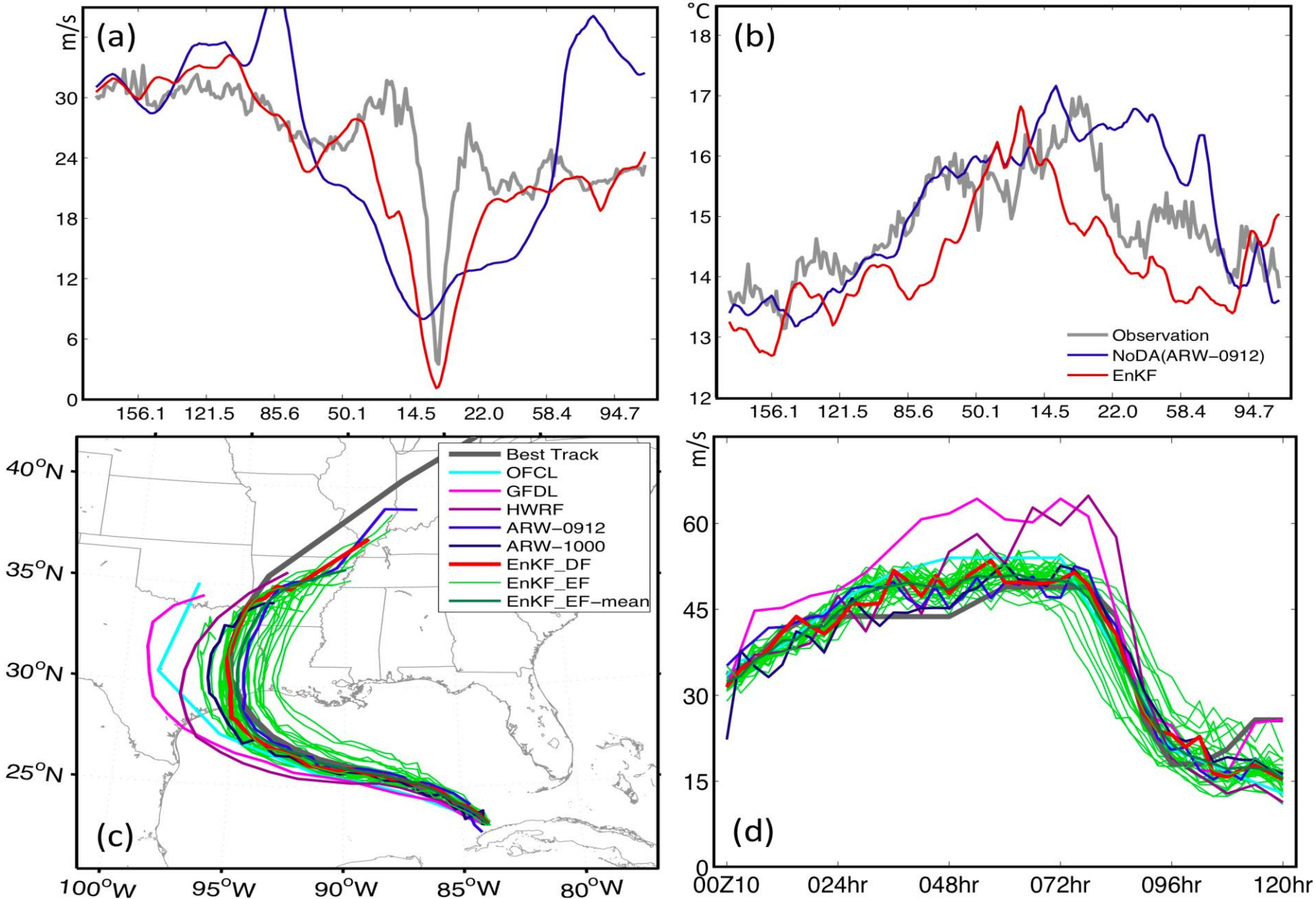
Hurricane Ike (2008)

103 deaths, $19.3 billion in estimated damage

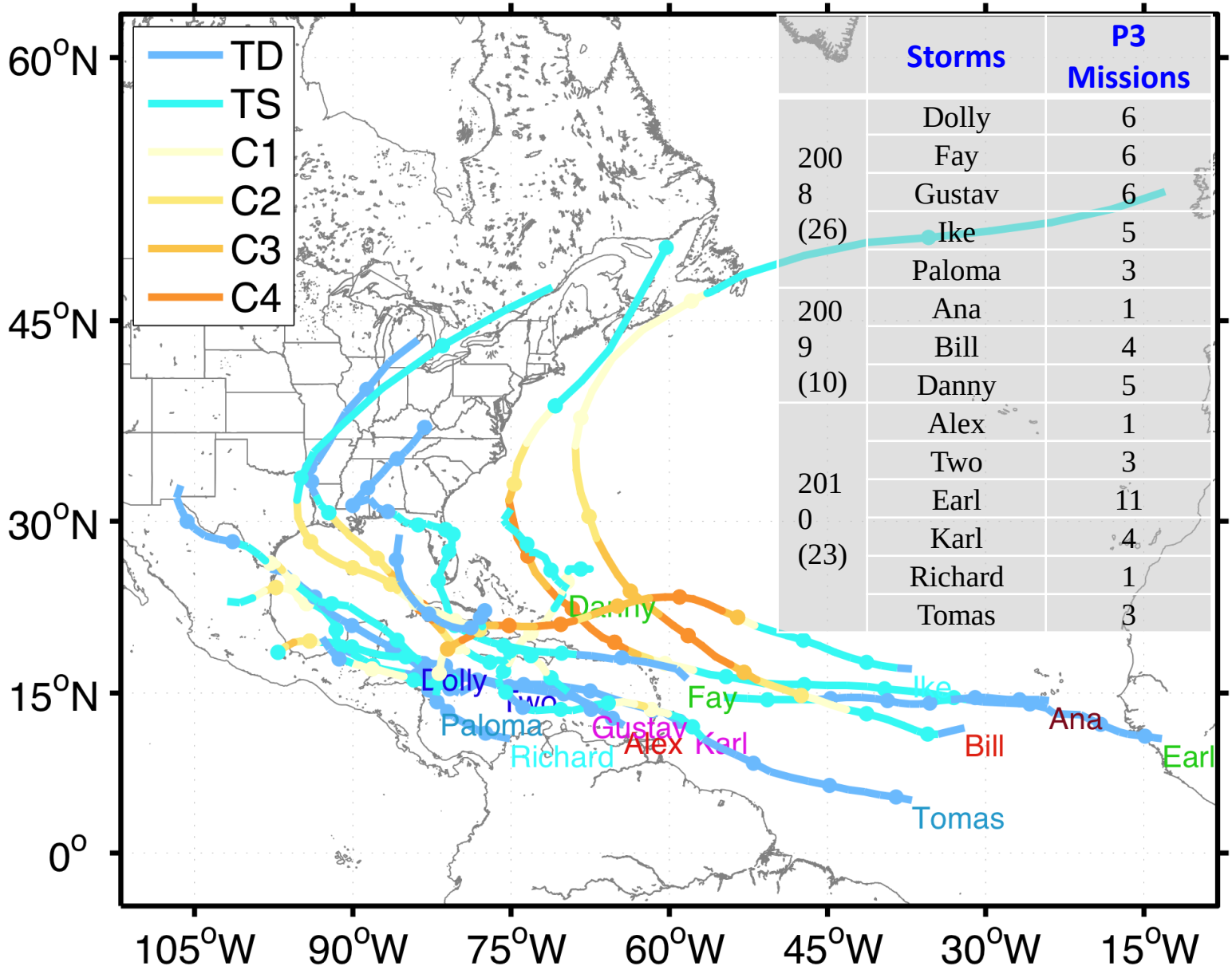
In-flight Pictures of Ike by Jason Sippel



Real-time EnKF Performance for Hurricane Ike (2008)
With assimilation of airborne Doppler winds



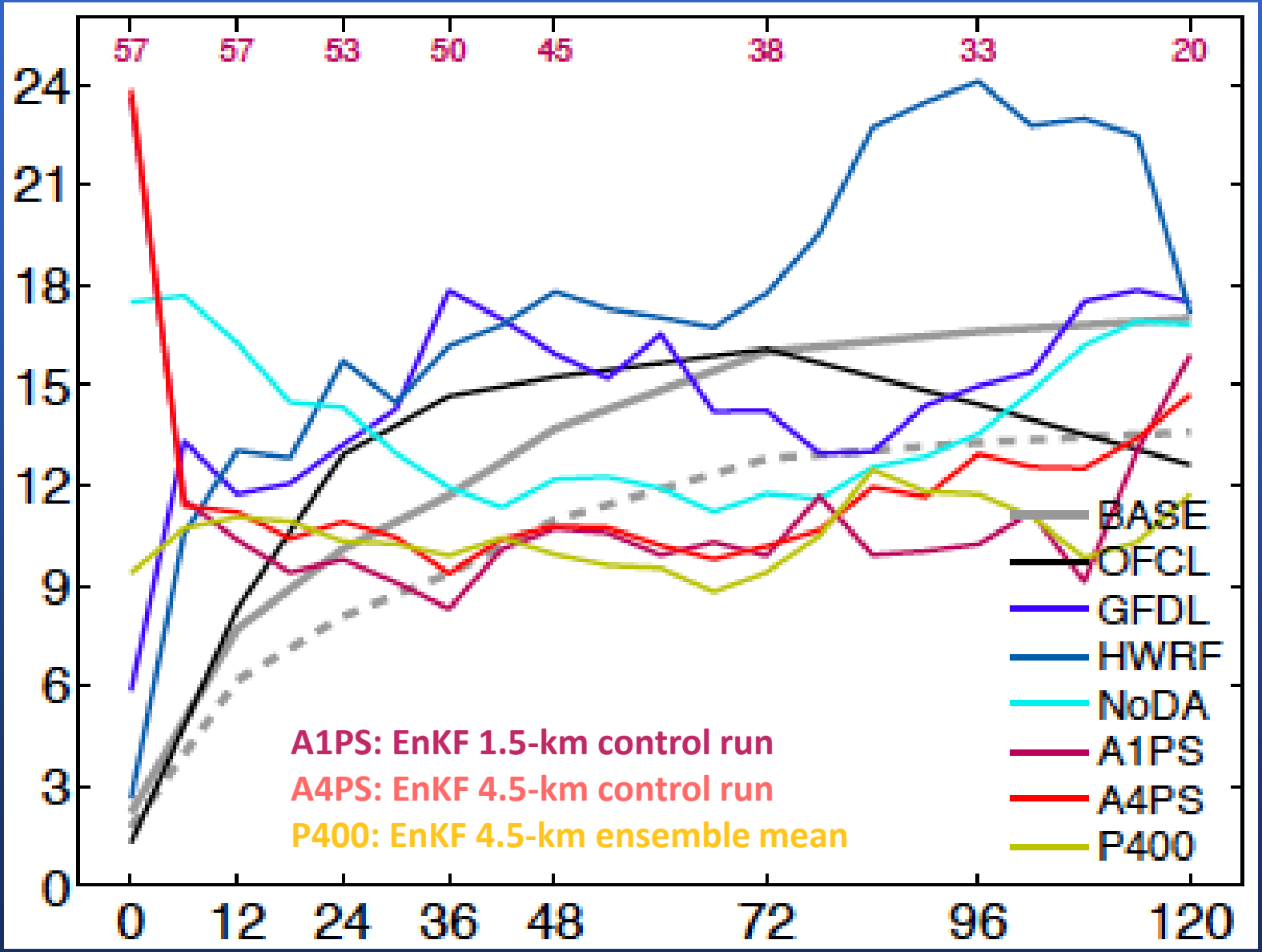
AL2008–2010 59 TDR Cases



	Storms	P3 Missions
2008 (26)	Dolly	6
	Fay	6
	Gustav	6
	Ike	5
	Paloma	3
2009 (10)	Ana	1
	Bill	4
	Danny	5
2010 (23)	Alex	1
	Two	3
	Earl	11
	Karl	4
	Richard	1
	Tomas	3

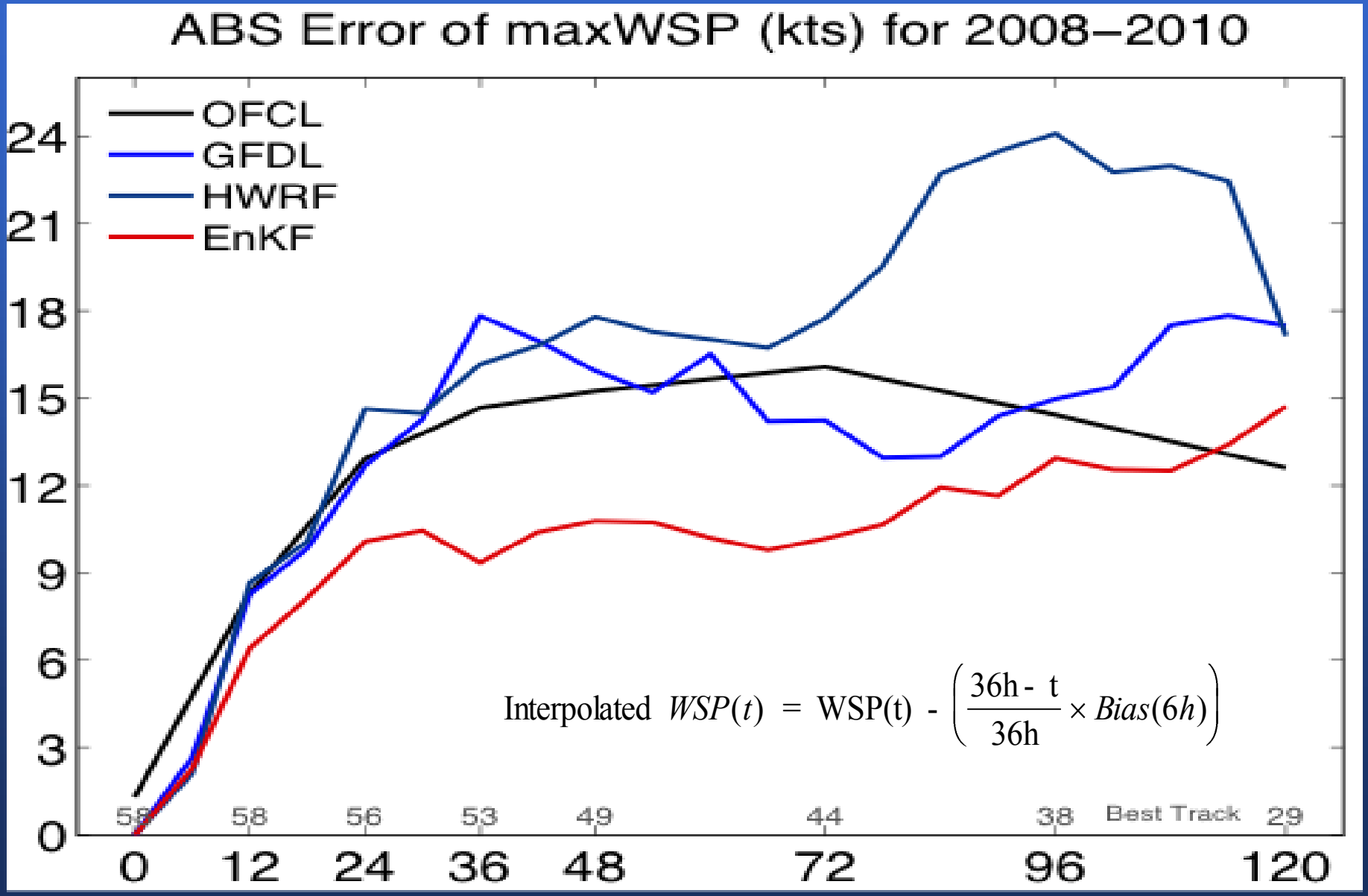
WRF-EnKF Performance Airborne Vr for 2008-2010

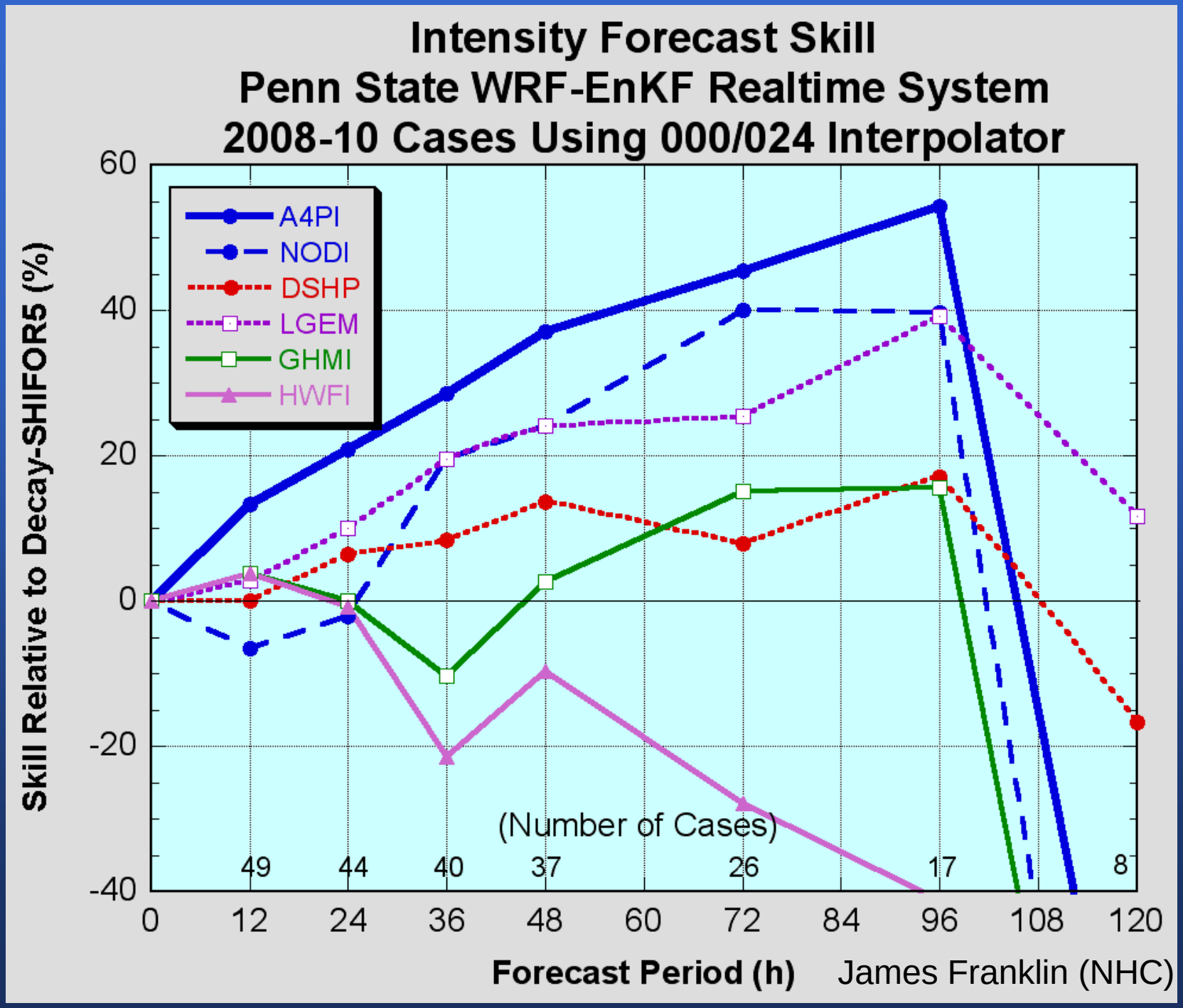
Mean Absolute Maximum Wind Speed Error (kts) for all 59 P3 TDR Missions



WRF-EnKF Performance Airborne Vr for 2008-2010

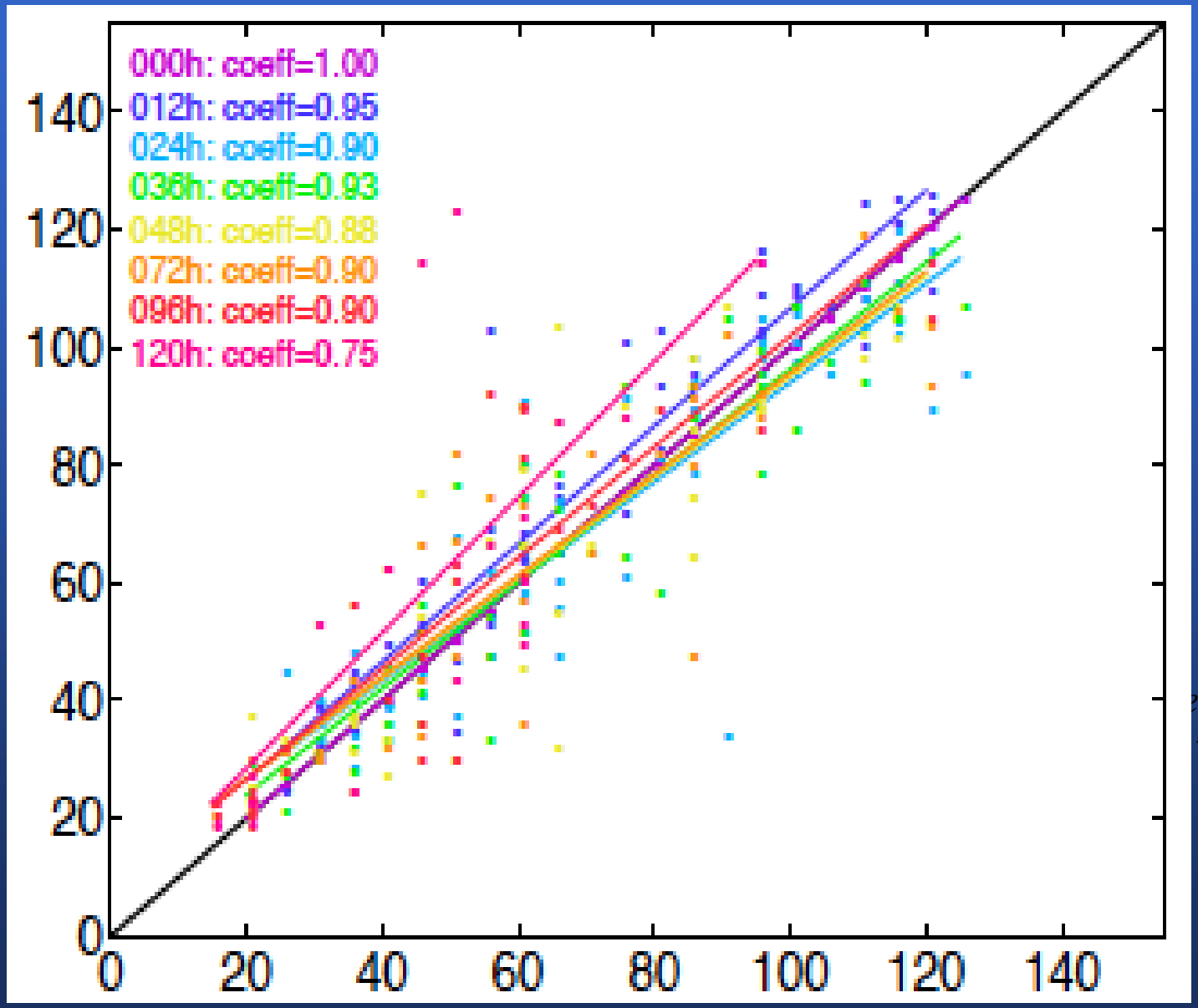
Mean Absolute Maximum Wind Speed Error (kts) for all 59 P3 TDR Missions



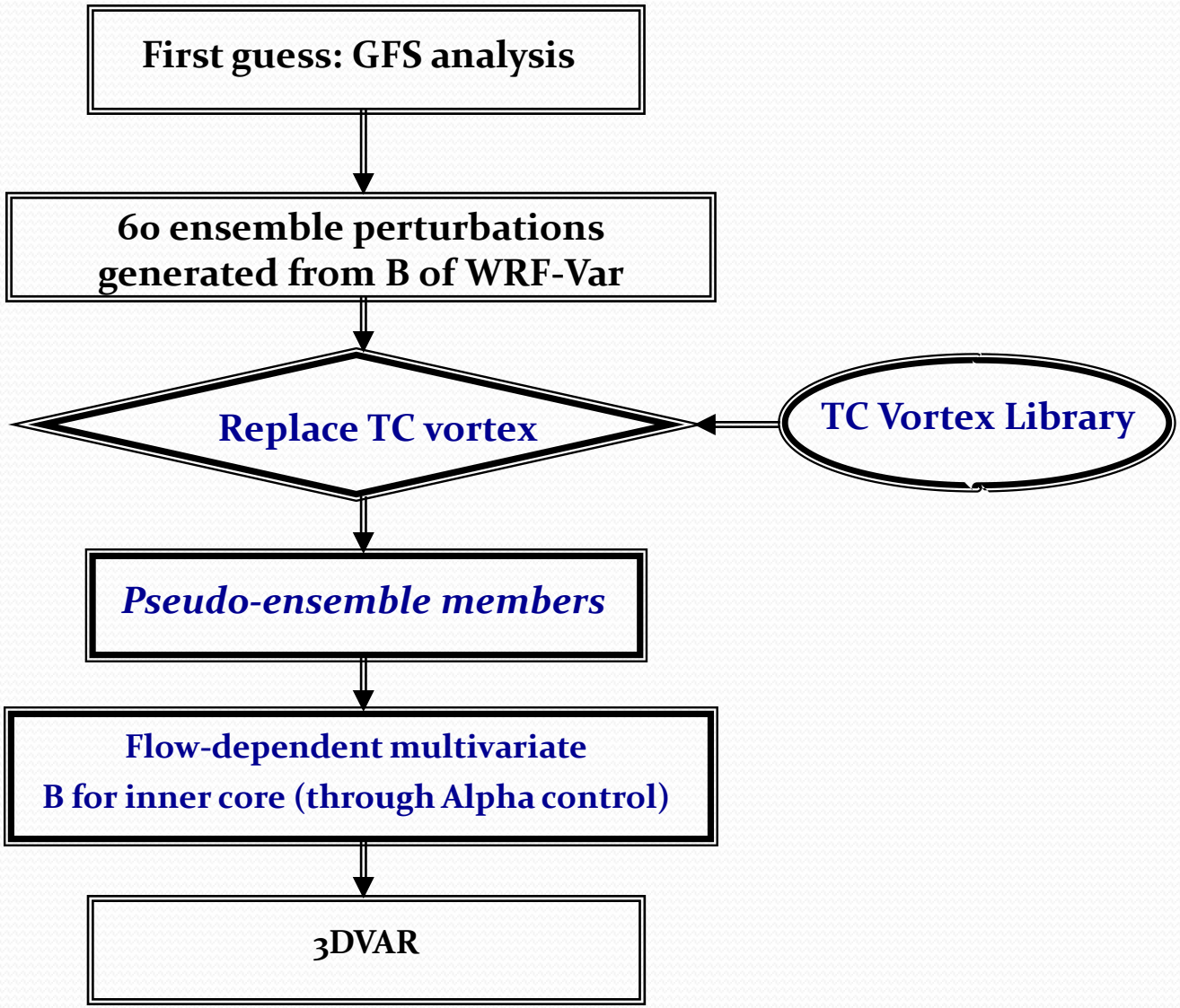

Intensity Forecast Skill
Penn State WRF-EnKF Realtime System
2008-10 Cases Using 000/024 Interpolator
A4PI
NODI
DSHP
LGEM
GHMI
HWFI
Skill Relative to Decay-SHIFOR5 (%)
60
40
20
0
-20
-40
(Number of Cases)
49
44
40
37
26
17
8
0
12
24
36
48
60
72
84
96
108
120
Forecast Period (h)
James Franklin (NHC)

WRF-EnKF Performance Airborne Vr for 2008-2010

1.5-km EnKF Predicted versus Best-track Maximum Wind Speed Error (kts)



A pseudo-ensemble hybrid data assimilation system (PEDA) for TC initialization with airborne Doppler radar data



Hybrid Algorithm within WRF-Var Framework

Adapt the background term with weighted ensemble covariance

$$J_b = J_{b1} + J_{b2} = \frac{1}{2}\delta x^T \left[1-\beta \ \mathbf{B} + \beta \mathbf{P}^f \circ \mathbf{C} \right]^{-1} \delta x$$

Use additional Alpha-control variables in the incremental cost function

$$J_b = \frac{1}{1-\beta} J_{b1} + \frac{1}{\beta} J_{b2}$$

$$= \frac{1}{1-\beta}\left(\frac{1}{2} v^T v\right) + \frac{1}{\beta}\left[\frac{1}{2}\alpha^T \begin{pmatrix} \mathbf{C} & & 0 \\ & \dots & \\ 0 & & \mathbf{C} \end{pmatrix} \alpha\right]$$

The background term in cost function is then calculated by traditional preconditioning control variable v (Barker et al. 2004) with the ensemble-based Alpha-control variable (Lorenc 2003), which is also localized with Schur product.

Pseudo-ensemble: Establish a TC Vortex Library

- **WRF-ARW 3.1**

  ***f*-plane in a resting environment with constant SST**

  Alternative: thousands of real-case TC vortex from HFIP

- **Initial conditions for the idealized WRF runs:**

  1) initial vortex size/Rmax

  2) perturb sounding profile (i.e., moisture field)

  3) latitude effect

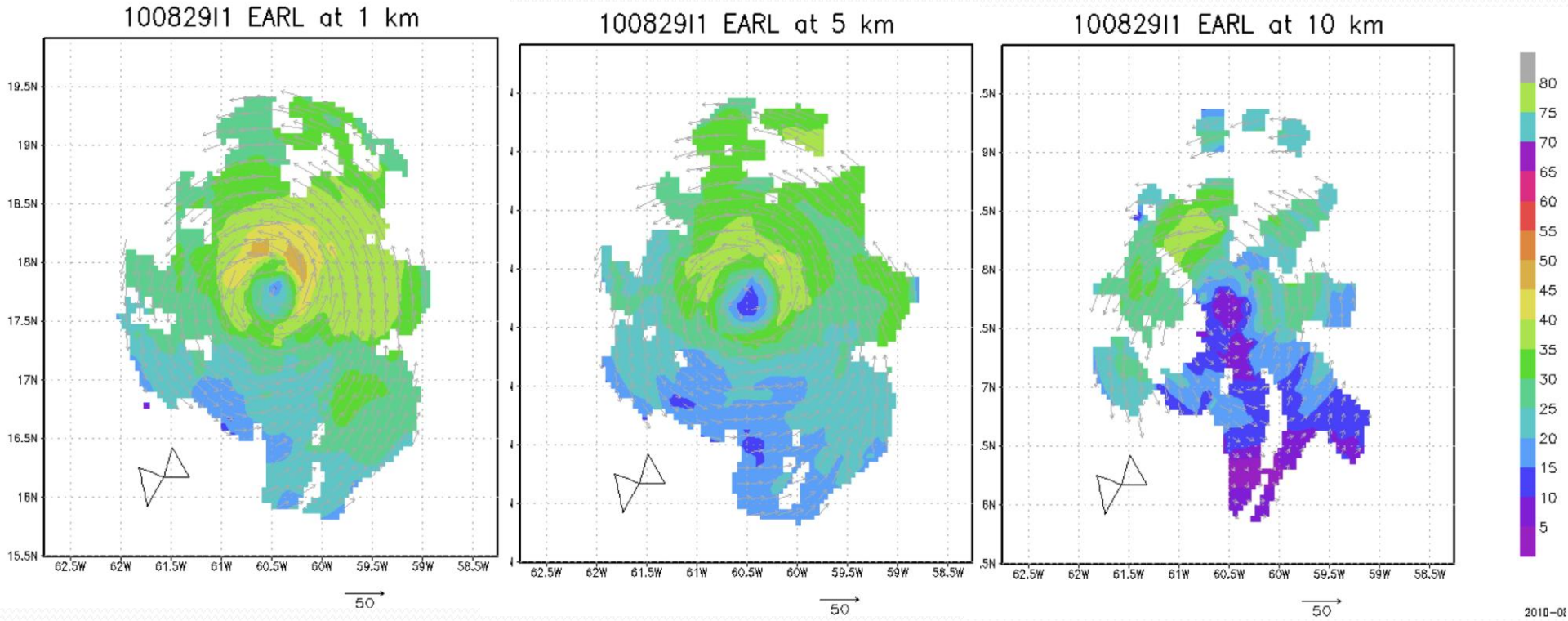
  4) physics options

TC Vortices at different output times are binned according to *Vmax*

(more binning criteria to be added: size, …)

12.5<Vmax ≤17.5m/s	17.5<Vmax ≤22.5m/s	22.5<Vmax ≤27.5m/s	27.5<Vmax ≤32.5m/s	32.5<Vmax ≤37.5m/s	… …

Example of Inner-core Wind Observation to be Assimilated 3D dual Doppler radar wind analysis for Earl (2010)



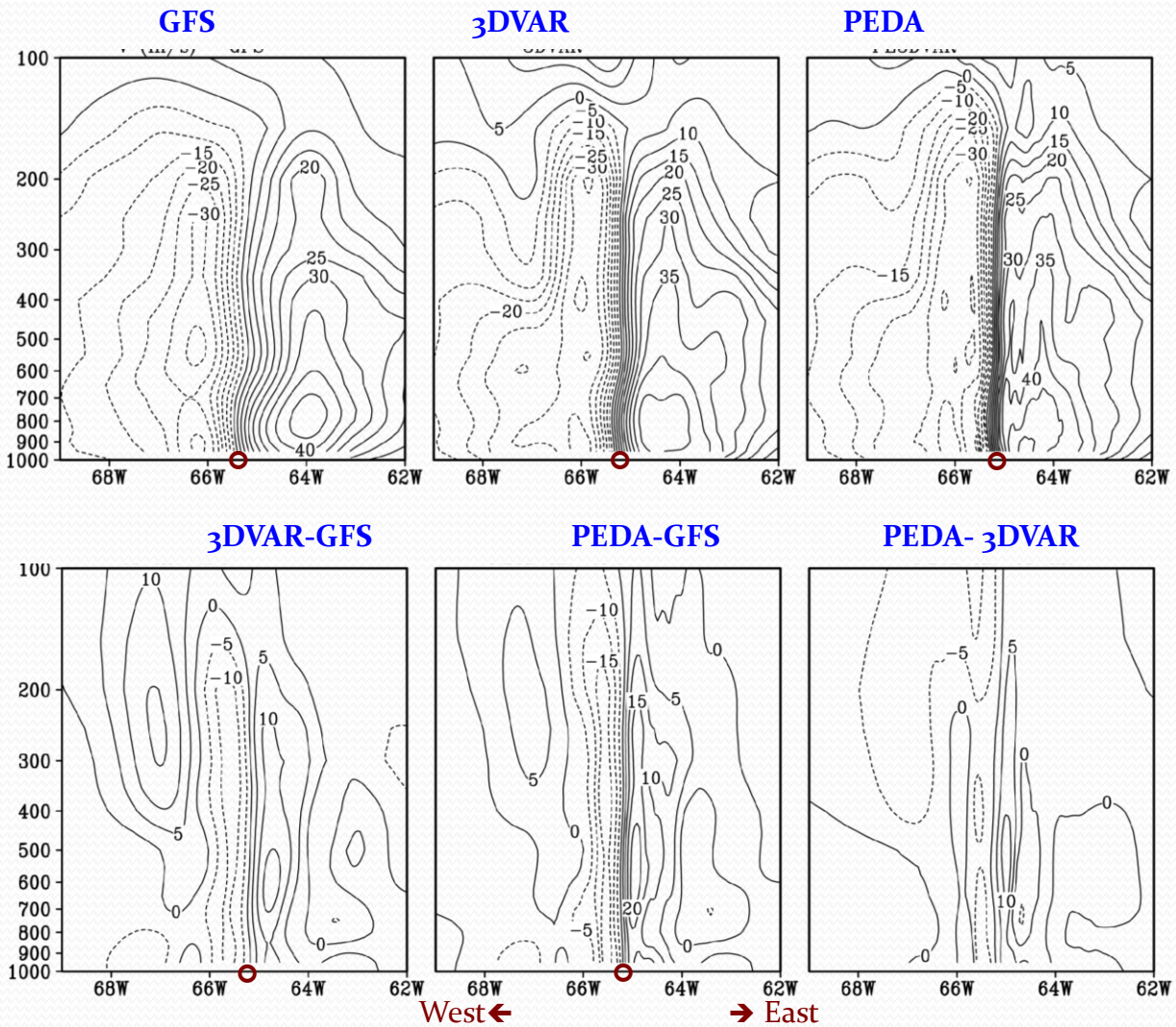
Courtesy of NOAA/HRD: There are a total of 32 cases of such 3D wind analyses for Atlantic storms during 2008-2010 available directly through the NOAA/HRD website; raw Doppler radial Vr to be tested in future

PEDA vs. GFS and 3DVar: Inner-core wind structure

Earl (2010) 00Z31August : *938hPa; 115kts*

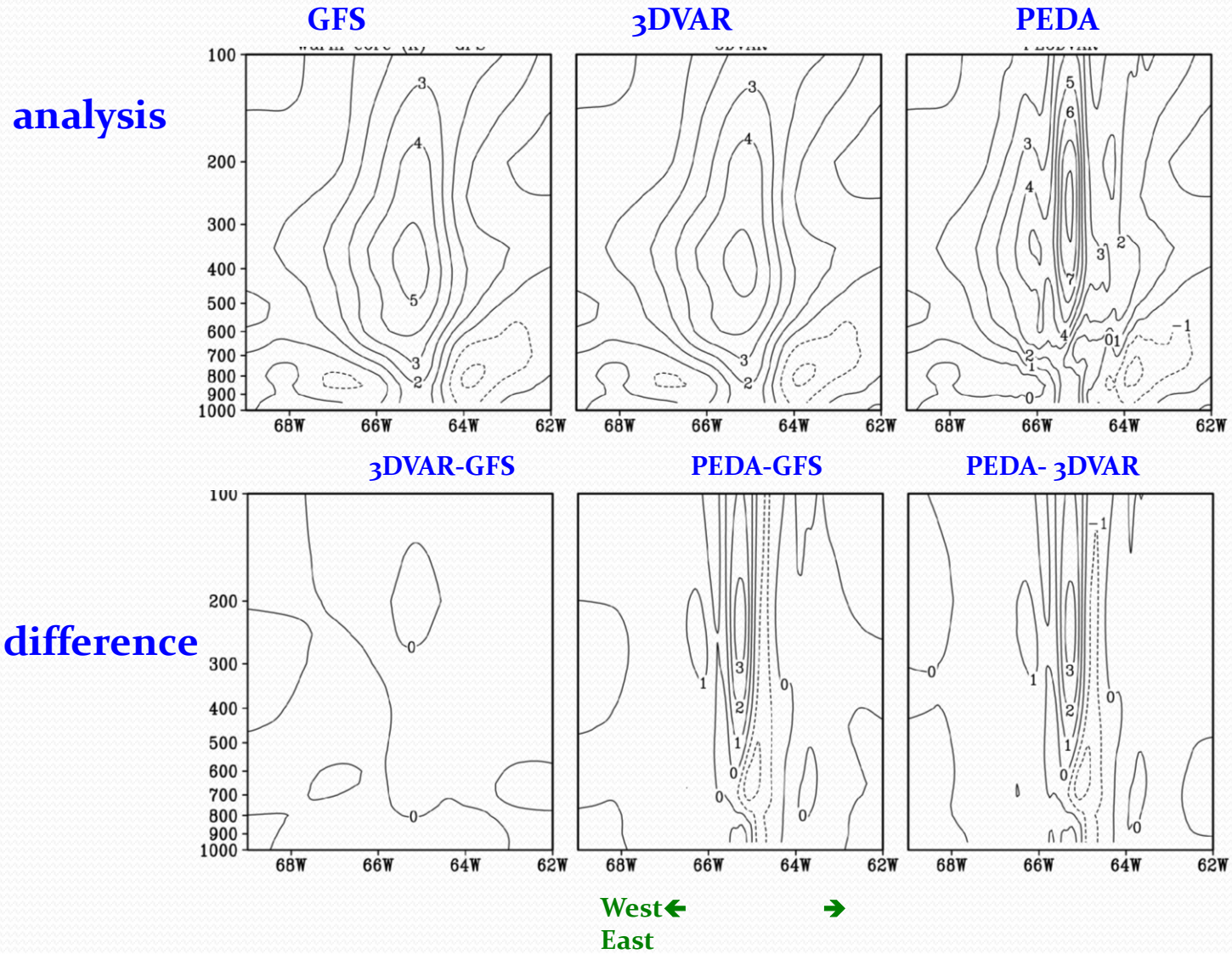
analysis

difference

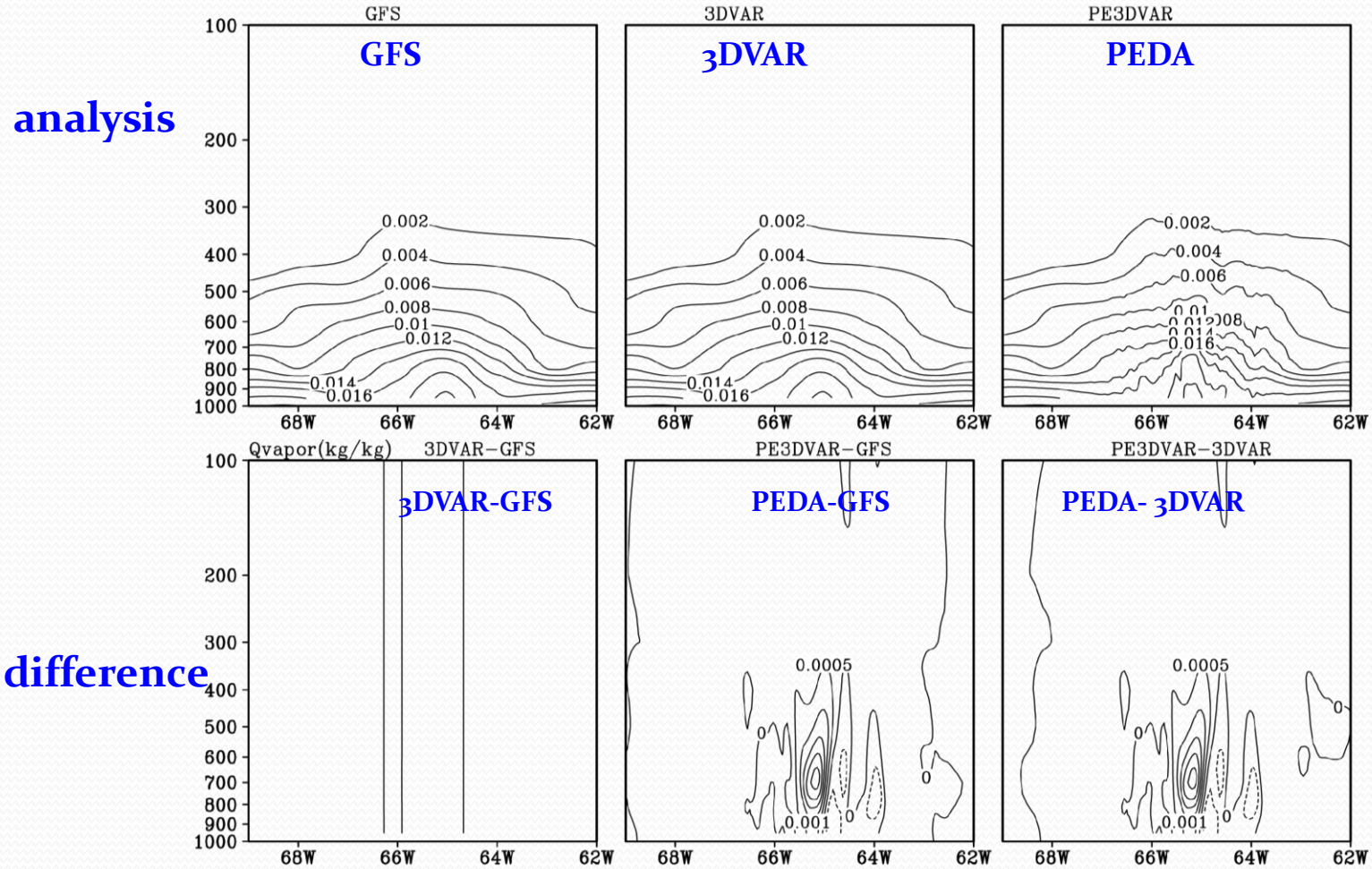


Both 3DVAR and PEDA can improve wind structure. **However…**

PEDA vs. GFS and 3DVar: warm-core structure



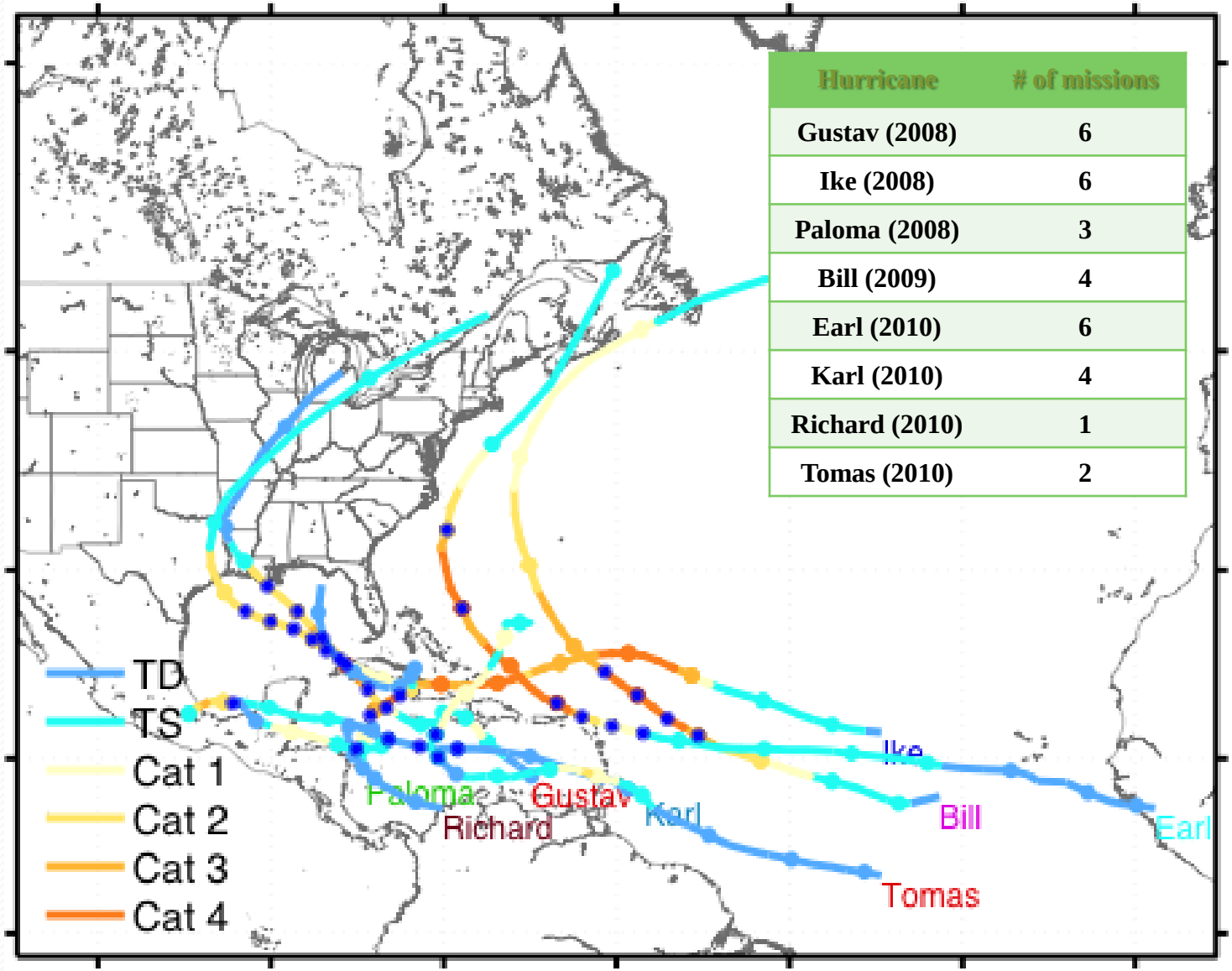
PEDA vs. GFS and 3DVar: inner-core moisture field



A clear advantage of PEDA over conventional 3DVAR in the thermodynamical fields, signifying the benefit of using a flow-dependent background error covariance.

WRF-PEDA Performance Airborne Vr for 2008-2010

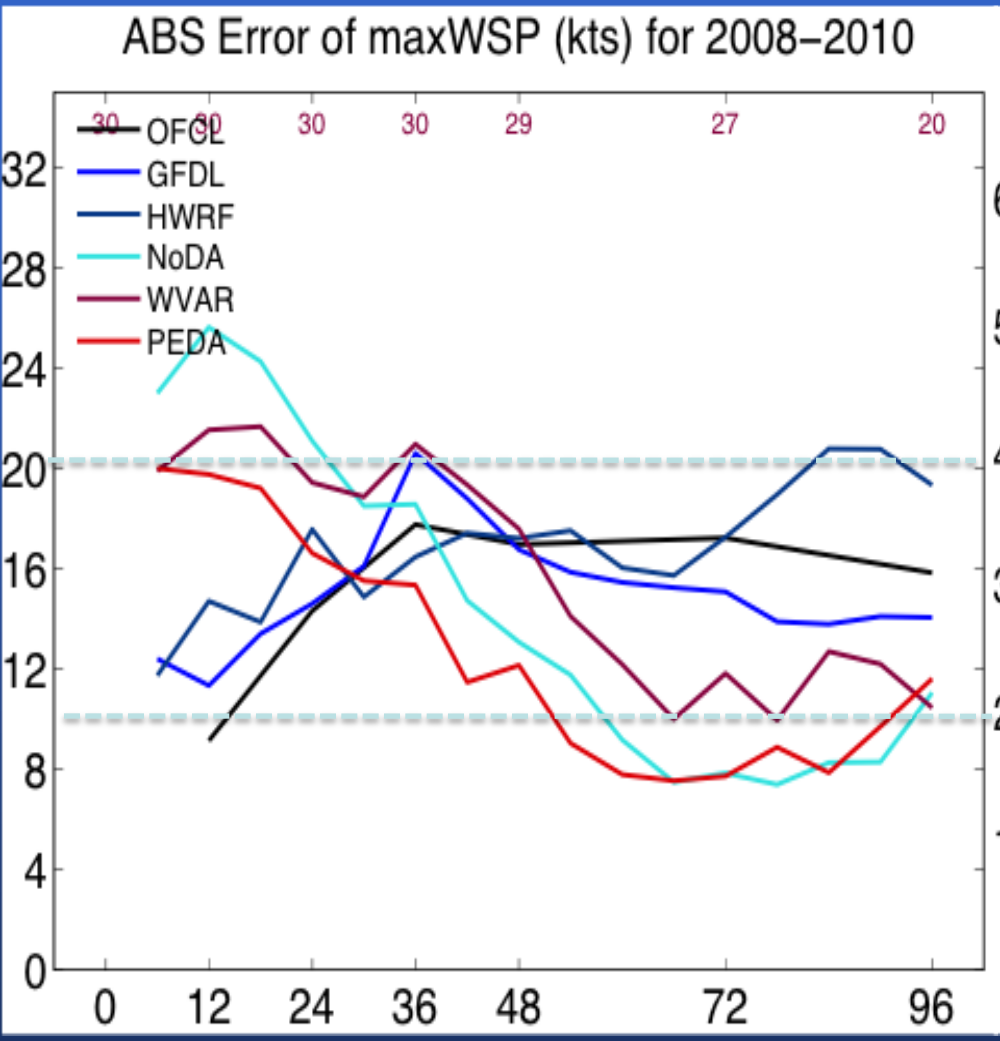
Track, intensity and position of the 32 cases with Dual-Doppler analysis

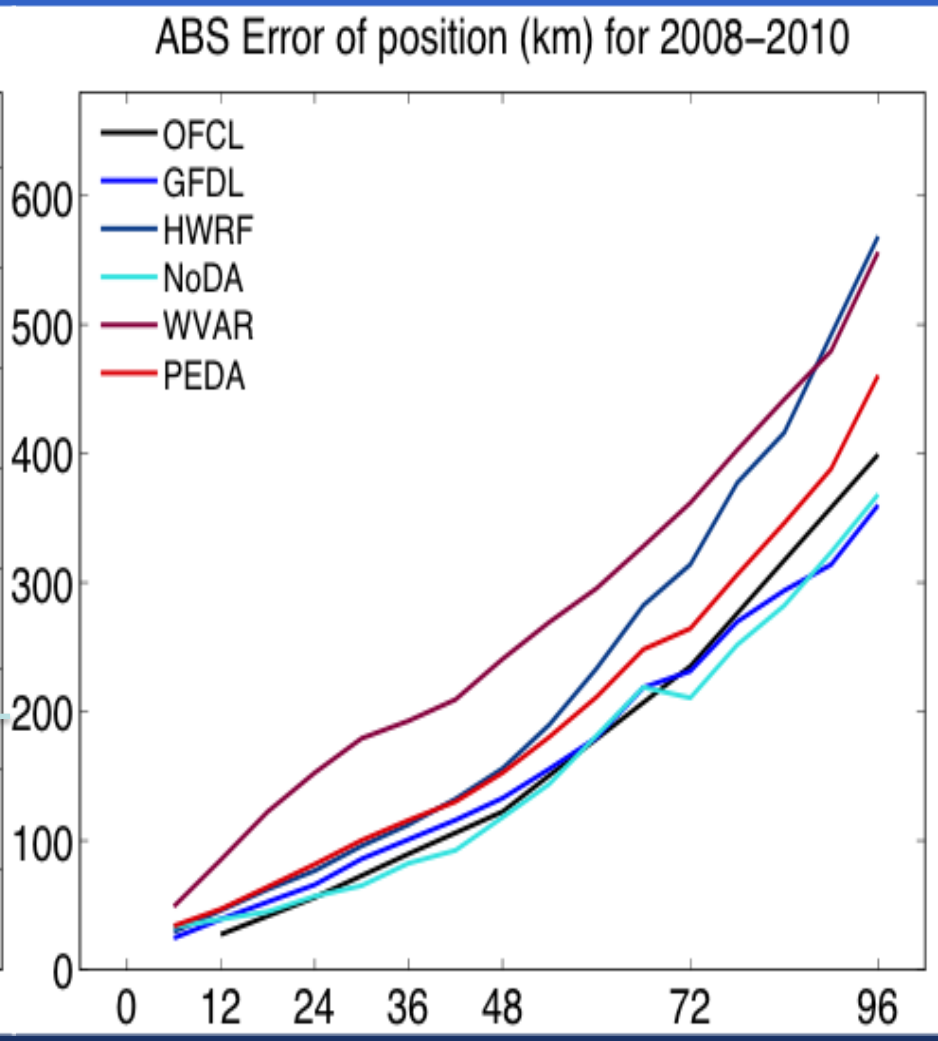


Hurricane	# of missions
Gustav (2008)	6
Ike (2008)	6
Paloma (2008)	3
Bill (2009)	4
Earl (2010)	6
Karl (2010)	4
Richard (2010)	1
Tomas (2010)	2

WRF-PEDA Performance Airborne Vr for 2008-2010

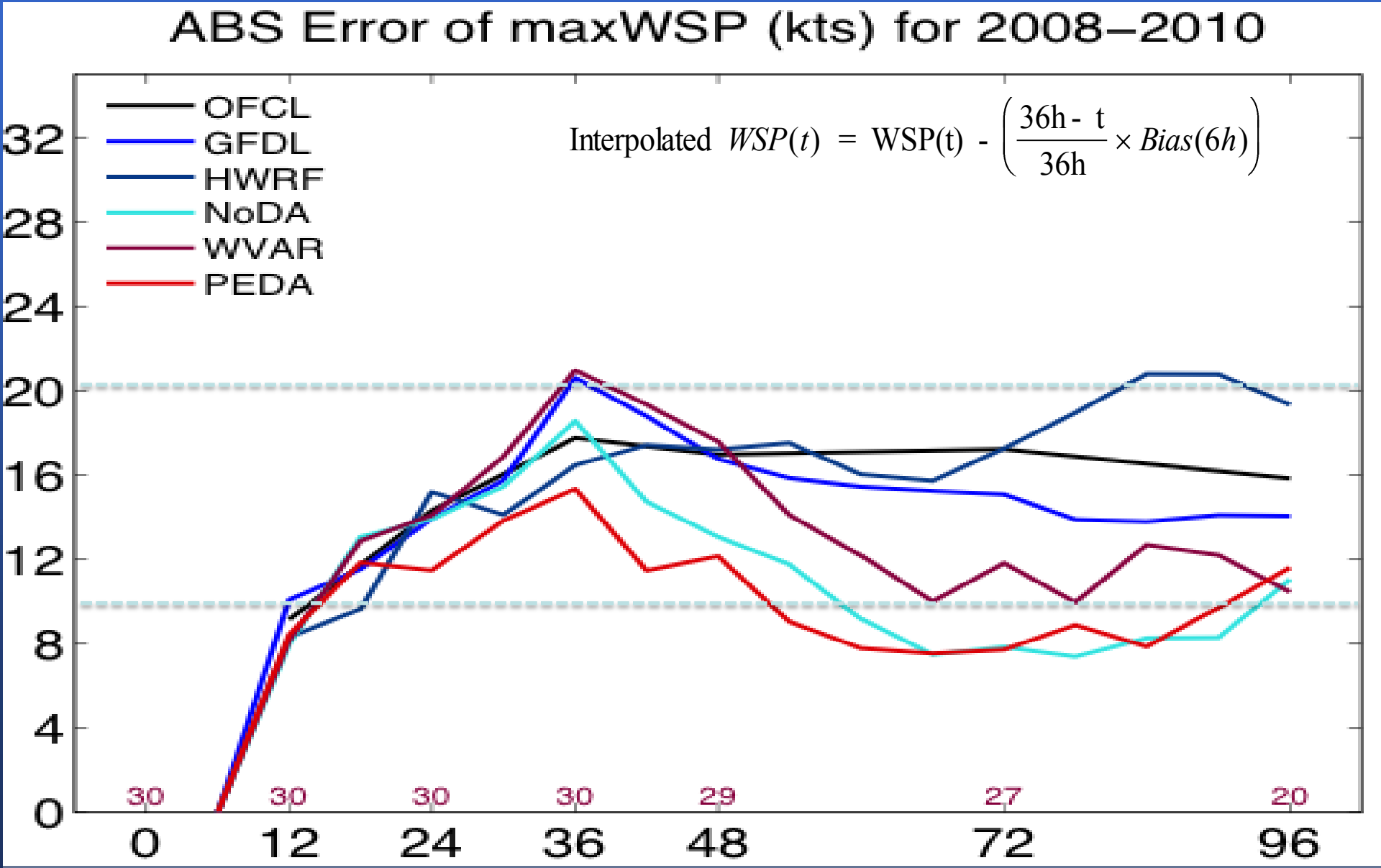
Mean Absolute intensity and track error for 32 cases with Dual-Doppler analysis





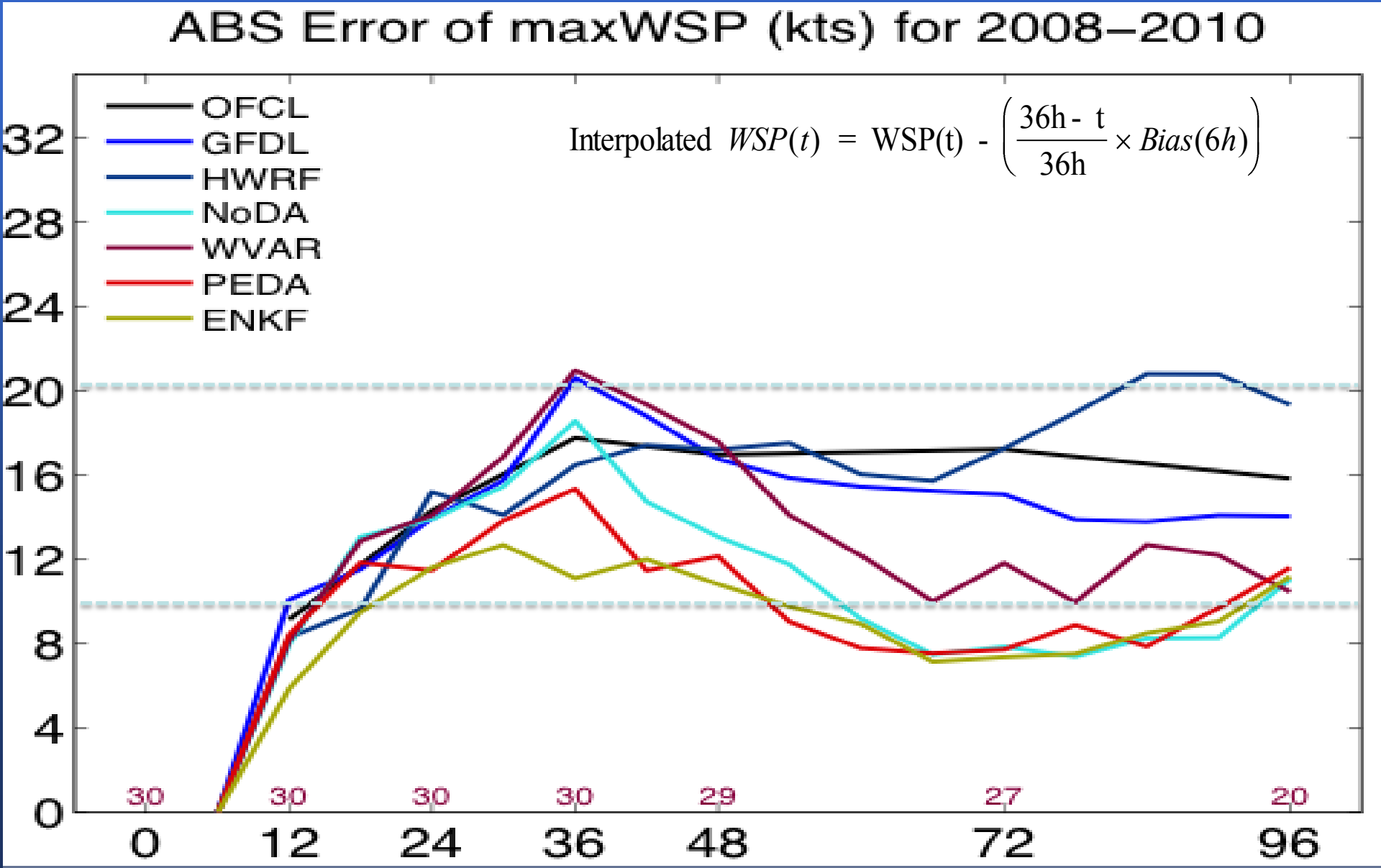
WRF-PEDA Performance Airborne Vr for 2008-2010

Mean Absolute intensity error with bias correction (NHC variable interpolator)



WRF-PEDA Performance Airborne Vr for 2008-2010

Mean Absolute intensity error with bias correction (NHC variable interpolator)

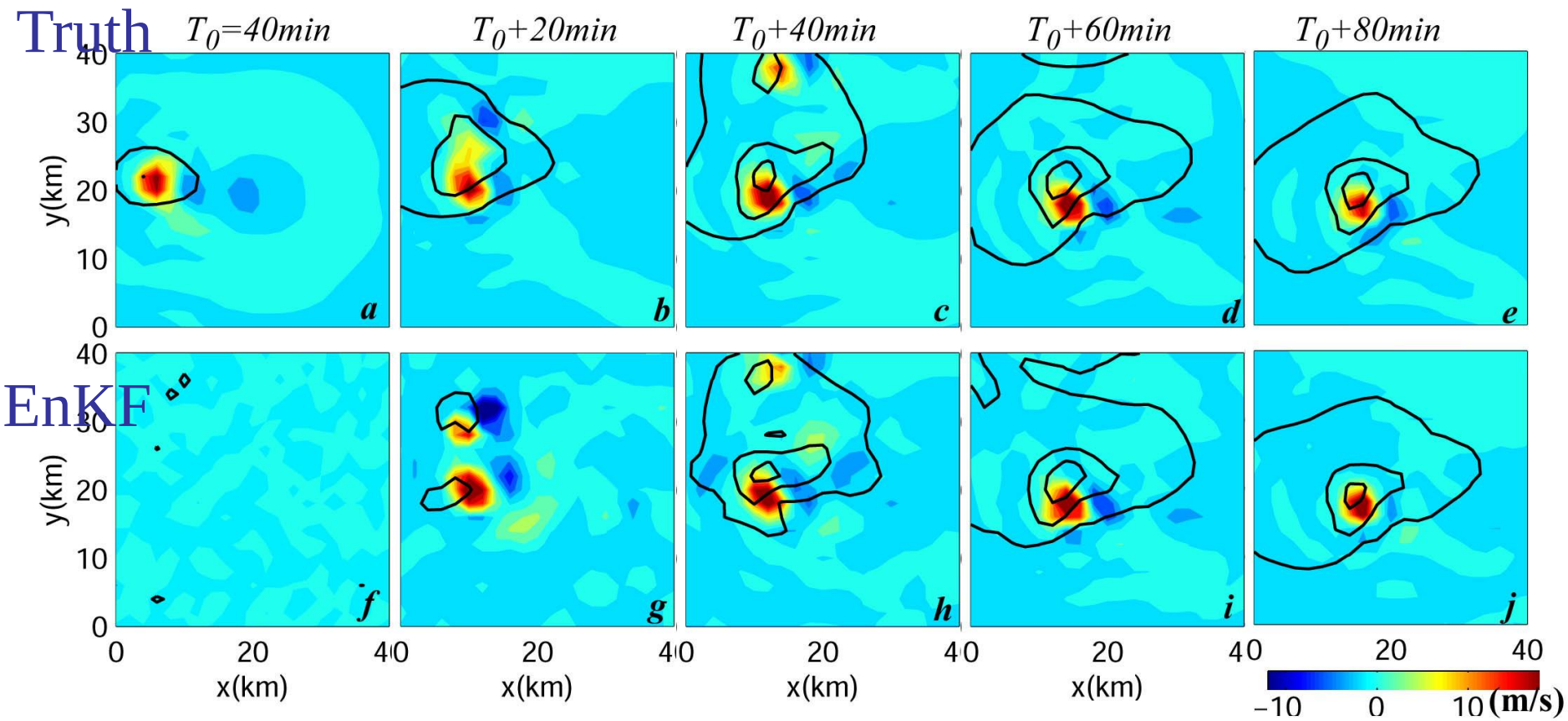


Concluding Remarks on Future Hurricane Prediction

- Better understanding of under-resolved, under-observed, less-predictable moist convection and air-sea interaction and their impacts on hurricane intensity
- Improve models through better physics and finer resolution
- Design and improve observing network including routine inner-core high-resolution observations, e.g., airborne Doppler radars
- Implement and develop advanced data assimilation techniques to better utilize existing and future observations
- Going probabilistic: ensemble-based initialization and forecasting
- Design computationally efficient numerics for model integration and data assimilation
- Giant computers like the TACC Ranger cluster or NOAA T-jet

First Test of EnKF for Limited-area Models: Assimilation of Radar Observations of Supercells

(Snyder and Zhang 2003; Zhang, Snyder and Sun 2004; Dowell et al. 2004; all in MWR)

Observations: radial velocity V_r only, available every 5 min where reflectivity dBZ>12

Vertical velocity at 5km (colored) and surface cold pool (black lines, every 2K)