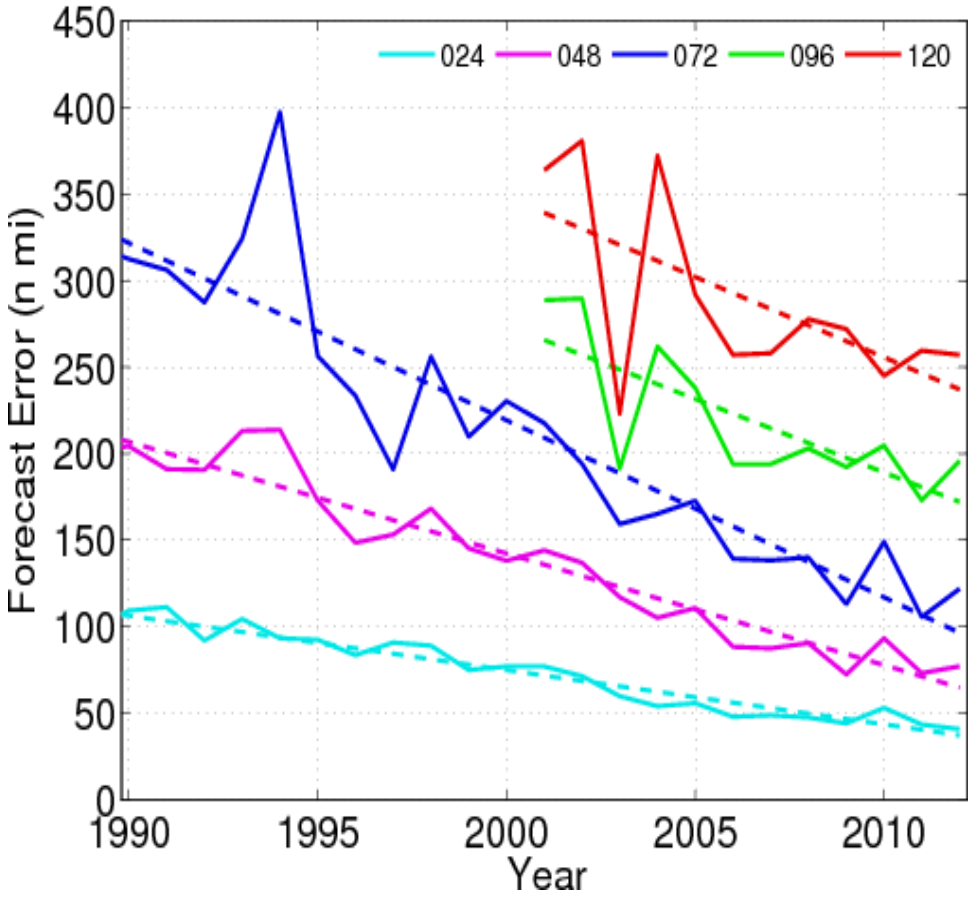
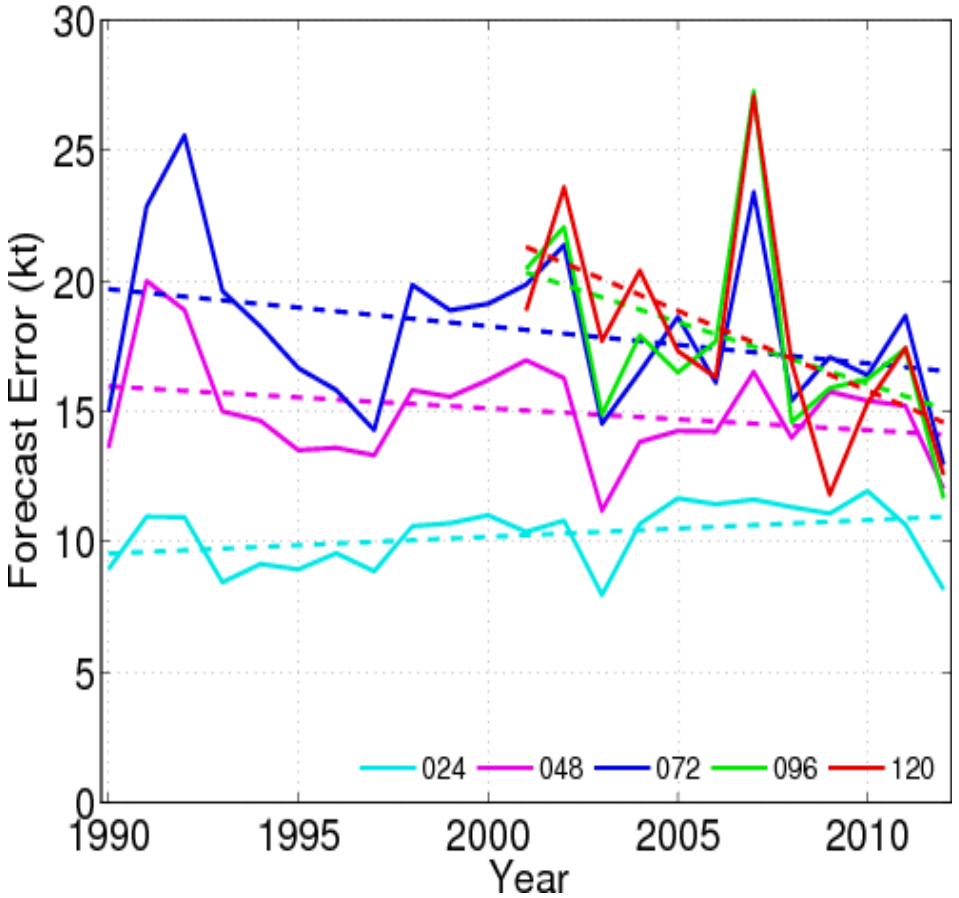
Real-time Cloud-Permitting Hurricane Prediction with Assimilation of Inner-core Airborne Doppler Observations

Fuqing Zhang and Yonghui Weng
Penn State University

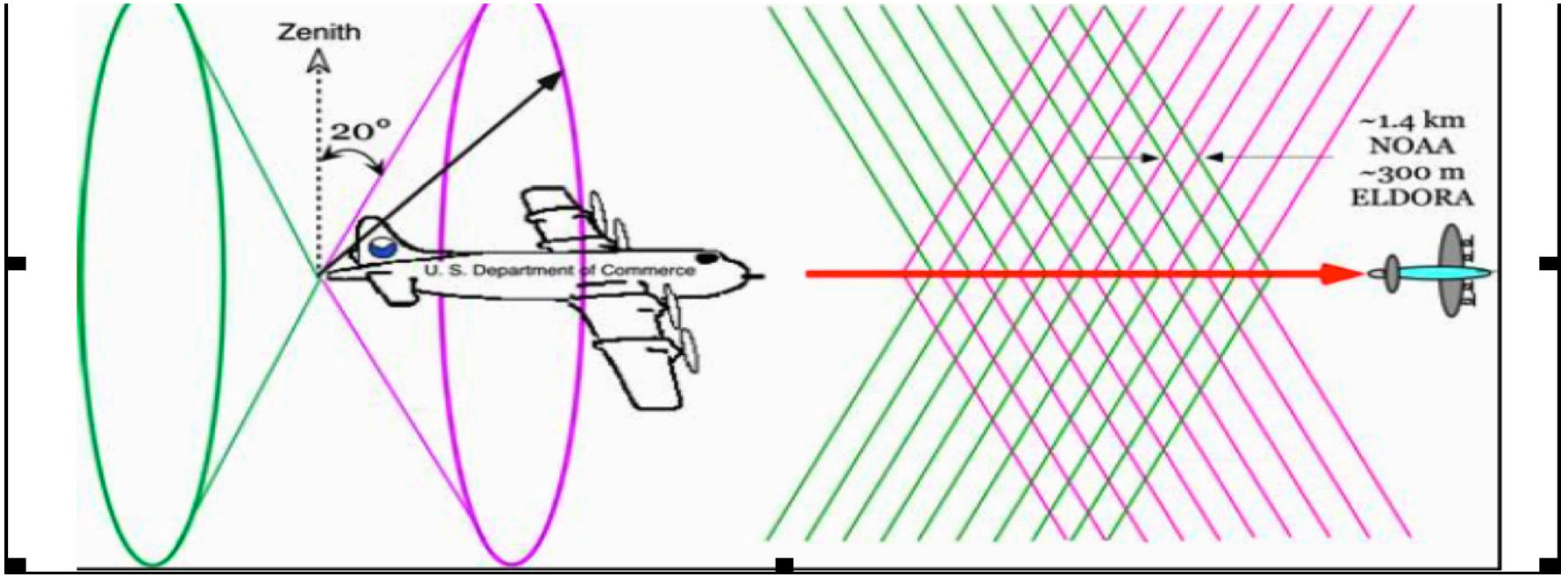
NOAA/NHC Official Track and Intensity Errors





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



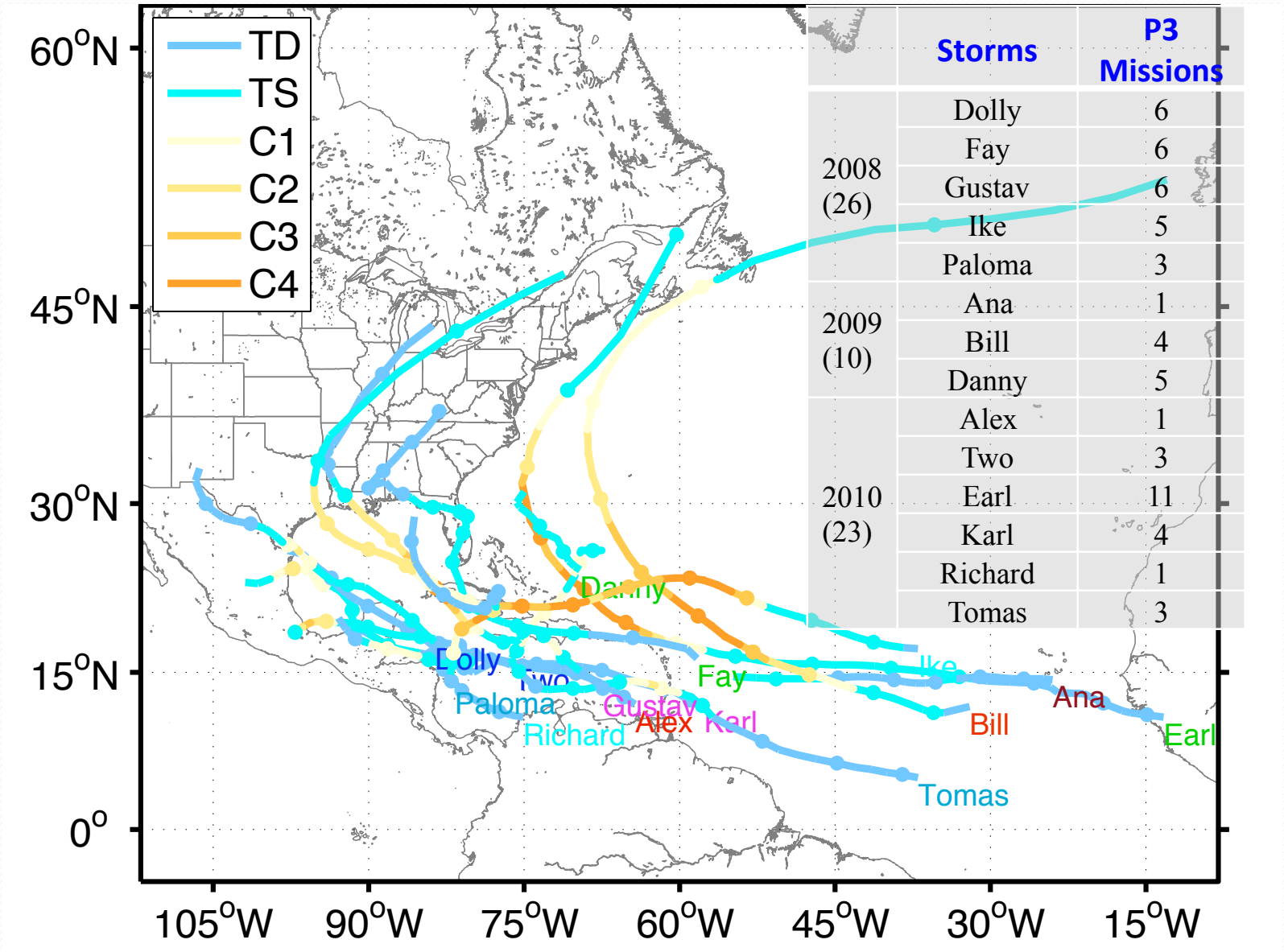
Superobservations: 1. Separate forward and backward scans; 2. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 3. thinning ---one bin for 2 km in radial distance and 3 degree in scanning angle; 4. use medium as SO after additional QC checking

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 2012 MWR)

WRF-EnKF Performance with Airborne Vr for 2008-2010

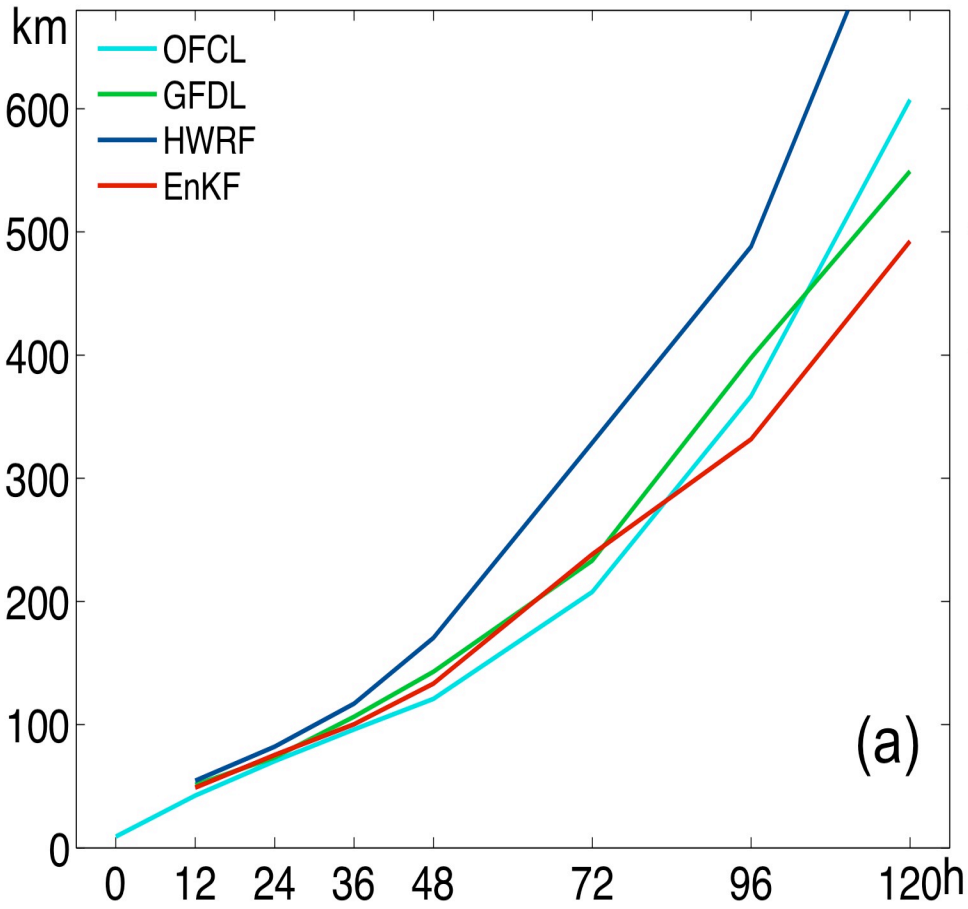


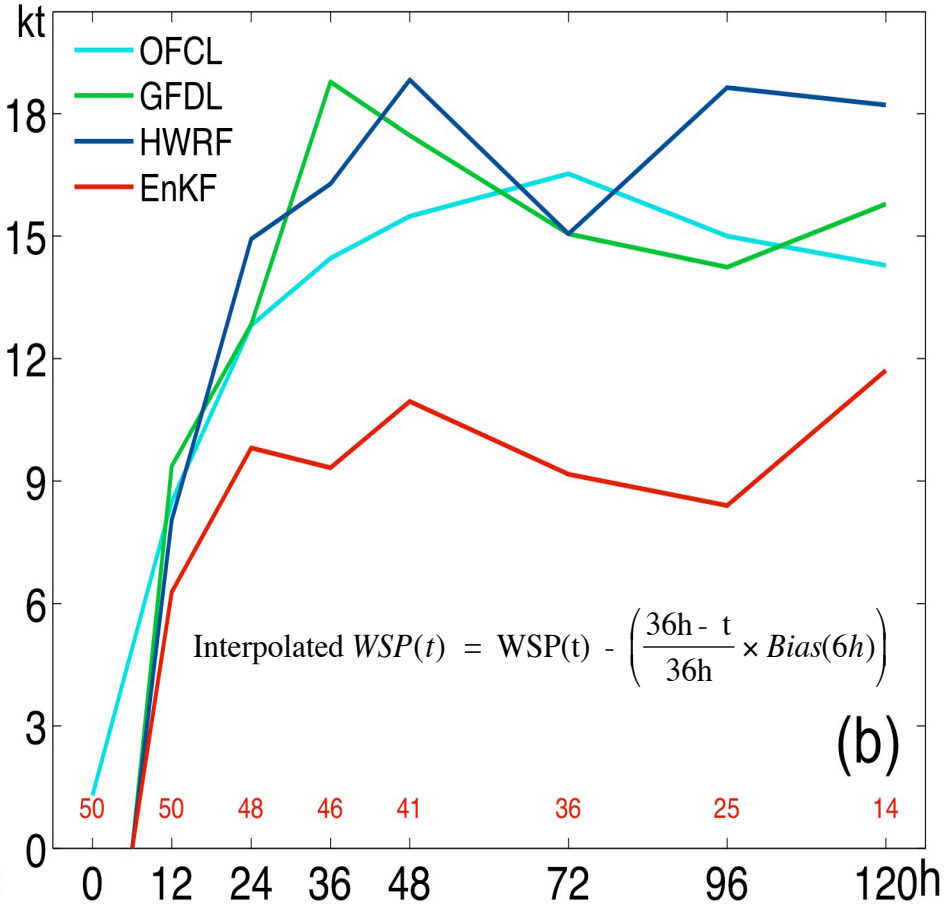
	Storms	P3 Missions
2008 (26)	Dolly	6
	Fay	6
	Gustav	6
	Ike	5
	Paloma	3
2009 (10)	Ana	1
	Bill	4
	Danny	5
2010 (23)	Alex	1
	Two	3
	Earl	11
	Karl	4
	Richard	1
	Tomas	3

(Zhang et al. 2011 GRL)

WRF-EnKF Performance Assimilating Airborne Vr

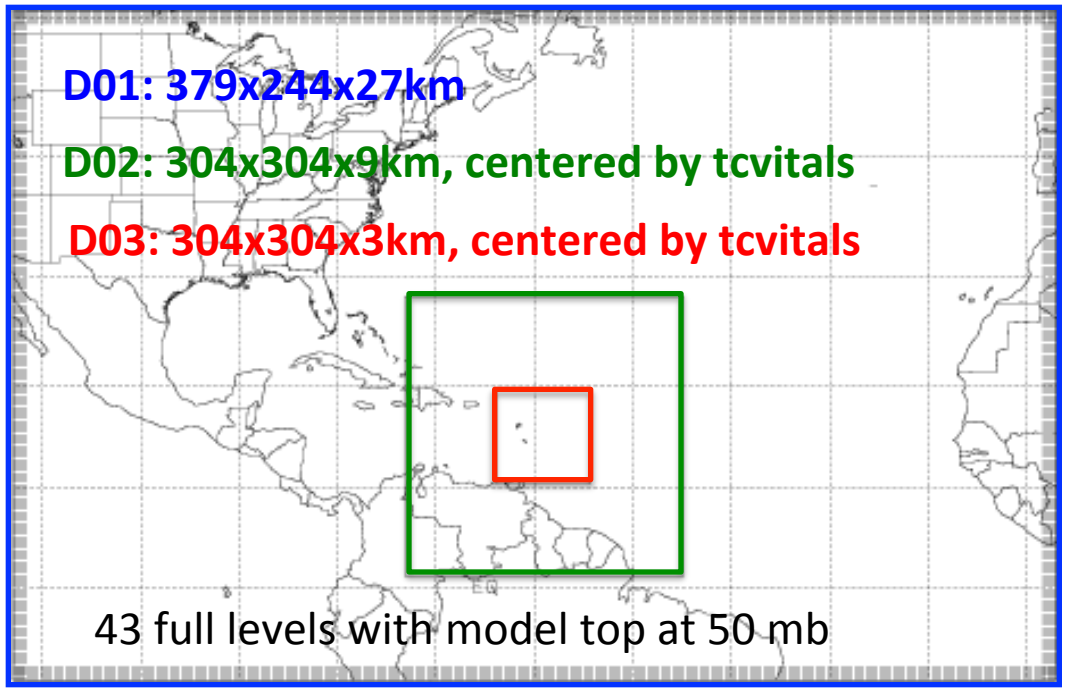
Mean absolute track (km) & intensity (kts) error for all 2008-2010 P3 missions





(Zhang et al. 2011 GRL)

PSU WRF-EnKF HFIP Stream1.5 Model and Filter Configurations for 2012



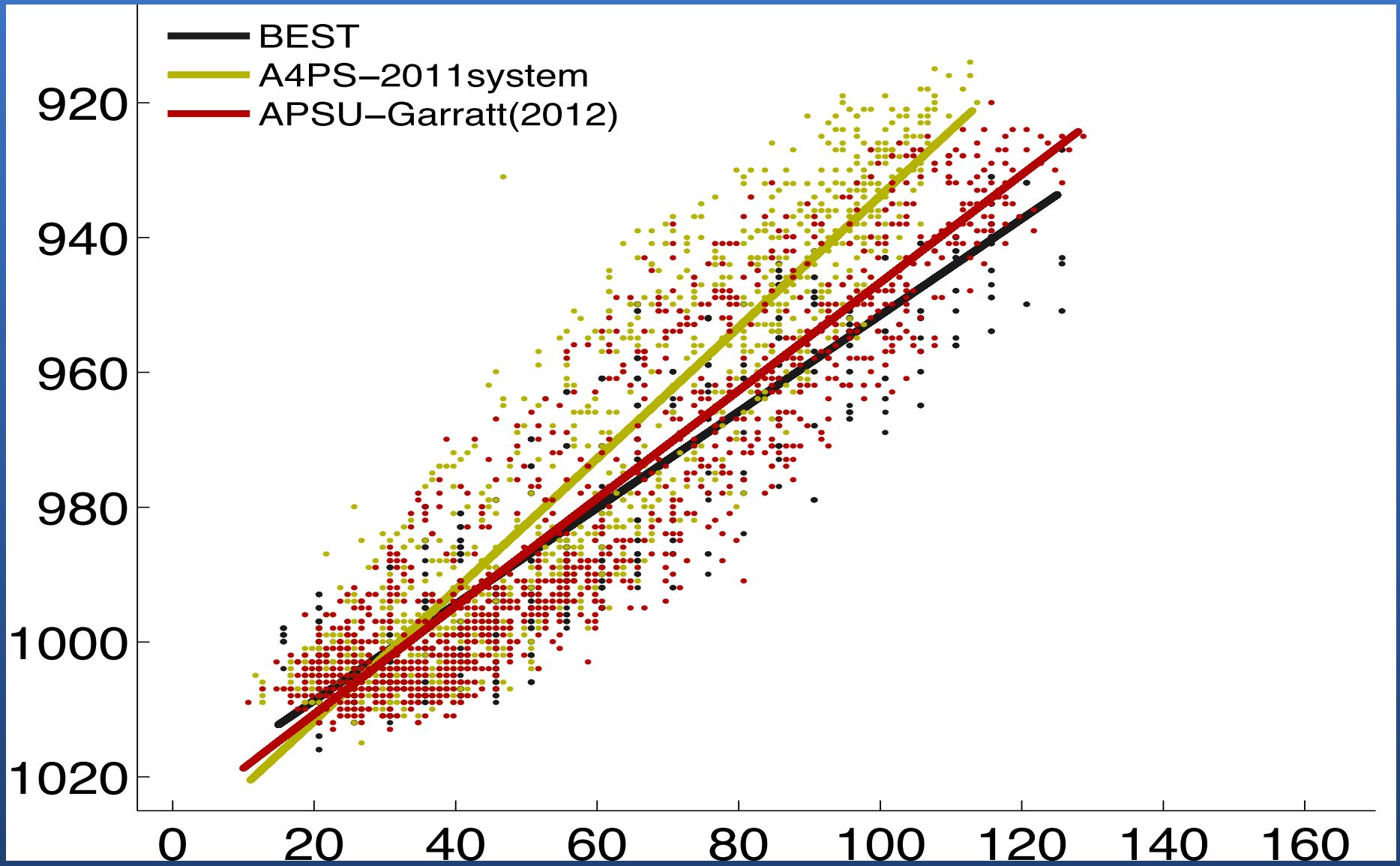
- WRF V3.3.1
- YSU PBL
- Monin-Obukov Surface Layer
- PSU Cd (Green & Zhang 2012)
- Garret Ck

- EnKF: 60 members
- Radius of Influence: SCL
- Covariance relaxation: 0.6

- ICs & BCs: GFS analysis and its forecasts

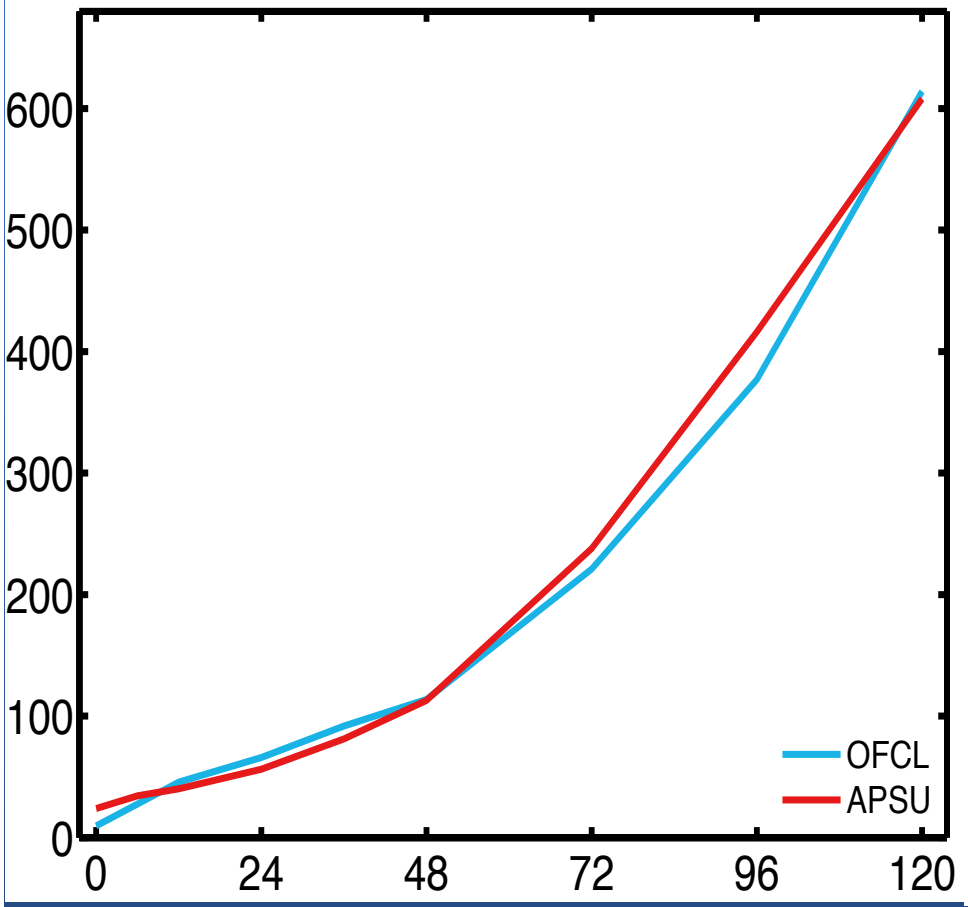
Key differences from 2011: high resolution (4.5→3km), more vertical levels (30→43), surface flux (PSU Cd, Garret Ck)

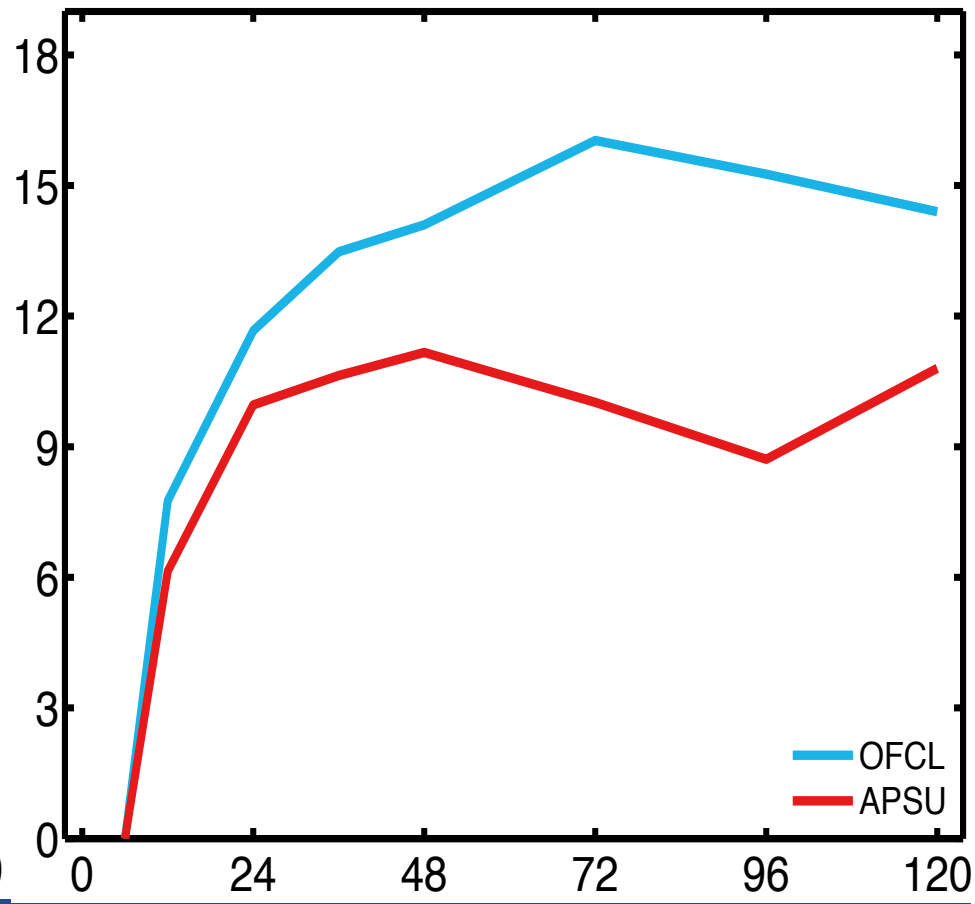
Improvement of Wind-Pressure Relationship 2008-11 from 2011 to 2012 PSU WRF-EnKF Stream1.5 system



WRF-EnKF Performance Assimilating Airborne Vr

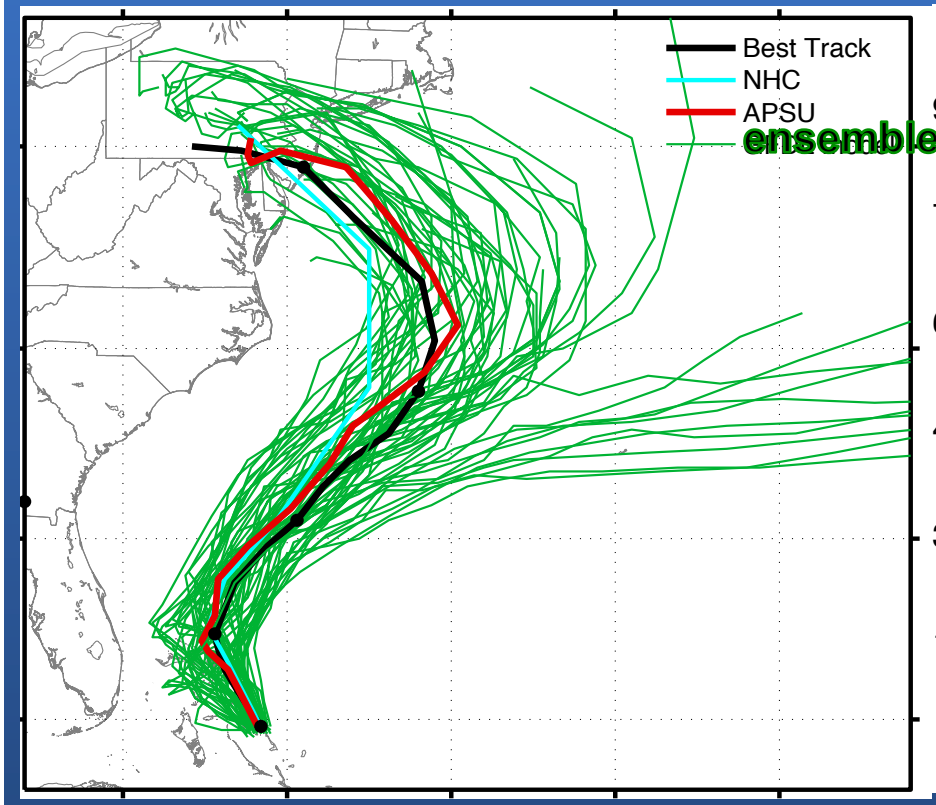
Mean track (km) & intensity (kts) error for all 107 P3 missions over 2008-2012

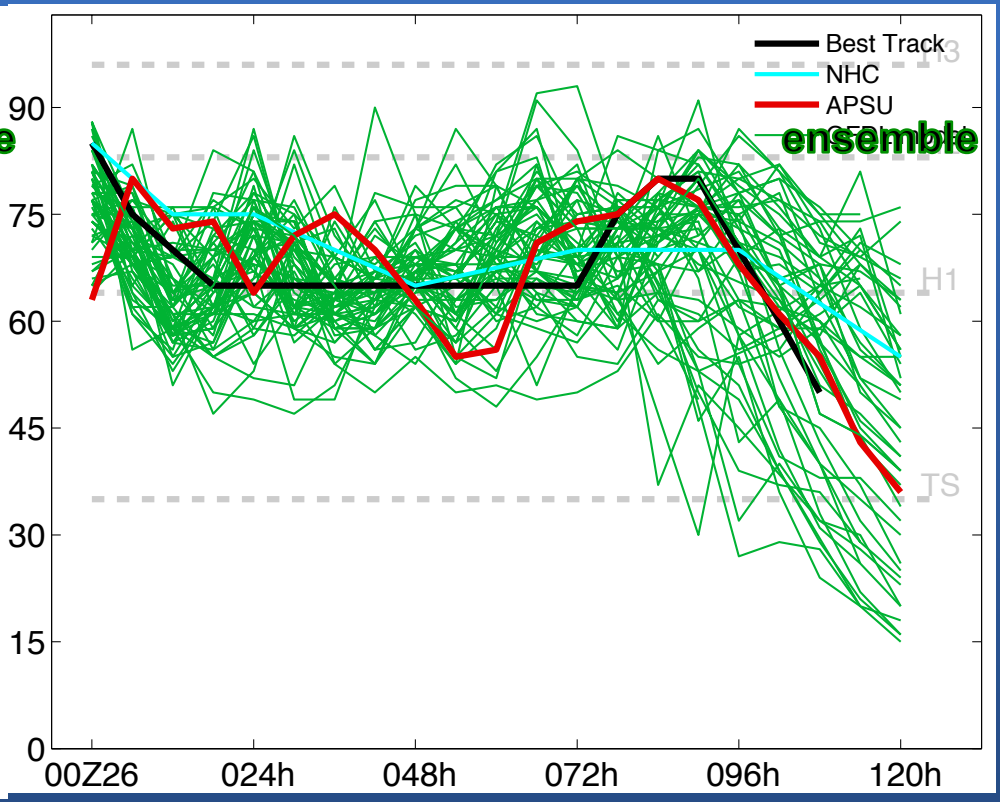




PSU WRF-EnKF Performance for Superstorm Sandy

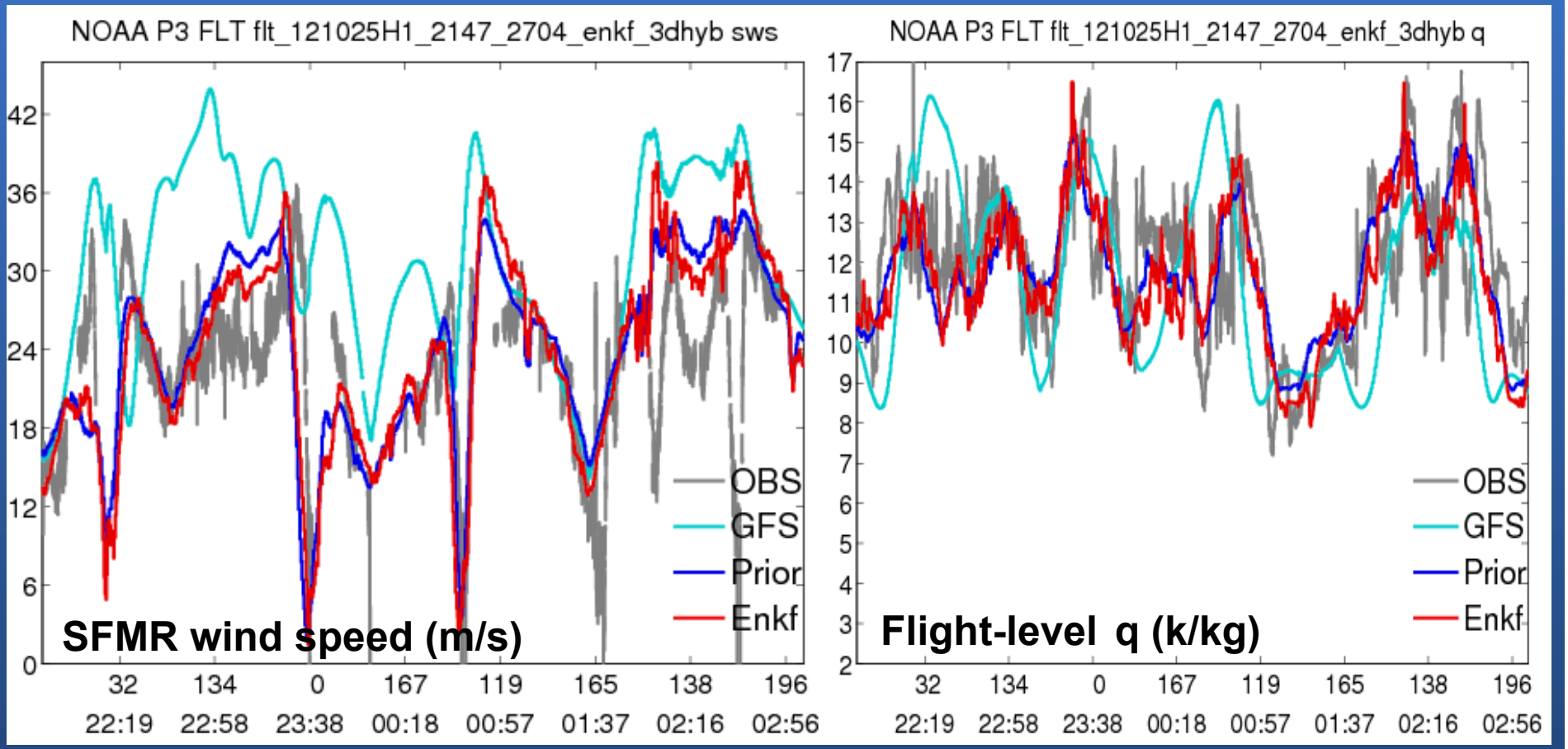
60-member 3-km cloud-resolving ensemble analysis forecast from 00Z Oct 26





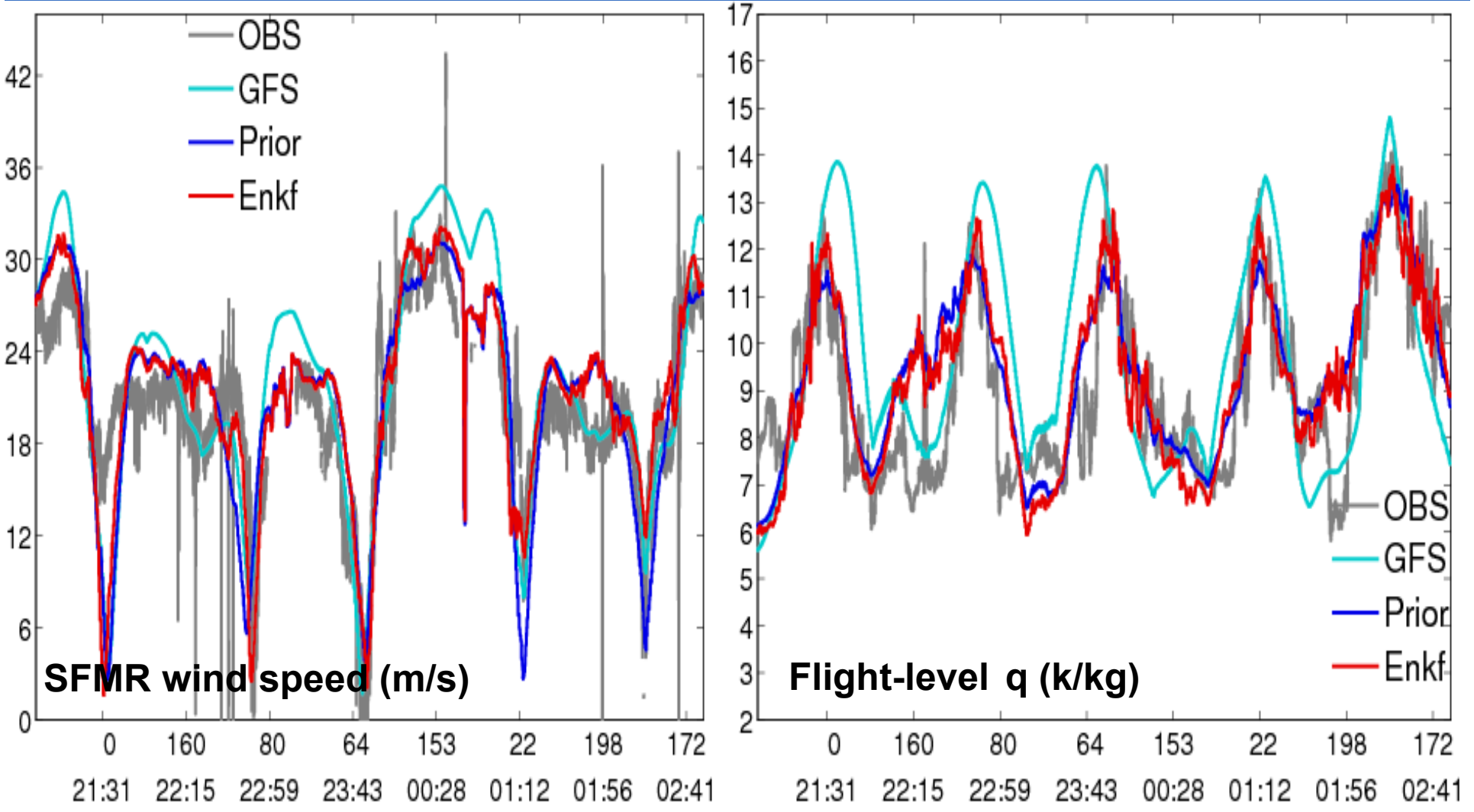
PSU WRF-EnKF Performance for Superstorm Sandy

EnKF analysis vs. independent observations from SFMR and flight-level obs



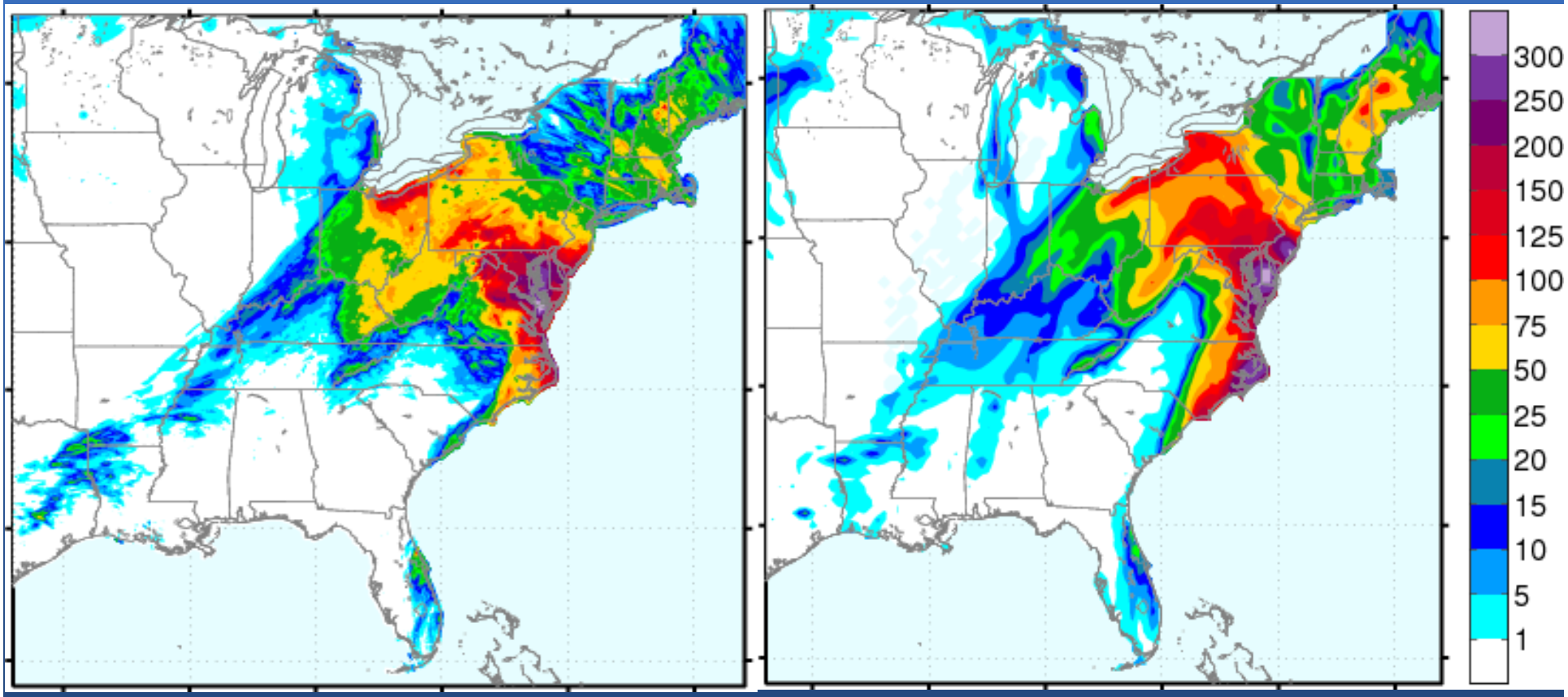
PSU WRF-EnKF Performance for Superstorm Sandy

EnKF analysis vs. independent observations from SFMR and flight-level obs



PSU WRF-EnKF Performance for Superstorm Sandy

108-h 3-km cloud-resolving deterministic precipitation forecast from 00Z Oct 26

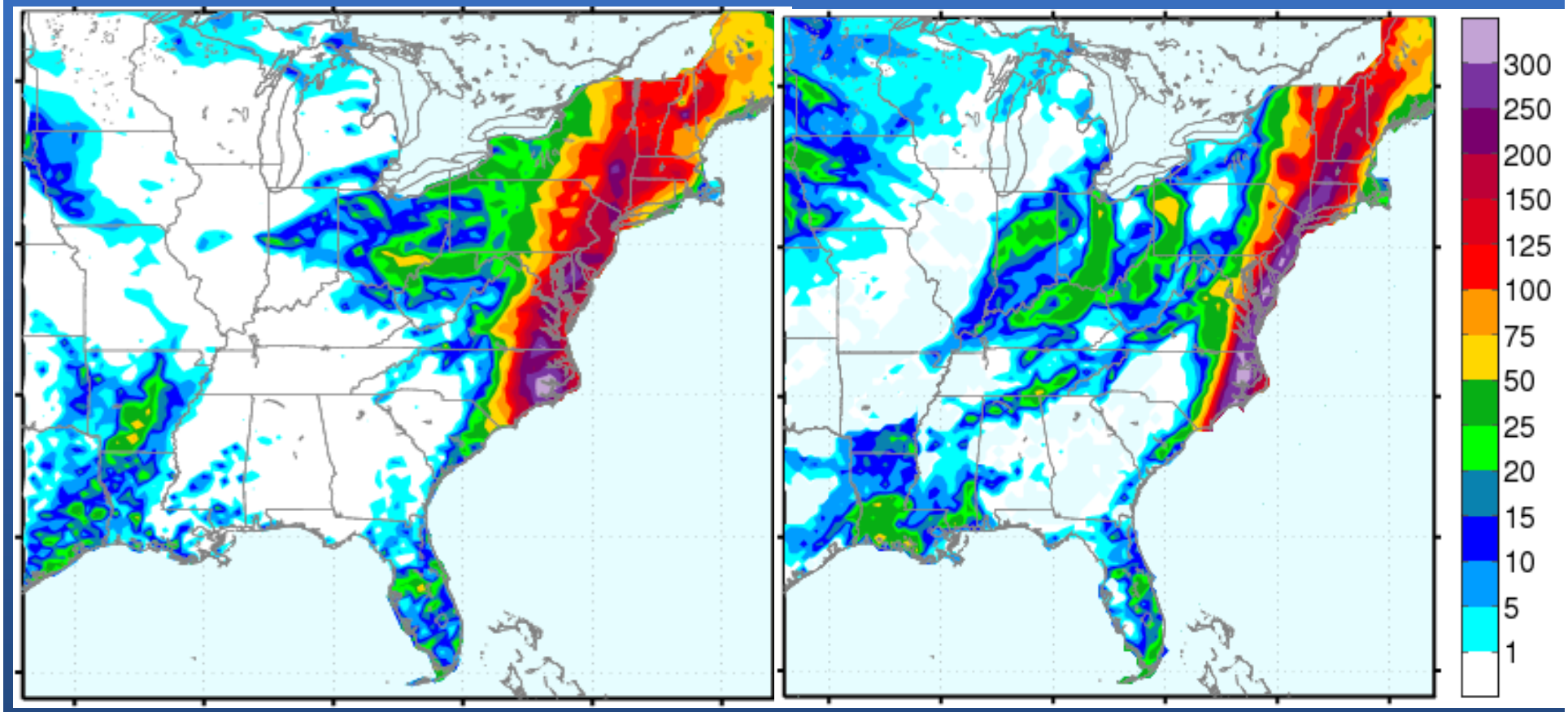


HPC Observation 12Z/26-30 Oct

PSU WRF-EnKF deterministic forecast

PSU WRF-EnKF Performance for Irene (2011)

3-km cloud-resolving deterministic hindcast of precipitation from 00Z Aug 24

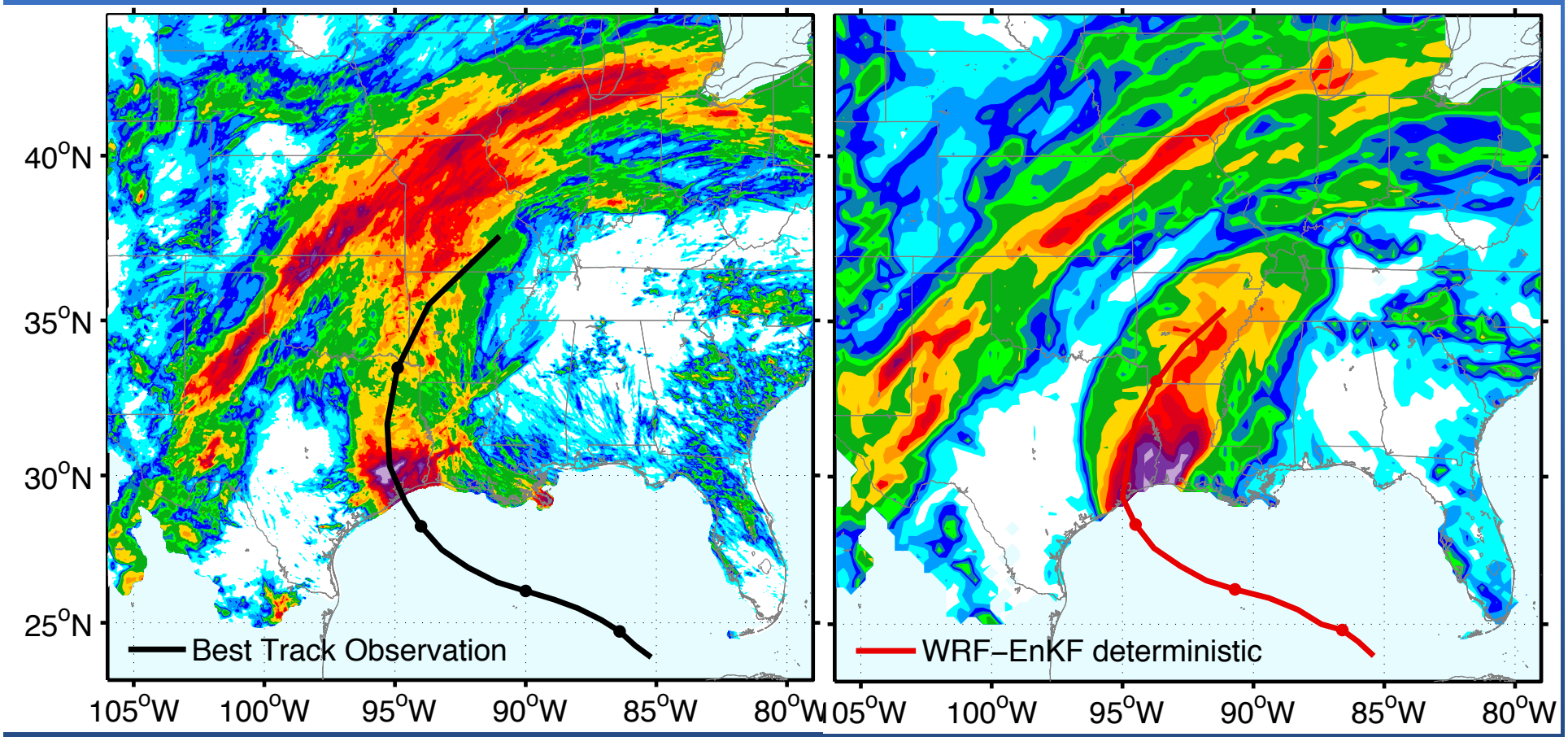


120h accumulated rainfall observation

PSU WRF-EnKF 120h deterministic forecast

PSU WRF-EnKF Performance for Ike (20108

3-km cloud-resolving deterministic hindcast of precipitation from 00Z Sept 10



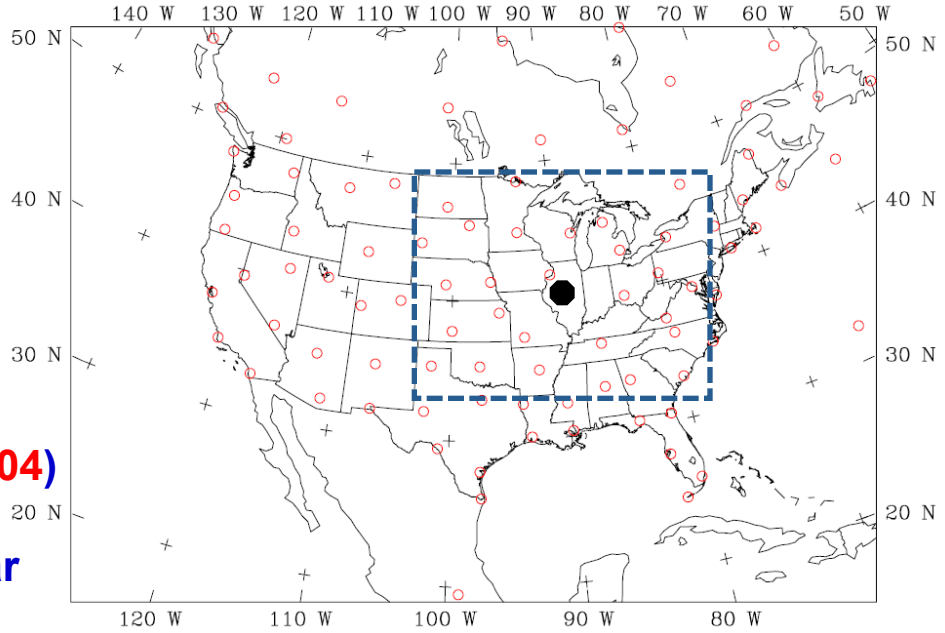
120h accumulated rainfall observation

PSU WRF-EnKF 120h deterministic forecast

Month-long Comparison EnKF, 3/4DVar & E3/4DVar

- **WRF-ARW V3.1 (*Skamarock et al. 2005*)**
  - **90-km grids covering North America;**
  - **27 vertical levels up to 50 hPa;**
  - **LBCs interpolated from FNL analysis with 6-h interval**

June 1-30, 2003

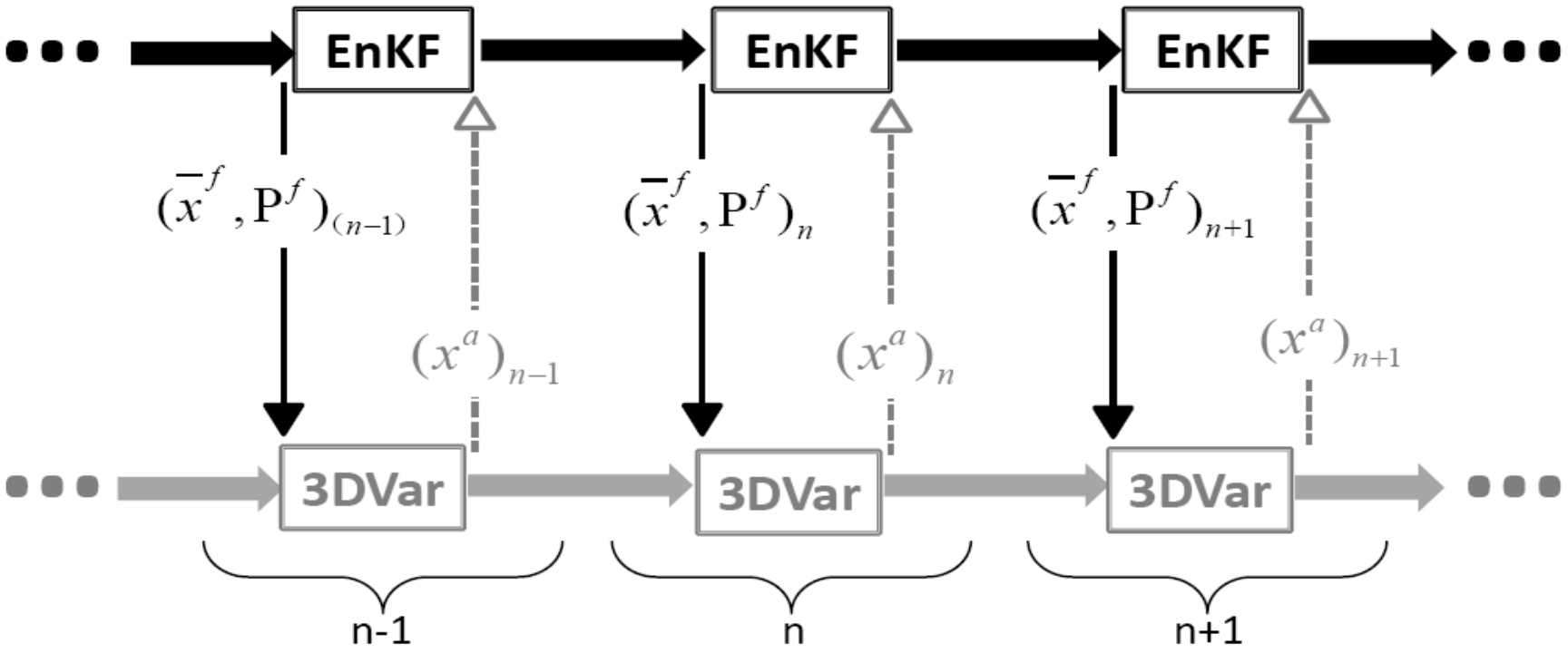


- **EnKF (*Meng and Zhang 2008a, b*)**
  - **40-member ensemble**
  - **Multi-physics parameterations**
  - **1800-km influence radius for localization**
  - **0.8 relaxation coefficient (Zhang et al. 2004)**
  - **Initial ensembles are perturbed at 00Z June 1 2003, via "CV5" option in WRF-Var**
  - **Perturbed LBCs**

- **3D/4DVar of WRF-Var V3.1 (*Barker et al. 2004; Huang et al. 2009; Zhang et al. 2011*)**
  - **"NMC" background error covariance (B); Var-scale at 3.0 and Length-scale at 1.0**
  - **"CV5" option derived from forecast difference statistics from pre-experimental month**
  - **6-h assimilation window (covering -3 to +3 h at every analysis time)**

- **E3DVAR:** coupling of EnKF and 3DVar (Zhang 2010, Zhang et al. 2013)
- **E4DVAR:** coupling of EnKF and 4DVar (Zhang et al 2009, Zhang 2010, Zhang&Zhang 2012)

E3DVAR: 2-way Coupling of EnKF with 3DVar



Necessary Variable Changes:

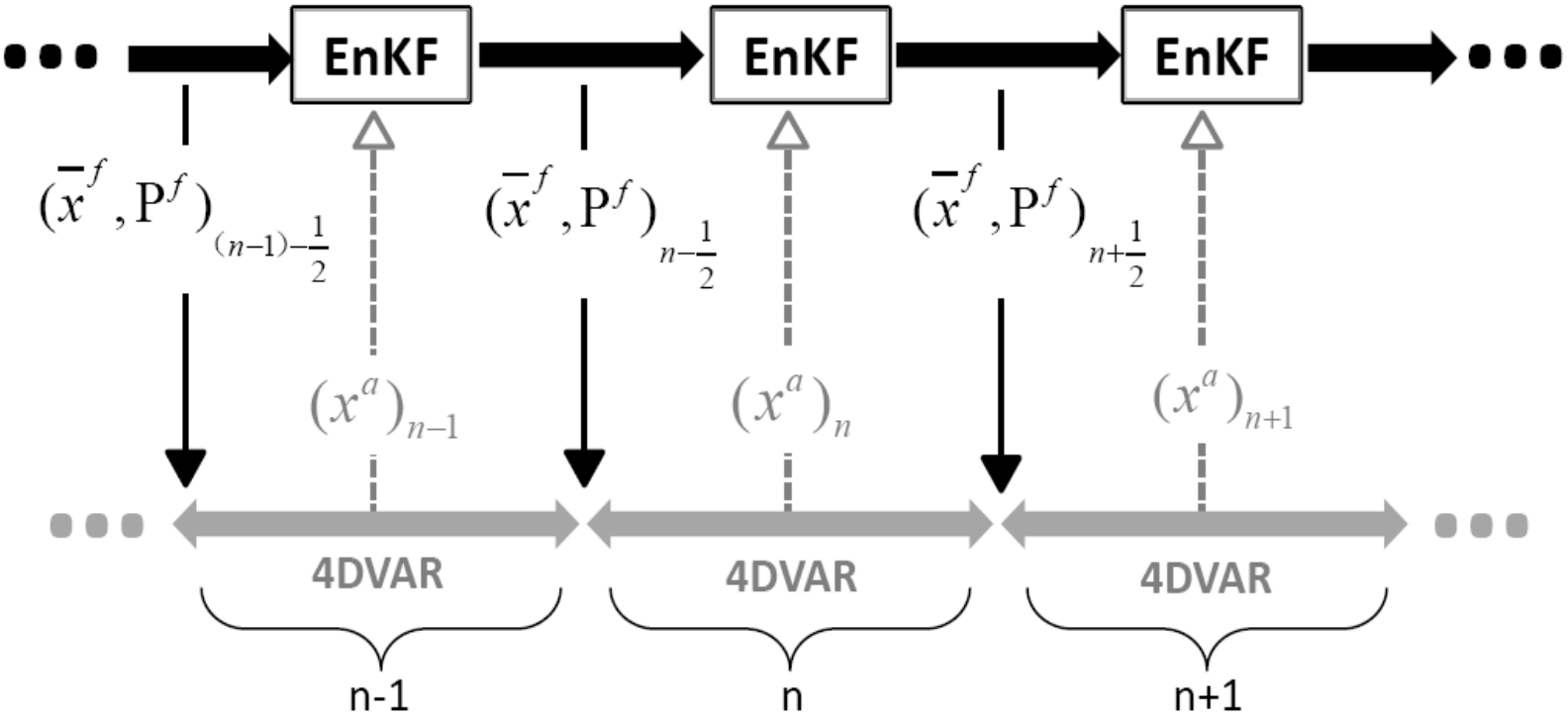
EnKF provides ensemble-based background error covariance ($\boldsymbol{P^f}$) for 3DVar

EnKF provides the prior ensemble mean ($\bar{x}^f$) as the first guess for 3DVar

3DVar provides deterministic analysis ($\bar{x}^a$) to replace the posterior ensemble mean for the next ensemble forecast

Zhang 2010, Zhang et al. 2013

E3DVAR: 2-way Coupling of EnKF with 4DVar



Necessary Variable Changes:

EnKF provides ensemble-based background error covariance (P^f) for 4DVar

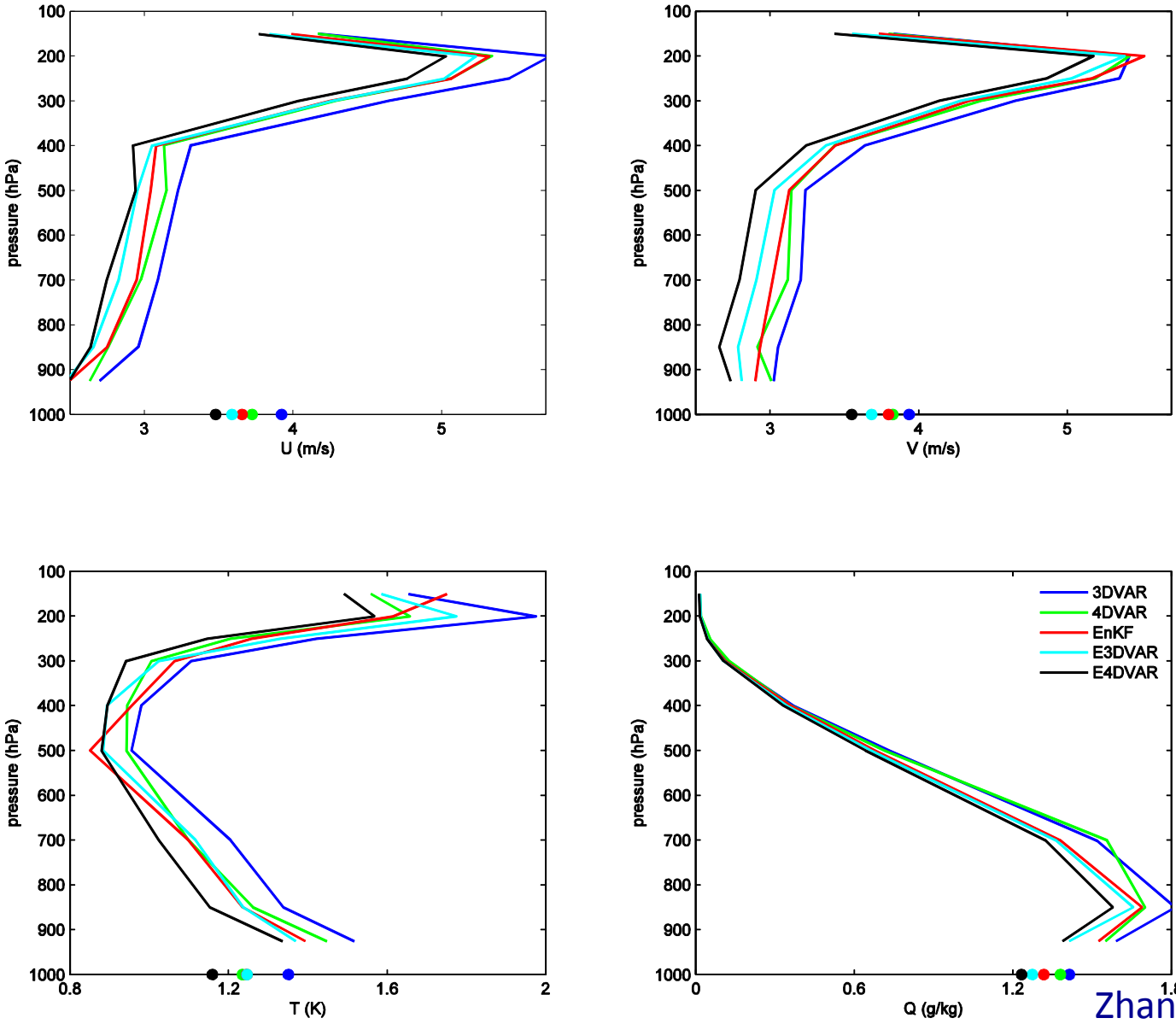
EnKF provides the prior ensemble mean ($\bar{x}^f$) as the first guess for 4DVar

4DVar provides deterministic analysis ($\bar{x}^a$) to replace the posterior ensemble mean for the next ensemble forecast

Zhang et al 2009, Zhang 2010, Zhang & Zhang 2012

3DVar, 4DVar, EnKF, E3DVar and E4DVar

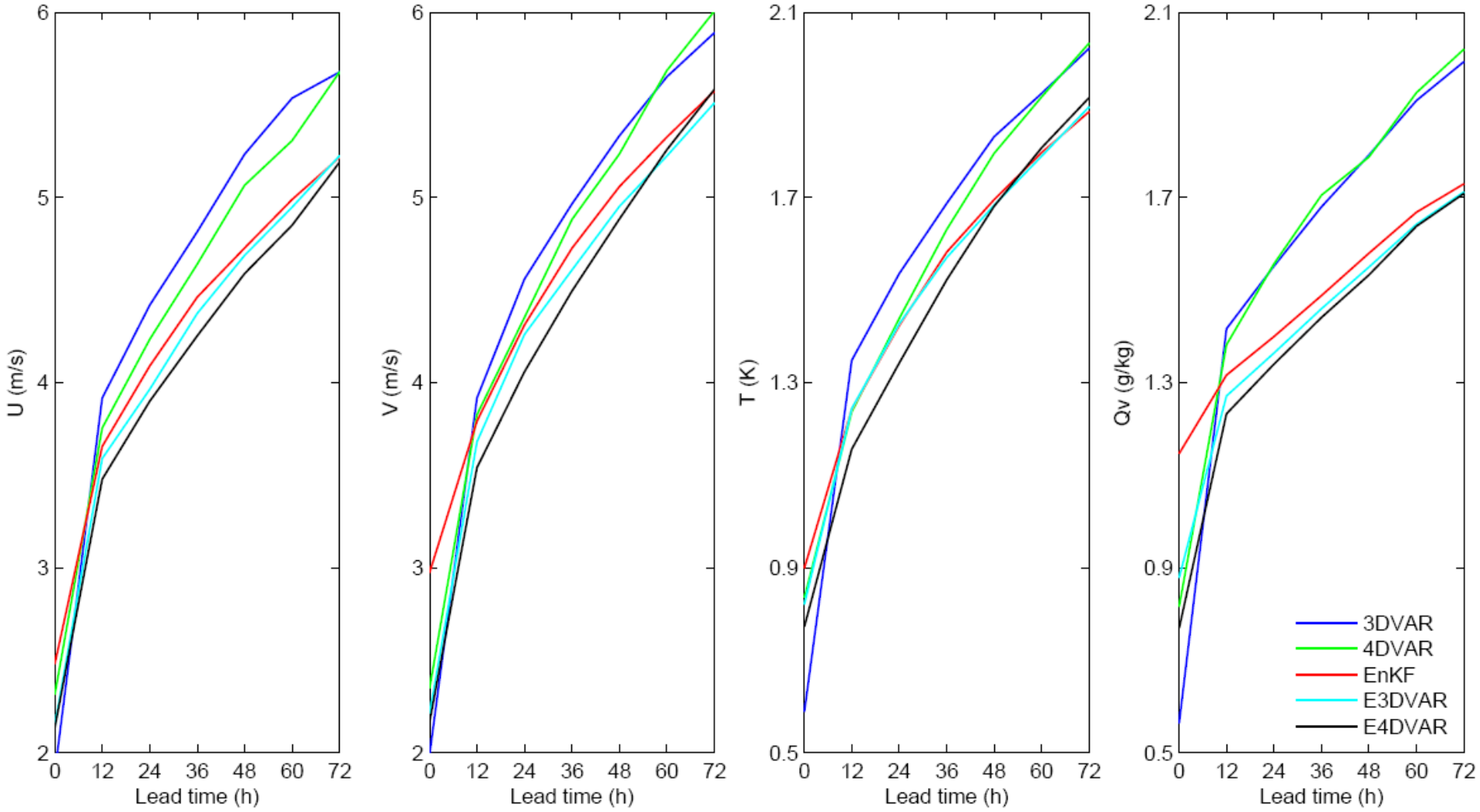
Mean vertical profiles of month-averaged 12-h forecast RMSE



Zhang et al. (2012)

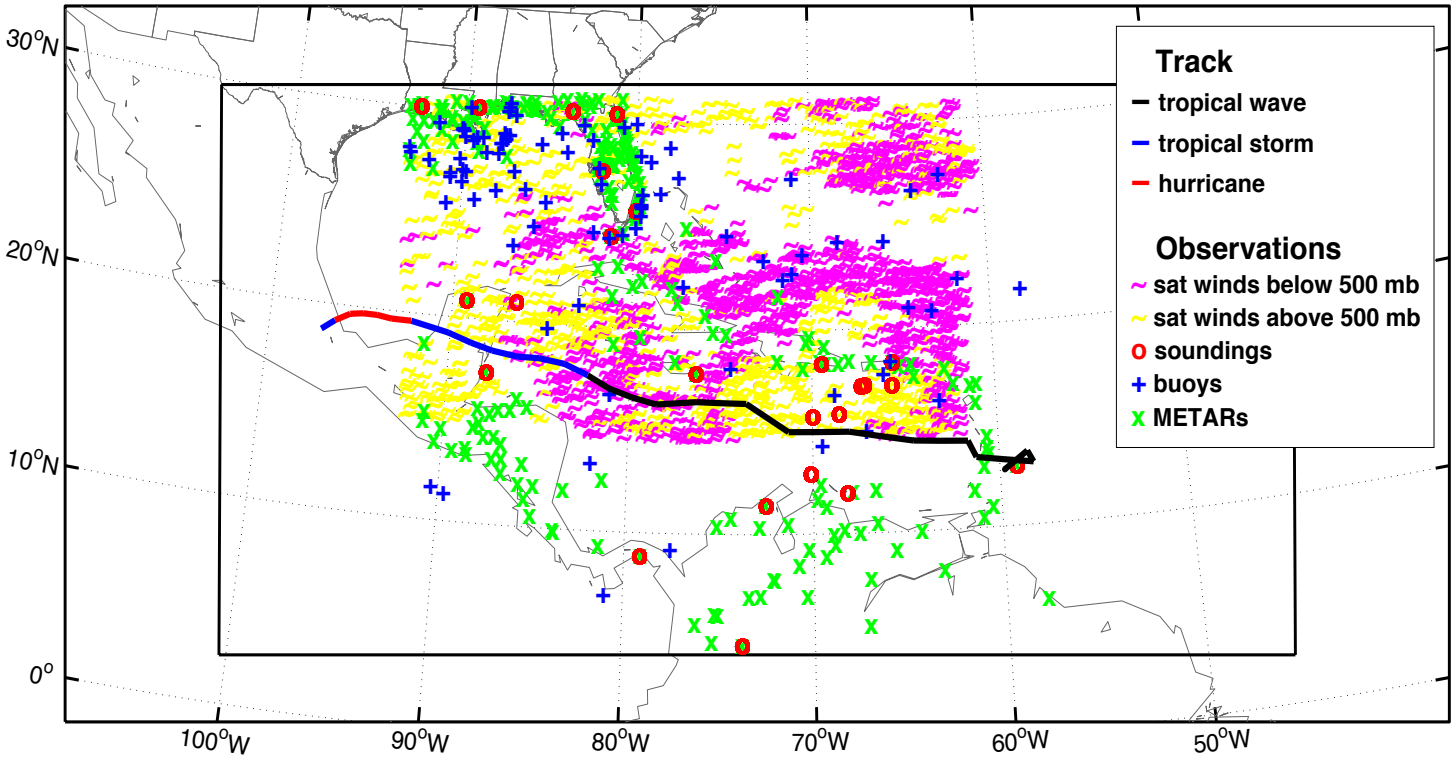
3DVar, 4DVar, EnKF, E3DVar and E4DVar

Total RMSE of U, V, T and Q with 0~72 lead time



(Zhang and Zhang 2012; Zhang et al. 2012a)

Case study: Hurricane Karl (2010)

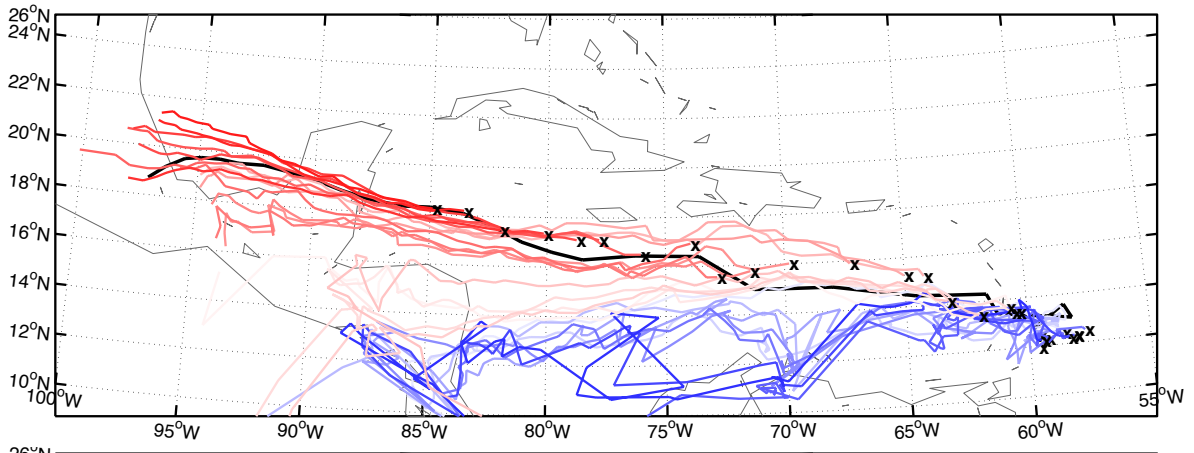


- ARW V3.4
- 451 x 226 x 35 domain
- 13.5 km grid spacing, 30 ensemble members, 0.8 covariance relaxation
- Data assimilated every 6 h from 06 UTC 08 Sept. to 00 UTC 15 Sept.
- Observations include all MADIS data (except radiance) and dropsondes from the Pre-depression Investigation of Cloud Systems in the Tropics (PREDICT) field campaign

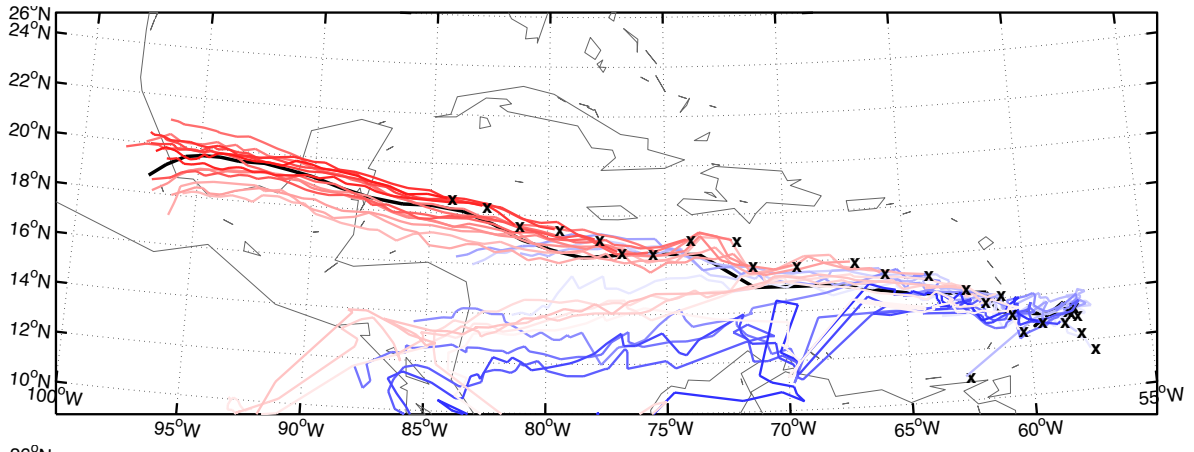
Poterjoy and Zhang, in prep.

Deterministic track forecasts with PREDICT obs

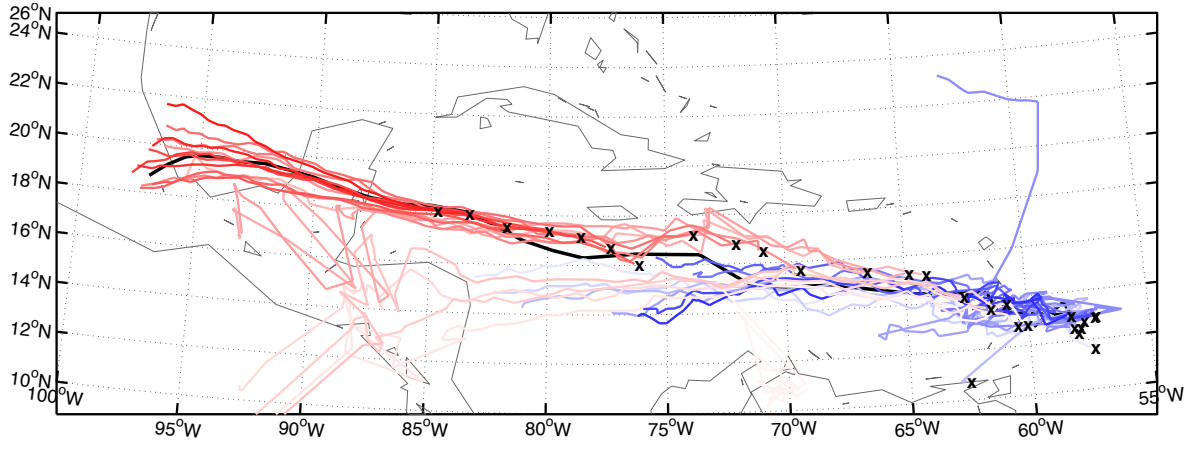
EnKF



4DVar

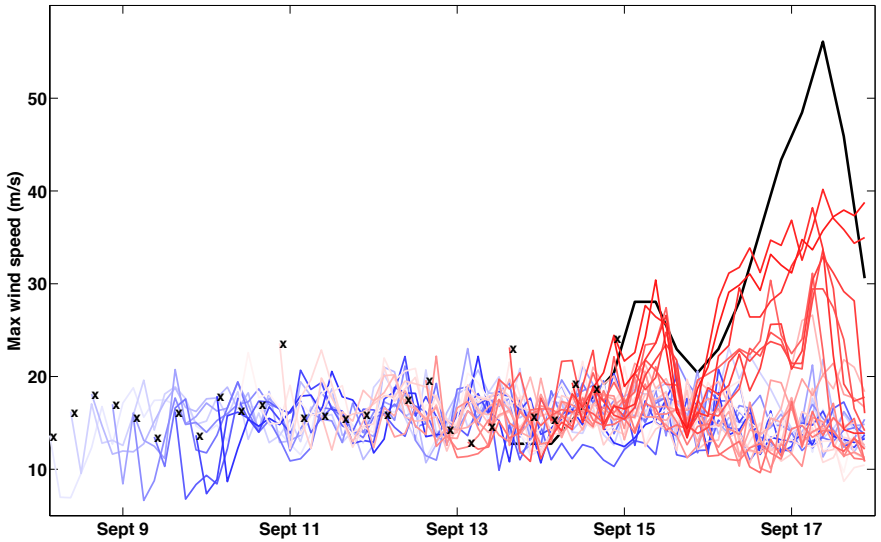


E4DVar

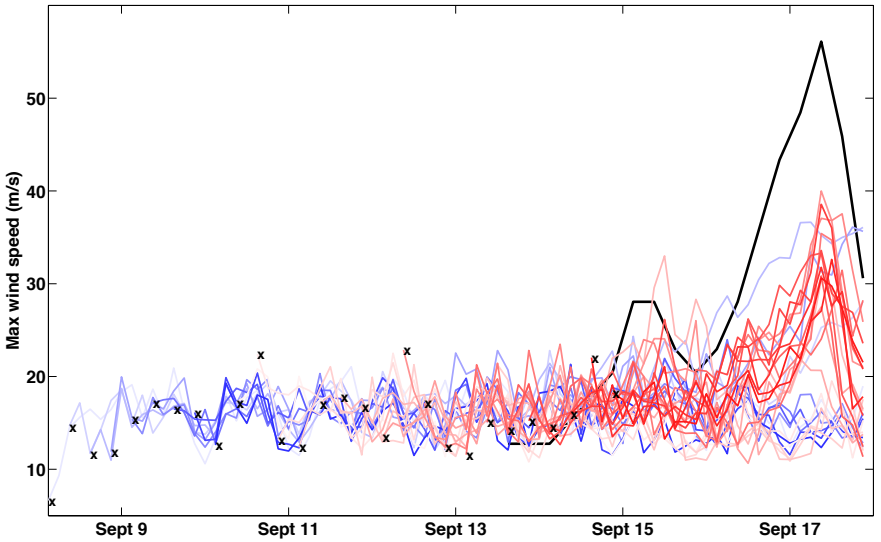


Deterministic intensity forecasts with PREDICT obs

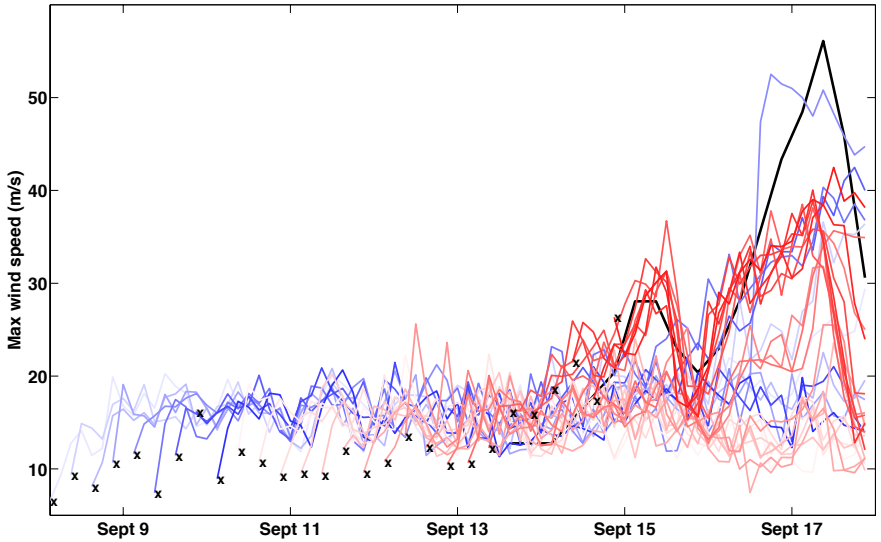
EnKF



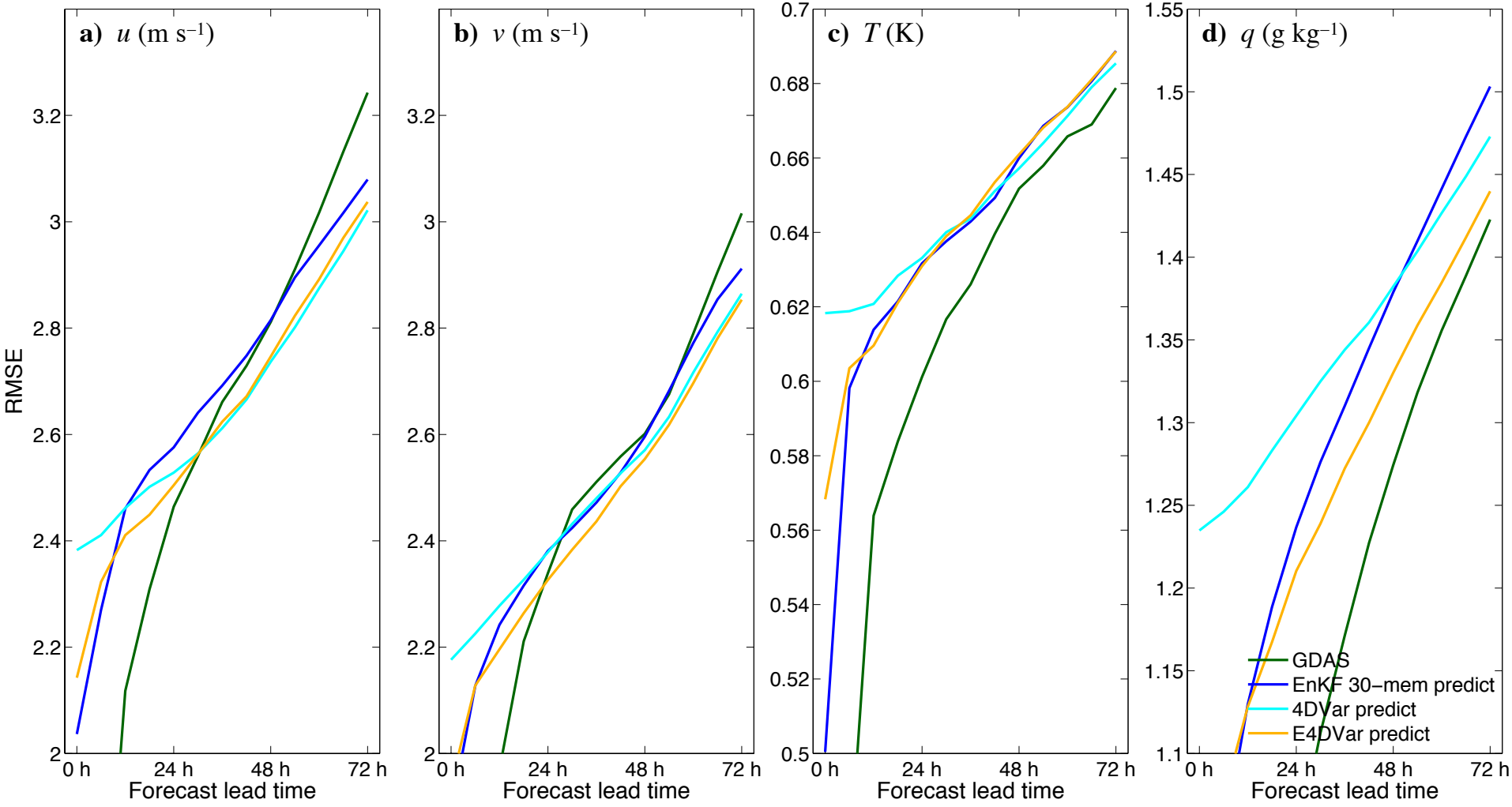
4DVar



E4DVar



Deterministic forecast errors with PREDICT obs



- Only data within 2500 km of the NHC best-track center are used

Concluding Remarks

- ***TC intensity forecasts can significantly improved with cloud-permitting EnKF assimilation of high-resolution inner-core radar observations***

- ***EnKF has great promise at meso- and convective scales but additional benefits may come from hybrid/coupling with 3D/4DVar***

- ***It might be premature to write off the adjoint-based 4DVar***

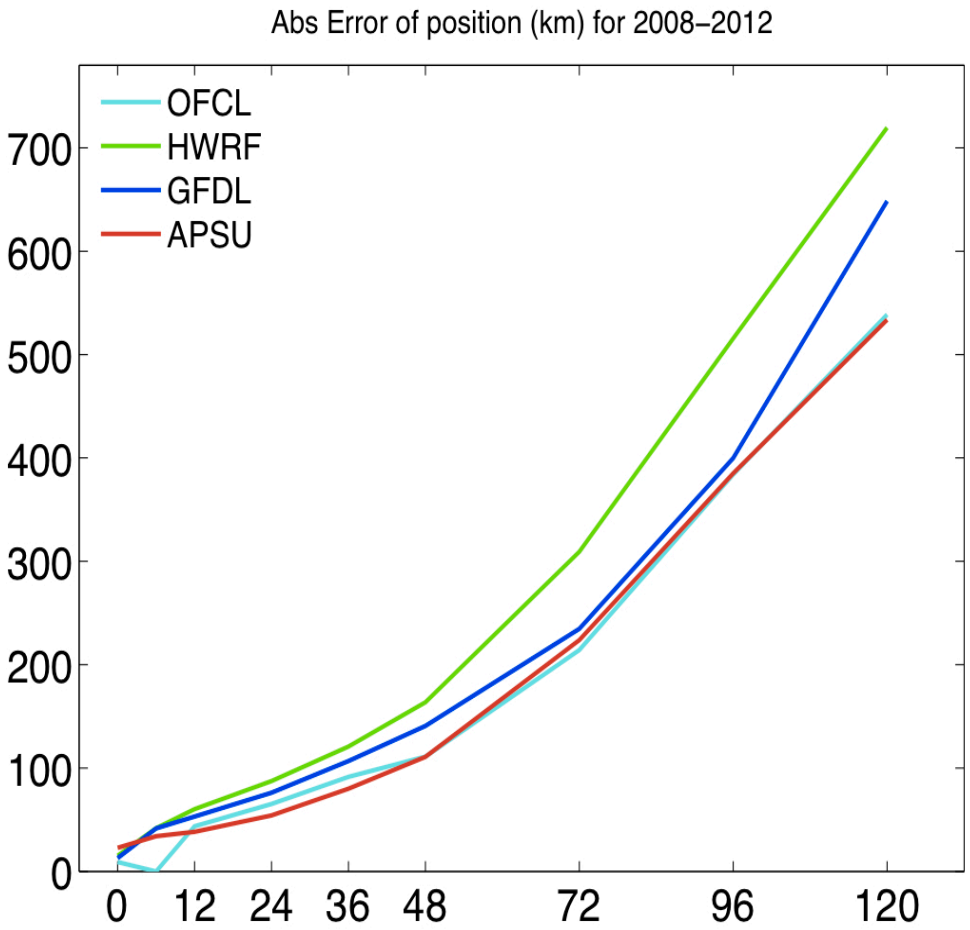
- ***We need to more effectively account for model error in DA and EF***

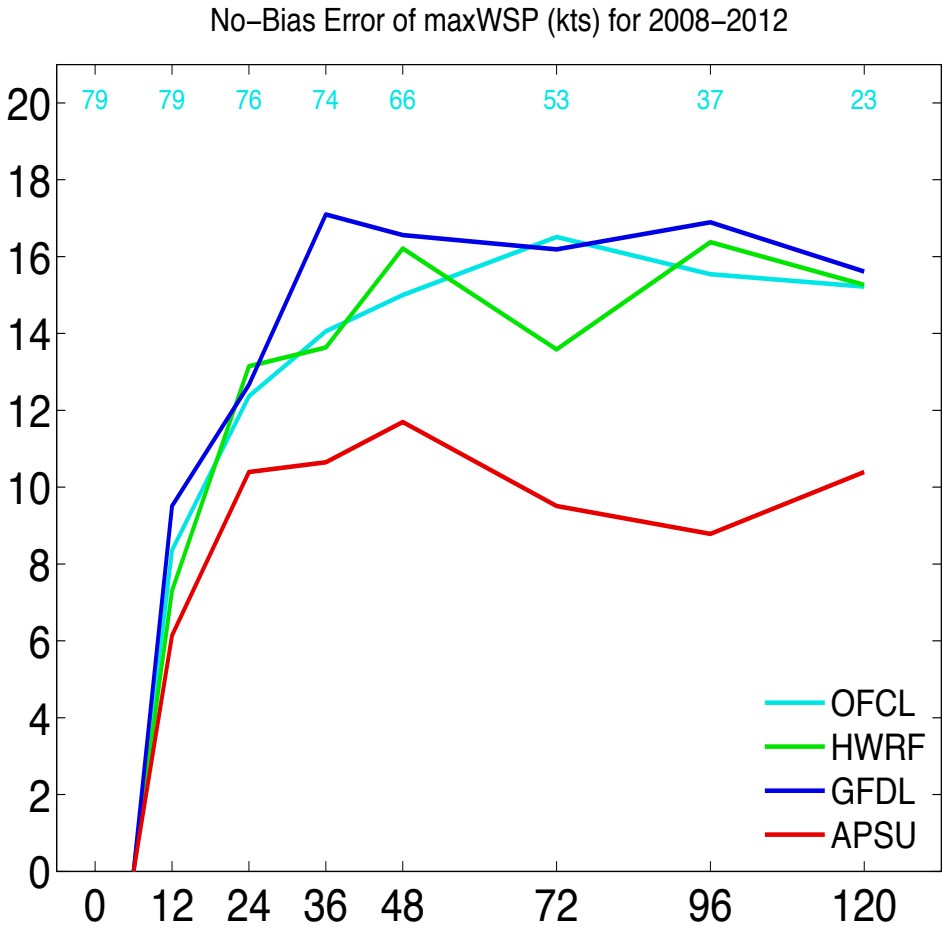
Summary on WRF-EnKF Hurricane Prediction

- **Hurricane intensity forecast can be greatly improved through using advanced DA techniques and a cloud resolving NWP model with assimilation of high-resolution inner-core observations**
- **Average over 100+ NOAA P3 Doppler missions, the PSU WRF-EnKF forecasts with assimilation of Vr has the day 1 to 5 mean intensity forecast error 20-40% smaller than NHC official forecasts**
- **The PSU WRF-EnKF experimental system performed well for all landfalling hurricanes during 2008-2012. It also shows great promise in predicting hurricane-induced rainfalls, as well as uncertainties**
- **Future of hurricane prediction: better inner-core observations, better data assimilation, better forecast model, better computing resources**

WRF-EnKF Performance Assimilating Airborne Vr

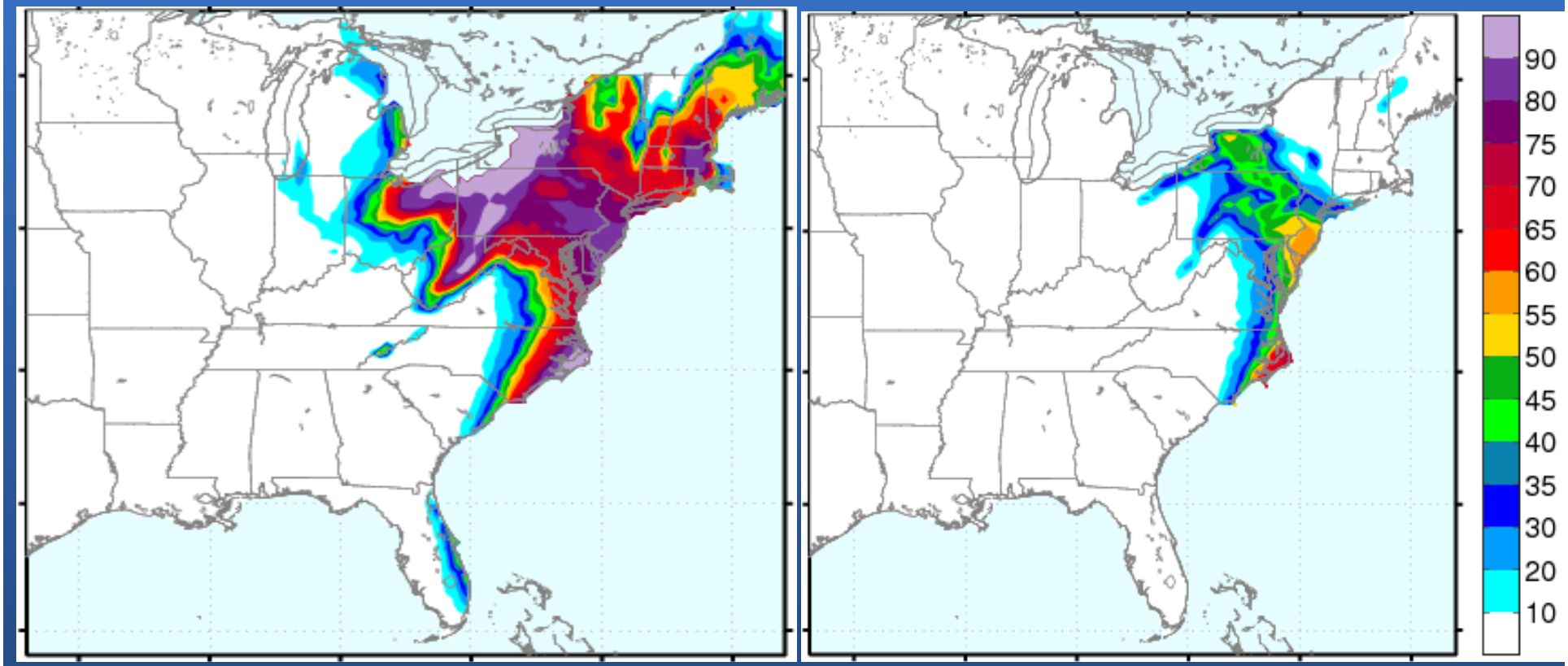
Mean track (km) & intensity (kts) error for 93 P3 missions over 2008-2012





PSU WRF-EnKF Performance for Superstorm Sandy

60-member 3-km cloud-resolving ensemble analysis forecast from 00Z Oct 26



Forecasted Probability of 96h accumulated rainfall >25&100mm