Hybrid Variational-Ensemble Data Assimilation for Tropical Cyclone Forecasts

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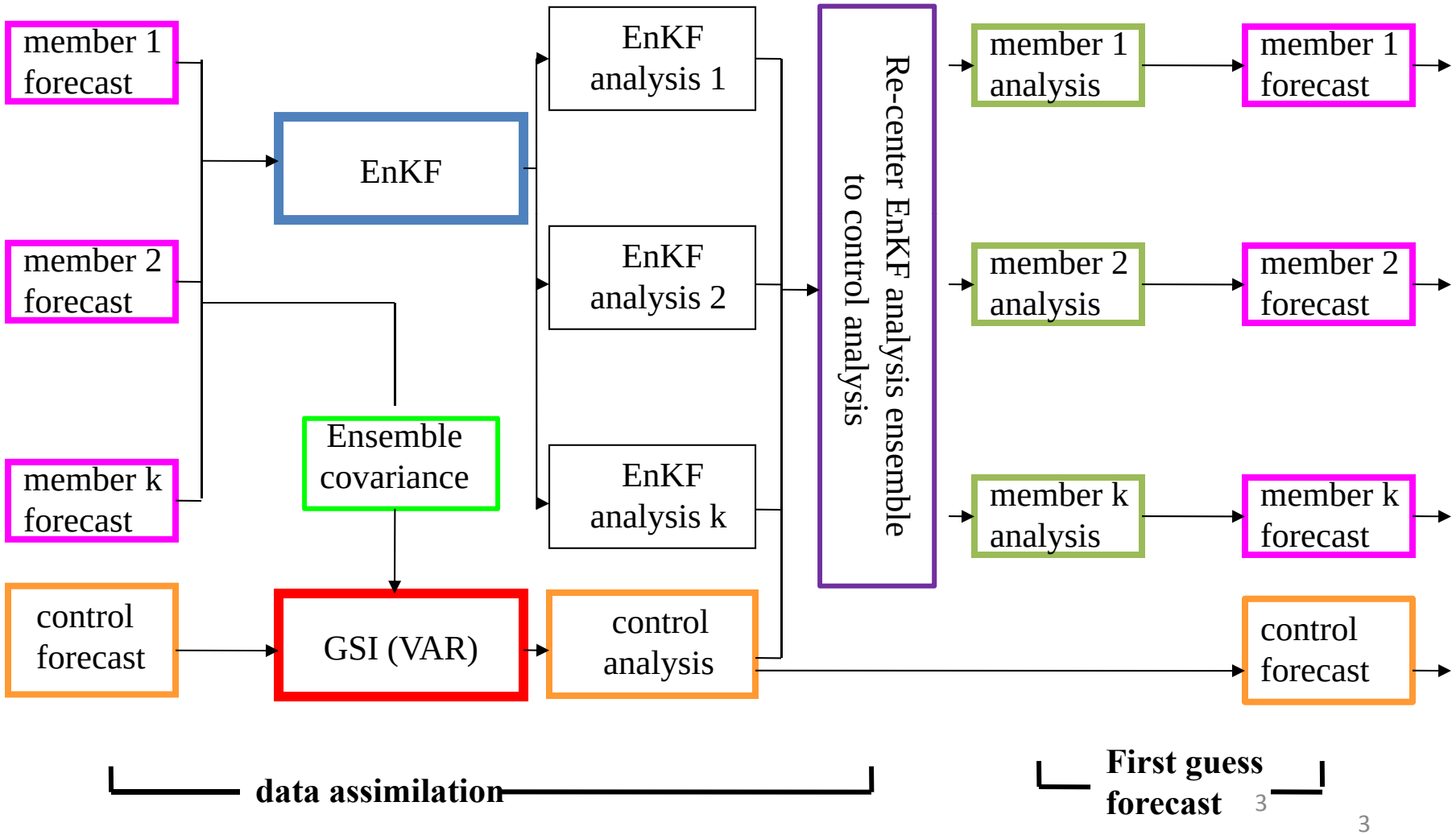
Outline

Introduction: what and why hybrid?

Results of hybrid DA for

a). GFS Hurricane Track forecast 2010: ENS4DVAR vs. ENS3DVAR vs. GSI
b). Diagnostics study on why hybrid provided better track forecast for Ike 2008
c). High resolution radar data assimilation for hurricane Ike 2008
d). Integration of global hybrid GSI-EnKF with regional: an encouraging story

Hybrid GSI-EnKF DA system



Wang et al. 2011

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Why Hybrid? "Best of both worlds"

	VAR (3D, 4D)	EnKF	hybrid	References
Benefit from use of flow dependent ensemble covariance instead of static B		x	x	Hamill and Snyder 2000; Wang et al. 2007b,2008ab, 2009b, Wang 2011; Buehner et al. 2010ab
Robust for small ensemble			x	Wang et al. 2007b, 2009b; Buehner et al. 2010b
Better localization for integrated measure, e.g. satellite radiance; radar with attenuation			x	Campbell et al. 2010
Easiness to add various constraints	x		x	
Outer loops	x		x	
More use of various existing capability in VAR	x		x	

Summarized in Wang 2010, MWR

How to incorporate ensemble in GSI?

- Extended control variable method (Wang 2010, MWR):

$$J\left(\mathbf{x}_1^{'}, \boldsymbol{\alpha}\right) = \beta_1 J_1 + \beta_2 J_e + J_o$$

$$= \beta_1 \frac{1}{2} \mathbf{x}_1^{'T} \mathbf{B}^{-1} \mathbf{x}_1^{'} + \beta_2 \frac{1}{2} \boldsymbol{\alpha}^T \mathbf{C}^{-1} \boldsymbol{\alpha} + \frac{1}{2} \left(\mathbf{y}^{o'} - \mathbf{H}\mathbf{x}^{'}\right)^T \mathbf{R}^{-1} \left(\mathbf{y}^{o'} - \mathbf{H}\mathbf{x}^{'}\right)$$

Extra term associated with extended control variable

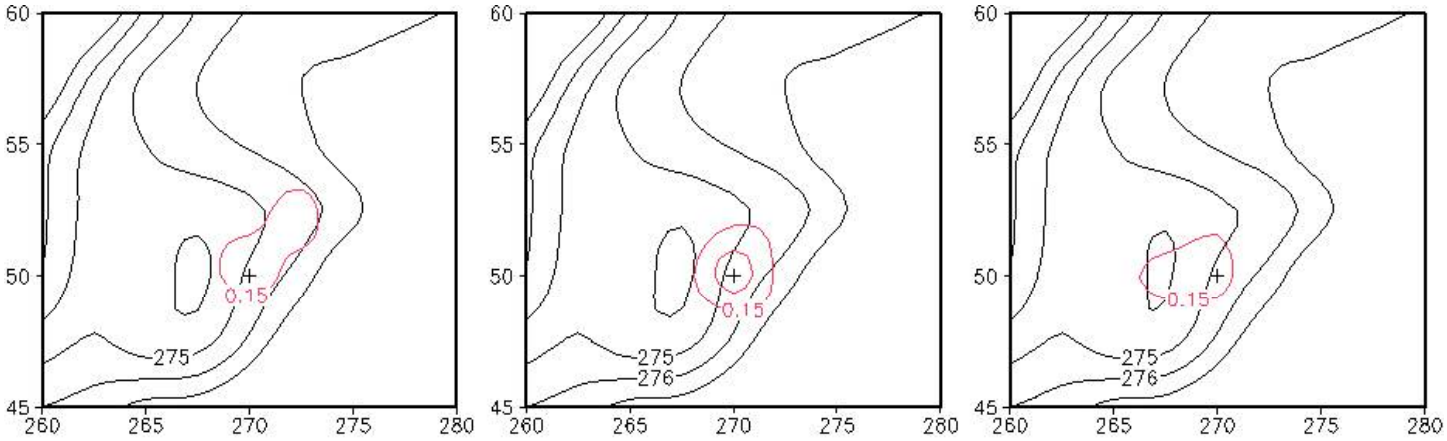
$$\mathbf{x}^{'} = \mathbf{x}_1^{'} + \sum_{k=1}^{K} \left(\boldsymbol{\alpha}_k \circ \mathbf{x}_k^e\right)$$

Extra increment associated with ensemble

$\mathbf{B}$ 3DVAR static covariance; $\mathbf{R}$ observation error covariance; K ensemble size;
$\mathbf{C}$ correlation matrix for ensemble covariance localization; $\mathbf{x}_k^e$ kth ensemble perturbation;
$\mathbf{x}_1^{'}$ 3DVAR increment; $\mathbf{x}^{'}$ total (hybrid) increment; $\mathbf{y}^{o'}$ innovation vector;
$\mathbf{H}$ linearized observation operator; β_1 weighting coefficient for static covariance;
β_2 weighting coefficient for ensemble covariance; $\boldsymbol{\alpha}$ extended control variable.

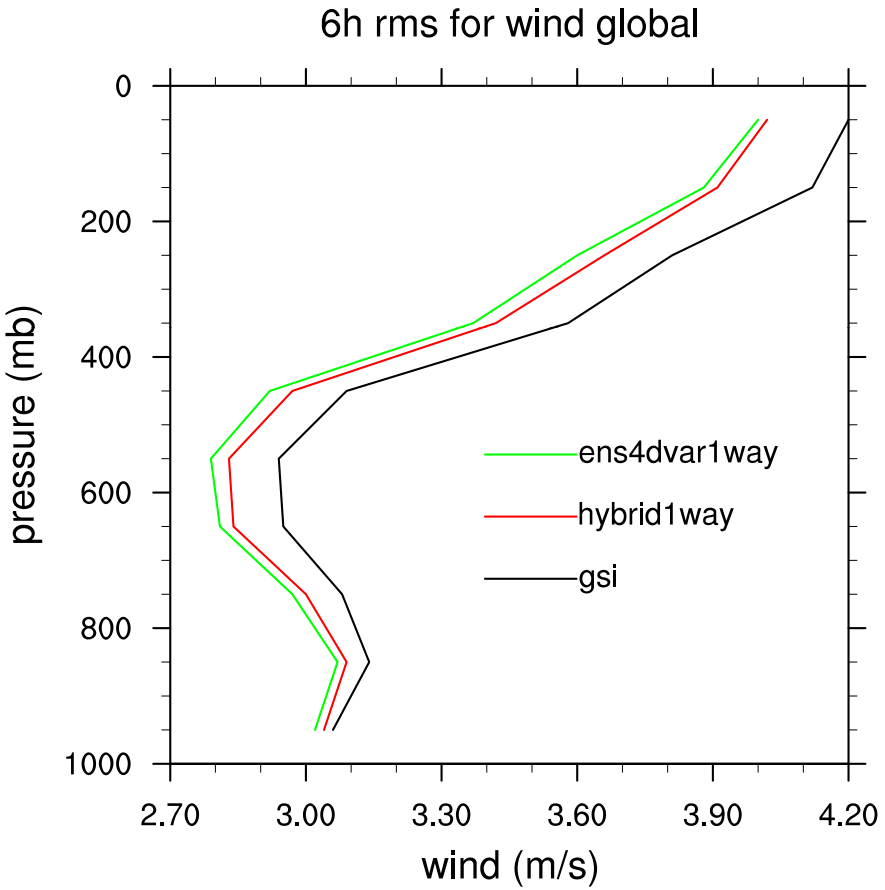
Ensemble 4DVAR (ENS4DVAR) for GSI

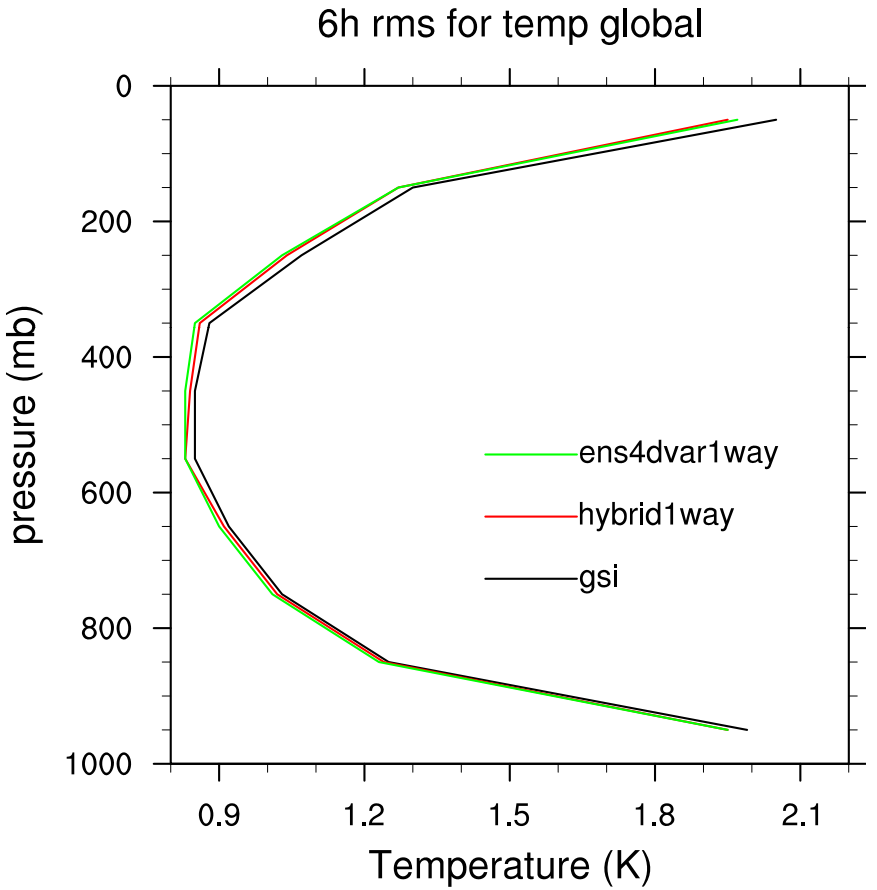
- Like traditional 4DVAR, 4D analyses are obtained by fitting observations spanning the assimilation window.
- Unlike traditional 4DVAR, ens4dvar does not need to develop the tangent linear and adjoint of the forecast model (Liu et al. 2009).



Lei, Wang et al. 2011

RMSE of global forecasts by GFS





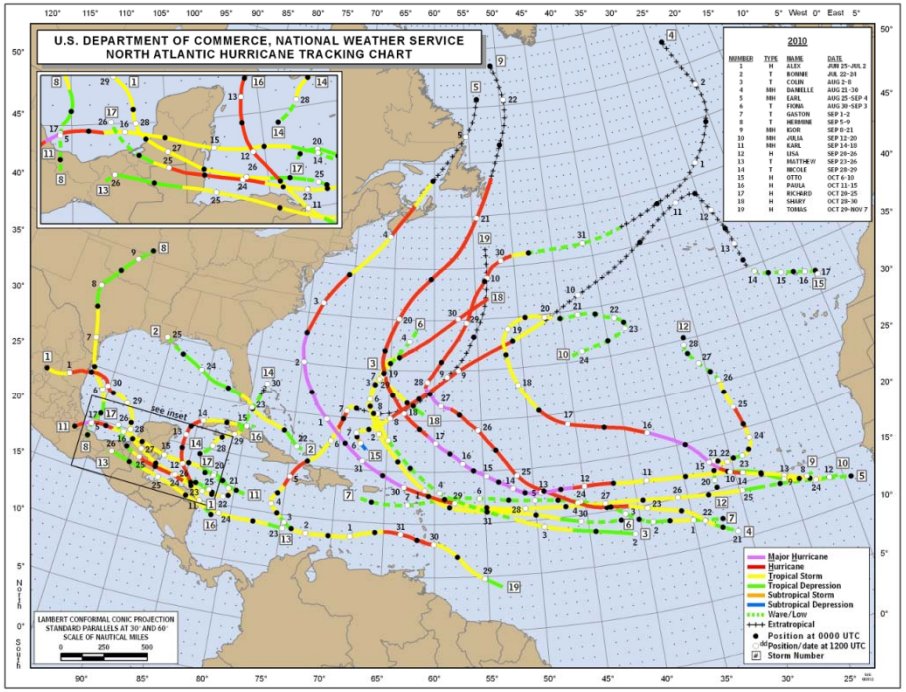
- Significant improvement of ens3dvar hybrid and ens4dvar hybrid over GSI
- ens4dvar showed further improvement over ens3dvar especially for wind

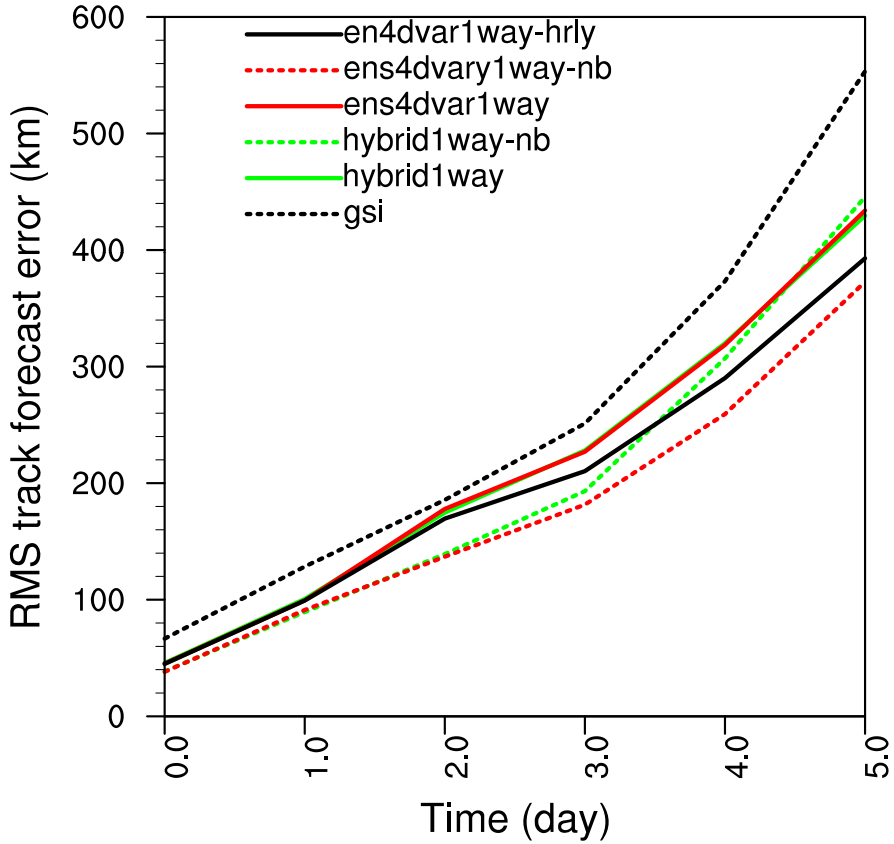
Lei, Wang et al. 2011

Hurricane track forecasts by GFS

2010 Aug.-Sep.

2010 hurricane

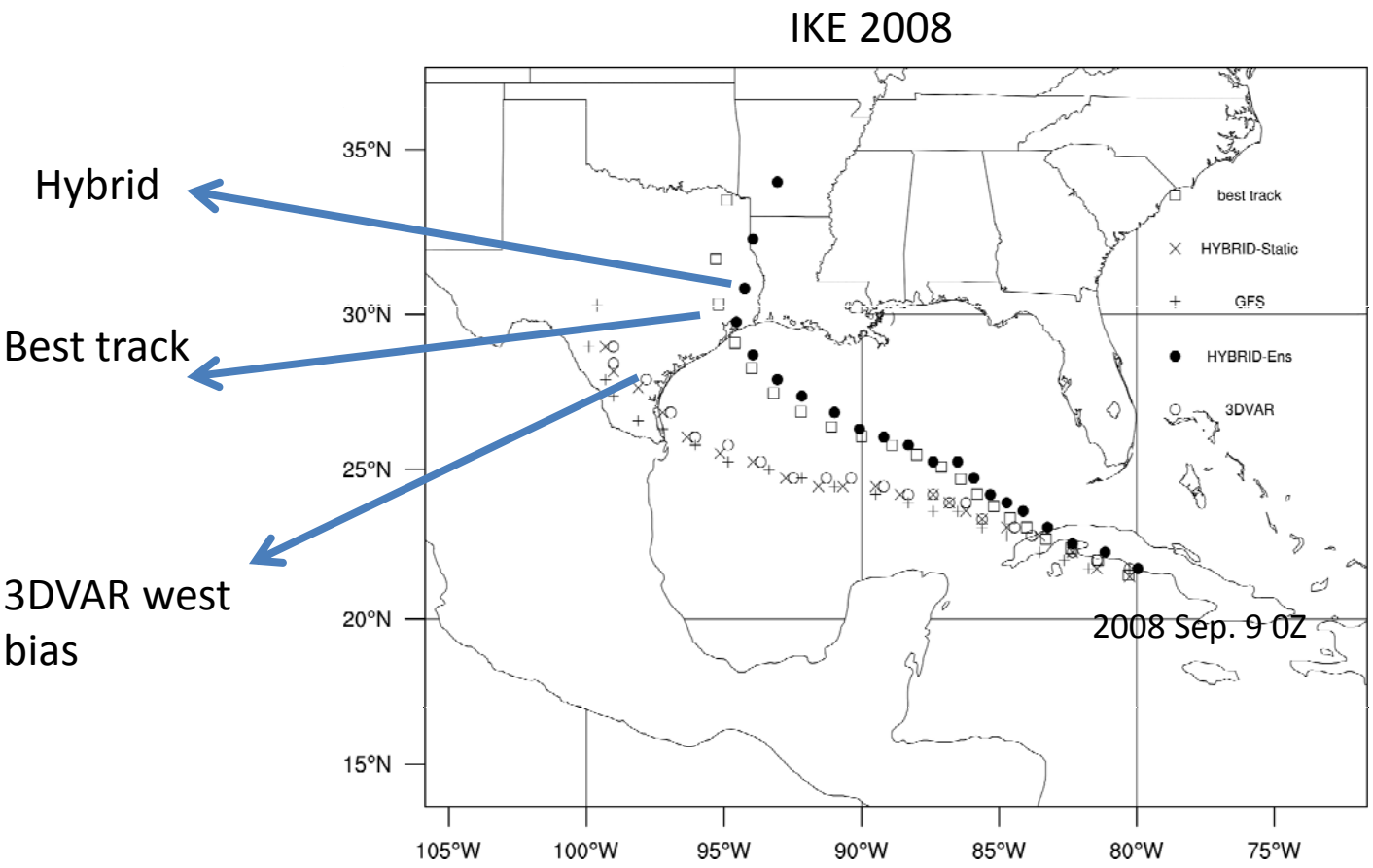




- Improvement of TC track forecasts by ens3dvar hybrid than GSI and further improvement by ens4dvar hybrid.
- Balance constraint in GSI hurt TC forecast of hybrid.

Lei, Wang et al. 2011

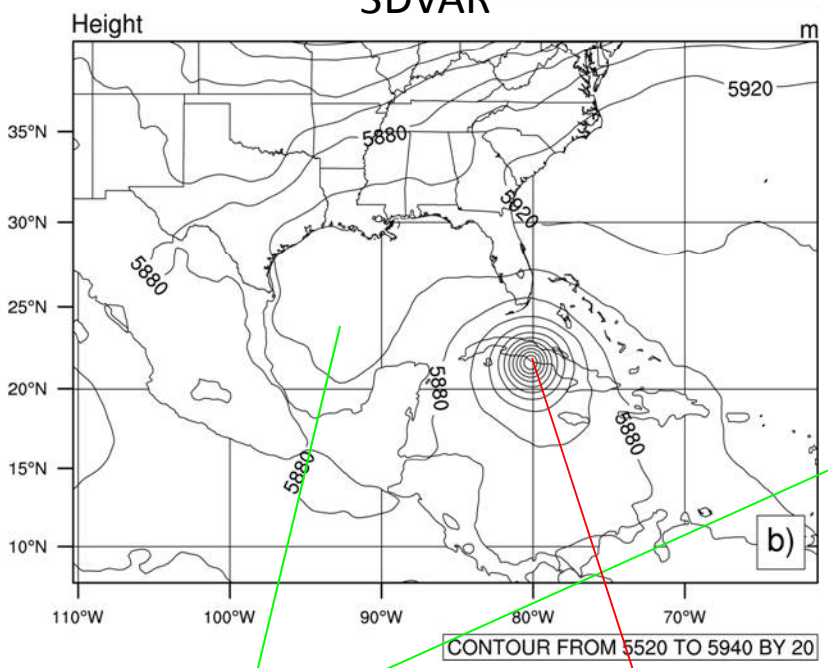
Why hybrid produced better track forecast?



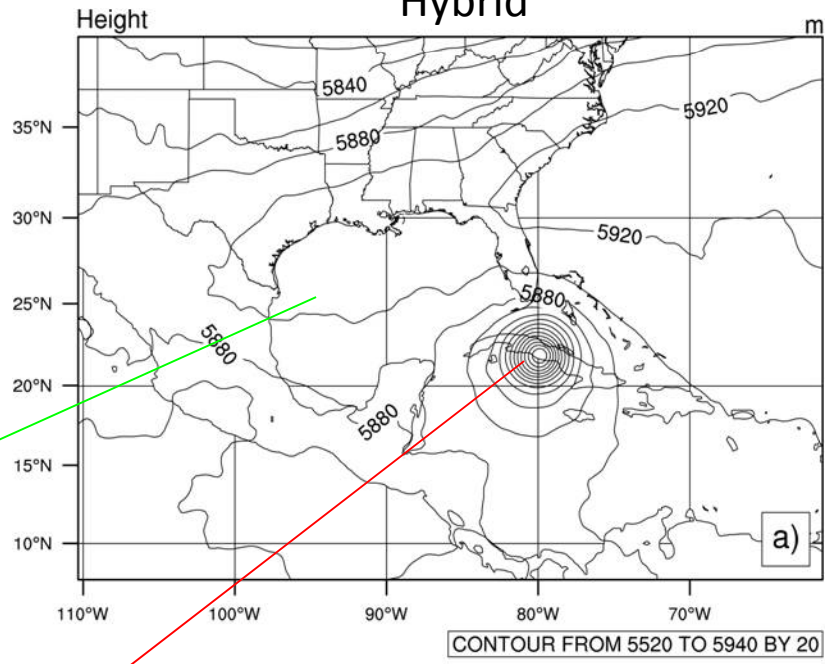
Wang 2011, WAF

Initial analyses: 500mb height

3DVAR



Hybrid

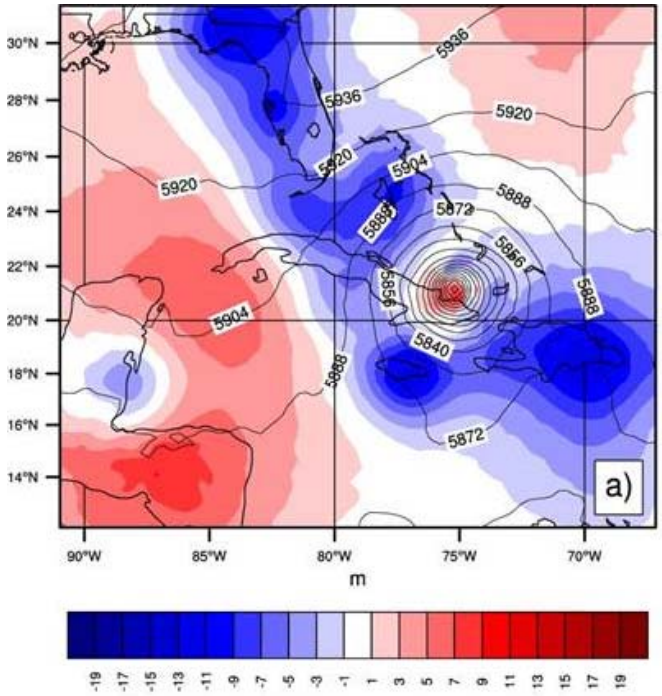


- The subtropical high in the 3DVAR analysis extended more to the south in the southwest quadrant of Gulf of Mexico than HYBRID.

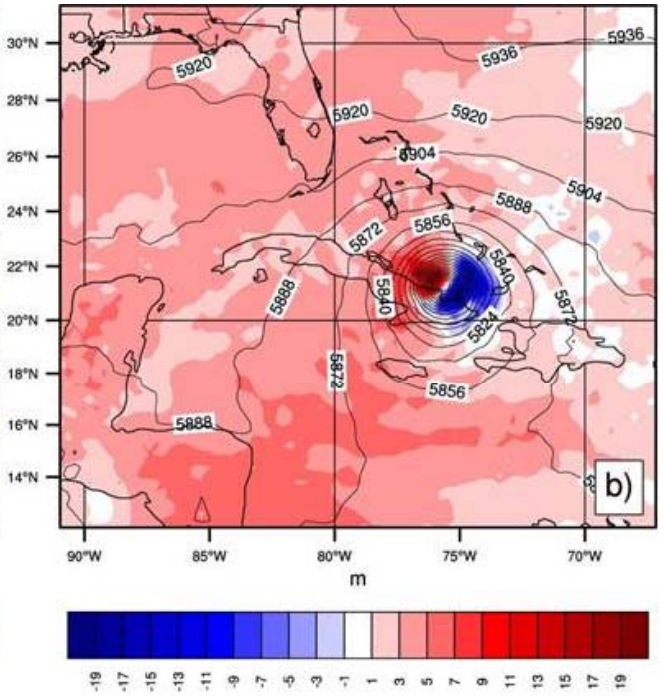
- Weaker and smaller IKE estimated by 3DVAR.

Analysis increment difference

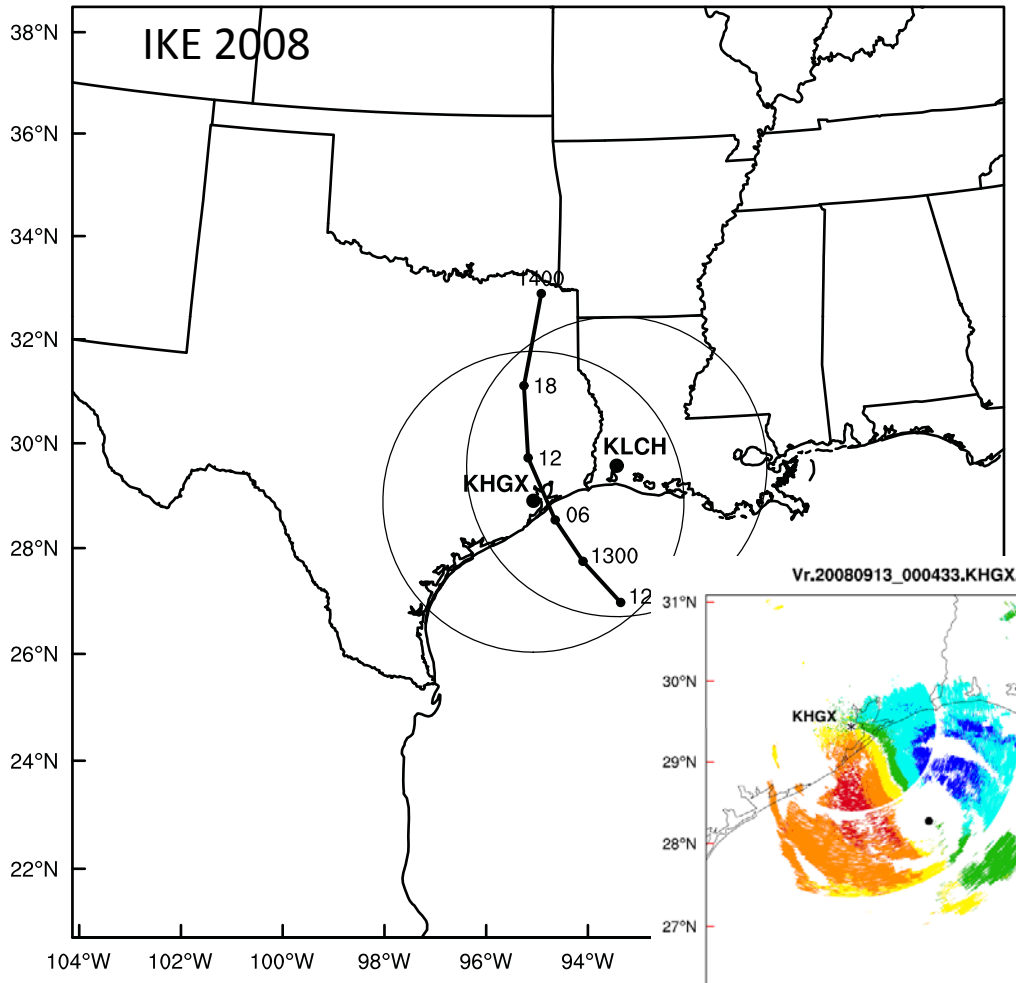
3DVAR

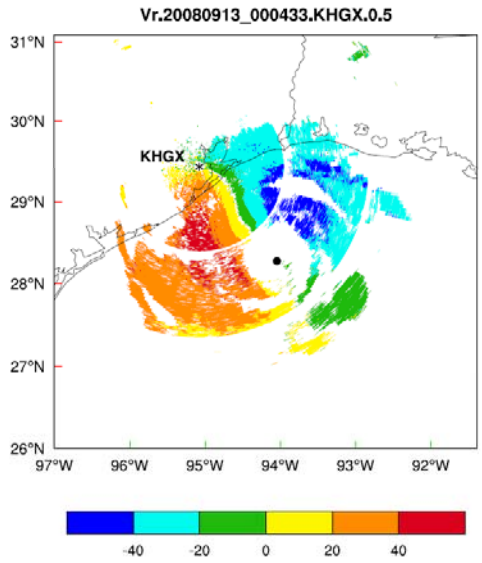


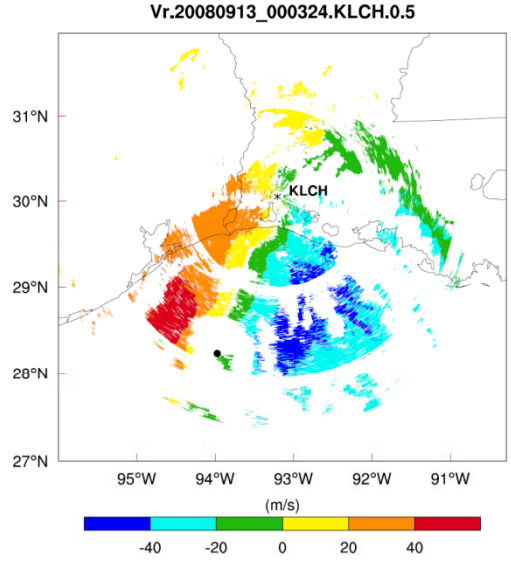
Hybrid



Radar hybrid DA for hurricane





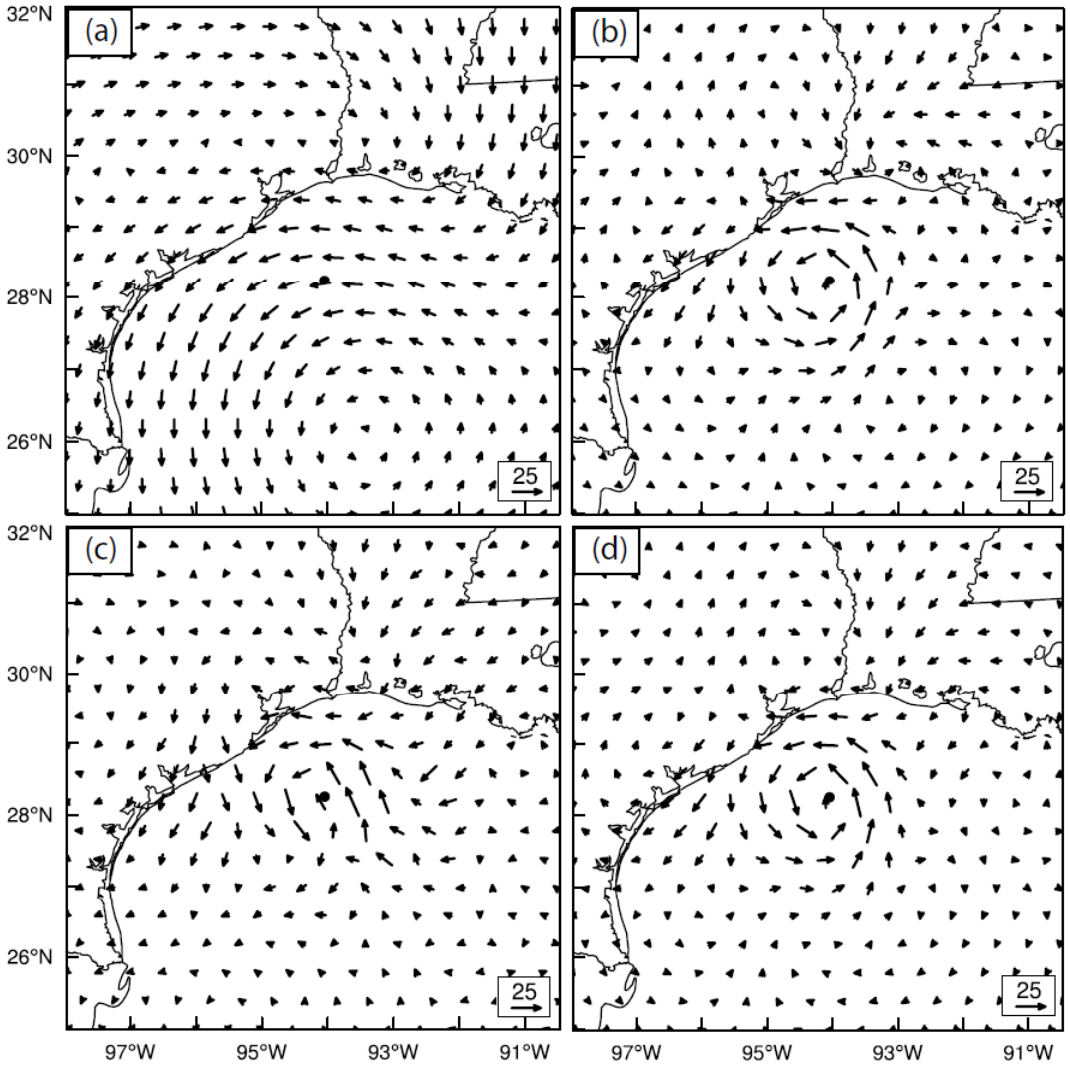


- WRF: Δx=5km
- Observations: radial velocity from two WSR88D radars (KHGX, KLCH)

Li, Wang, Xue 2011

Wind increment

3DVAR with un-tuned static covariance (3DVARa)

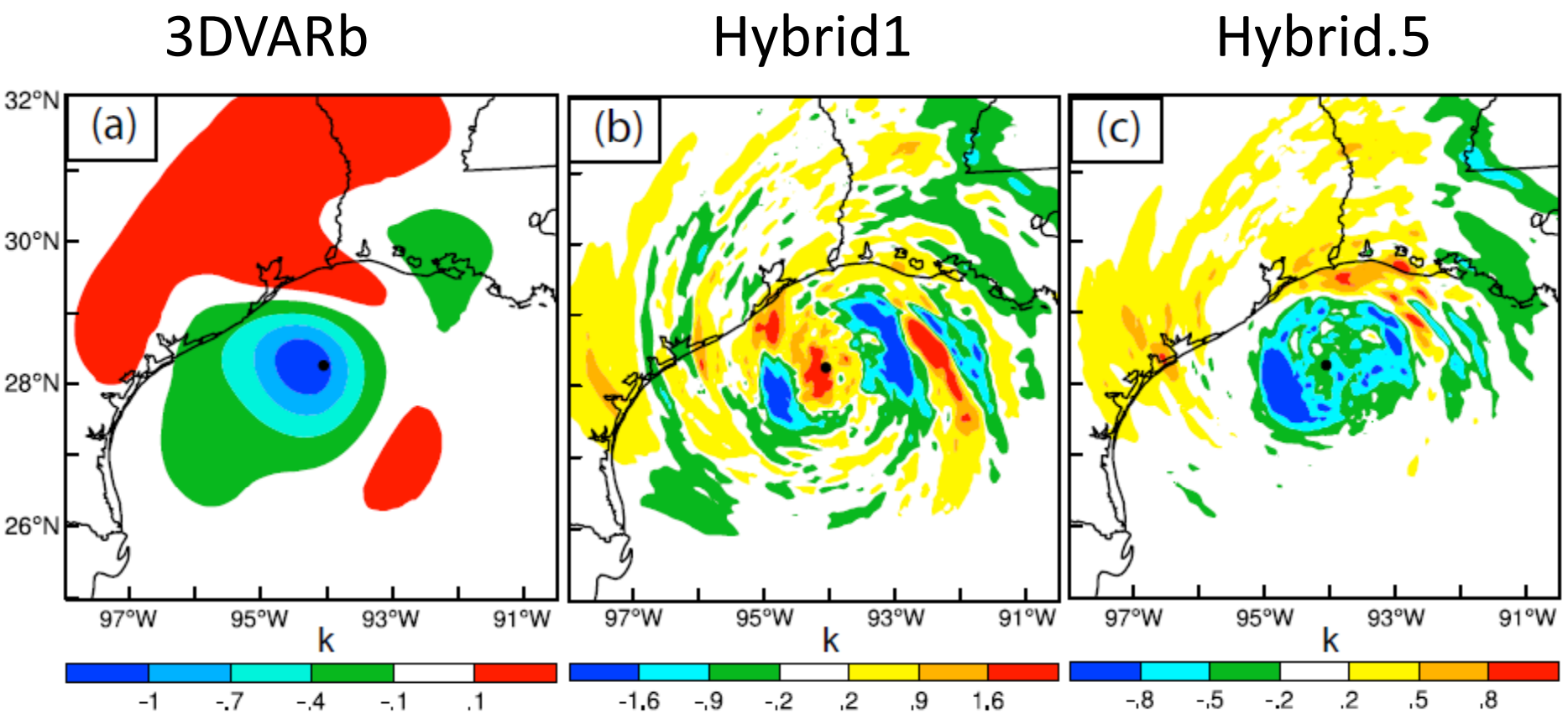


3DVAR with tuned static covariance (3DVARb)

Hybrid with full ensemble covariance (hybrid1)

Hybrid with half ensemble covariance and half static covariance (hybrid.5)

Temperature increment



Wind and pot. temperature analyses

No Radar DA

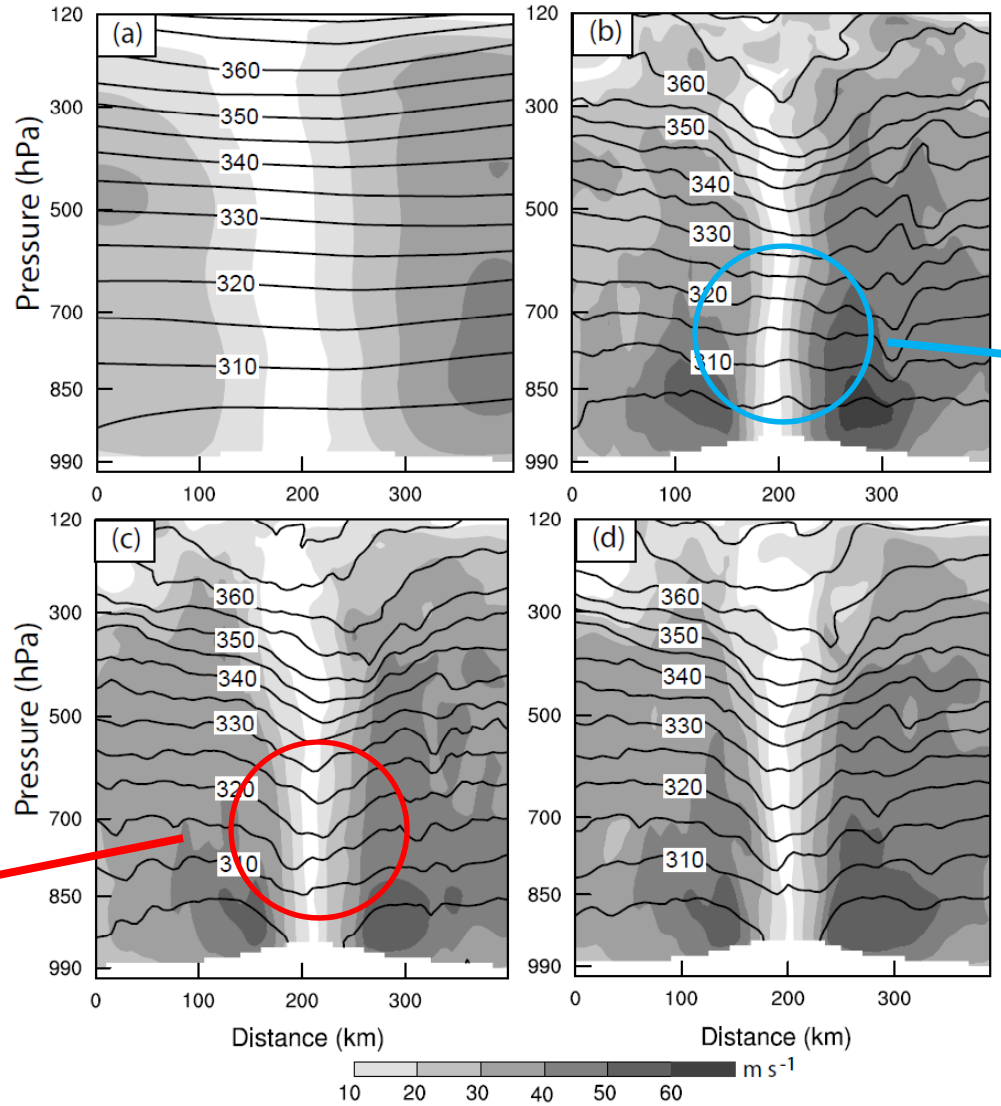
3DVARb

Hybrid1

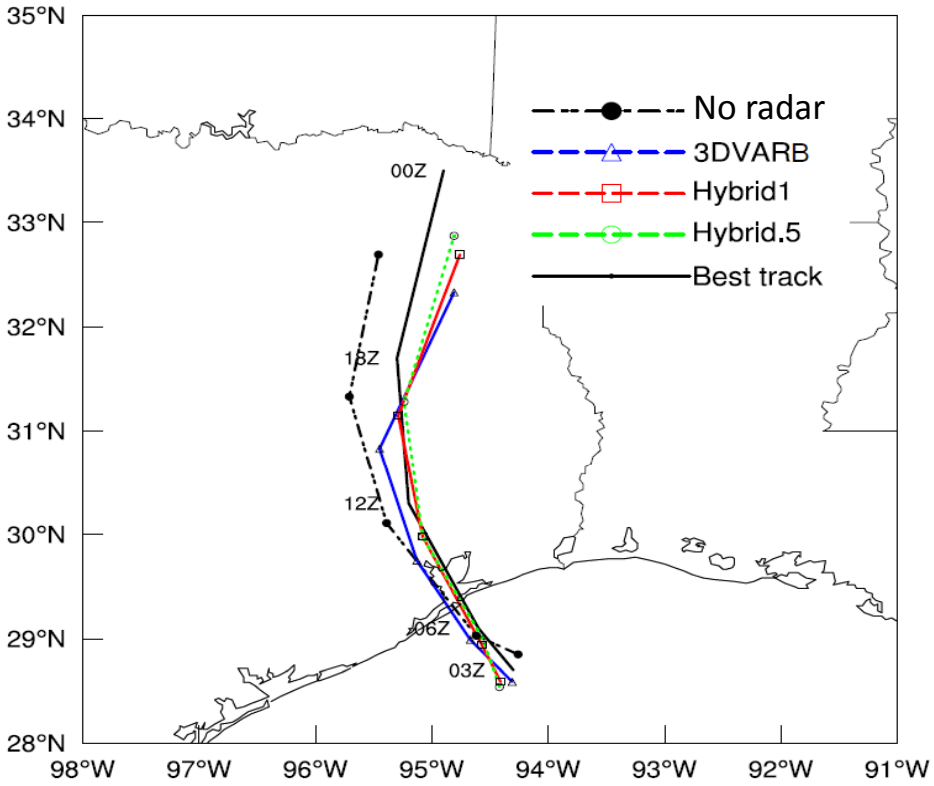
Hybrid.5

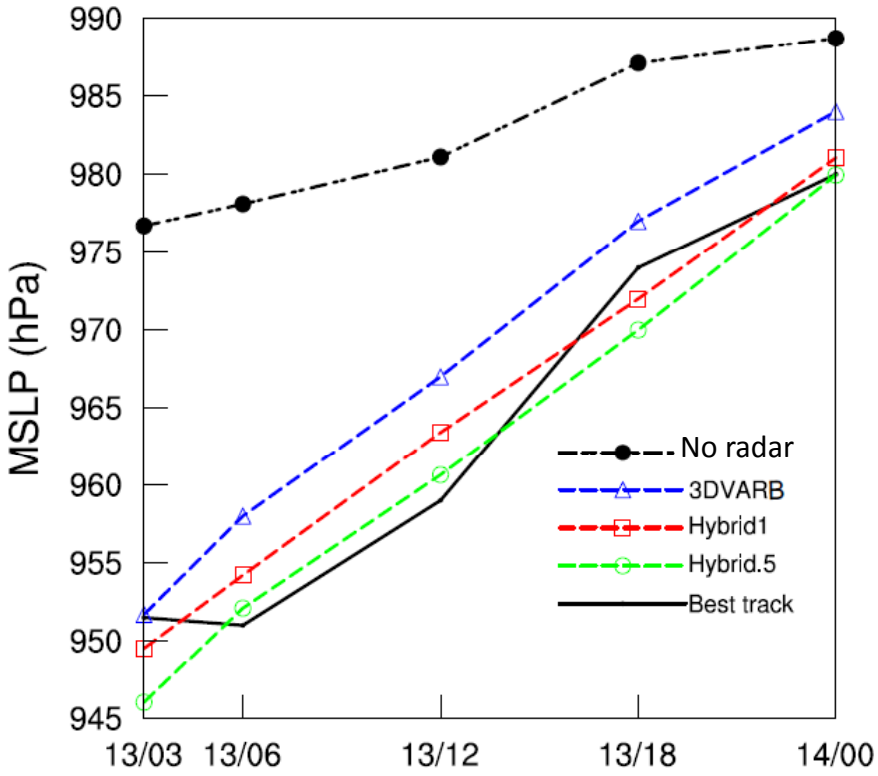
Warm core

Cold core

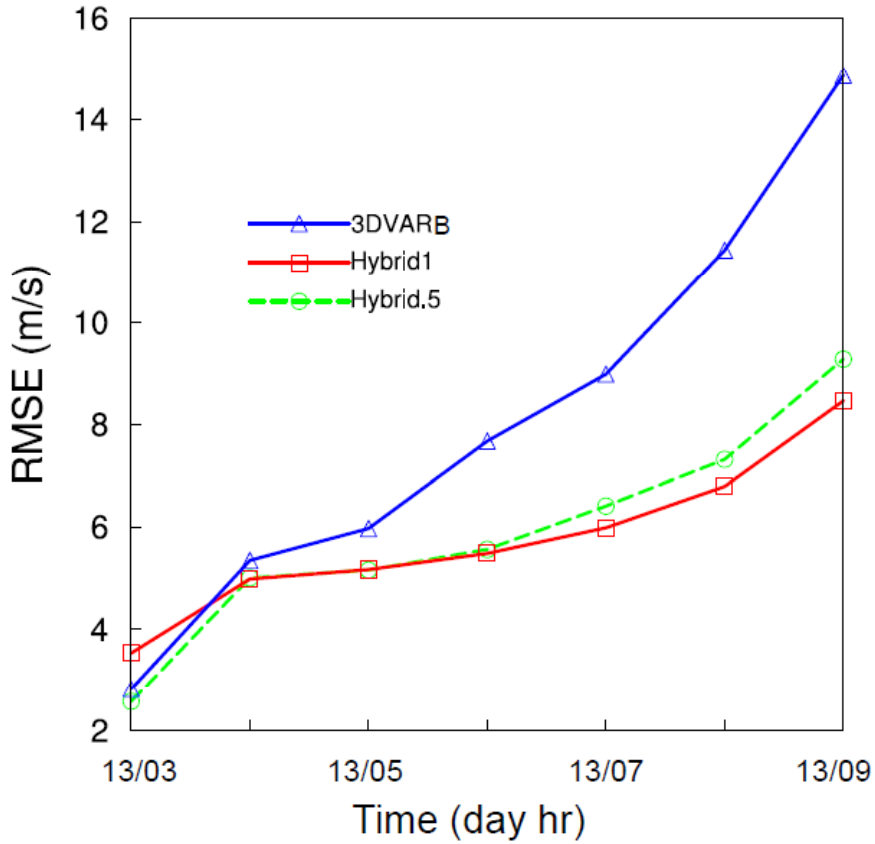


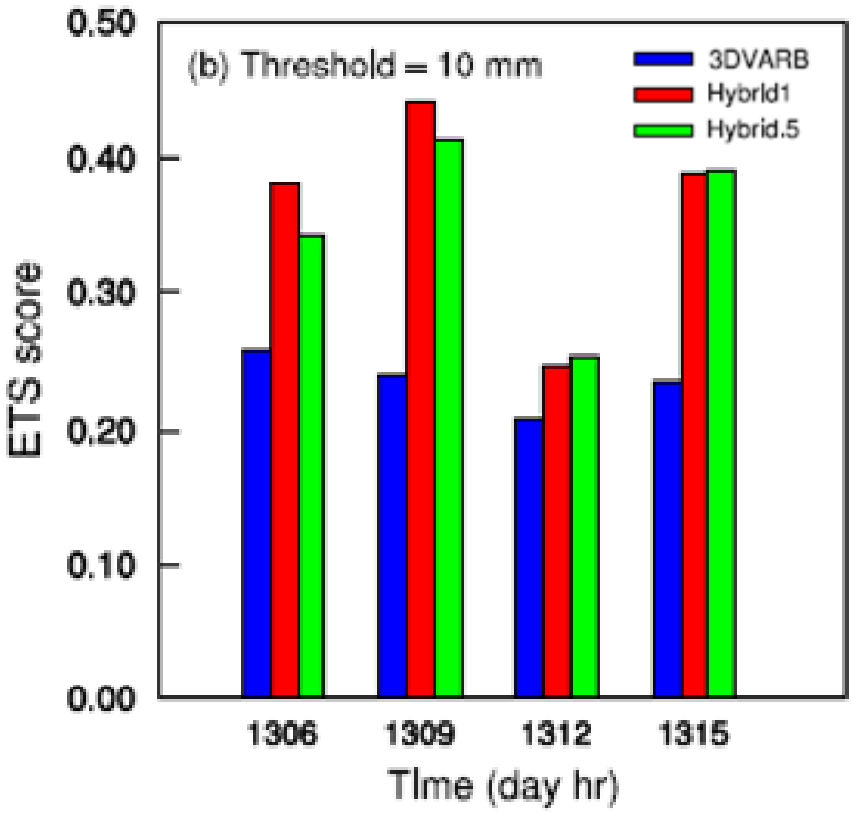
Track and intensity forecasts



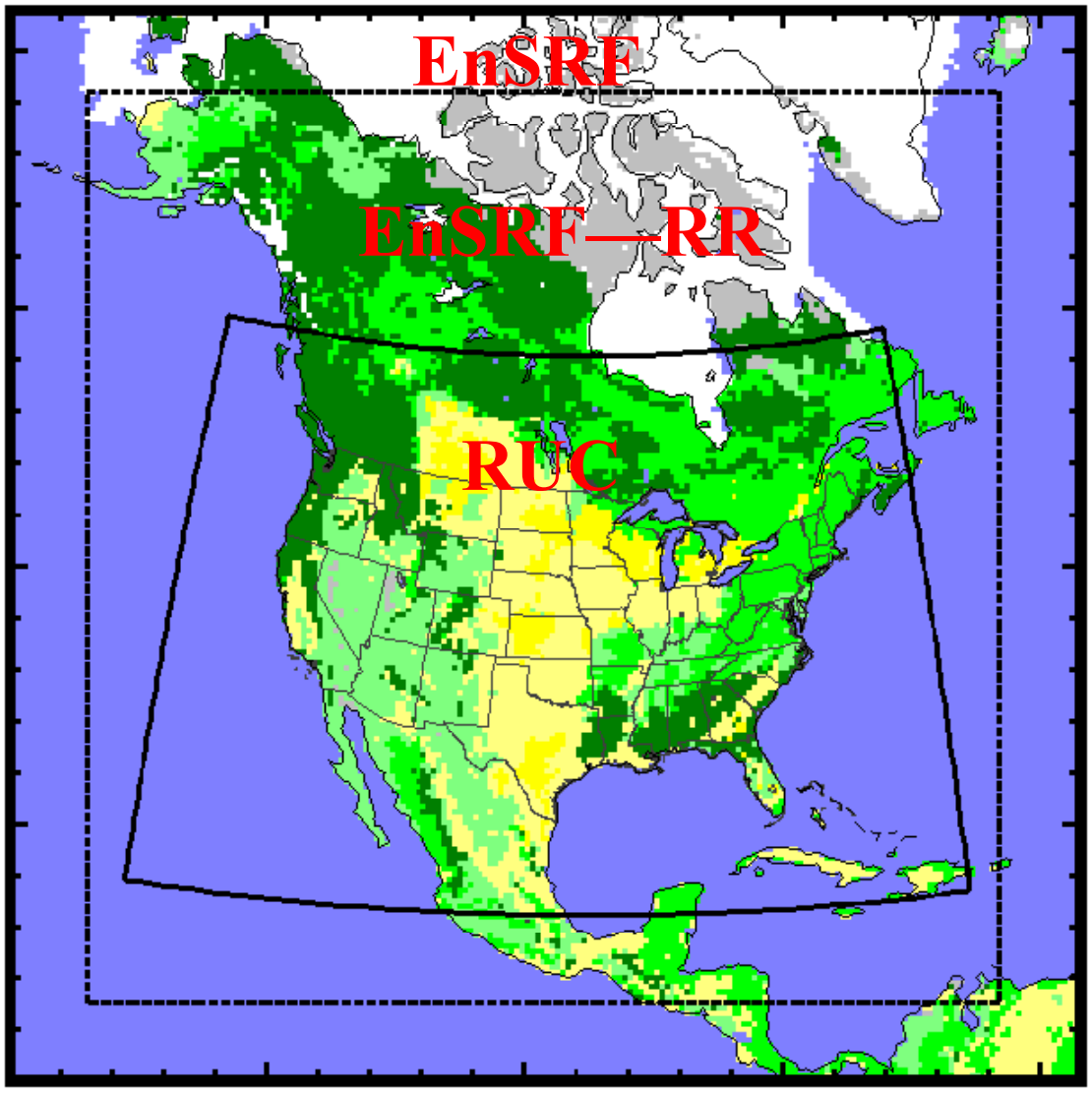


Wind and Precipitation forecasts





Integration of the global hybrid to the regional



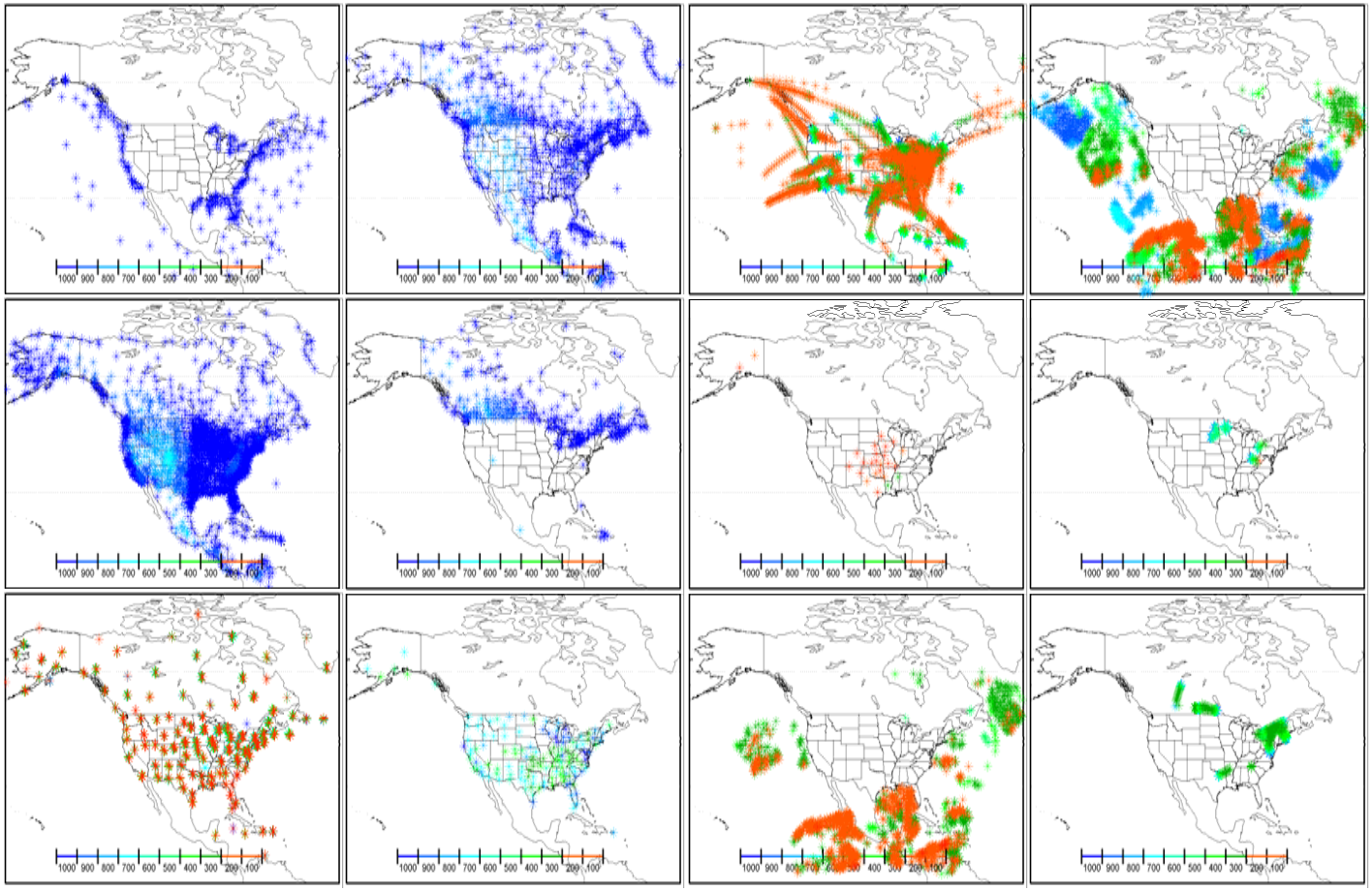
Model: WRF ARW,

Ensemble size: 40

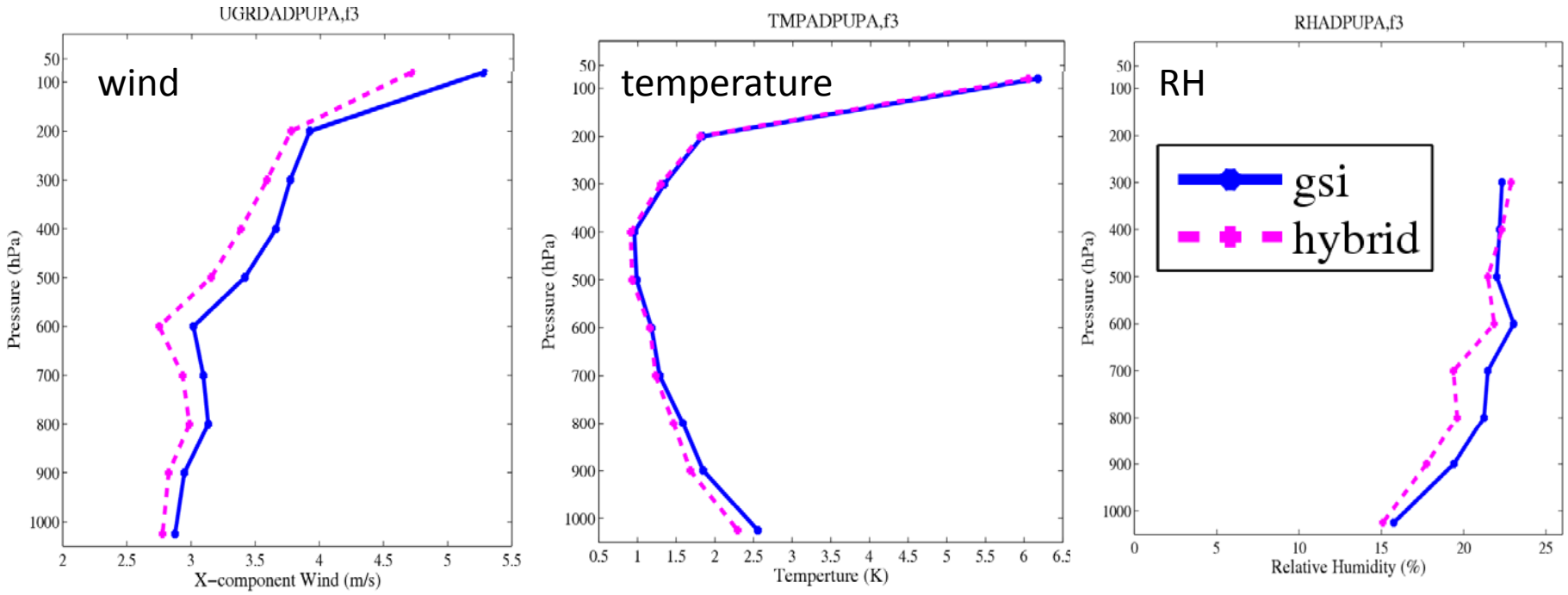
Observations: operational data except satellite radiances

May 8-16, 2010

Sample observations



Successful integration



- The global hybrid GSI-EnKF system is successfully integrated with the regional WRF ARW model for operational Rapid Refresh system.
- Experience gained will help conduct the same integration for HWRF!

Summary

- Ensemble-4DVAR (no tangent linear and adjoint needed) was developed for GSI and tested for GFS. Ensemble-4DVAR further improved upon the ENS3DVAR hybrid for TC track forecasts. Balance constraint in GSI hurt TC forecasts using hybrid.

- Diagnostic study revealed why hybrid could be better than 3DVAR in TC track forecast: environment + TC.

- The hybrid was also implemented for high resolution radar data assimilation for TC forecast and showed improvement over 3DVAR.

- The global hybrid system was successfully integrated with the regional WRF ARW model for operational RR system.

- Ongoing work:
  - Further improve the algorithm of hybrid GSI-EnKF
  - Test ENS4DVAR for operational resolution
  - Further integration and application of hybrid for regional applications
  - Etc.

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