Hybrid 4D EnVar for the NCEP GFS: Progress towards operational implementation

Daryl Kleist

Univ. of Maryland-College Park, Dept. of Atmos. & Oceanic Science

with acknowledgements to Dave Parrish, Jeff Whitaker, John Derber, Russ Treadon, Wan-shu Wu, Kayo Ide, and many others

Central Weather Bureau, Taipei, Taiwan – 5 November 2014

Outline

- 3D Hybrid Summary
- 2014 GFS Implementation
  - T1534 L64 Semi-Lagrangian GFS
  - Stochastic Physics
- 4D-Ensemble-Var
- Implementation plans

Hybrid Variational-Ensemble

- Incorporate ensemble perturbations directly into variational cost function through extended control variable
  - Lorenc (2003), Buehner (2005), Wang (2010), etc.

$$J(\mathbf{x}_f', \boldsymbol{\alpha}) = \beta_f \frac{1}{2}(\mathbf{x}_f')^T \mathbf{B}_f^{-1}(\mathbf{x}_f') + \beta_e \frac{1}{2}\sum_{n=1}^{N}(\boldsymbol{\alpha}^n)^T \mathbf{L}^{-1}(\boldsymbol{\alpha}^n) + \frac{1}{2}(\mathbf{H}\mathbf{x}_t' - \mathbf{y}')^T \mathbf{R}^{-1}(\mathbf{H}\mathbf{x}_t' - \mathbf{y}')$$

$$\mathbf{x}_t' = \mathbf{x}_f' + \sum_{n=1}^{N}(\boldsymbol{\alpha}^n \circ \mathbf{x}_e^n)$$

β_f & β_e: weighting coefficients for fixed and ensemble covariance respectively

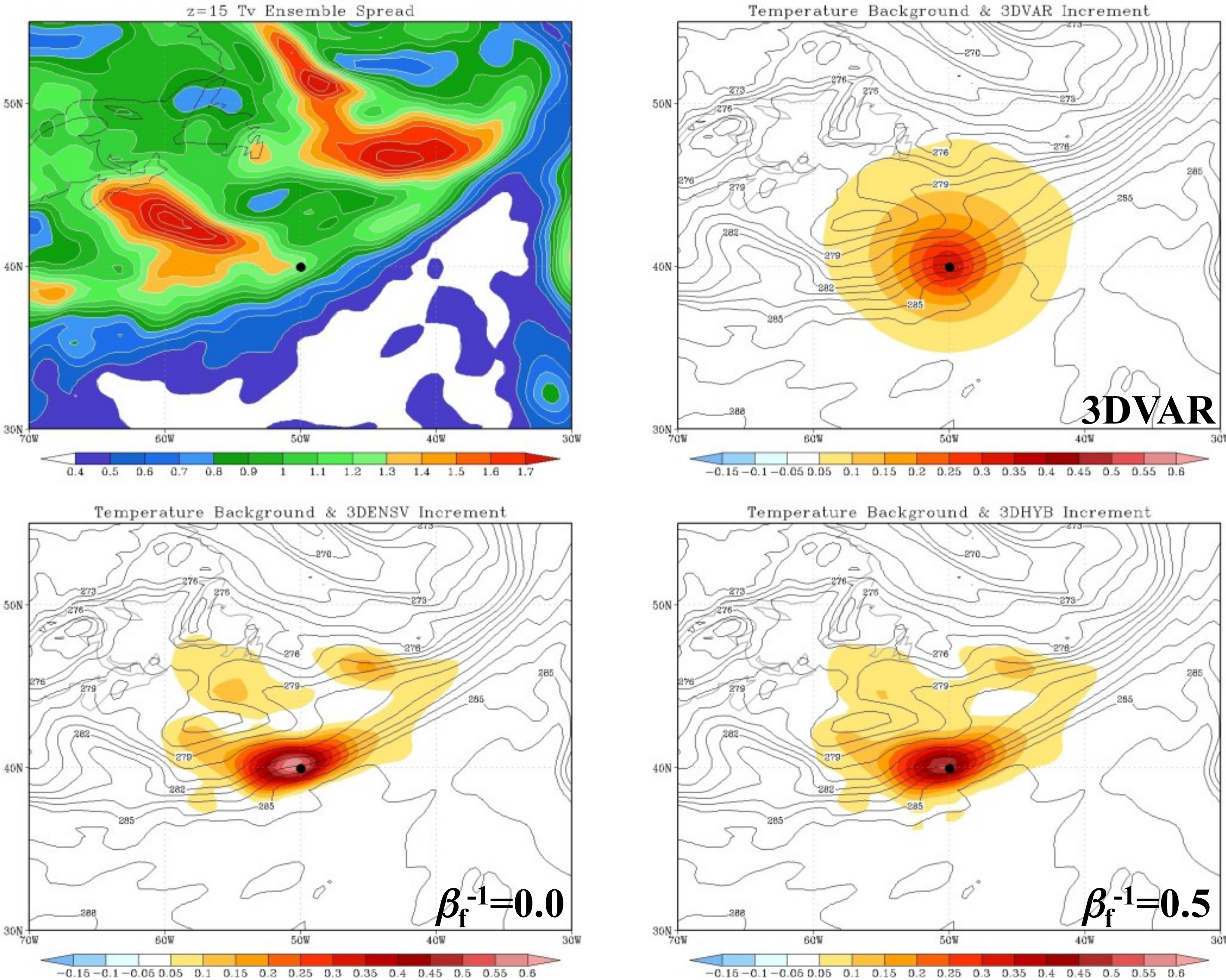
$\mathbf{x}_t'$: (total increment) sum of increment from fixed/static **B** ($\mathbf{x}_f'$) and ensemble **B**

α^n: extended control variable; $\mathbf{x}_k^e$:ensemble perturbations

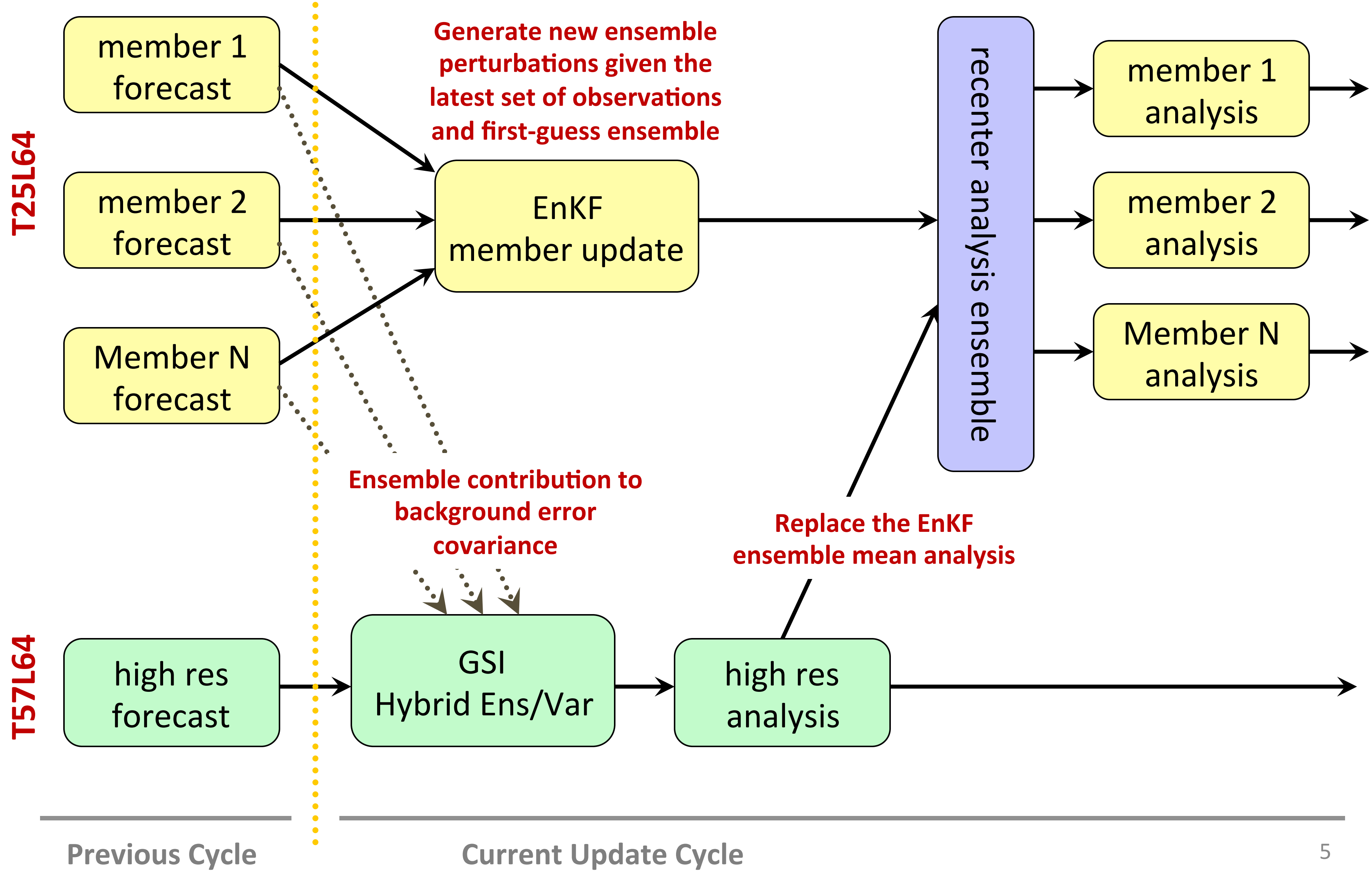
- analogous to the weights in the LETKF formulation

L: correlation matrix [effectively the localization of ensemble perturbations]

Single Temperature Observation



GDAS Operational Hybrid 3DEnVar



Global Data Assimilation System Upgrade

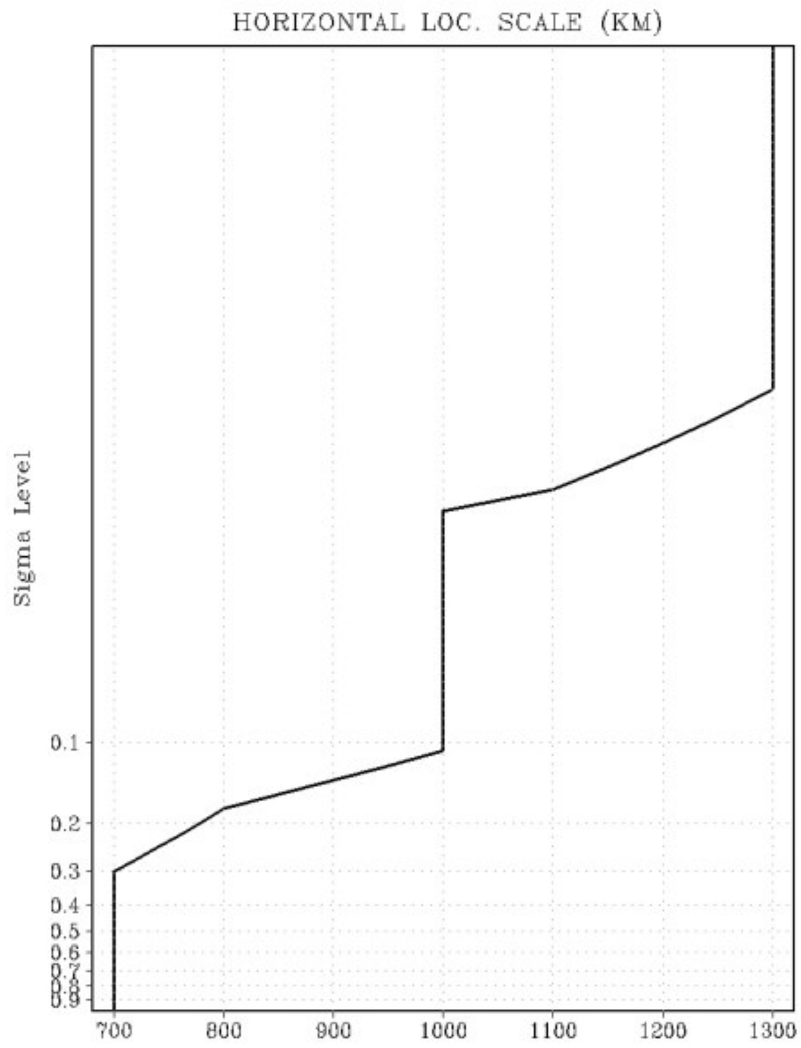
Implemented 22 May 2012

- **Hybrid system**
  - Most of the impact comes from this change
  - Uses ensemble forecasts to help define background error
- **NPP (ATMS) assimilated**
  - Quick use of data after launch
- **Use of GPSRO Bending Angle rather than refractivity**
  - Allows use of more data (especially higher in atmos.)
  - Small positive impacts
- **Satellite radiance monitoring code**
  - Allows quicker awareness of problems (run every cycle)
  - Monitoring software can automatically detect many problems
- **Post changes**
  - Additional fields requested by forecasters (80m variables)
- **Partnership between research and operations**

Operational Configuration

- Full **B** preconditioned double conjugate gradient minimization
- Spectral filter for horizontal part of **L**
  - Eventually replace with (anisotropic) recursive filters
- Recursive filter used for vertical
  - 0.5 scale heights
- Same localization used in Hybrid (**L**) and EnSRF
- TLNMC (Kleist et al. 2009) applied to total analysis increment*

$$\mathbf{x}_t' = \mathbf{C}\left[\mathbf{x}_f' + \sum_{n=1}^{N}\left(\boldsymbol{\alpha}^n \circ \mathbf{x}_e{}^n\right)\right]$$



Hybrid Impact in Pre-implementation Tests (to appear in BAMS article)

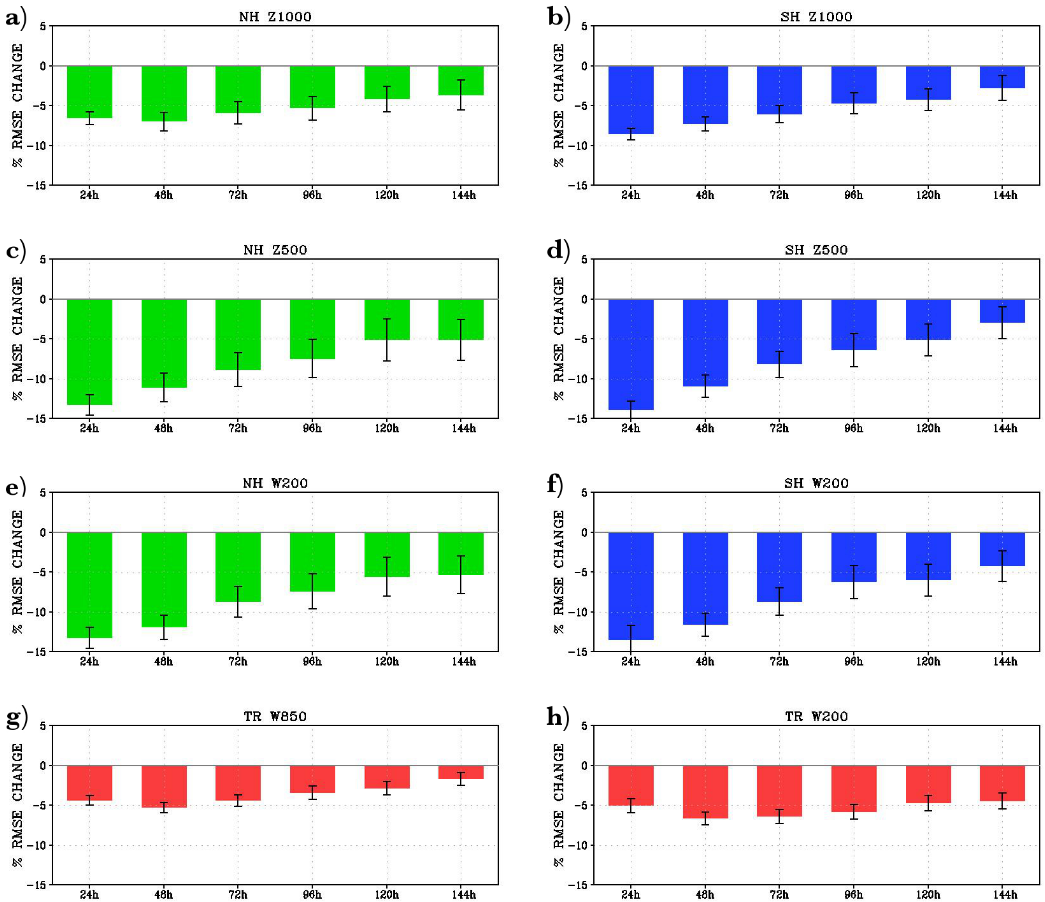


Figure 01: Percent change in root mean square error from the experimental GFS minus the operational GFS for the period covering 01 February 2012 through 15 May 2012 in the northern hemisphere (green), southern hemisphere (blue), and tropics (red) for selected variables as a function of forecast lead time. The forecast variables include 1000 hPa geopotential height (a, b), 500 hPa geopotential eight (c, d), 200 hPa vector wind (e, f, h), and 850 vector wind (g). All verification is performed using self-analysis. The error bars represent the 95% confidence threshold for a significance test.

Hybrid Impact in Pre-implementation Tests (to appear in BAMS article)

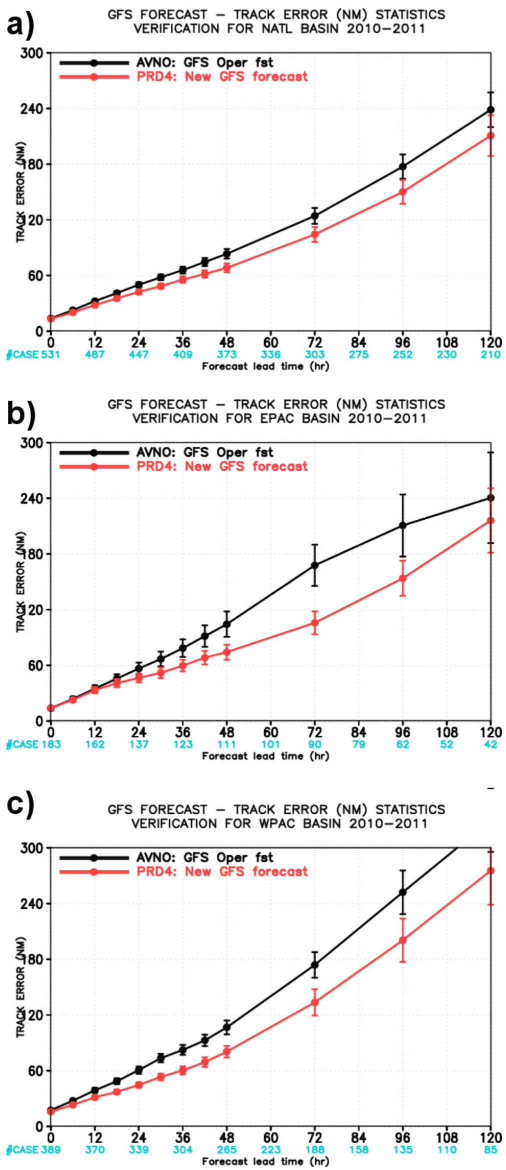


Figure 02: Mean tropical cyclone track errors (nautical miles) covering the 2010 and 2011 hurricane seasons for the operational GFS (black) and experimental GFS including hybrid data assimilation (red) for the a) Atlantic basin, b) eastern Pacific basin, and c) western Pacific basin. The number of cases is specified by the blue numbers along the abscissa. Error bars indicate the 5th and 95th percentiles of a resampled block bootstrap distribution.

Outline

- 3D Hybrid Summary
- 2014 GFS Implementation
  - T1534 L64 (~13km) Semi-Lagrangian GFS
  - Stochastic Physics
- 4D-Ensemble-Var
- Implementation plans

Implementation Overview

- This upgrade is planned for December 9, 2014
- System description
  - This is a change to the GDAS and GFS.
- What's being changed in the system
  - Analysis
  - Model
    - T1534 (to 10 days) Semi-Lagrangian
    - Use of high resolution daily SST and sea ice analysis
    - Physics
    - Land Surface
  - Post Processor
- Expected benefits to end users associated with upgrade
  - Upgrade in global modeling capability.
  - Improvement in forecast skill
- This implementation will put GFS/GDAS into EE process.

Analysis Highlights

- Structure
  - T574 (35 km) analysis for T1534 (13 km) deterministic
  - Code optimization
- Observations
  - GPSRO enhancements – improve quality control
  - Updates to radiance assimilation
    - Assimilate SSM/IS UPP LAS and MetOp-B IASI radiances
    - CRTM v2.1.3
    - New enhanced radiance bias correction scheme
    - Additional satellite wind data – hourly GOES, EUMETSAT
- **EnKF modifications**
  - **Stochastic physics in ensemble forecast**
  - **T574L64 EnKF ensembles**

Model Highlights (1)

- T1534 Semi-Lagrangian (~13 km)
- Use of high resolution daily SST and sea ice analysis
- High resolution until 10 days
- Dynamics and structure upgrades
  - Hermite interpolation in the vertical to reduce stratospheric temperature cold bias.
  - Restructured physics and dynamics restart fields and updated sigio library
  - Divergence damping in the stratosphere to reduce noise
  - Added a tracer fixer for maintaining global column ozone mass
  - Major effort to make code reproducible

Model Highlights (2)

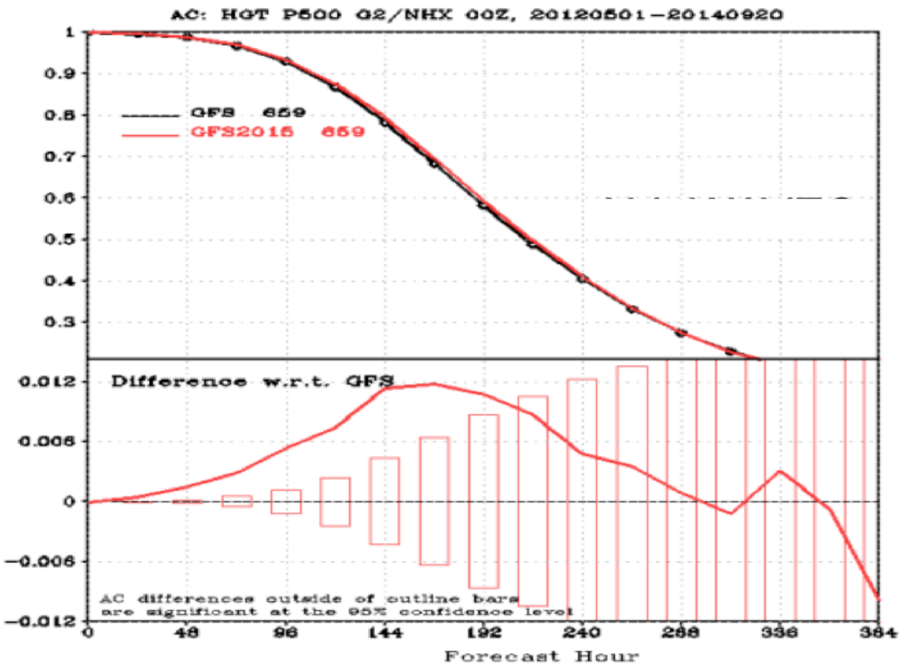
- Physics upgrades
  - Radiation modifications -- McICA
  - Reduced drag coefficient at high wind speeds
  - Hybrid EDMF PBL scheme and TKE dissipative heating
  - Retuned ice and water cloud conversion rates, background diffusion of momentum and heat, orographic gravity-wave forcing and mountain block etc
  - Stationary convective gravity wave drag
  - Modified initialization to reduce a sharp decrease in cloud water in the first model time step
  - Correct a bug in the condensation calculation after the digital filter is applied

Model Highlights (3)

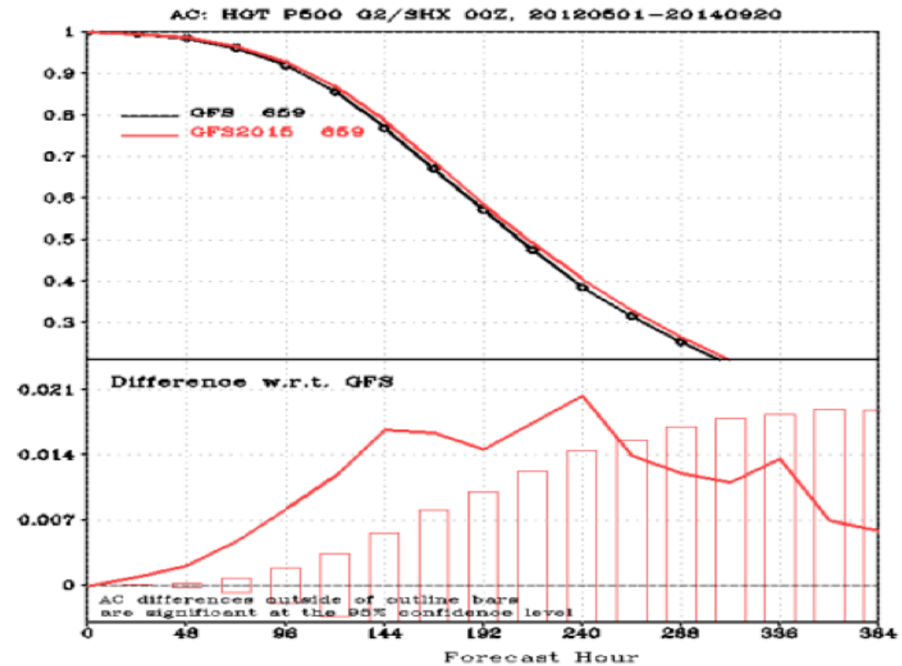
- Boundary condition input and output upgrades
  - Consistent diagnosis of snow accumulation in post and model
  - Compute and output frozen precipitation fraction
  - New blended snow analysis to reduce reliance on AFWA snow
  - Changes to treatment of lake ice to remove unfrozen lake in winter
  - Land Surface
    - Replace Bucket soil moisture climatology by CFS/GLDAS
    - Add the vegetation dependence to the ratio of the thermal and momentum roughness, Fixed a momentum roughness issue

500 hPa Die Off Curves
4 month sample v. Op GFS

NH

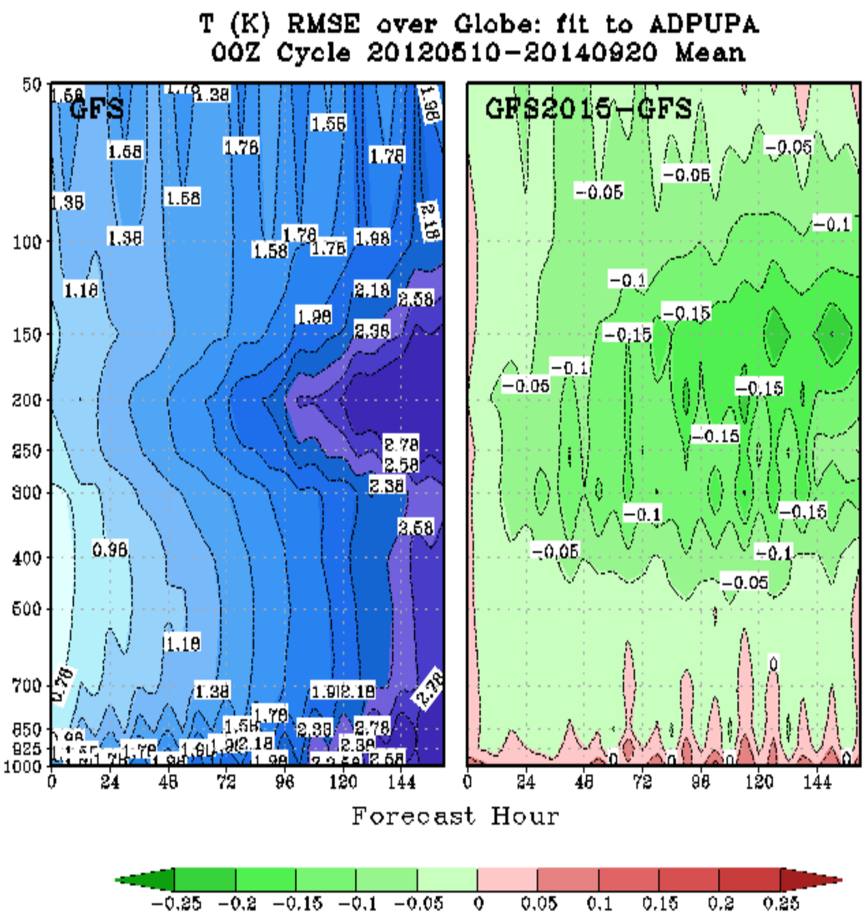


SH

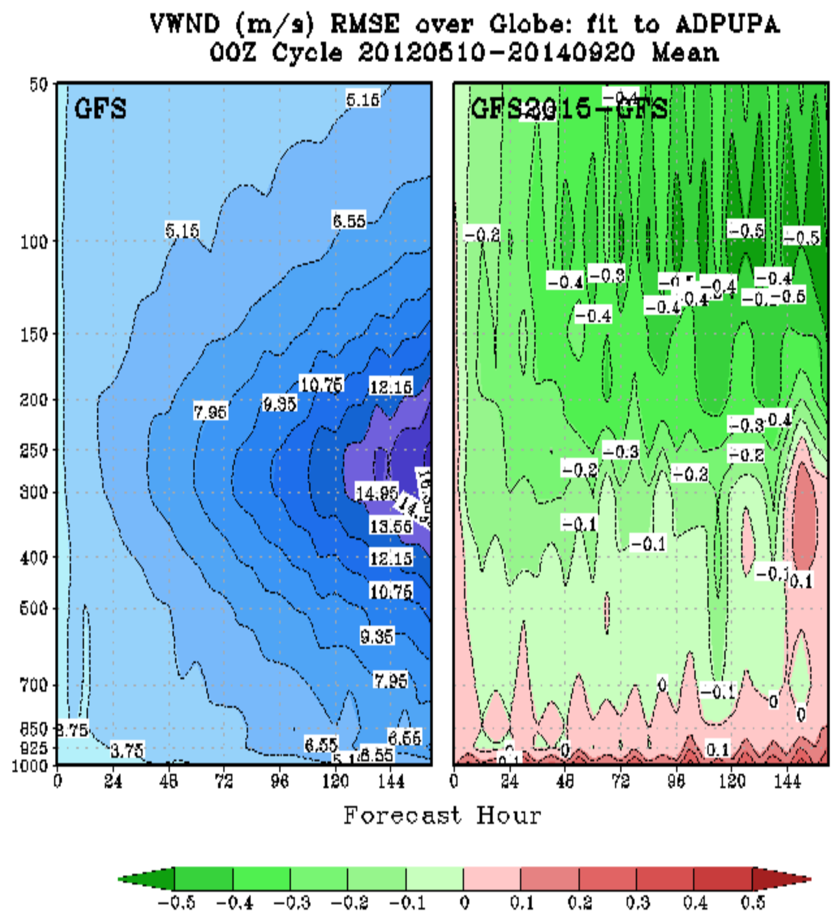


Fit to RAOBS, RMSE
Merged 2012/2013/2014

Global Mean Temperature RMSE

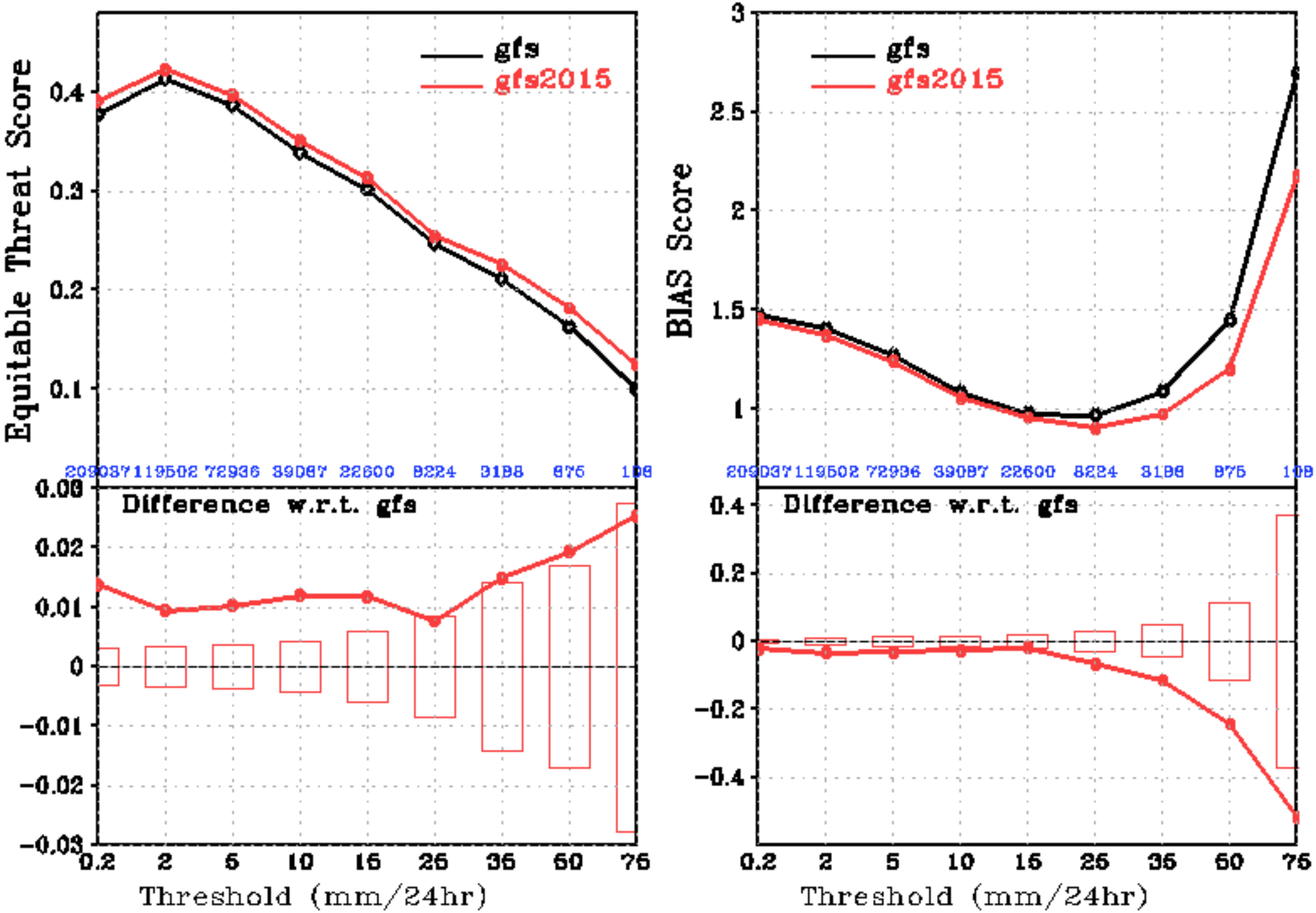


Global Mean Wind RMSE



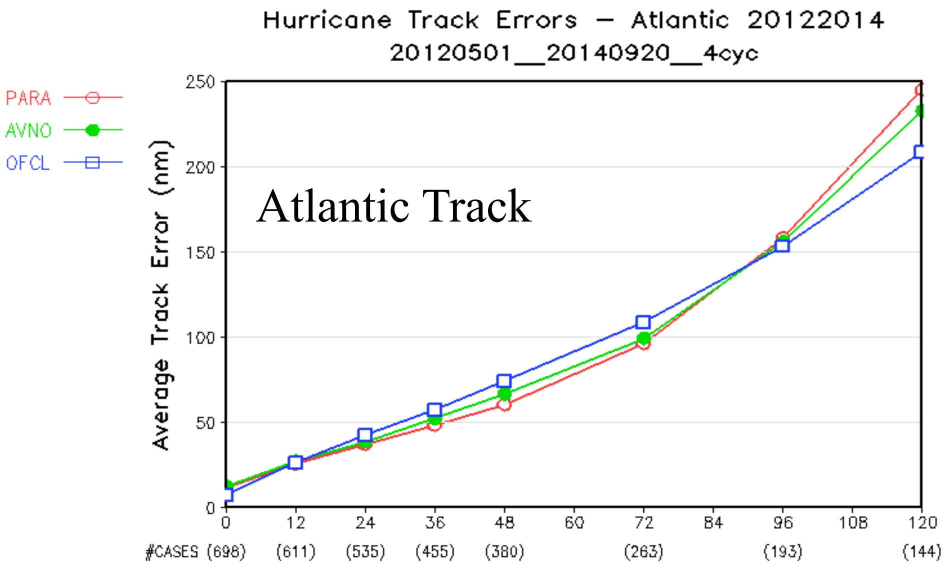
http://www.emc.ncep.noaa.gov/gmb/wx24fy/vsdb/gfs2015/g2o/index.html

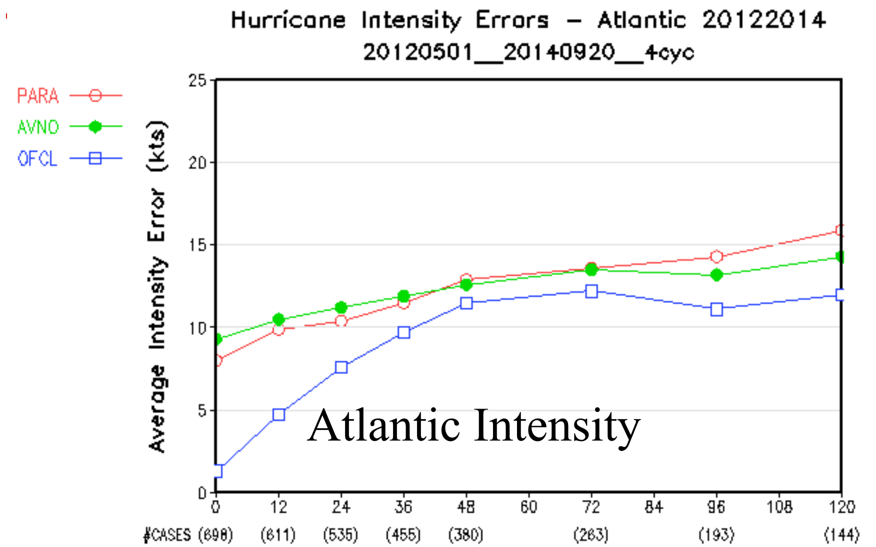
CONUS Precip Skill Scores, f00-f24, 03may2012-20sep2014 12Z Cycle

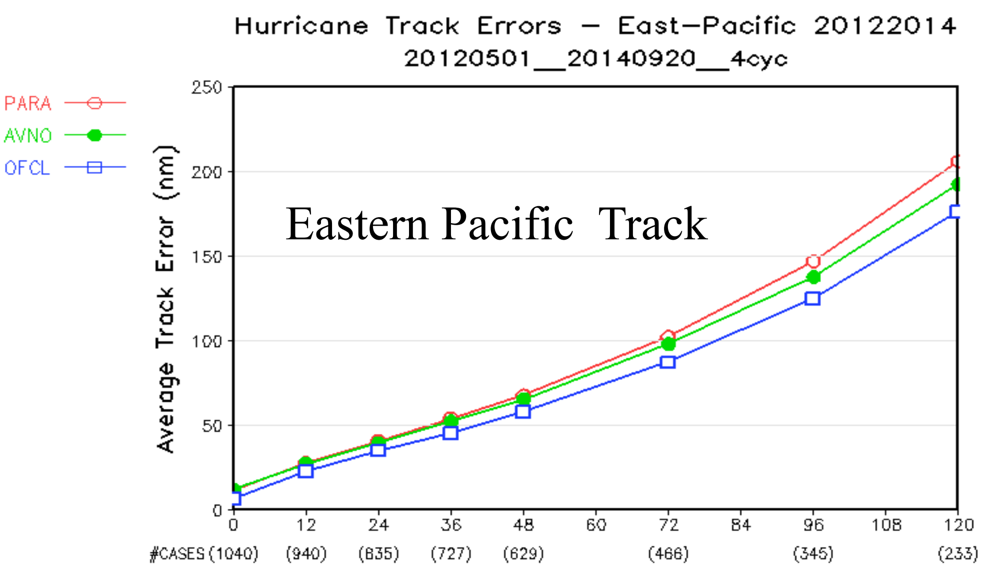


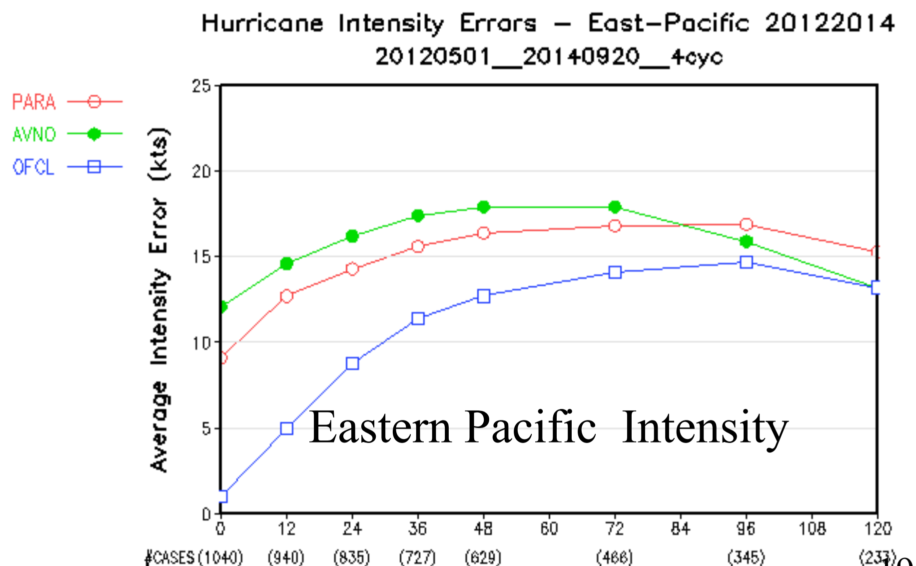
Differences outside of the hollow bars are 95% significant based on 10000 Monte Carlo Tests

Hurricane Verification 2012/2013/2014

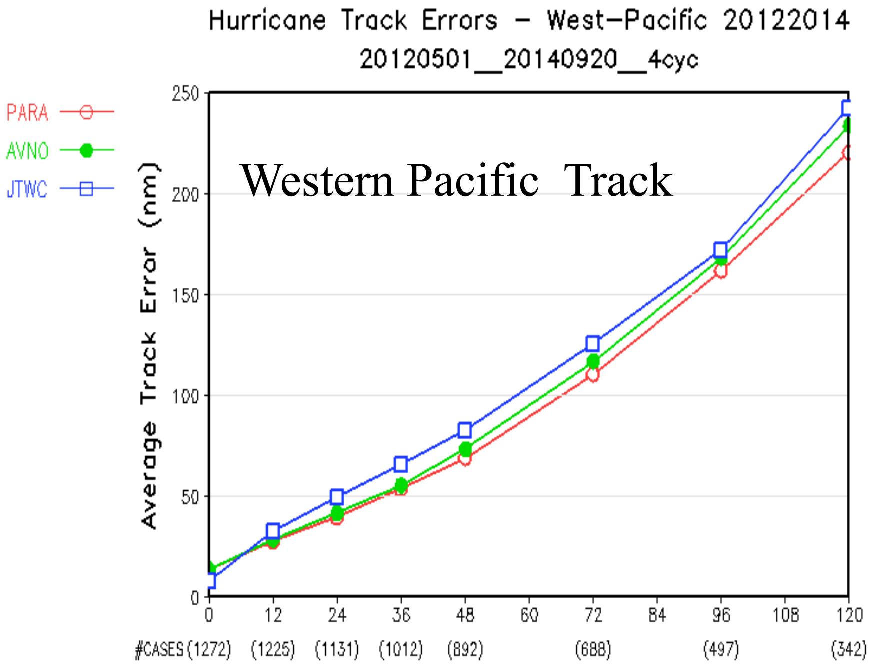


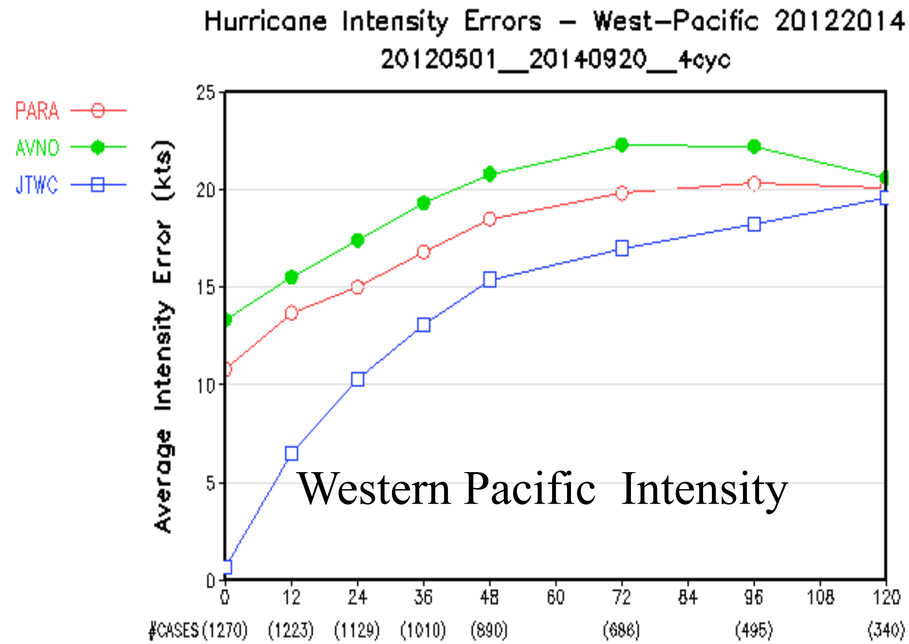






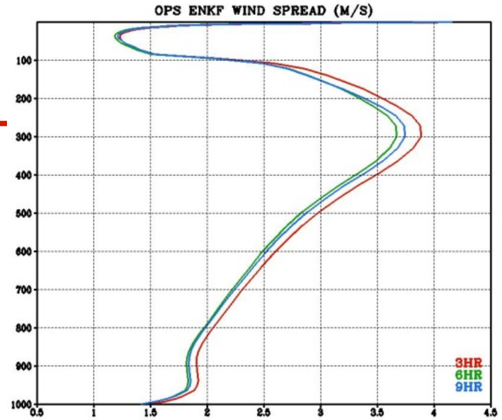
Hurricane Verification 2012/2013/2014

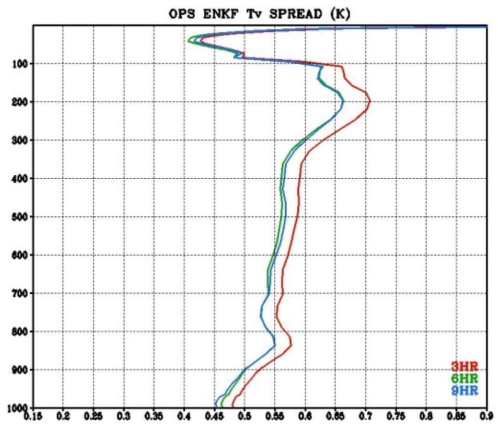


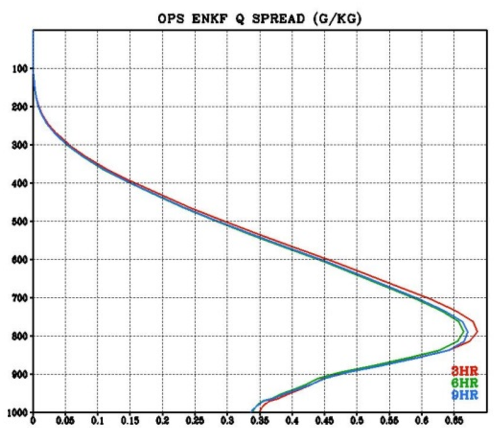


Stochastic Physics vs Additive Inflation

Spread behavior (2014042400)







3HR

6HR

9HR

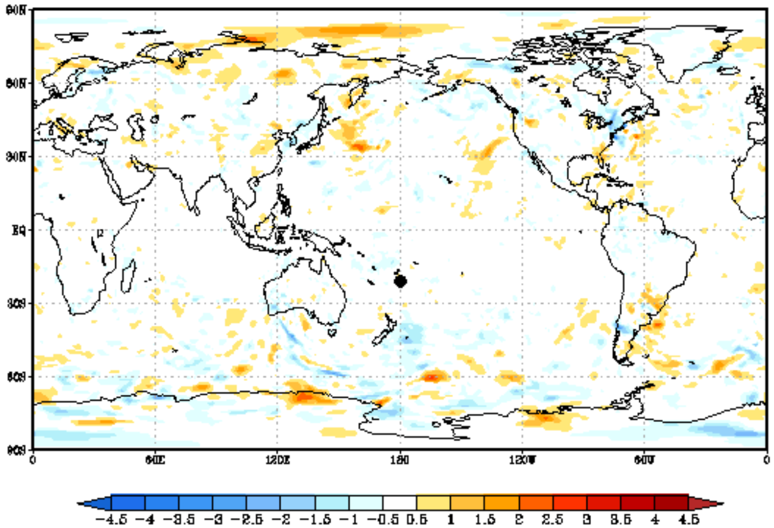
- Current operations
  - Spread too large
  - Spread decays and recovers

22

Ensemble Member 01 increments

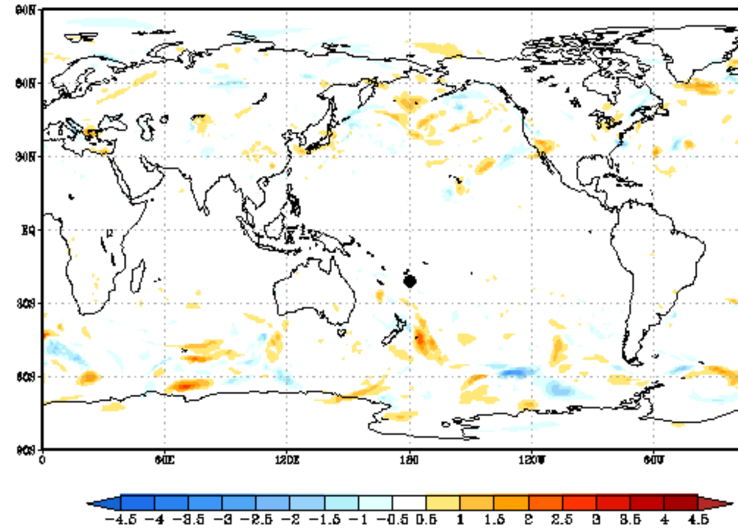
$$\delta \mathbf{x}_a^n = \delta \mathbf{x}_0^n + \delta \mathbf{x}_r + \delta \mathbf{x}_e^n$$

EnKF Tinc Mem001



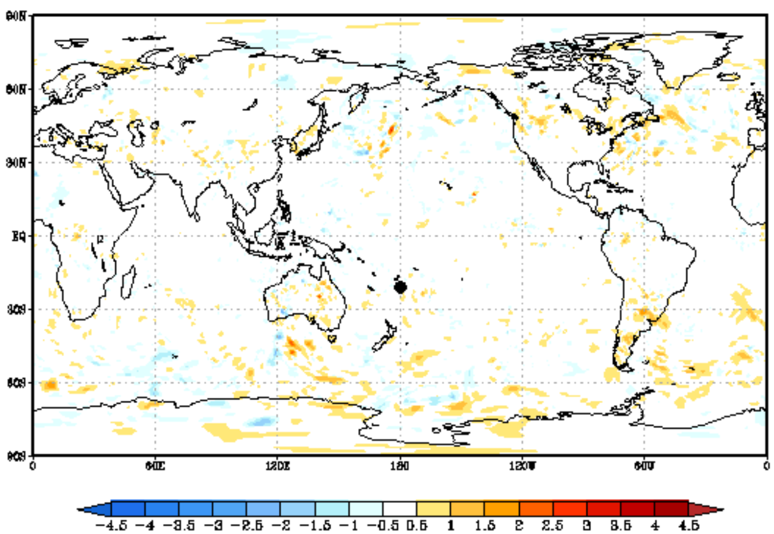
$\delta \mathbf{x}_0^n$

EnKF T Mem001 ADDInflation ONLY



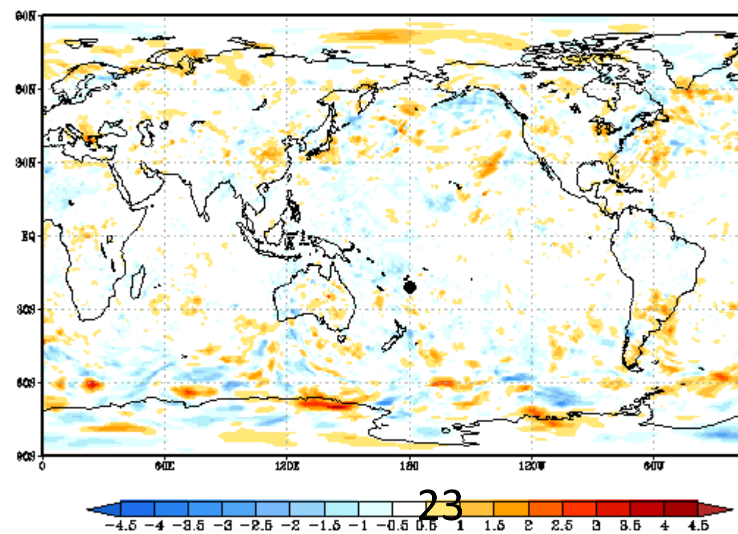
$\delta \mathbf{x}_e^n$

EnKF T Mem001 Recentering ONLY



$\delta \mathbf{x}_r$

EnKF Tinc Mem001 + ADDInflation + Recentering



$\delta \mathbf{x}_a^n$

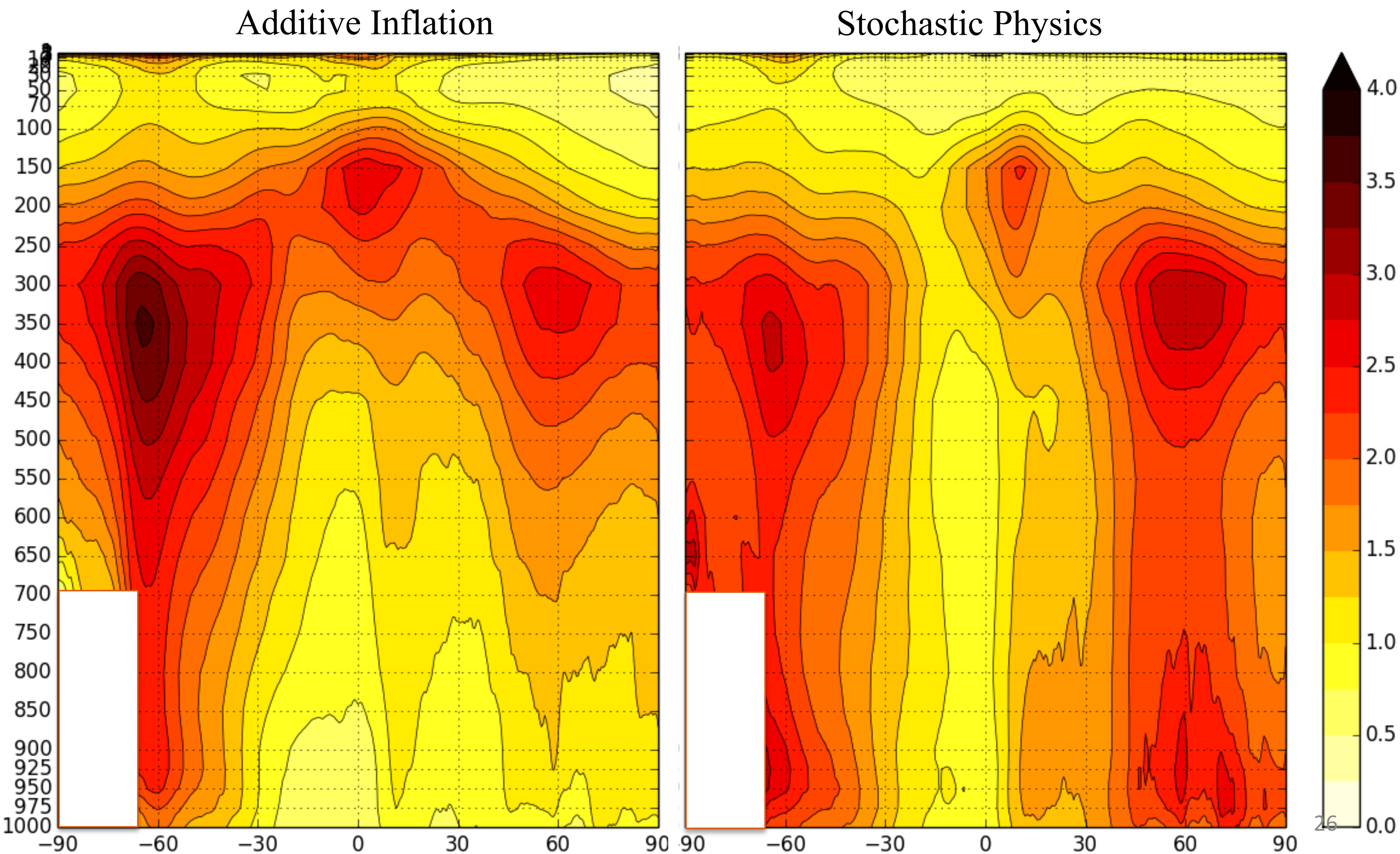
Can we replace the additive inflation by adding stochastic physics to the model?

- Schemes tested:
  - SPPT (stochastically perturbed physics tendencies – ECWMF tech memo 598)
    - *Designed to represent the structural uncertainty of parameterized physics.*
  - SHUM (perturbed boundary layer humidity, based on Tompkins and Berner 2008, *DOI: 10.1029/2007JD009284)*
    - *Designed to represent influence of sub-grid scale humidity variability on the the triggering of convection.*
  - SKEB (stochastic KE backscatter – also see tech memo 598)
  - VC (vorticity confinement, based on Sanchez et al 2012, *DOI: 10.1002/qj.1971).* Can be deterministic and/or stochastic.
    - *Both SKEB and VC aim to represent influence of unresolved or highly damped scales on resolved scales.*
- All use stochastic random pattern generators to generate spatially and temporally correlated noise.

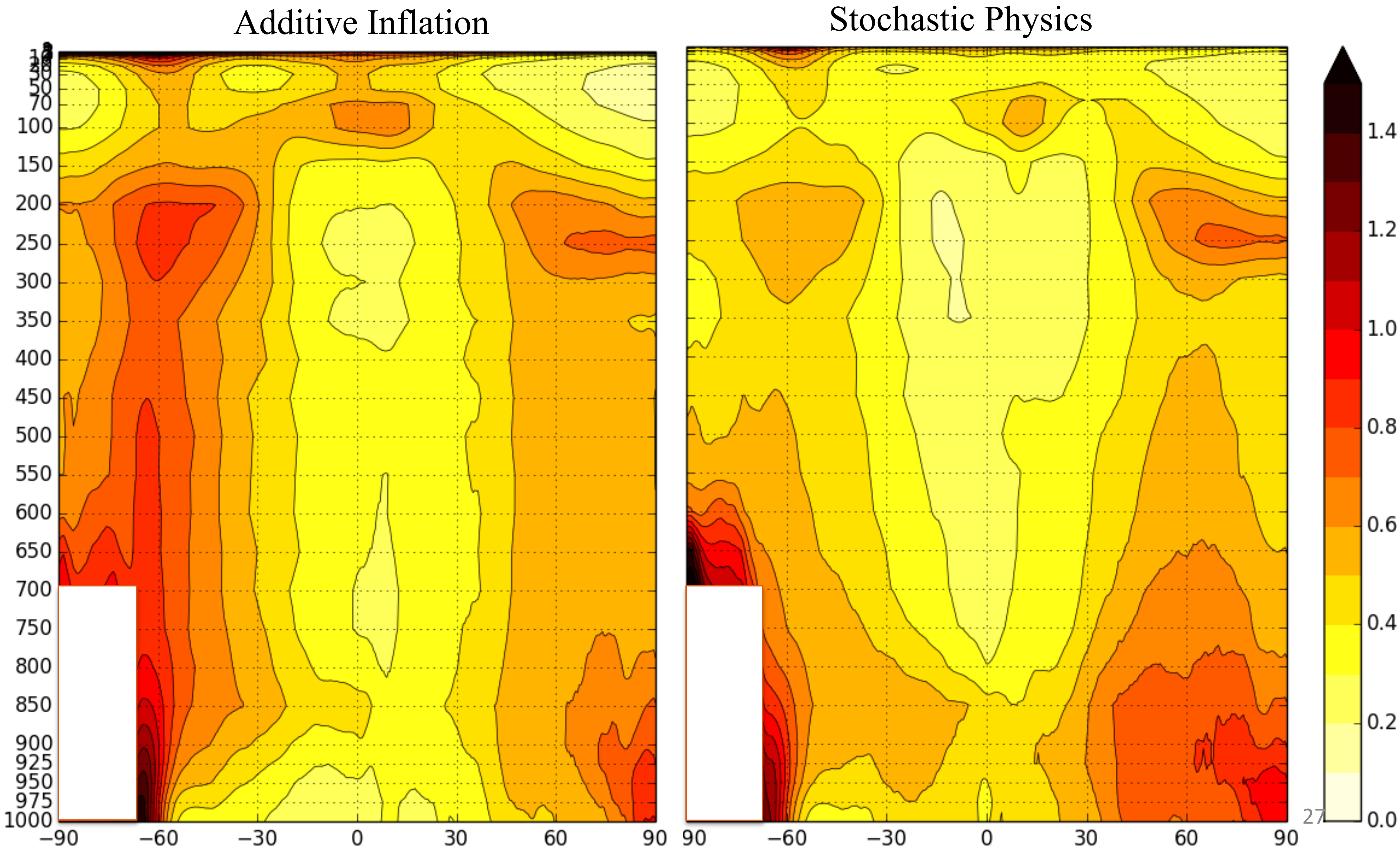
Experiments

- **Control**:
  - As in NCEP ops (using additive inflation), but using semi-lagrangian GFS with T574 ensemble.
- **Expt**:
  - Replace additive inflation with combination of SPPT, SHUM, SKEB and VC. Spatial/temporal scales of 250km/6 hrs for each (except 1000 km/6 hrs for VC). VC purely stochastic. Amplitudes set to roughly match additive inflation spread. Multiplicative inflation as in NCEP ops.
- **Period**: Sept 1 to Oct 15 2013, after 7 day spinup.

6-hr forecast spread (zonal wind)



6-hr forecast spread (temperature)

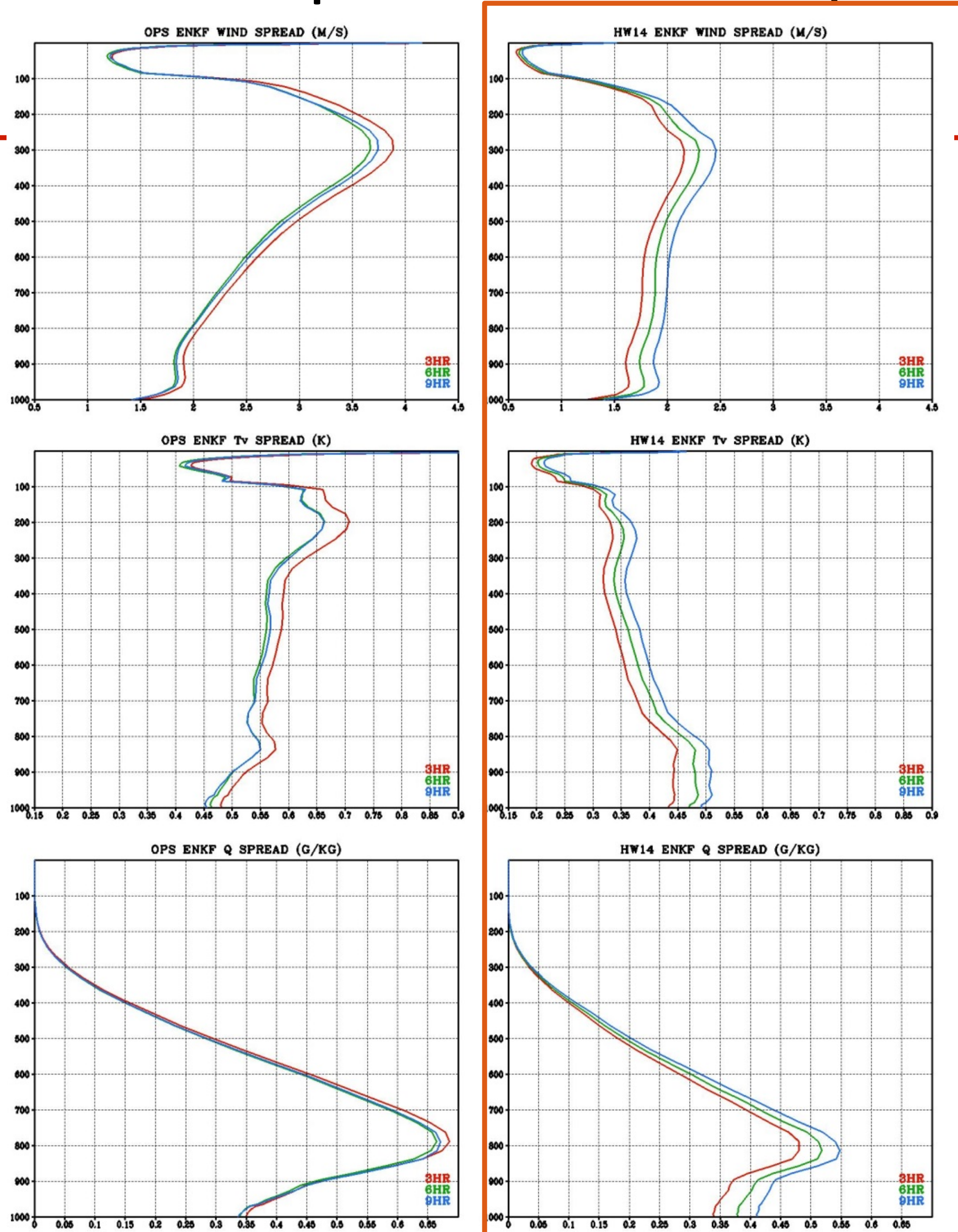


Better spread behavior (2014042400)

3HR

6HR

9HR



- Current operations
  - Spread too large
  - Spread decays and recovers
- Stochastic Physics
  - Spread decreased overall (consistent with error estimates)
  - Spread grows through assimilation

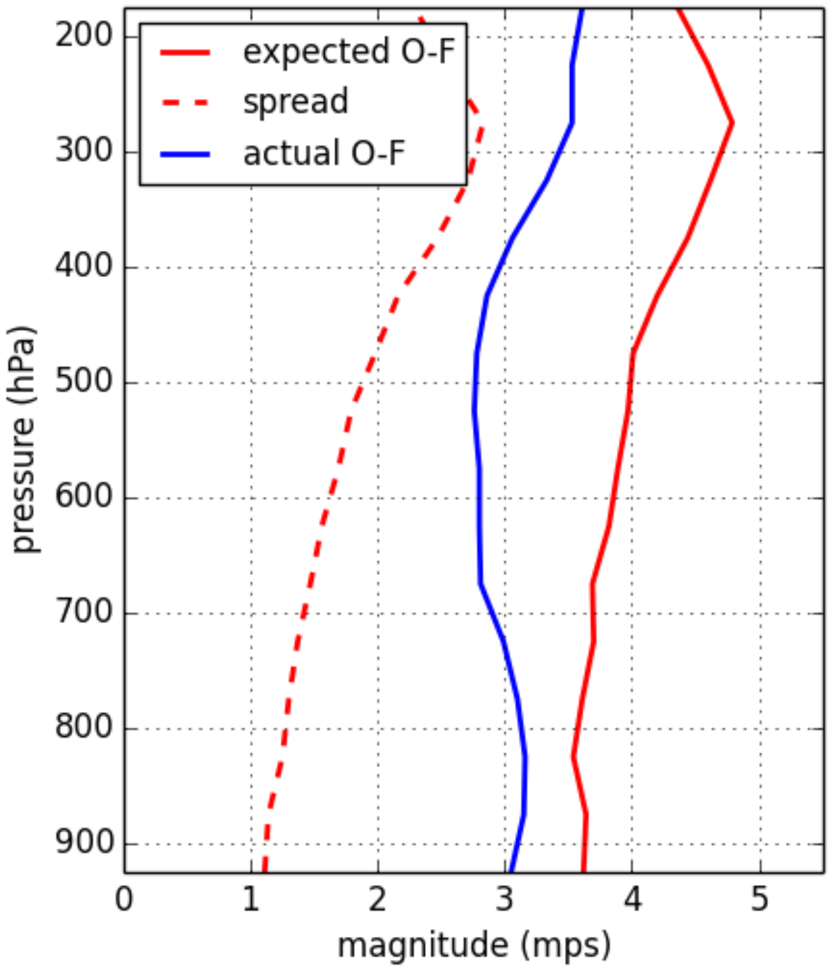
Actual vs Expected O-F std. dev. (Vector Wind)

$$E[\mathbf{d}_b^o(\mathbf{d}_b^o)^T] = E[\boldsymbol{\epsilon}^o(\boldsymbol{\epsilon}^o)^T] + \mathbf{H}E[\boldsymbol{\epsilon}^b(\boldsymbol{\epsilon}^b)^T]\mathbf{H}^T \quad \text{where} \quad \mathbf{d}_b^o = \mathbf{y}^o - H(\mathbf{x}^b)$$

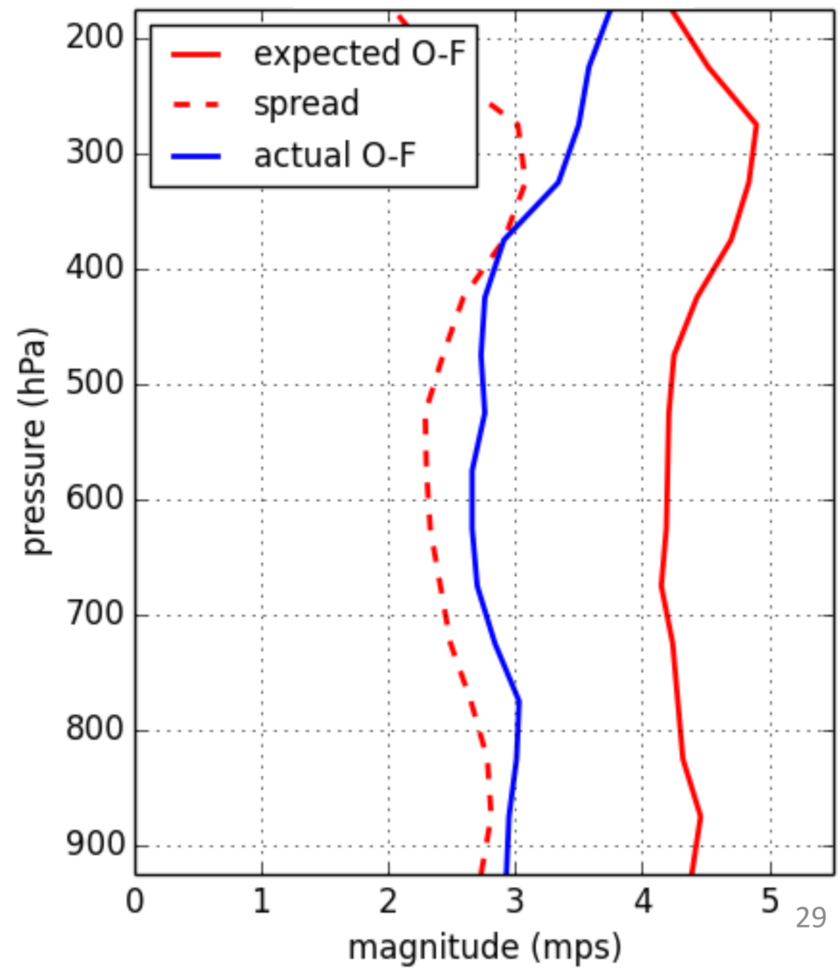
obs. error

spread

Additive Inflation



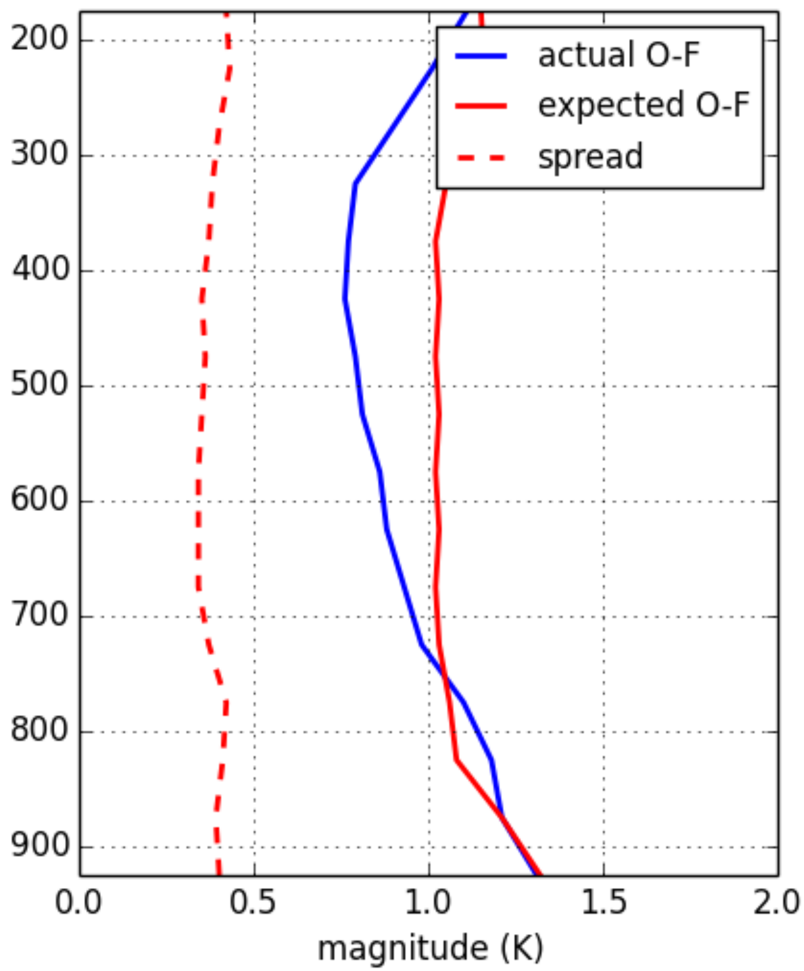
Stochastic Physics



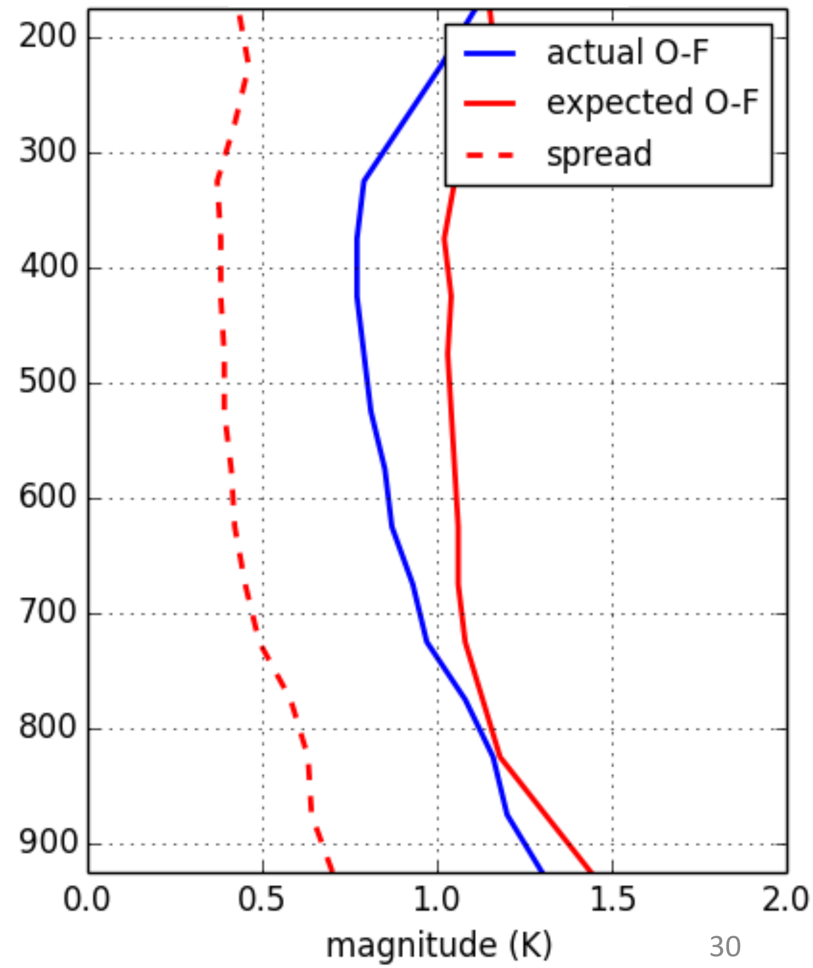
Expected vs Actual O-F std. dev. (Temp)

$$E[\mathbf{d}_b^o(\mathbf{d}_b^o)^T] = E[\boldsymbol{\epsilon}^o(\boldsymbol{\epsilon}^o)^T] + \mathbf{H}E[\boldsymbol{\epsilon}^b(\boldsymbol{\epsilon}^b)^T]\mathbf{H}^T \quad \text{where} \quad \mathbf{d}_b^o = \mathbf{y}^o - H(\mathbf{x}^b)$$

Additive Inflation



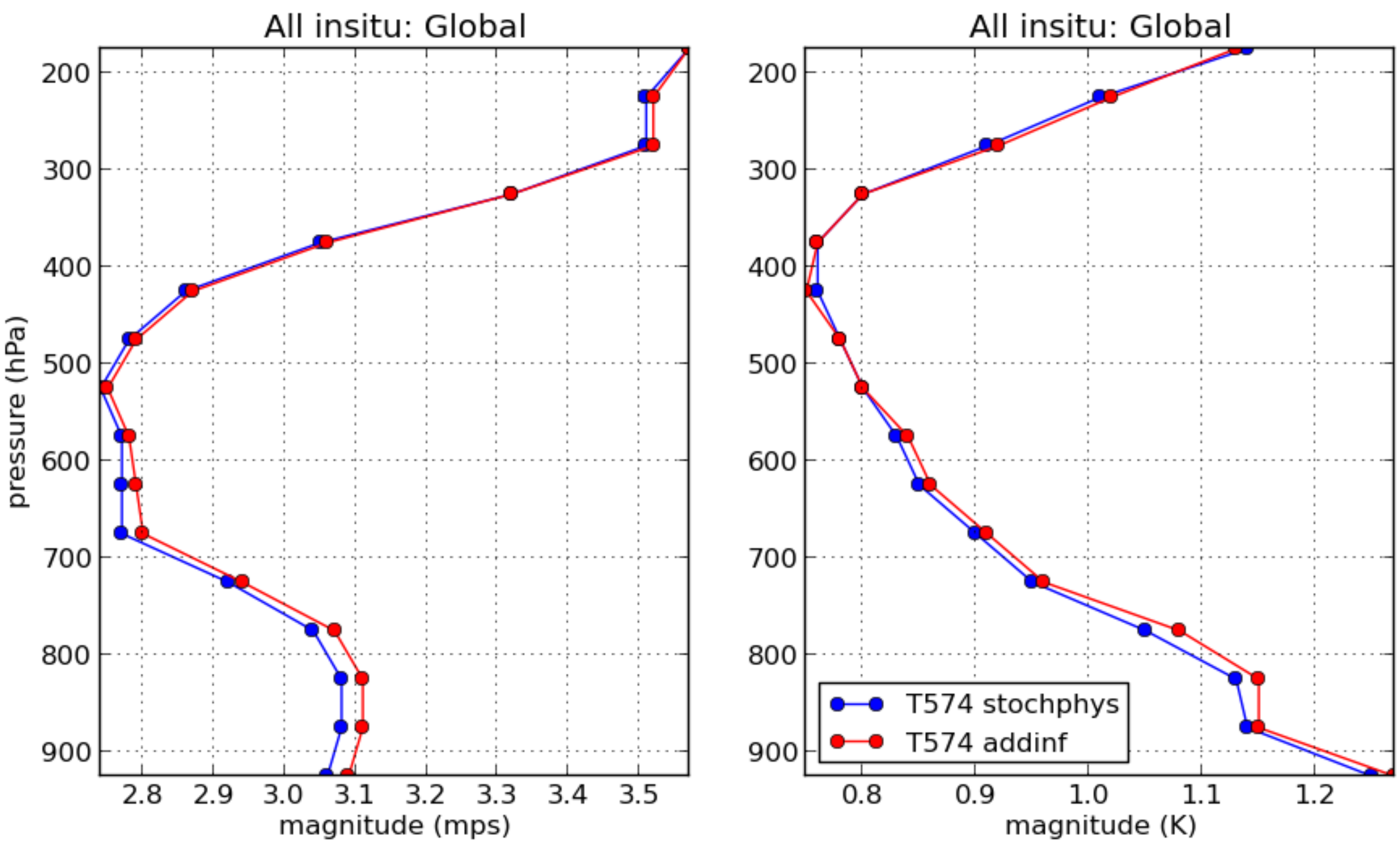
Stochastic Physics



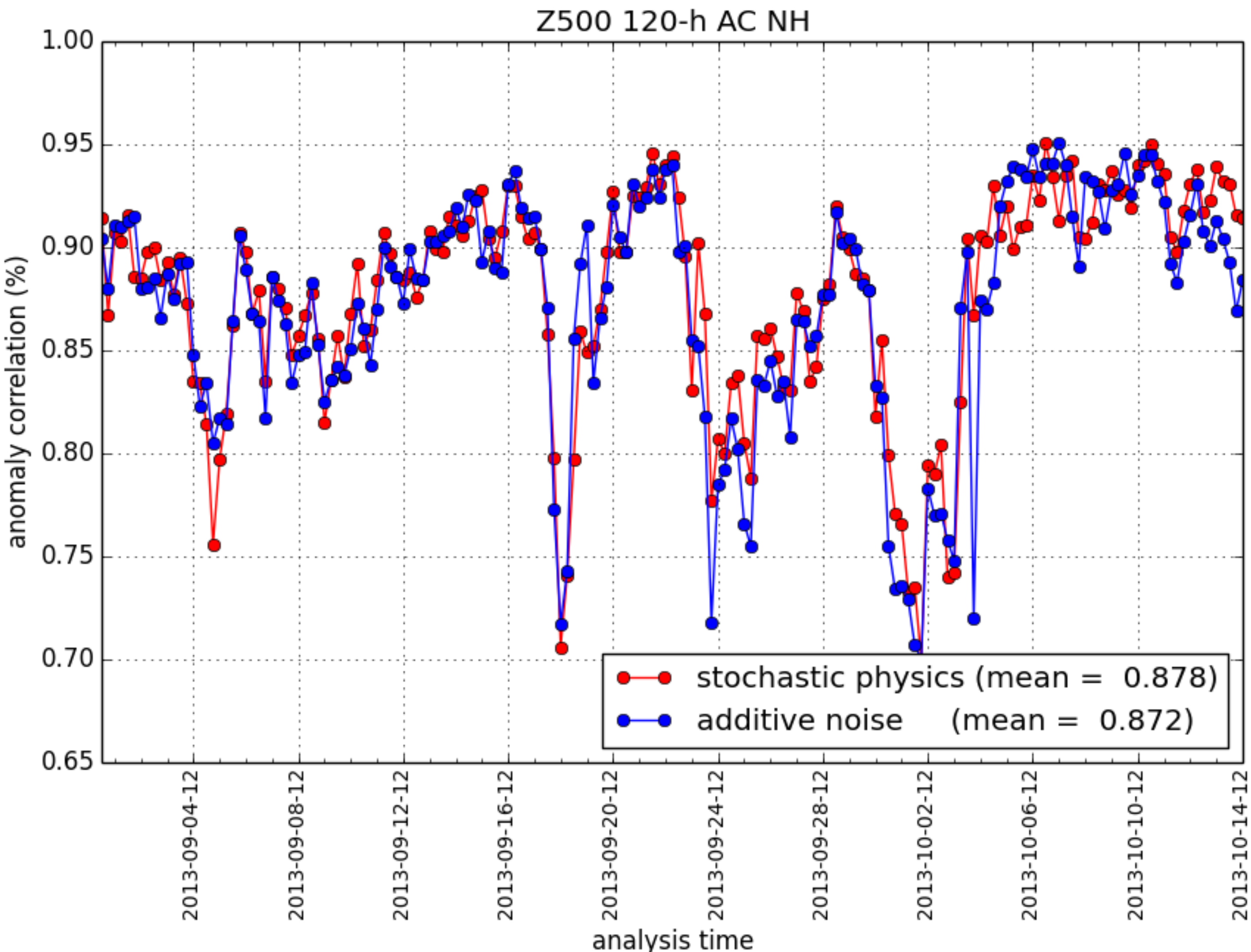
Impact on O-F (observation innovation std. dev)

sqrt of $\mathbf{d}_b^o(\mathbf{d}_b^o)^T$ where $\mathbf{d}_b^o = \mathbf{y}^o - H(\mathbf{x}^b)$

Vector Wind (left) and Temp (right) O-F (2013091000-2013101412)



Impact on 5-day *deterministic* forecast Z500 AC



Stoch. Physics Summary

- ‘first generation’ stochastic physics schemes can replace additive inflation in NCEP Ensemble/Var system (impact on forecasts is nearly neutral or slightly positive).
  - Included in December 2014 GDAS Package

- More tuning needed - spread for wind is too large.

- Can form basis for further improvements (in DA **and EPS**) by making parameterizations stochastic ‘from the ground up’.

Outline

- 3D Hybrid Summary
- 2014 GFS Implementation
  - T1534 L64 Semi-Lagrangian GFS
  - Stochastic Physics
- 4D-Ensemble-Var
- Implementation plans

Hybrid 4D-Ensemble-Var [H-4DEnVar]

The 4D EnVar cost function can be easily expanded to include a static contribution

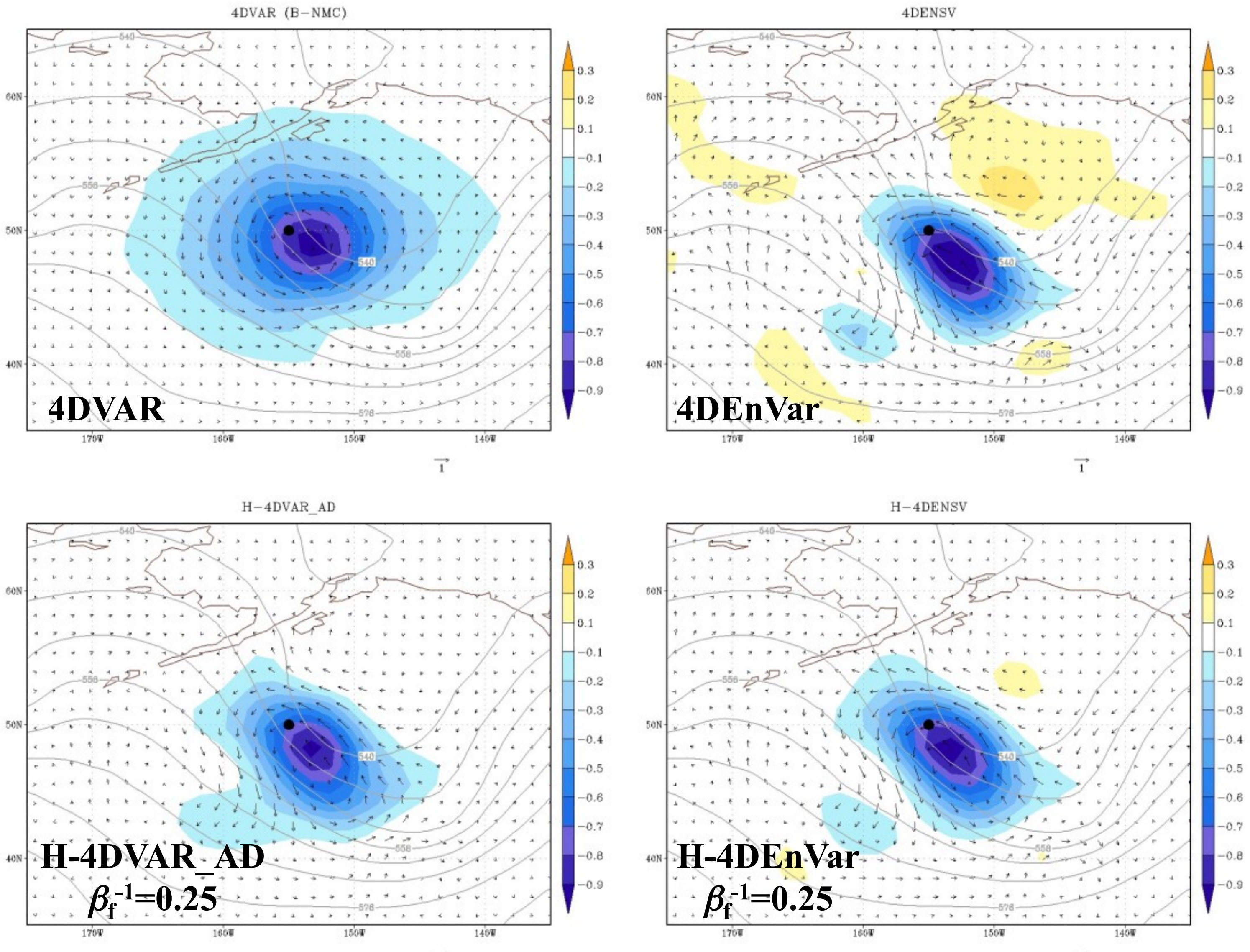
$$J(\mathbf{x}_\mathrm{f}', \boldsymbol{\alpha}) = \beta_\mathrm{f} \frac{1}{2}(\mathbf{x}_\mathrm{f}')^\mathrm{T} \mathbf{B}_\mathrm{f}^{-1}(\mathbf{x}_\mathrm{f}') + \beta_\mathrm{e} \frac{1}{2} \sum_{n=1}^{N} (\boldsymbol{\alpha}^n)^\mathrm{T} \mathbf{L}^{-1} (\boldsymbol{\alpha}^n) + \frac{1}{2} \sum_{k=1}^{K} (\mathbf{H}_k \mathbf{x}_k' - \mathbf{y}_k')^\mathrm{T} \mathbf{R}_k^{-1} (\mathbf{H}_k \mathbf{x}_k' - \mathbf{y}_k')$$

Where the 4D increment is prescribed exclusively through linear combinations of the 4D ensemble perturbations plus static contribution

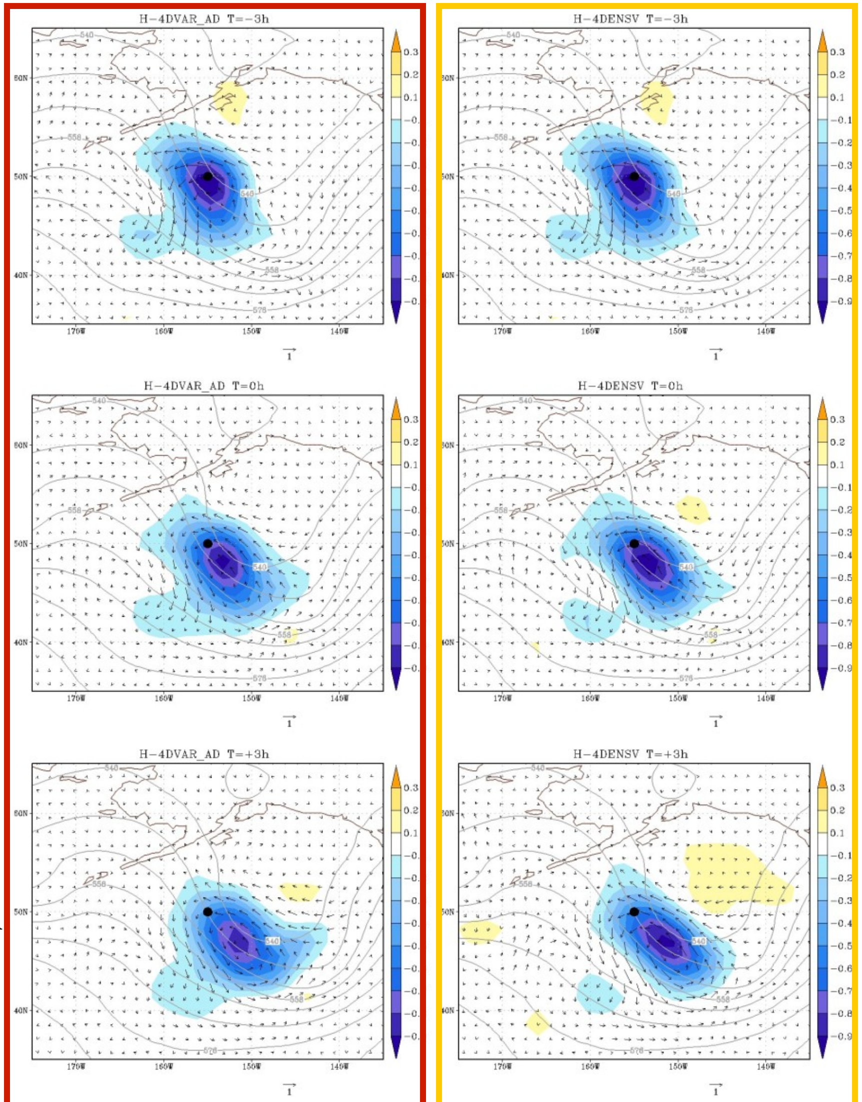
$$\mathbf{x}_k' = \mathbf{x}_\mathrm{f}' + \sum_{n=1}^{N} \left(\boldsymbol{\alpha}^n \circ (\mathbf{x}_\mathrm{e})_k^n \right)$$

Here, the static contribution is considered time-invariant (i.e. from 3DVAR-FGAT). Weighting parameters exist just as in the other hybrid variants.

Single Observation (-3h) Example for 4D Variants



Time Evolution of Increment



t=-3h

t=0h

t=+3h

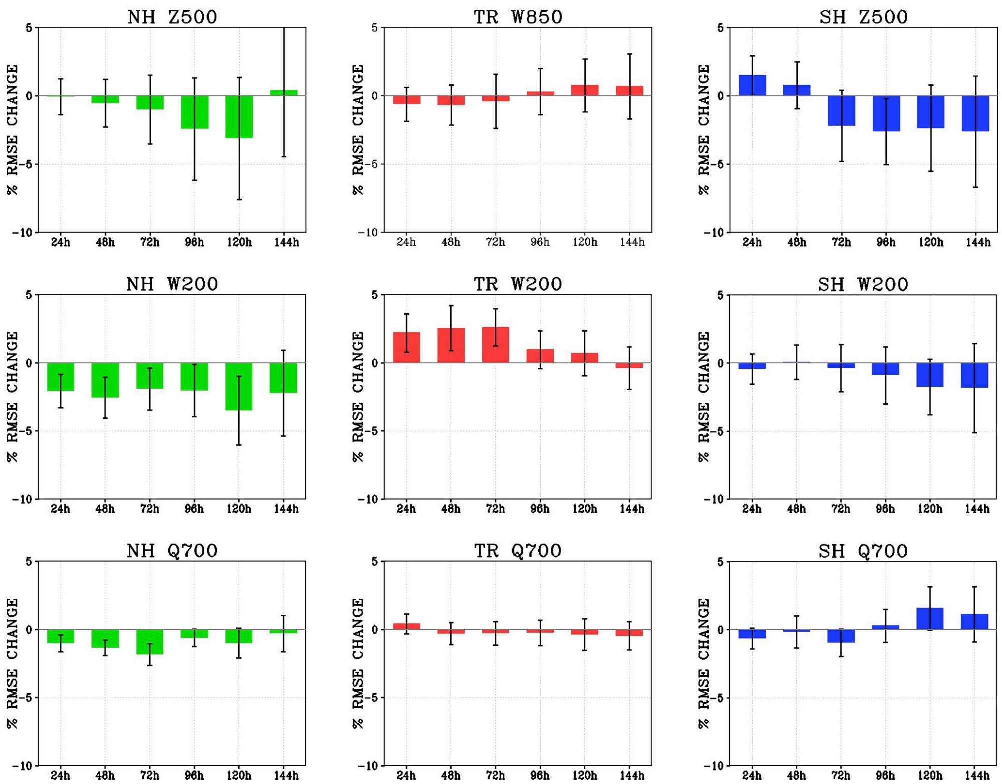
H-4DVAR_AD **H-4DEnVar**

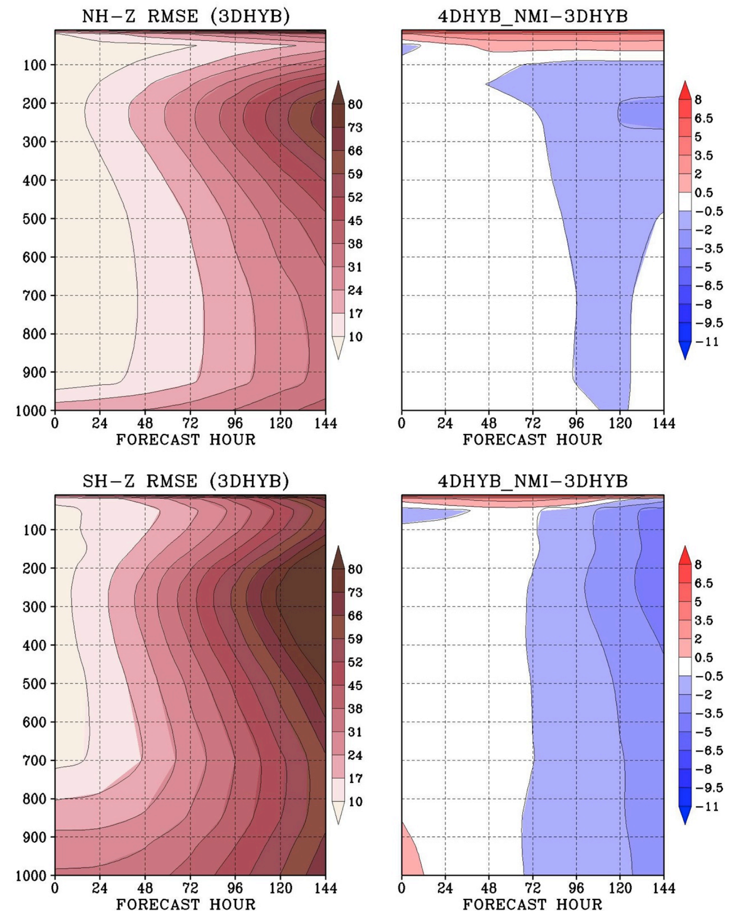
Solution at beginning of window same to within round-off (because observation is taken at that time, and same weighting parameters used)

Evolution of increment qualitatively similar between dynamic and ensemble specification

** Current linear and adjoint models in GSI are computationally unfeasible for use in 4DVAR other than simple single observation testing at low resolution

OSSE Cycling Experiments
Hybrid 4DEnVar relative to 3DEnVar
Kleist and Ide 2014 (MWR)

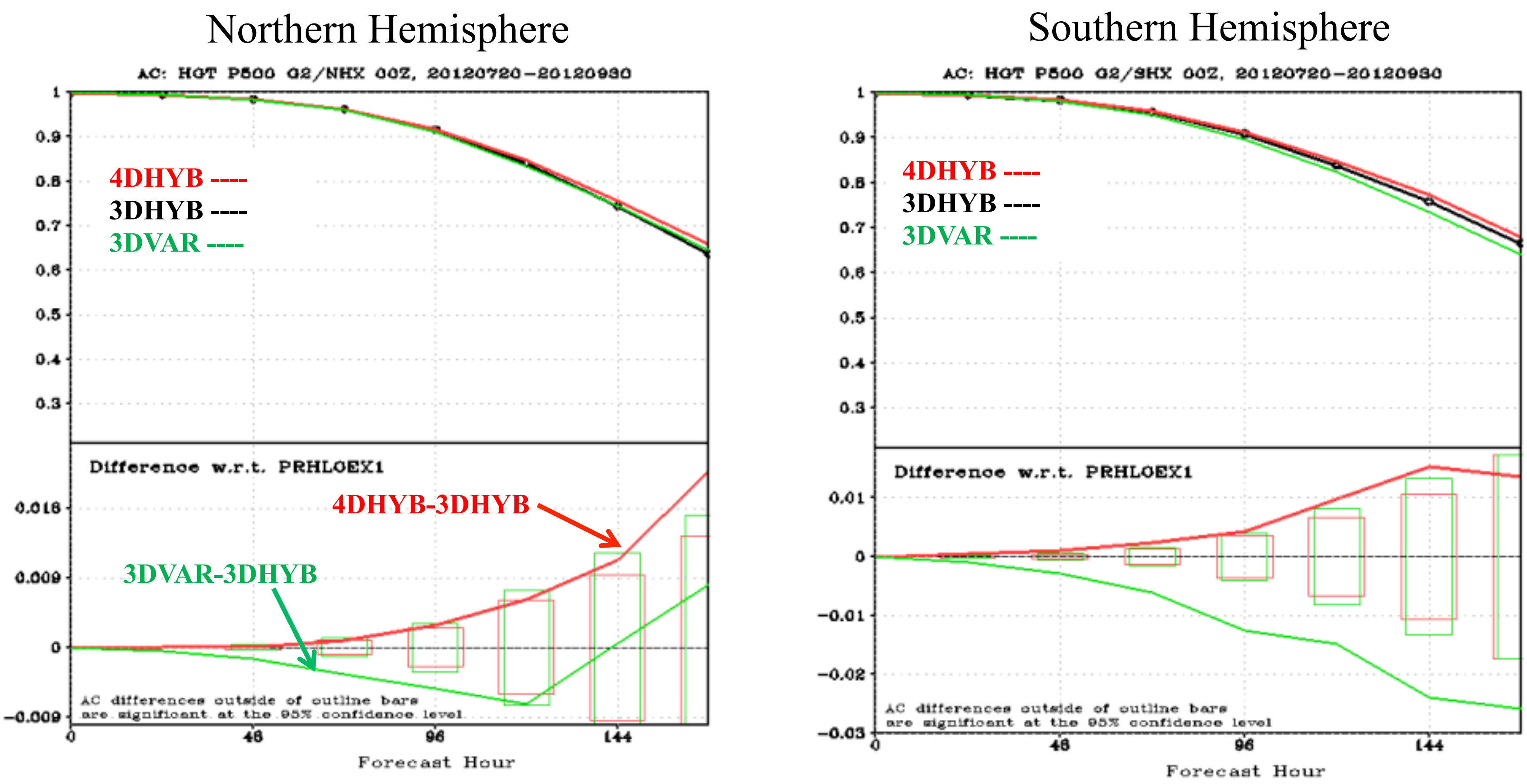




Initial Low Resolution GFS/GDAS Experiments with real observations

- Basic configuration
  - T254L64 GFS, operational observations, GFS/GDAS cycles, 2012070100-2012100100
- **PR3LOEX0**
  - **3DVAR**, 2x100 iterations, r25935 (EXP-ensvar-dev branch), operational "options"
- **PRHLOEX1**
  - **Hybrid 3D EnVar**, 80 member T126L46 ensemble with fully coupled (two-way) EnKF update, slightly re-tuned localization and inflation for lower resolution, TLNMC on total increment, 75% ensemble & 25% static
- **PRH4DEX1**
  - **Hybrid 4D EnVar**, TLNMC on all time levels, only 1x150 iterations (for now)
  - Hourly TC relocation, O-G, binning of observations (not 3-hourly)

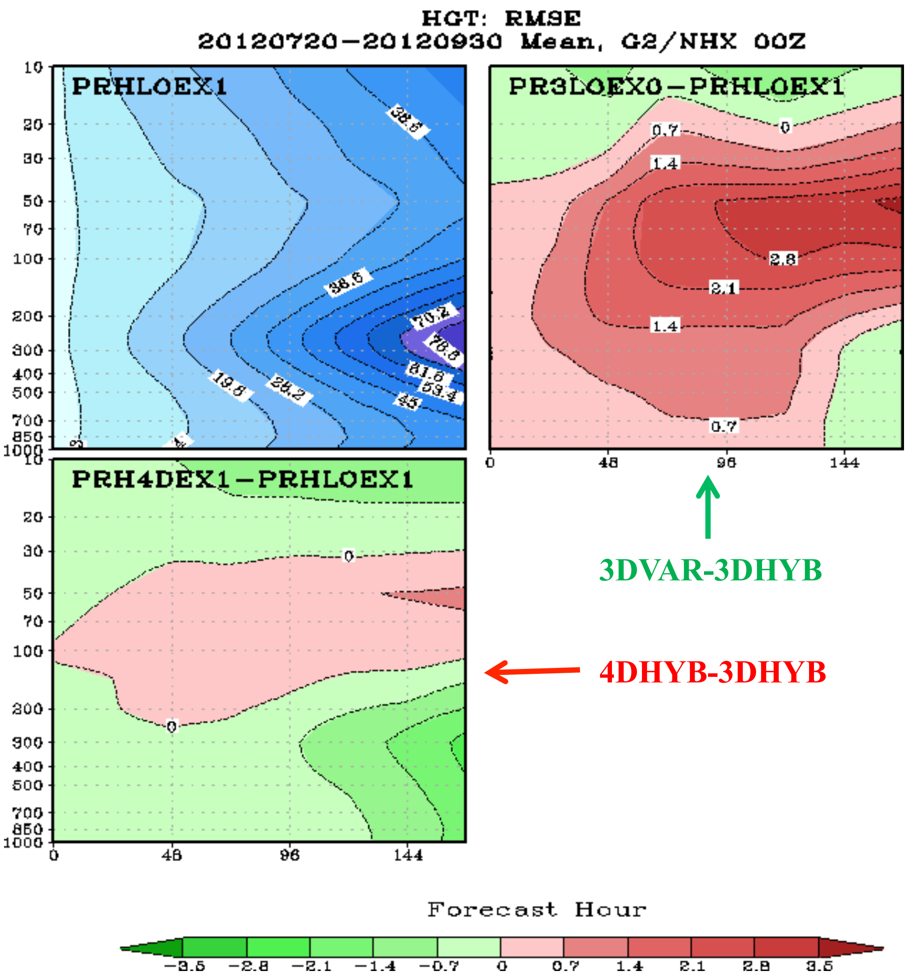
500 hPa Die Off Curves



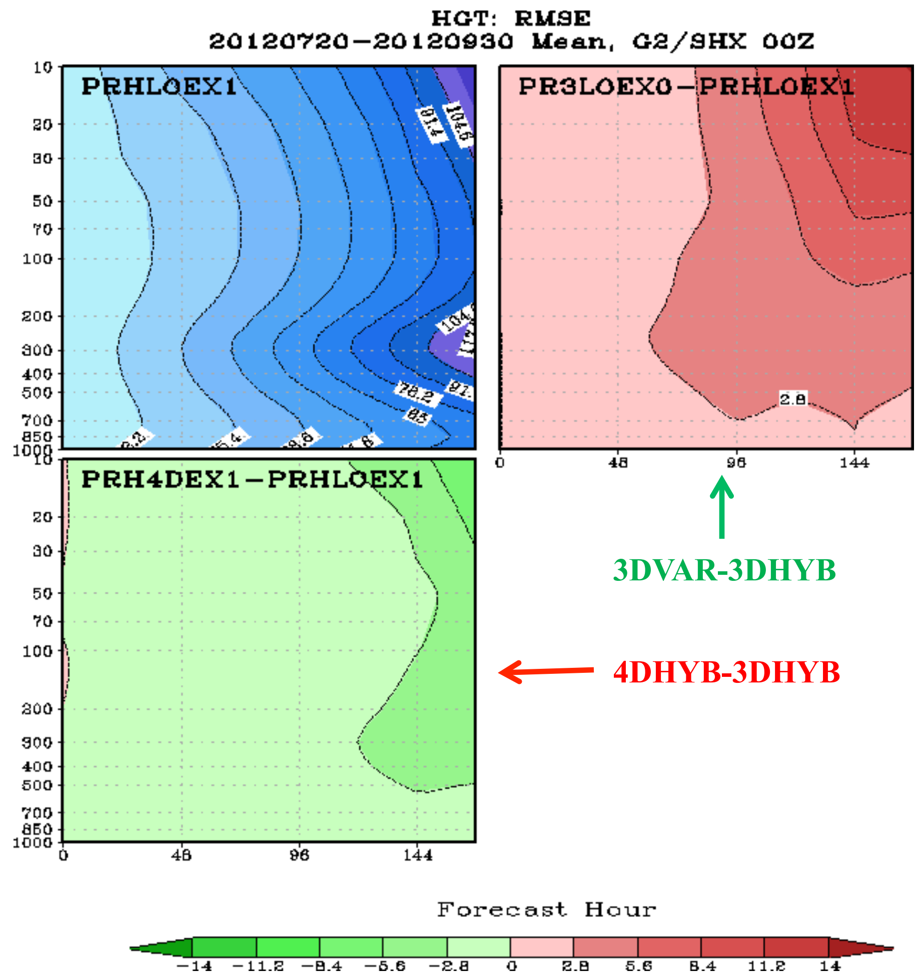
Move from 3D Hybrid (current operations) to Hybrid 4D-EnVar yields improvement that is about 75% in amplitude in comparison from going to 3D Hybrid from 3DVAR.

Extratropical Geop. Height RMSE Differences

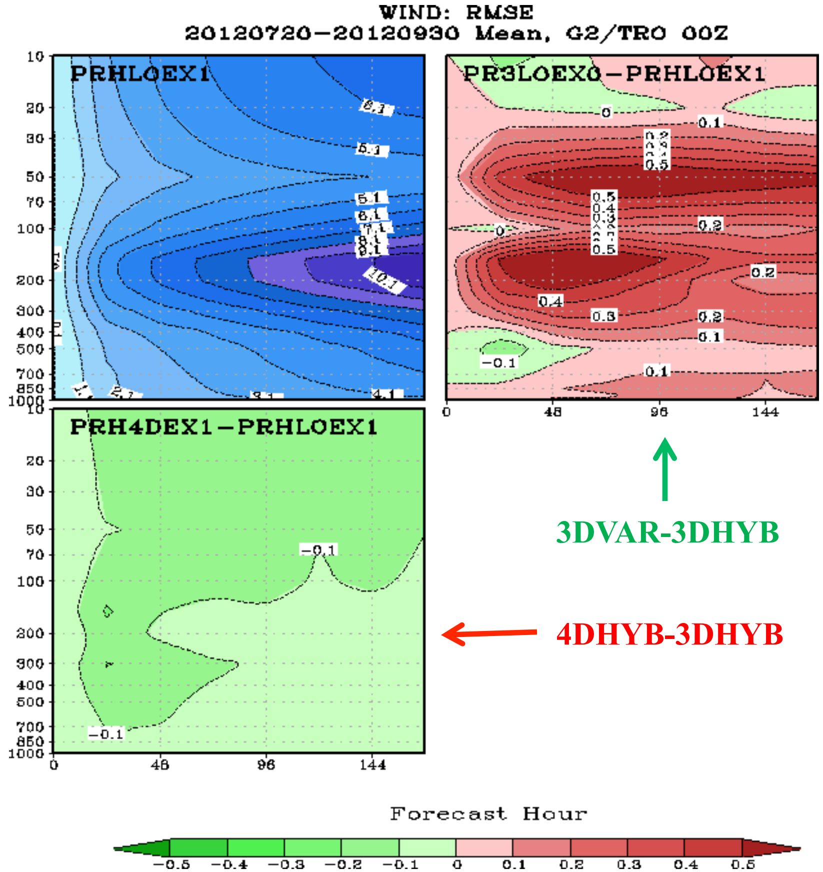
Northern Hemisphere



Southern Hemisphere



Tropical Wind RMSE Differences



Although going to 4D yields consistent, uniform improvement to tropical wind forecasts, biggest gains were seen by adding the ensemble covariances (i.e. 3D Hybrid).

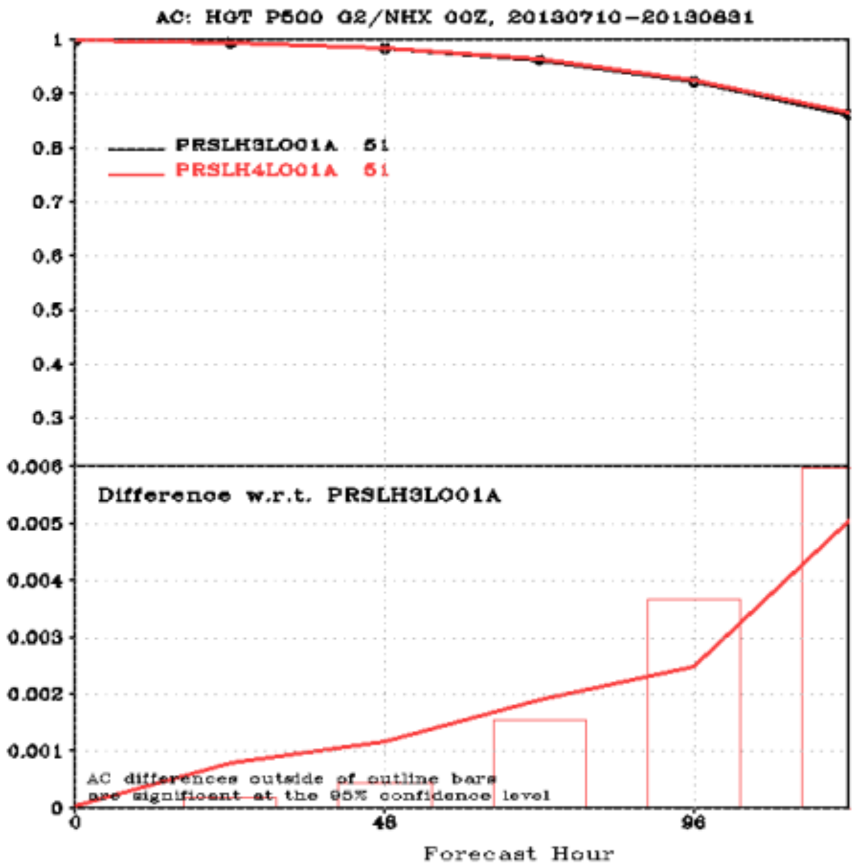
Recent Low Resolution GFS/GDAS Experiments with real observations

- Due to the impending implementation of the new Semi-Lagrangian model, tests needed to be redone with new model, configuration, etc.

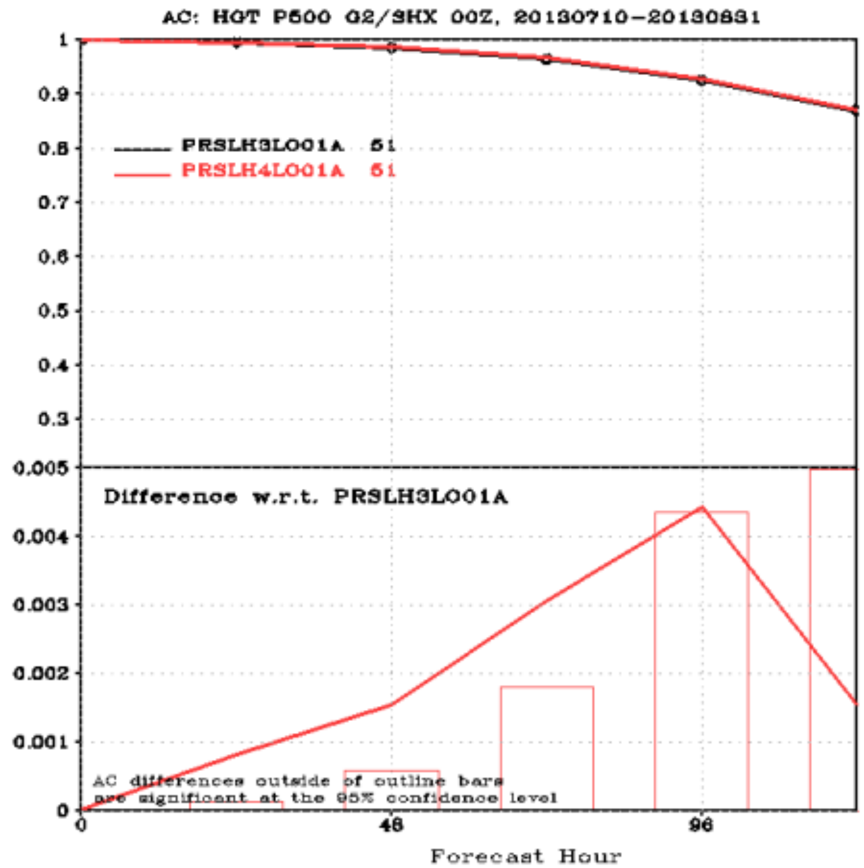
- T670 Semi-Lagrangian with an 80 member T254 Semi-Lagrangian ensemble
  – Similar ratio to what is to be implemented with T1543/T574 system
  – Experiments with both additive inflation and stochastic physics as replacement
    - Stoch. Physics is resolution sensitive, requires tuning.

- Compare hybrid 3DEnVar to 4DEnVar (minimal additional tuning such as localization, weights, etc.)

3D v 4D hybrid in SL GFS

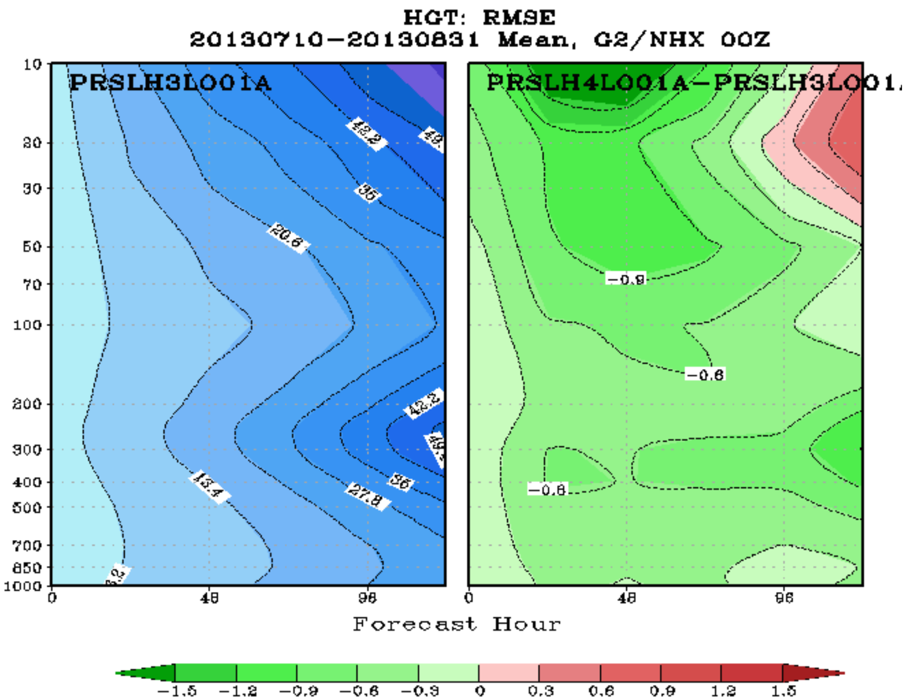


Northern Hemisphere

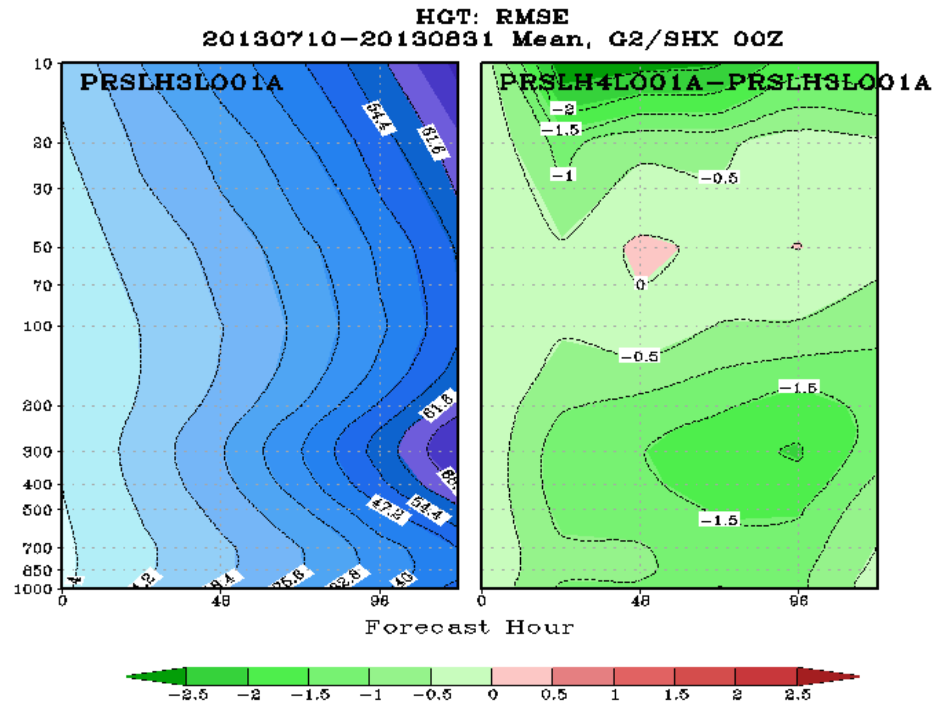


Southern Hemisphere

3D v 4D hybrid in SL GFS



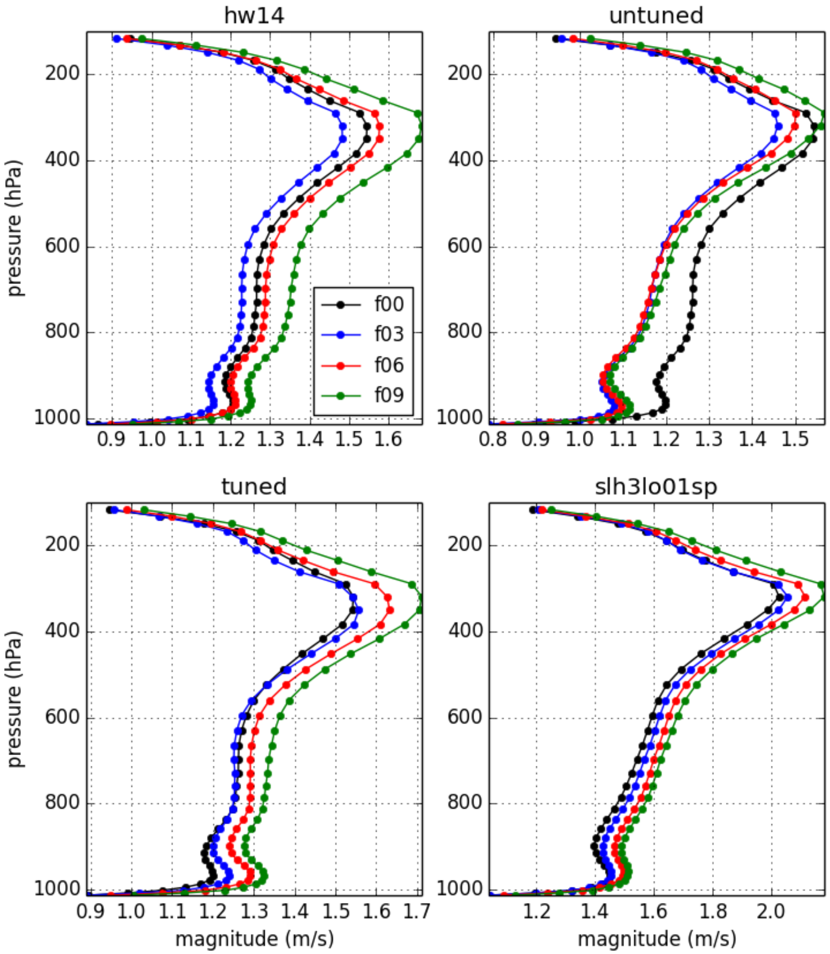
Northern Hemisphere



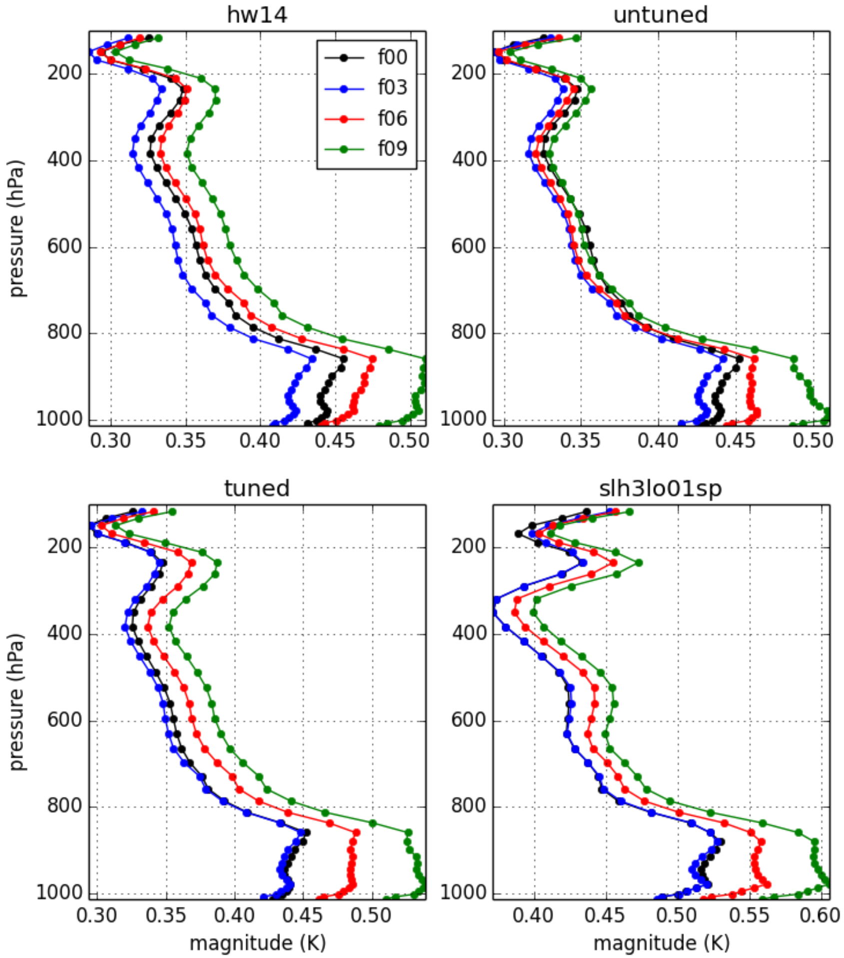
Southern Hemisphere

Stochastic Physics Tuning

Ens. Spread in U Wind
(Global)



Ens. Spread in Temp.
(Global)



Innovation statistics from 3D and 4D runs with tuned stoch. physics (preliminary)

UV, Counts and O-F, 3D (RMSE1) 4D (RMSE2)

lev1-lev2	COUNTS1	COUNTS2	RMSE1	RMSE2
1200-1000	16525	16527	**3.14**	3.16
1000- 900	51483	51485	3.27	3.27
900- 800	47937	47938	**3.15**	3.19
800- 600	93195	93192	3.26	**3.25**
600- 400	96109	96108	3.60	**3.58**
400- 300	75313	75315	3.84	3.84
300- 250	22882	22880	4.25	**4.23**
250- 200	48625	48624	4.18	**4.11**
200- 150	56236	56238	4.25	**4.18**
150- 100	101212	101218	4.31	**4.30**
100- 50	134273	134267	4.48	**4.45**
2000- 0	998436	998445	4.07	**4.04**

T, Counts and O-F, 3D (RMSE1) 4D (RMSE2)

lev1-lev2	COUNTS1	COUNTS2	RMSE1	RMSE2
1200-1000	19237	19242	**1.92**	1.93
1000- 900	48727	48739	1.74	**1.73**
900- 800	46272	46275	**1.19**	1.20
800- 600	90544	90549	0.98	**0.97**
600- 400	111865	111863	0.90	**0.89**
400- 300	78711	78727	0.85	0.85
300- 250	22780	22782	1.07	**1.05**
250- 200	43890	43899	1.31	**1.27**
200- 150	44370	44382	1.20	**1.18**
150- 100	76347	76366	1.30	1.30
100- 50	72433	72448	1.88	**1.86**
2000- 0	789836	789967	1.38	**1.37**

2013070106-2013071418

4D yielding consistent improvements in O-F with stochastic physics.
Experiments and evaluation are still ongoing to assess forecast impact.

O-F comparison (3D/4D) similar in additive inflation context

4D EnVar: Way Forward

- Natural extension to operational EnVar
  - Uses variational approach in combination with already available 4D ensemble perturbations (covariance estimates)
- No need for development of maintenance of TLM and ADJ models
  - Makes use of 4D ensemble to perform 4D analysis
  - Very attractive, modular, usable across a wide variety of applications and models
- Highly scalable
  - And can be improved even further
  - Aligns with technological/computing advances
- Computationally inexpensive relative to 4DVAR (with TL/AD)
  - Estimates of improved efficiency by 10x or more, e.g. at Env. Canada (6x faster than 4DVAR on half as many cpus)
- Compromises to gain best aspects of (4D) variational and ensemble DA algorithms
- Other centers pursuing similar path forward for deterministic NWP
  - UKMO, Canada (implemented this year)

Implementation Plans

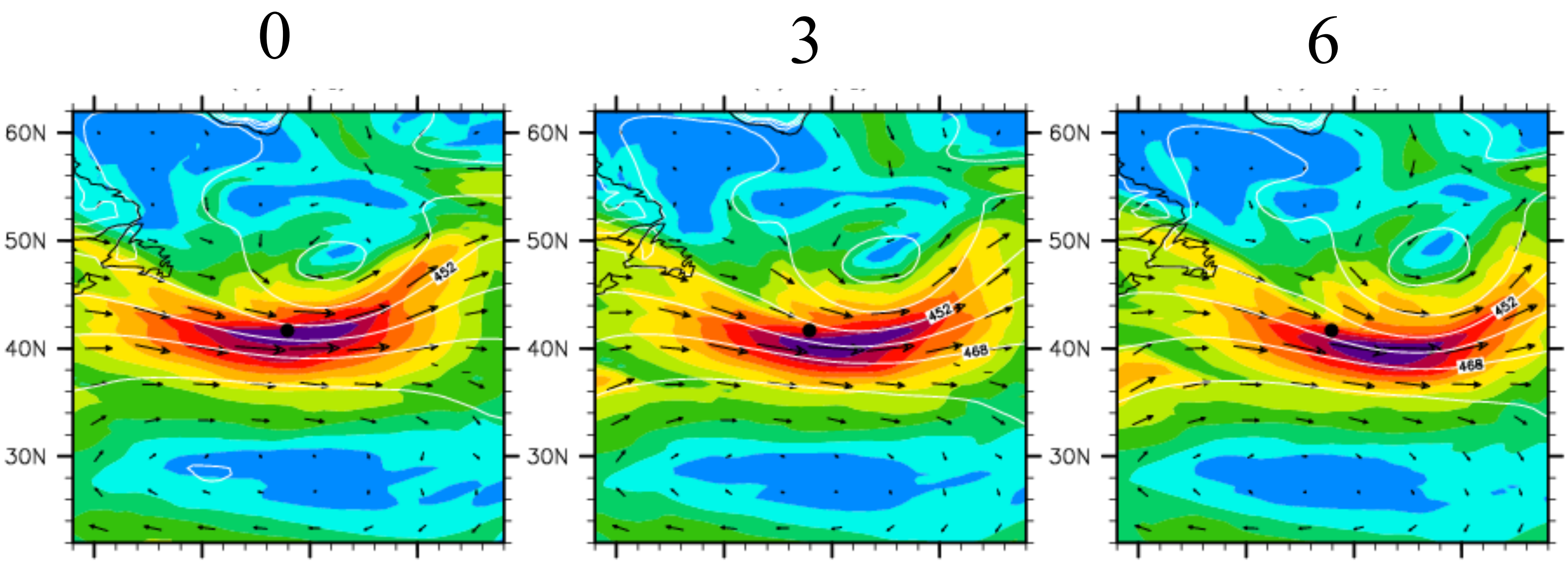
- Results are very encouraging, but much work remains
  - Computational efficiency improvements
  - Tuning (localization, weighting)
  - Initialization
    - Turn off DFI, use TLNMC (default is to currently use over all time levels), 4DIAU?
  - Outer loops
  - Variable choices for ensemble
    - Initial implementation simply relied on GSI control variables, perhaps not best choice
  - Exploring trade space between ensemble size and resolution
  - I/O becoming more and more of an issue, need to address problem head on
    - Short term solution is likely to utilize ensemble post-processor to precompute ensemble perturbations on GSI subdomains
- **Target: Late 2015/early 2016 (some of this is machine dependent as NCEP gets their next upgrade)**

More work to do

- Other potential things to add:
  - Ideas for improving static contribution (use slides from Andrew's Talk? VT guys?
  - Ensemble size sensitivity?

Single wind observation at start of 6 hour window, in jet

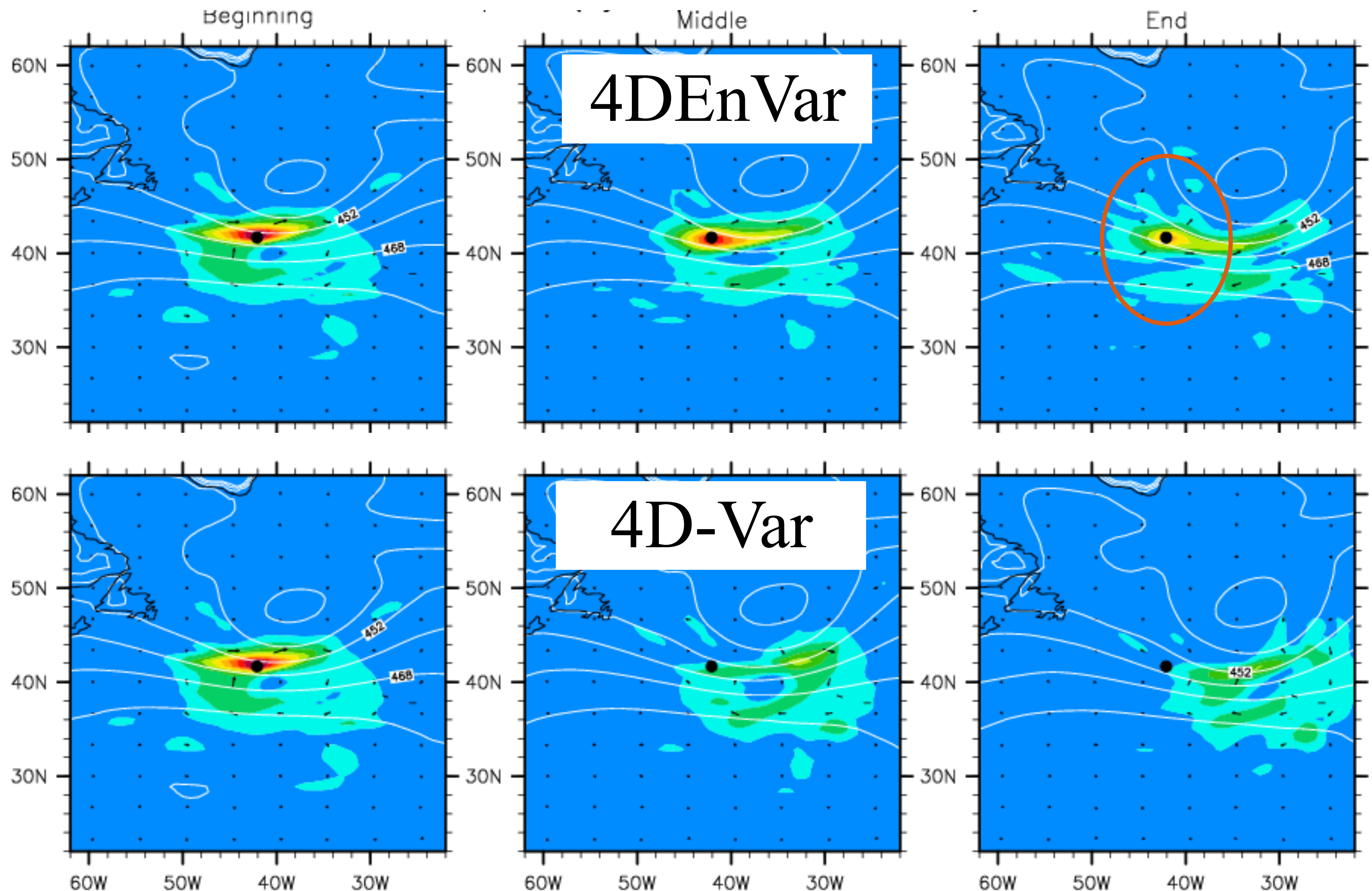
Background trajectory



Ob is at ● at time 0.

The following slides are from Lorenc et al. 2014

50-50% hybrid
1200km localization scale



Summary from Lorenc et al. 2014 for UKMO system

1. The main error in our hybrid-4DEnVar (v hybrid--4DVar) is that the climatological covariance is used as in 3D-Var.

2. 3D localization not following the flow is not an important error for our 1200km localization scale and 6hour window, but does become important for a 500km scale.

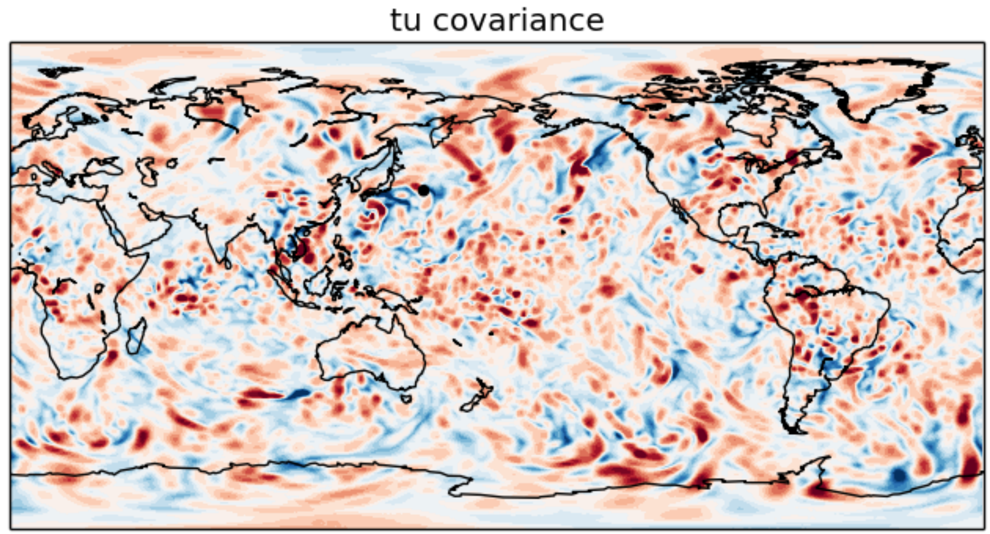
3. Proposed solutions: Bigger ensemble, better localization, better ensemble generation (for their system)

Impact of increasing ensemble size in the global EnKF
or
How much can we benefit get from increasing ensemble size before model error swamps sampling error?

Jeff Whitaker

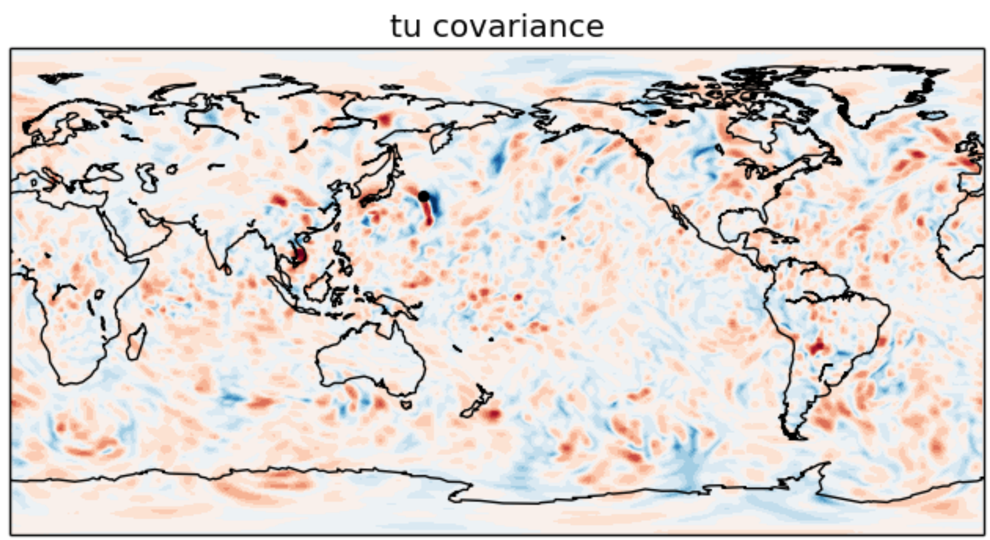
Cov(T,U) 250hPa 2013101500

80 members

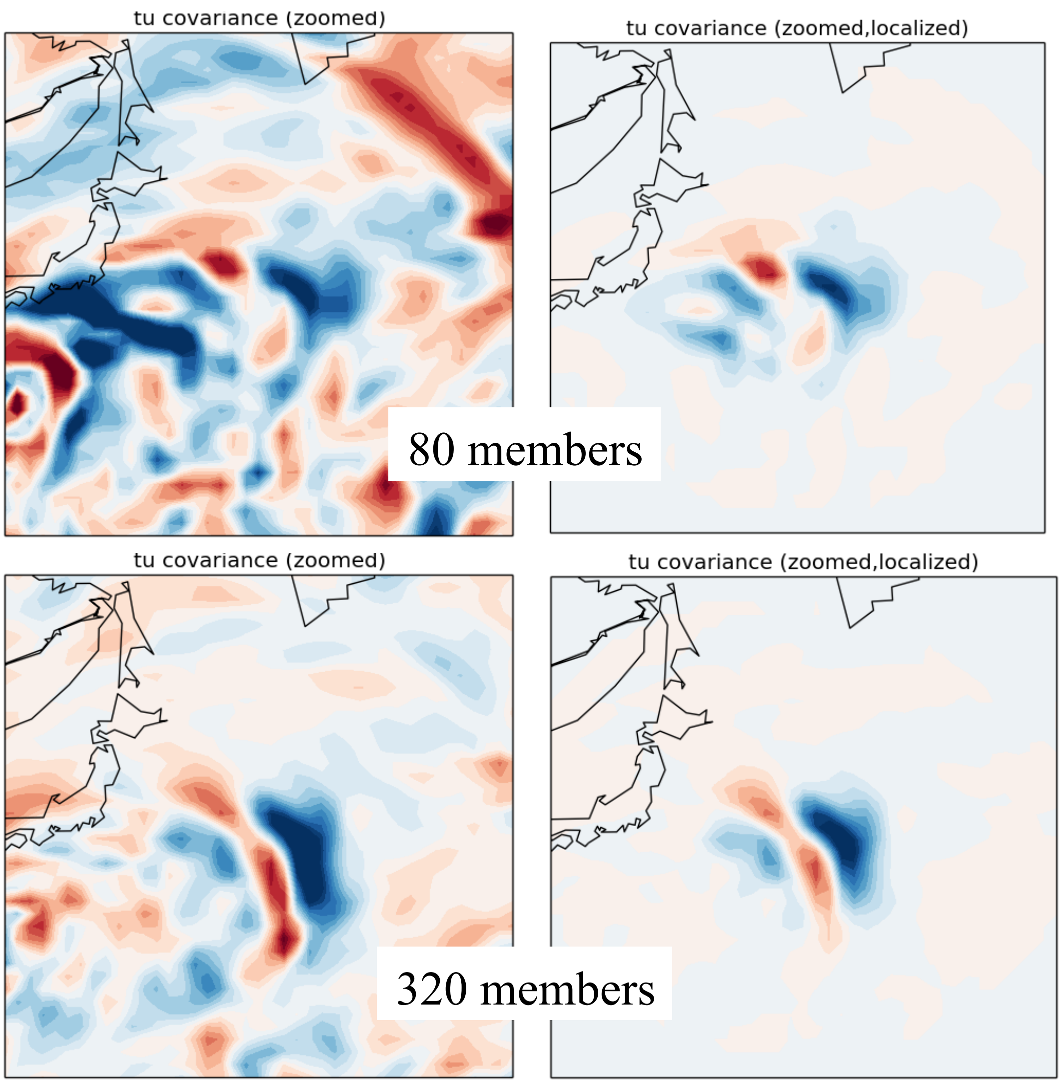


Cov of T at 153E, 35N and U everywhere else at 250hPa

320 members



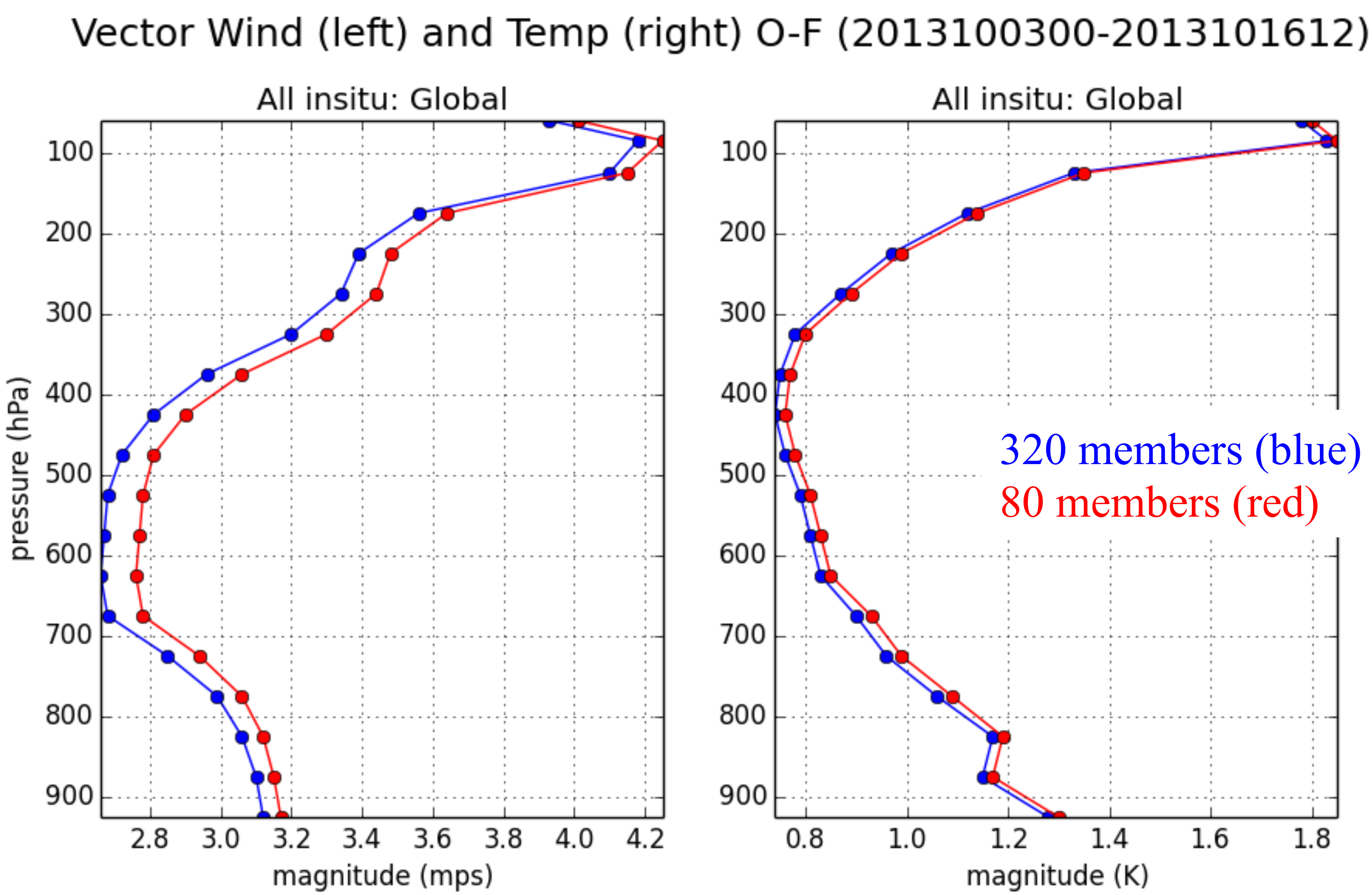
Cov(T,U) 250hPa 2013101500



Zoomed in around obs location.

No localization (left), 2000km localization (right)

Results with 1500/1.175 localization



Gap narrows: 80 member EnKF gets better, 320 member stays about the same

Ensemble Size Summary

- 80 member EnKF can be improved by reducing localization length scales from current settings (by about 25%).

- Going to 320 members will result in a significant increase in skill.

- Questions:
  - Could we increase ens size further?
  - Is impact on 4DEnVar similar?
    - Especially if we can minimize reliance on static B!
  - Can we do better with more sophisticated localization?

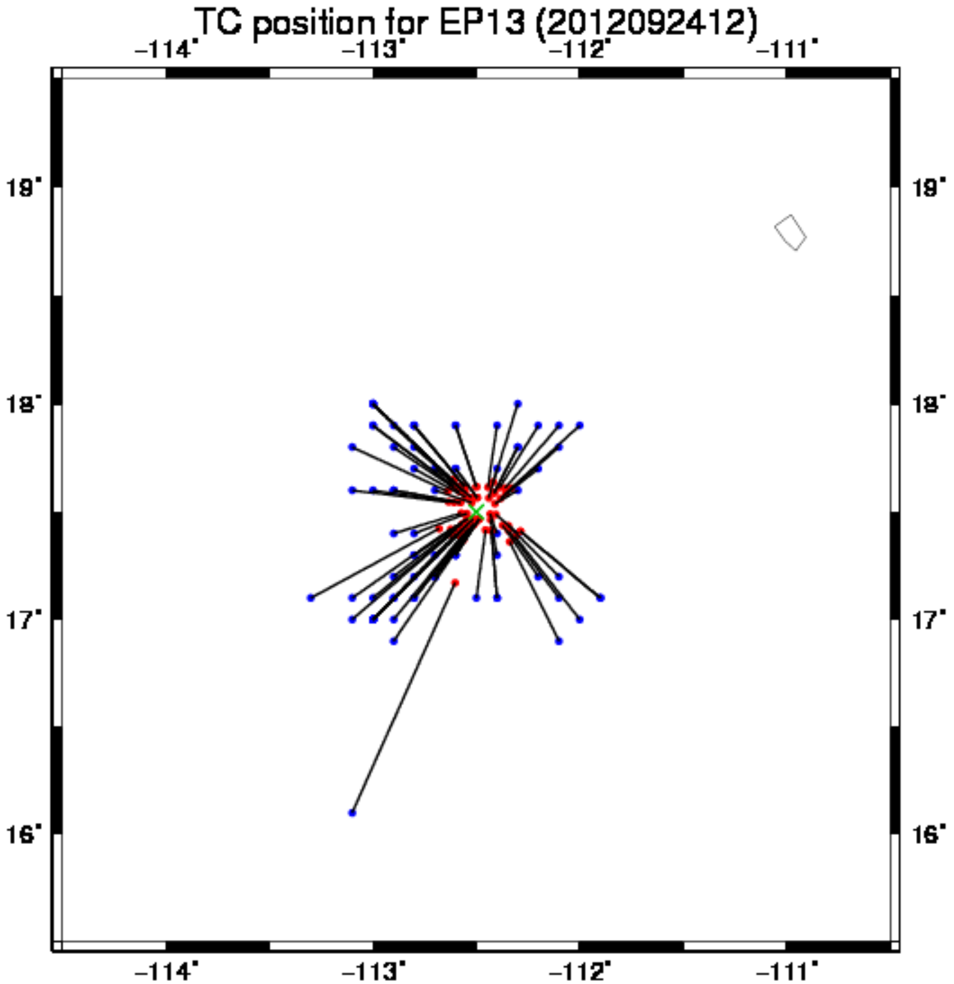
Summary

- Significant progress has been made on 4D EnVar development and testing for operational NWP at NCEP
- Further improvements expected through use of improved initialization
  - Removal of DFI, use of 4D IAU
  - What to do about TLNMC remains open question
  - Handing of ensemble also important
- Much of the literature shows that hybrid 4DEnVar is not quite as good as hybrid 4DVar
  - Can close some of this gap with initialization (4DIAU) and perhaps outer loop (to be determined)
  - Significant work remains in coming up with more optimal static B
    - Finding ways to add temporal component without need for dynamic model in minimization (is it even possible?)

- BACKUP

TC relocation for EnKF
(work done by Yoichiro Ota)

Apply TC relocation used in deterministic analysis to each ensemble member, but allowing TC structure perturbations and some TC position spread.

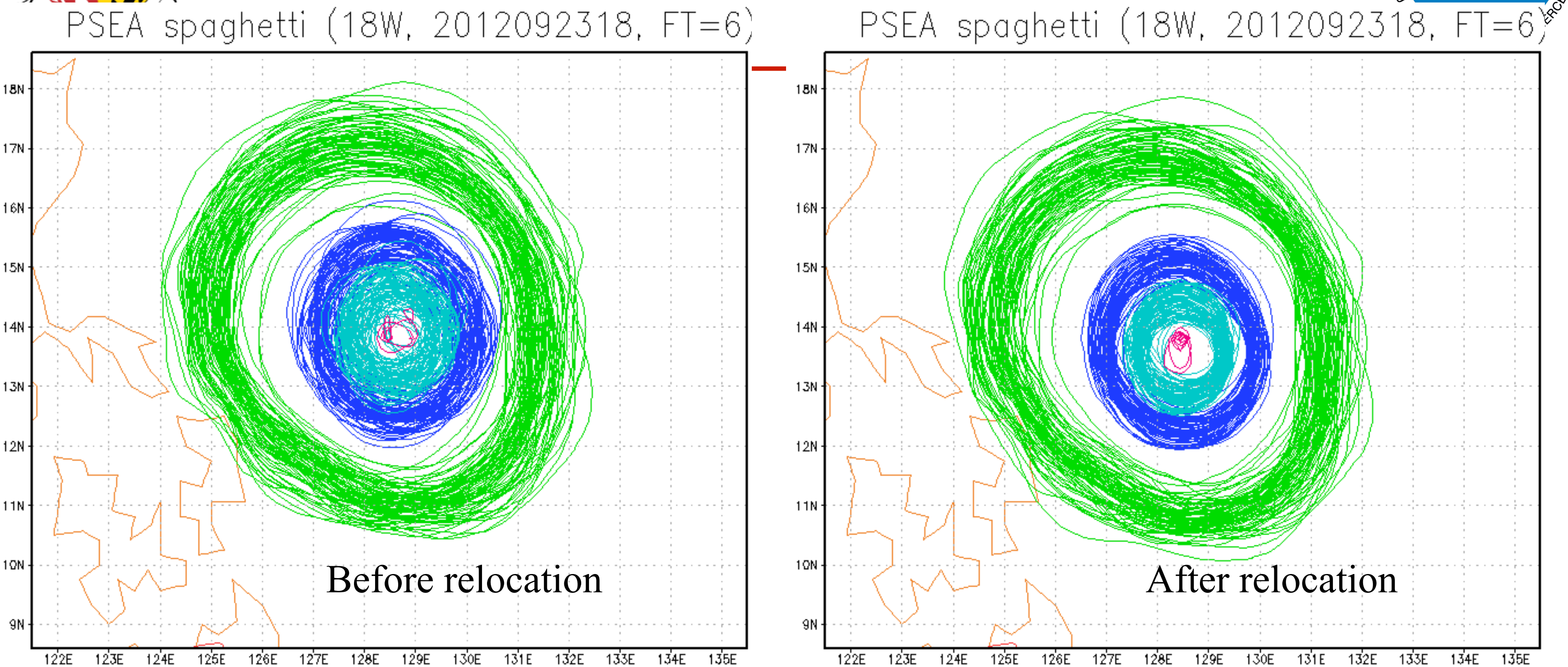


1. Update TC center position (latitude and longitude) by the EnKF
2. Use updated positions as inputs to the TC relocation
3. Apply this procedure before the EnKF analysis and GDAS analysis

The idea is to separate linear problem (TC location space) and nonlinear problem (actual relocation of fields).

Blue: first guess position
Red: Updated position
Green: TC vital position

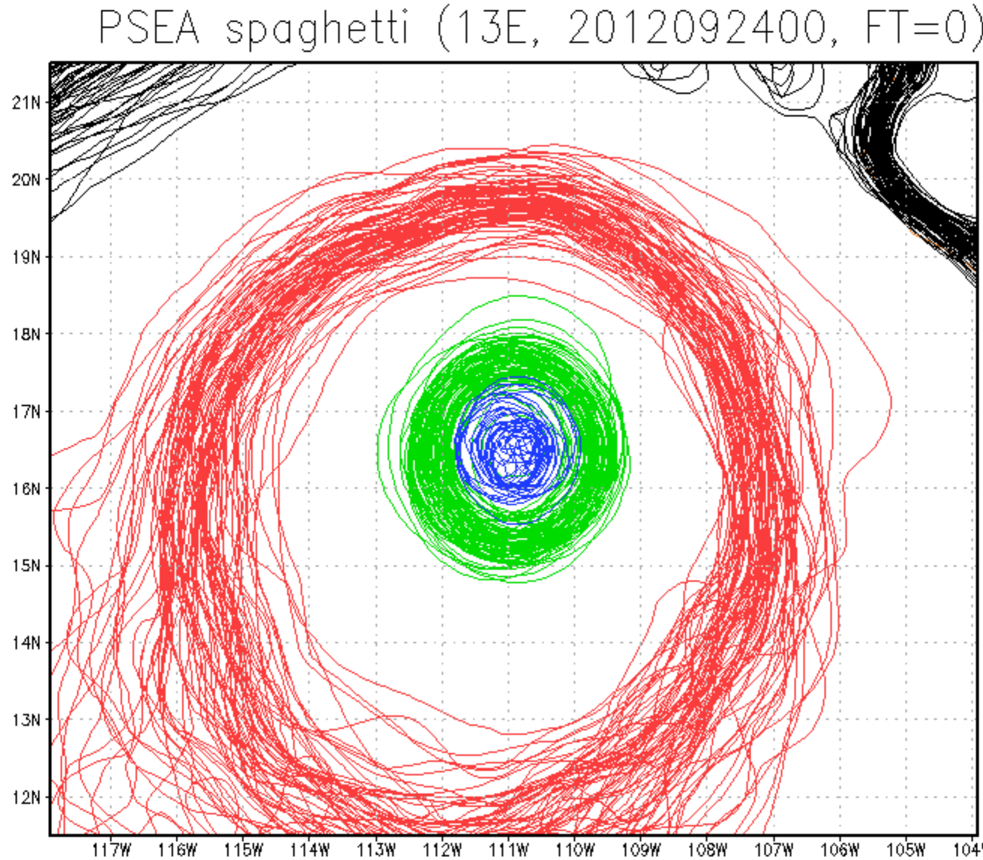
Example: spaghetti diagram



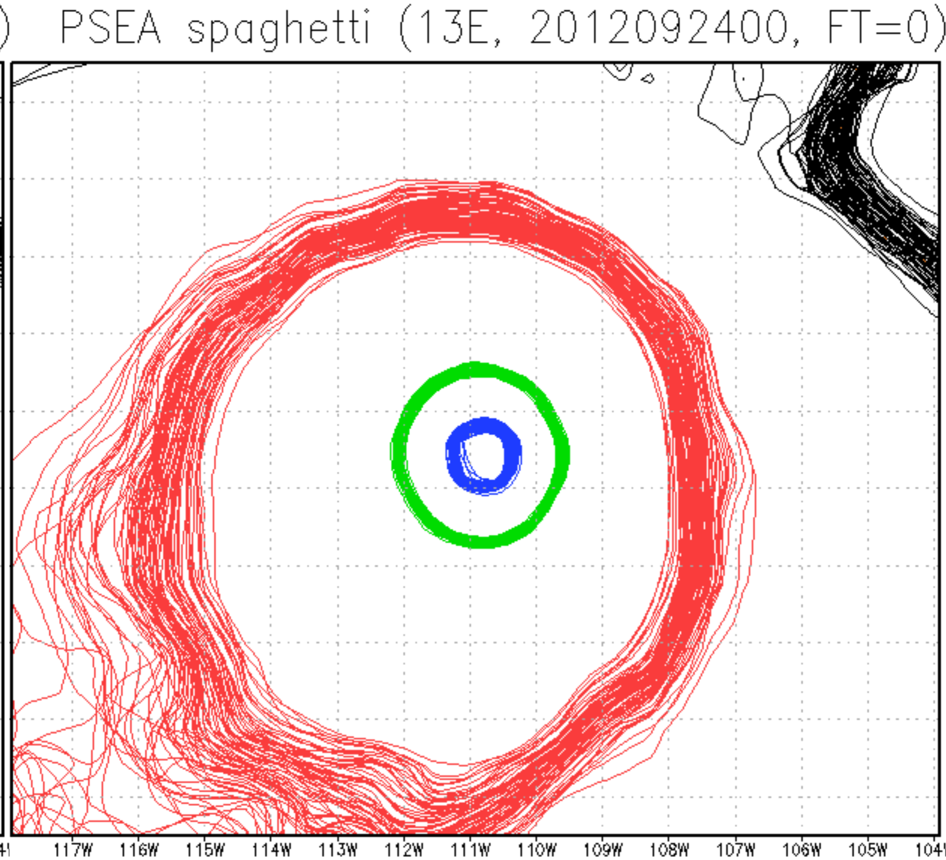
TC relocation of this method can reduce the uncertainty on the TC position, maintaining the TC structure perturbations and some of the position uncertainty.

Courtesy Yoichiro Ota

Comparison with GEFS TC relocation



EnKF analysis with TC relocation



EnKF 6 hour forecast perturbation + GEFS TC relocation

GEFS operational TC relocation scheme destroyed almost all initial position uncertainty and create very small spread around TC.

Courtesy Yoichiro Ota