Earth System Research Laboratory
Physical Sciences Division

Representing model uncertainty in data assimilation (using ensembles)

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- Spread-error in med-range ensembles (update on previous work).
- Replacement for additive inflation in ensemble-Var hybrid DA.
- If I have time..
  - *Improving balance in EnKF analysis ensemble.*
  - *Incremental Analysis Update (IAU).*
  - *TC relocation in the EnKF ensemble.*

Evaluating schemes for representing model uncertainty

- Using an EPS
  - Spread/error consistency, probabilistic scores.
  - Hard to know whether improvement comes simply from reducing spread deficiency.
- Using an ensemble-based DA system
  - Tougher test if inflation used as baseline, since scheme must do more than increase variance.
  - Evolution of all errors in DA cycle (not just model error) must be represented. Model error may not be dominant.

Un(der)-represented error sources in an EnKF ensemble

Model error	$\mathbf{M}\mathbf{x}_{\mathbf{a}}$
Sampling error	$\frac{1}{N}\sum_{j=1}^{N}(N << \infty)$
Observation error	$\mathbf{R}$
Boundary condition error	$T(z=0) \Rightarrow T_s$
Forward operator error	$\mathbf{H}\mathbf{x}_{\mathbf{b}}$

Methods to account for under-represented sources of error in ensemble DA: *Multiplicative Inflation*

Relaxation to prior spread (RTPS) $\sigma^a \leftarrow (1-\alpha)\sigma^a + \alpha\sigma^b$

which implies $\mathbf{x}_i'^{a} \leftarrow \mathbf{x}_i'^{a}\sqrt{\alpha\frac{\sigma^b-\sigma^a}{\sigma^a}+1}$

- Inflates more where observations have a strong tendency to reduce ensemble variance.
- Simple model study of Whitaker and Hamill (MWR 2012, *DOI:10.1175/MWR-D-11-00276.1*) shows that multiplicative inflation best for representing errors in the assimilation system itself (such as sampling error).
- Used in operational EnKF with α=0.9.

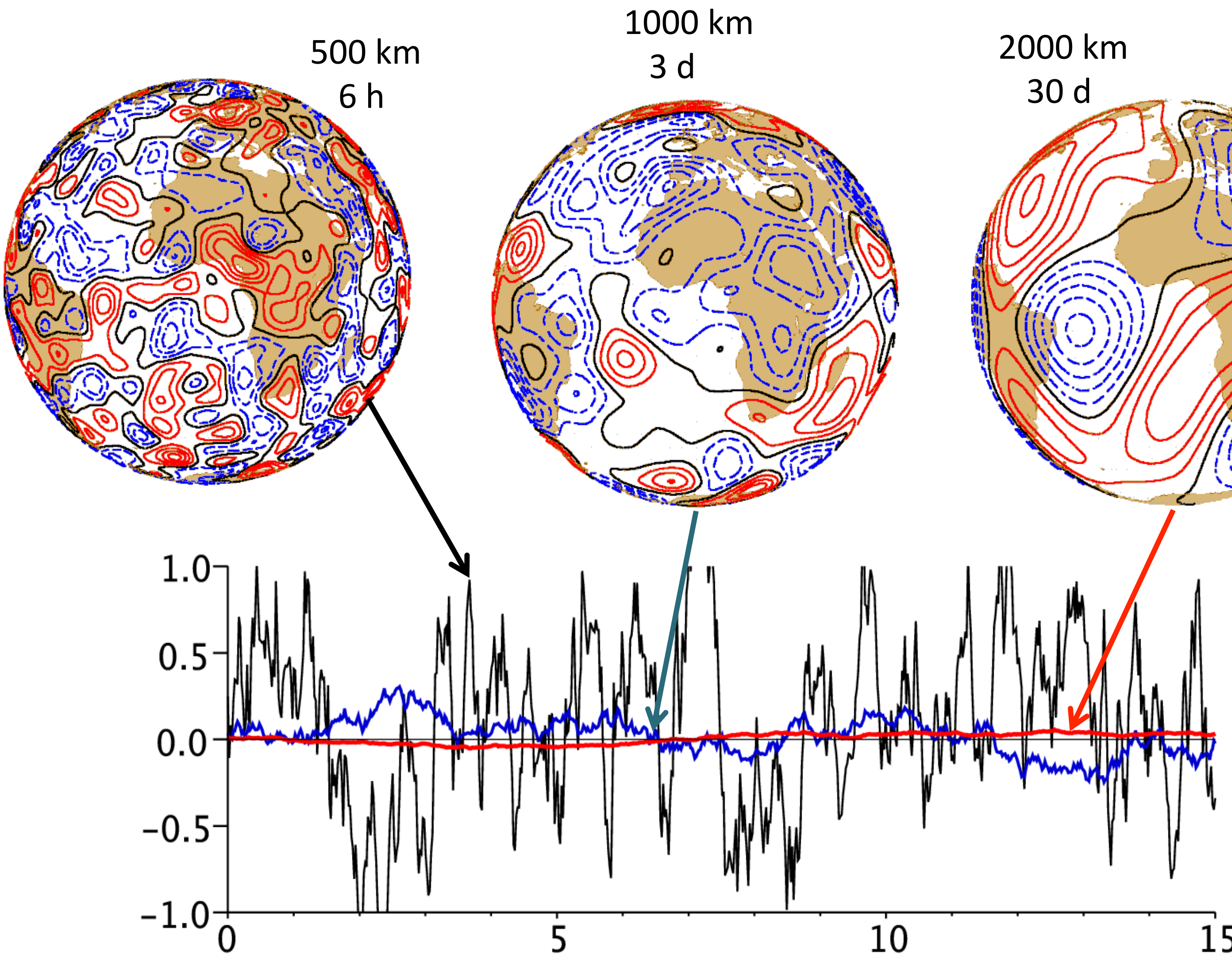
Methods to account for under-represented sources of error in ensemble DA: *Additive Inflation*

- Add random samples from a specified distribution to each ensemble member after the analysis step.
- Env. Canada uses random samples of isotropic 3DVar covariance matrix.
- NCEP uses random samples of 48-h – 24-h forecast error (fcsts valid at same time).
- Simple model study shows that additive inflation better than multiplicative inflation at representing model uncertainty.
- More desirable to simulate model uncertainty at the process level (in the model).

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

- Schemes tested:
  - SPPT (stochastically perturbed physics tendencies)
  - SKEB (stochastic KE backscatter)
  - VC (vorticity confinement) *– abandoned, since it increased ensemble mean error.*
  - SHUM (perturbed boundary layer humidity, based on Tompkins and Berner 2008, *DOI: 10.1029/2007JD009284)*
- All use stochastic random pattern generators to generate spatially and temporally correlated noise.

Examples of stochastic patterns



(from M Leutbecher)

ECMWF method (SPPT)

Stochastically Perturbed Physics Tendency

- Perturbed Physics tendencies

$$X_p = (1 + r\mu) X_c$$

Original physics tendencies

μ: vertical weights: decays to zero with height in stratosphere.

r: horizontal weights (random pattern) : range from -1.0 to 1.0, a red noise process with a

- temporal timescale of 6 hours
- e-folding spatial scale of 500 km

Stochastic boundary-layer humidity

- SPPT only modulates existing physics tendency (cannot change sign or structure, trigger new convection).
- Triggers in convection schemes very sensitive to BL humidity.

$$q_{perturbed} = (1 + r\mu)q$$

- Vertical weight **r** decays exponentially from surface. Added every time step after physics applied. Random pattern **μ** has a (very small) amplitude of ~0.001, horizontal/temporal scales same as SPPT.

Stochastic Kinetic Energy Backscatter

- Algorithm described in Shutts (2005), Berner et al (2009)
  - Designed to represent the effects of dissipated motions near truncation scale on resolved motions.
  - Random patterns are modulated by amplitude of KE dissipation (numerical, possibly other sources like convection – we only consider numerical dissipation here).

Vorticity confinement

(Sanches, Williams and Shutts, 2012 QJR doi 10.1002)

$$\frac{D\mathbf{V_H}}{Dt} + f\mathbf{k} \times \mathbf{V}_H + \nabla\phi = \mu\nabla^2\mathbf{V}_H + \epsilon\hat{\mathbf{n}} \times |\zeta|\,\widehat{\mathbf{k}}$$

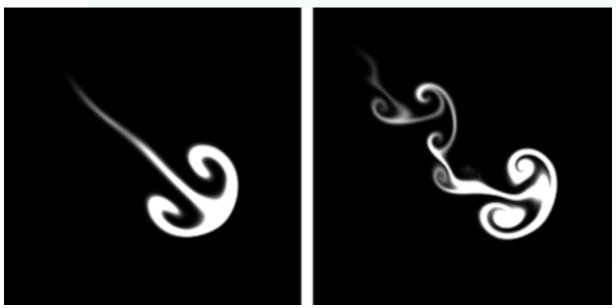
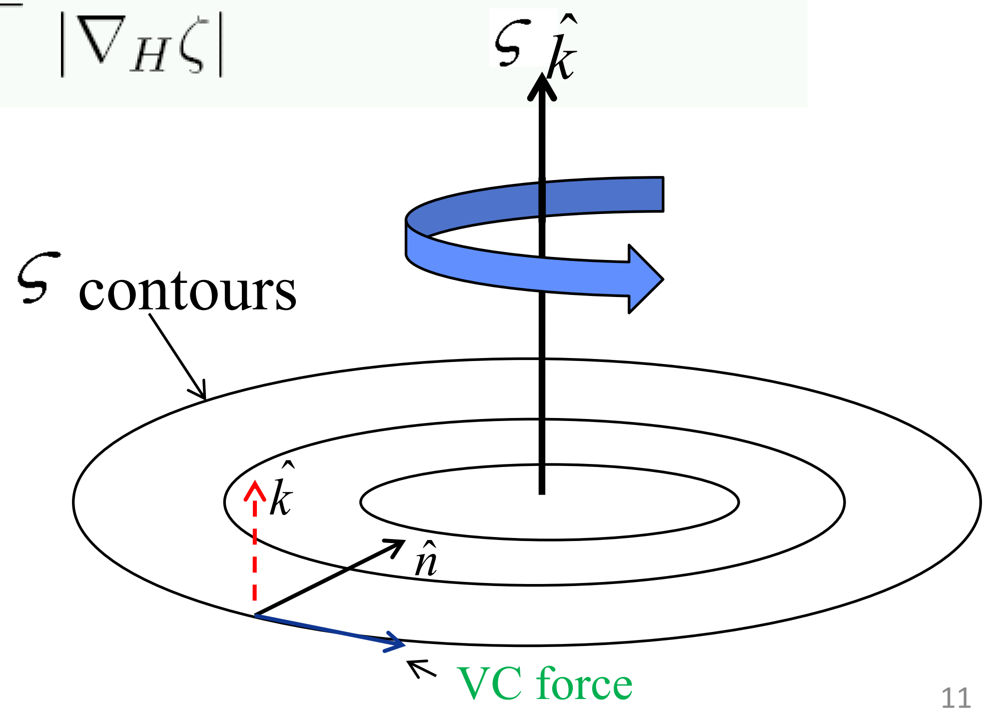


Figure 6: Two frames of animation from two mpeg movies created using `flowanim` and `mpeg2encode`. Both frames depict the 60th frame of the movie. The left animation is created without vorticity confinement, the one on the right with vorticity confinement and a *relatively* high force factor

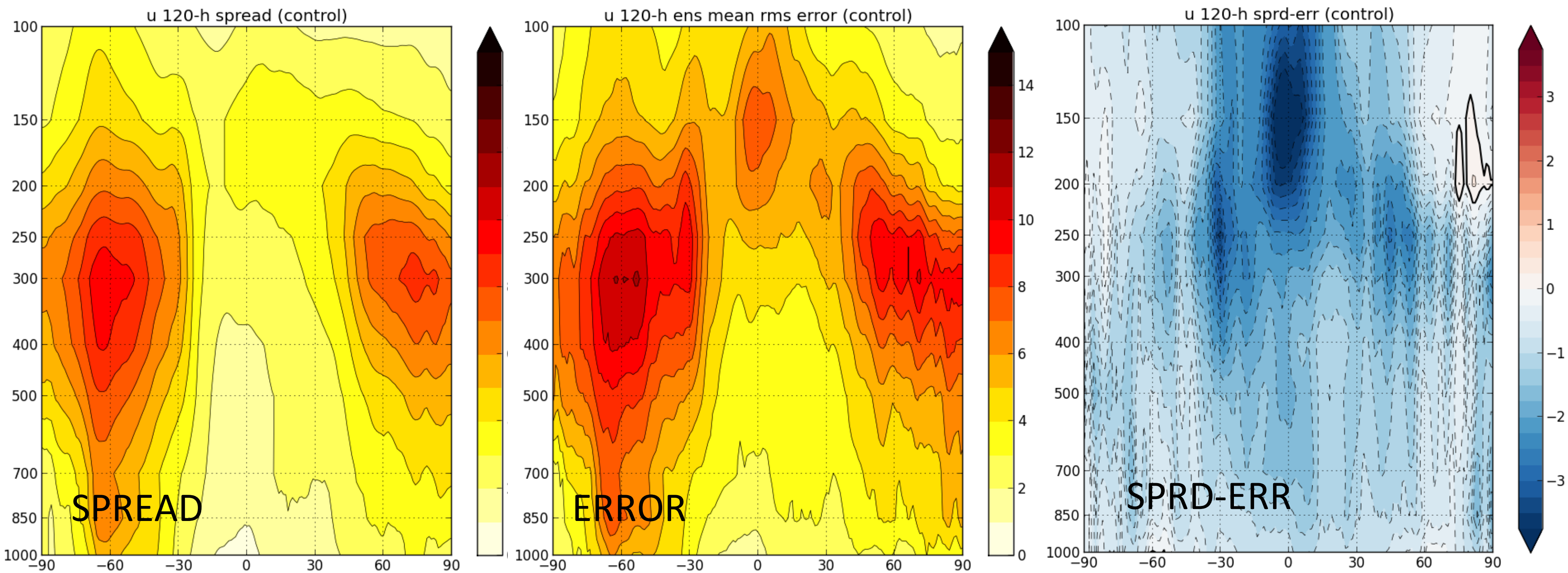
$$\hat{\mathbf{n}} = \frac{\nabla_H\zeta}{|\nabla_H\zeta|}$$



$\epsilon\hat{\mathbf{n}}$ acts as an advective velocity

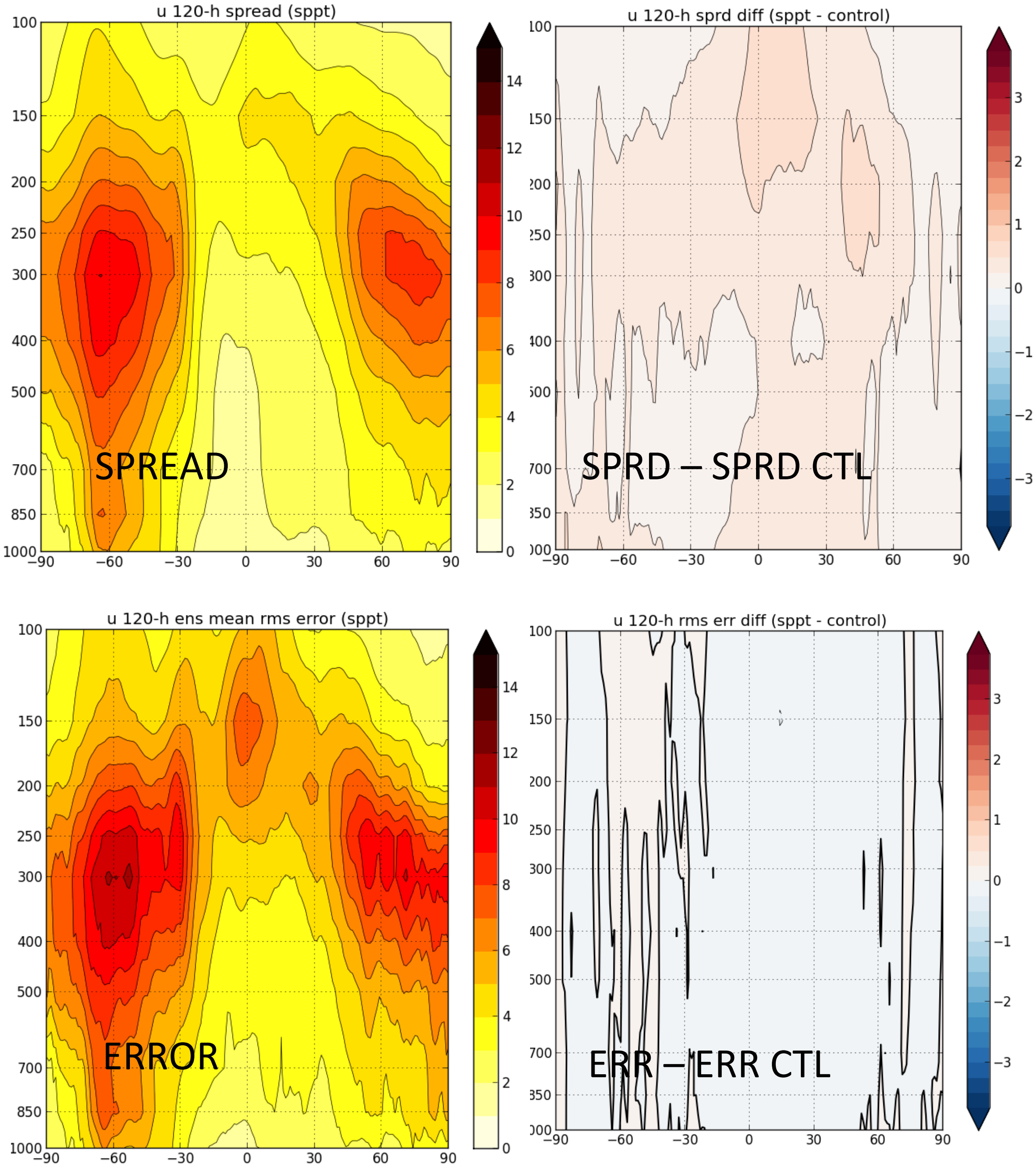
ε=0.6 in our experiments

120-h Control U (no stochastic physics)



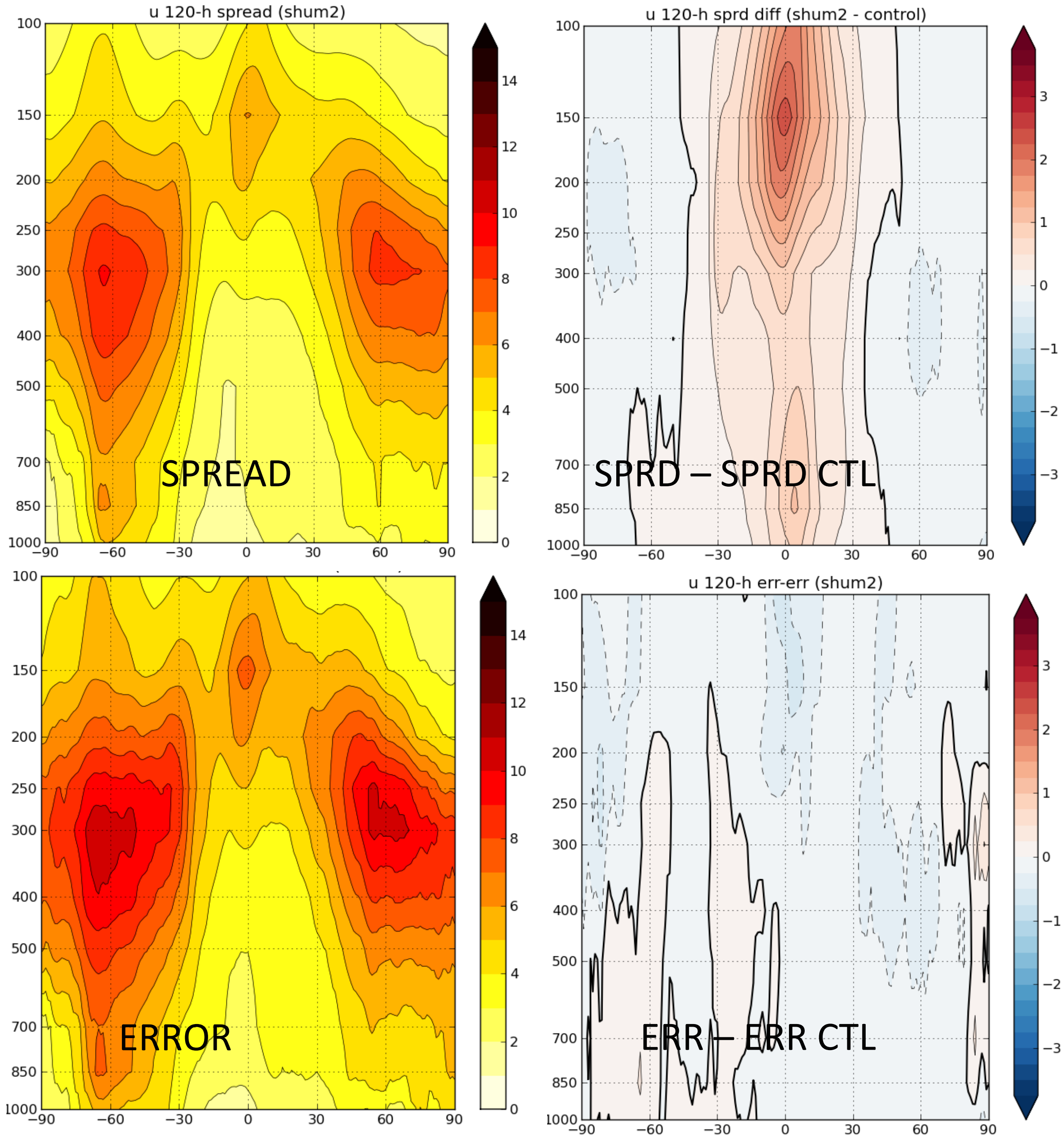
SPPT U

- Slight increase in spread, mostly in tropics. All in all, very little effect.
- Ens mean error unchanged.



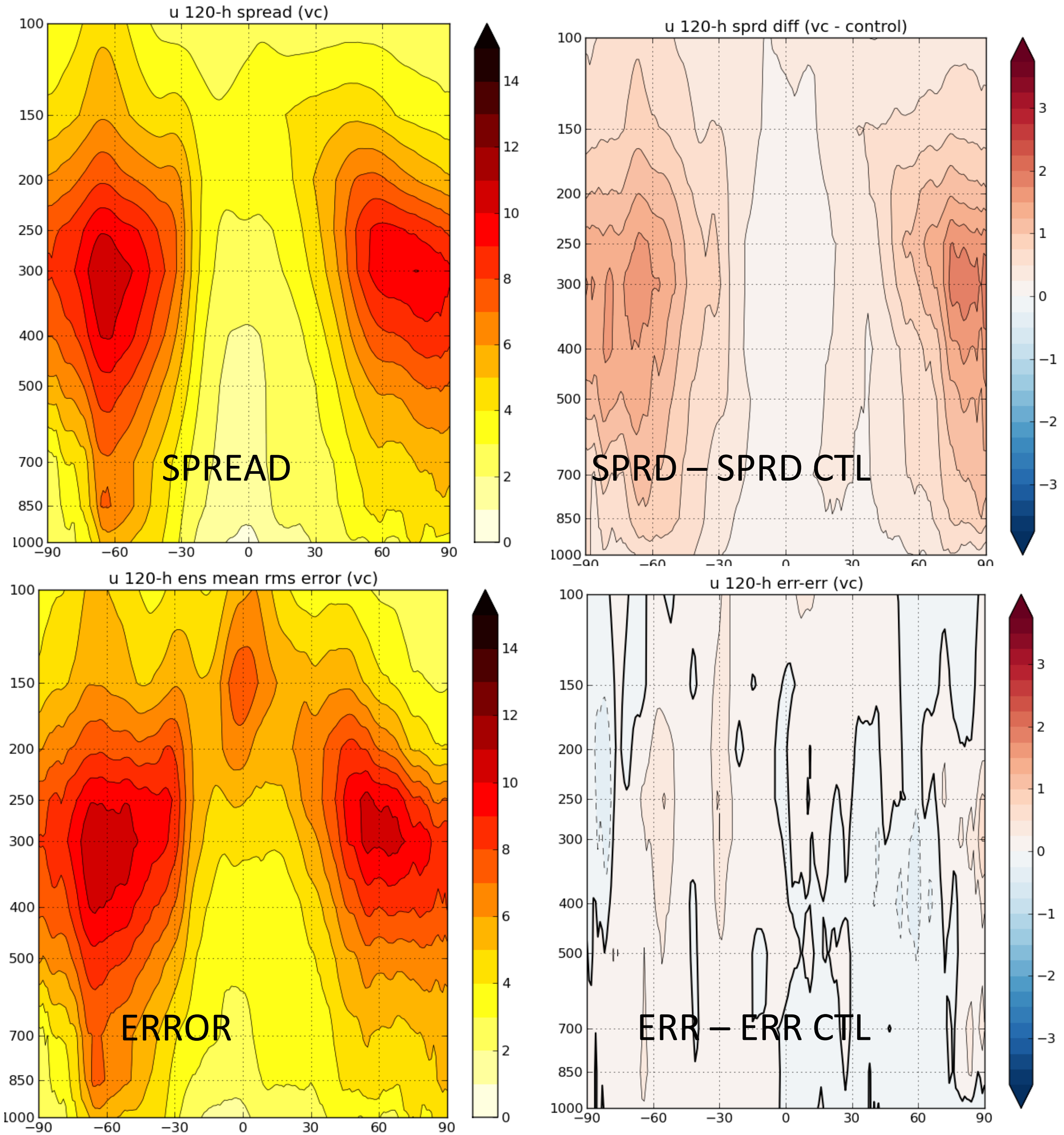
SHUM U

- Spread/error consistency improved in tropics, esp. in upper trop (max in error near tropopause reproduced in spread).
- Little or no effect in winter hemisphere poleward of 30.
- Ens mean error reduced in tropical upper trop and summer hem.



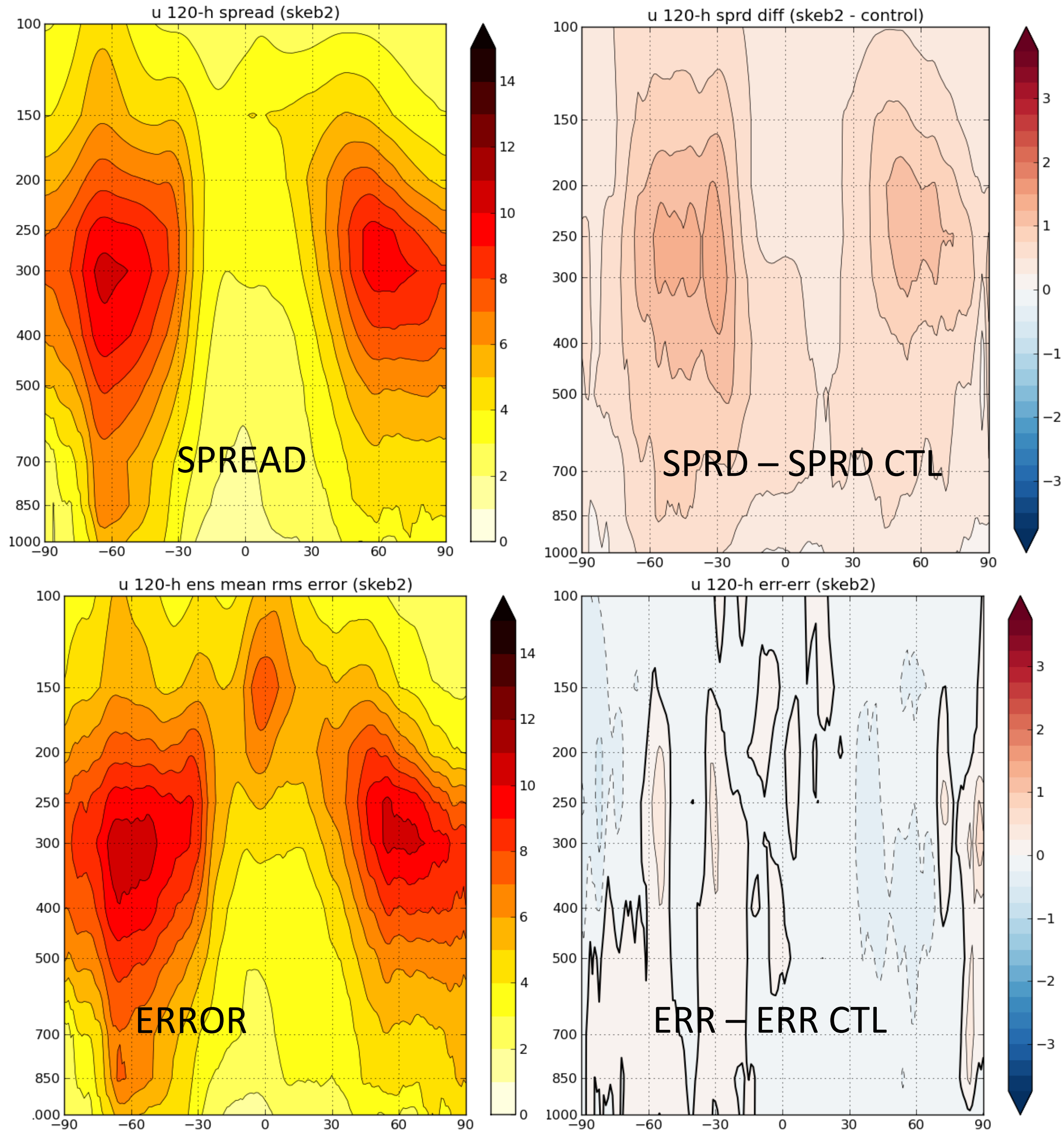
VC U

- Spread increase mainly in extratropics.
- Little or no spread increase in tropics..
- TCs made stronger.
- Ensemble mean error increased.



SKEB U

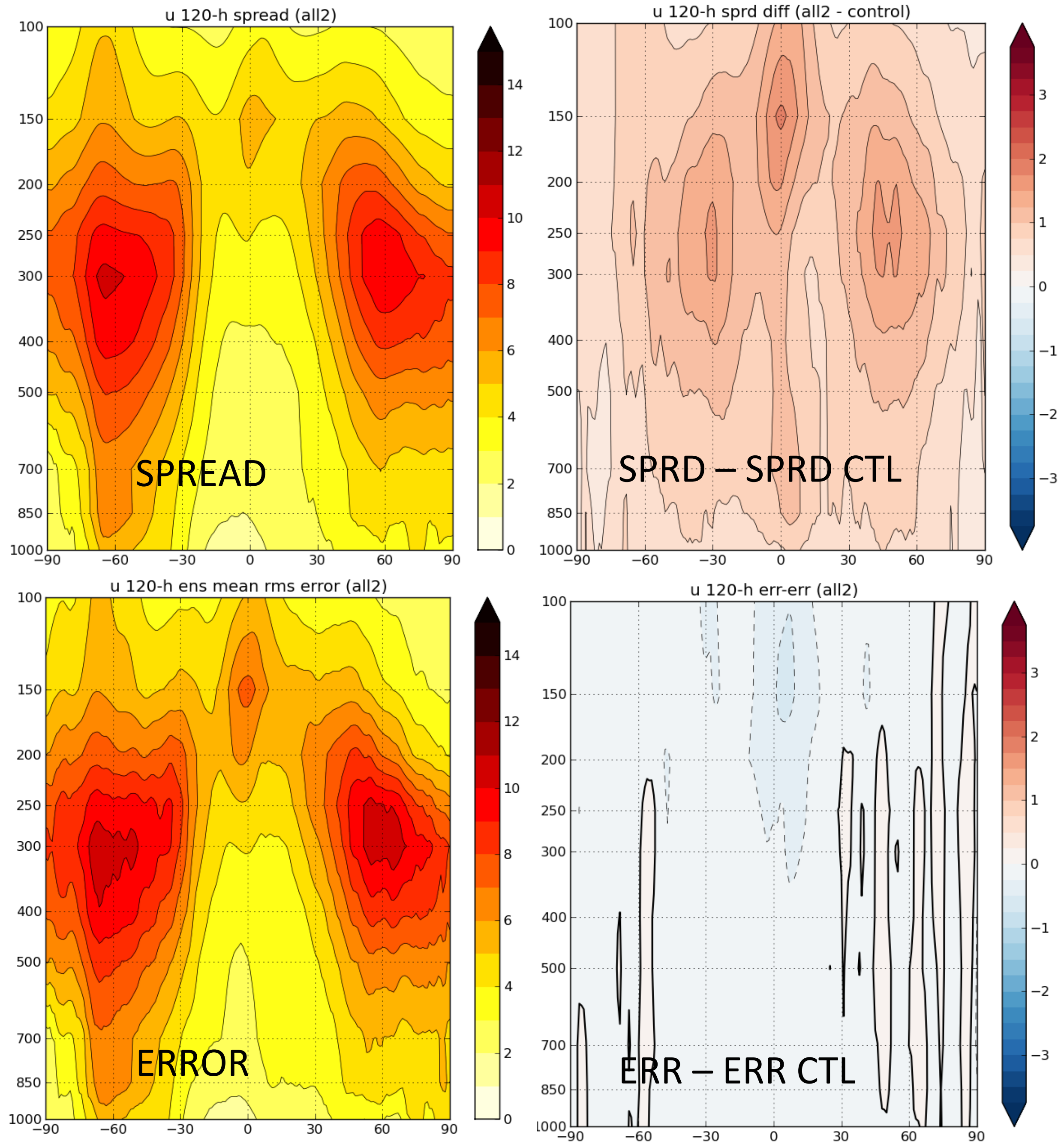
- Spread increased in mid-latitude jets (where numerical dissipation is active)
- Less effect in tropics (convective dissipation not included), but does add spread in lower trop.
- Neutral impact on ens mean error.



SPPT+SHUM +SKEB U

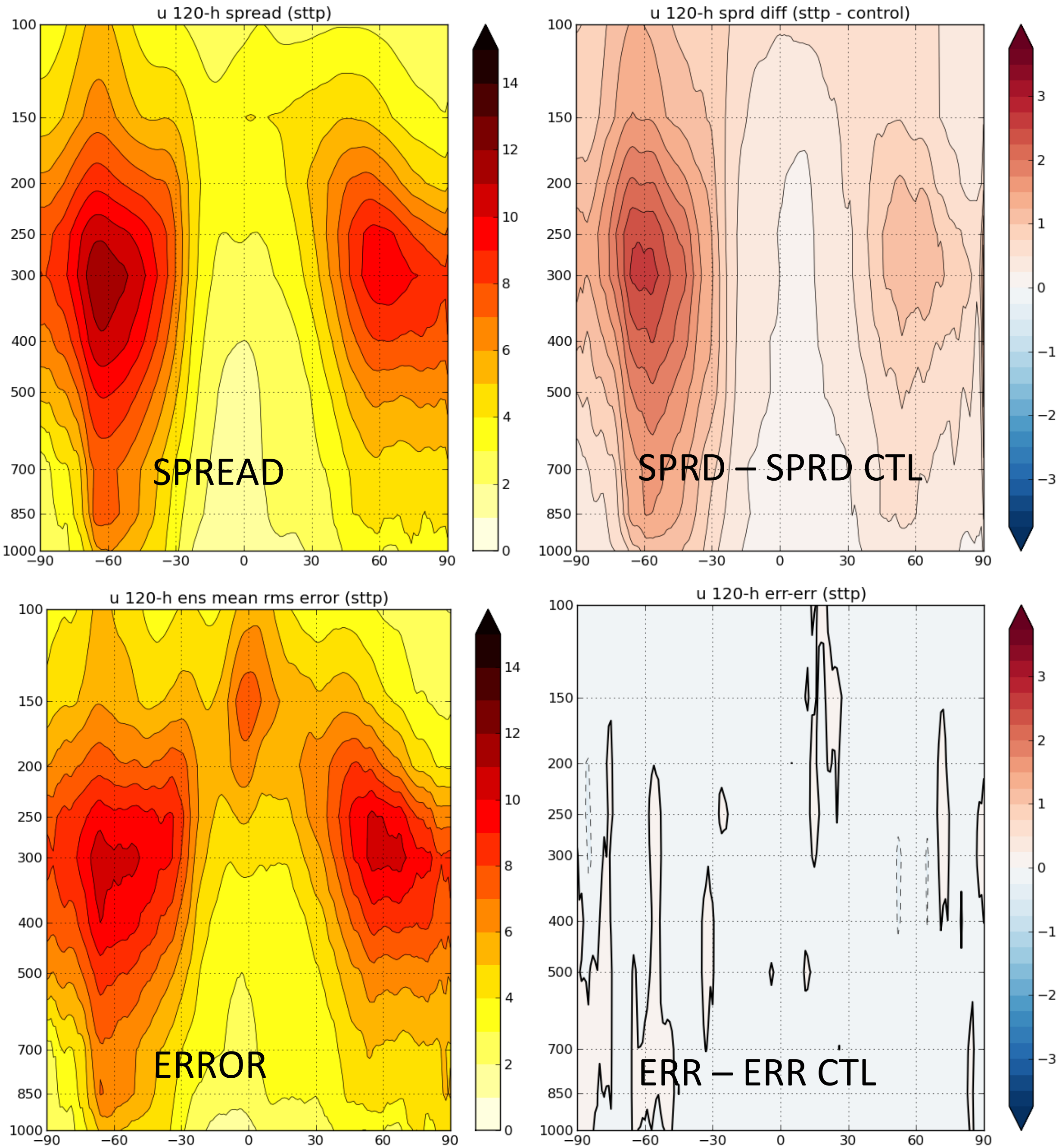
- Still slightly deficient in spread (not the case with height field)
- Ens mean error slightly reduced in tropics.

But is it "good" spread? Does it improve covariances in EnKF?



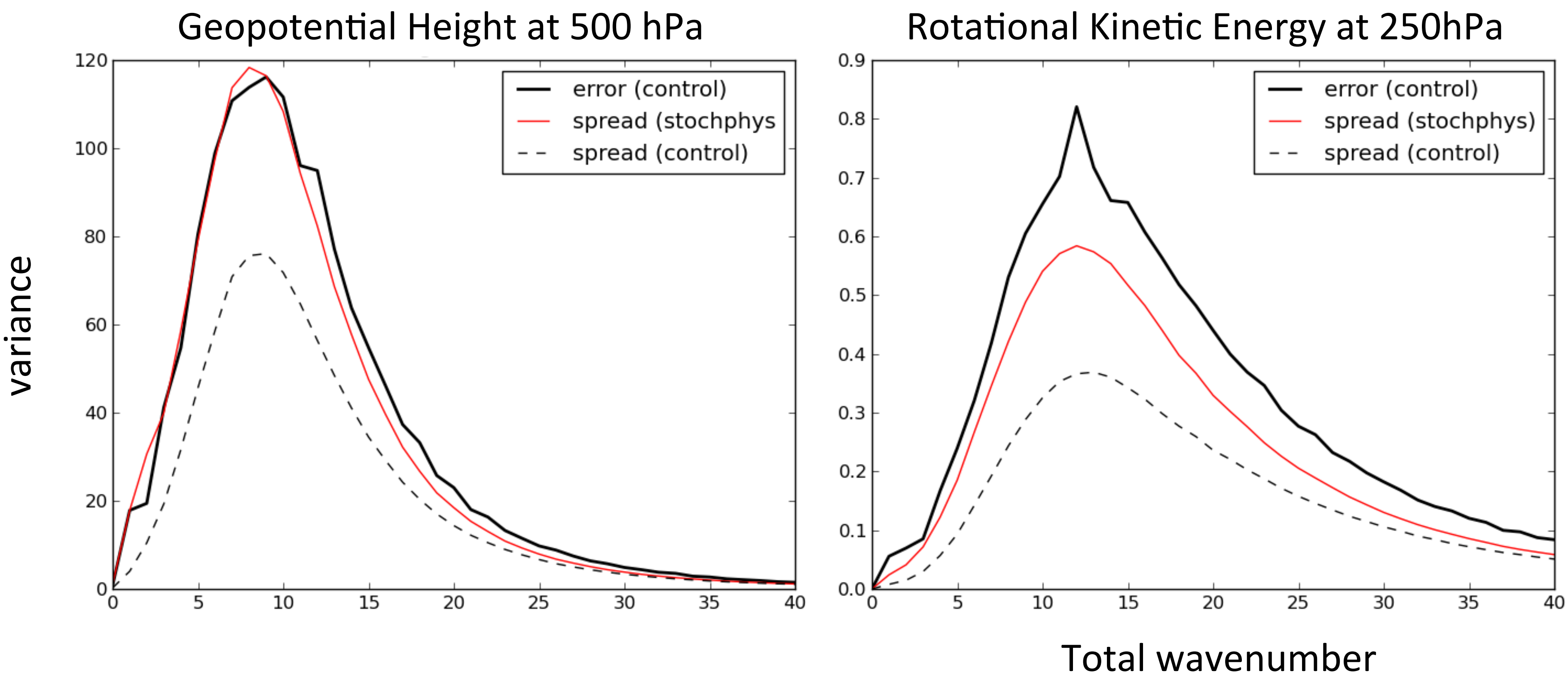
Operational STTP

- Spread added mainly in winter hemisphere
- Neutral impact on ens mean error.



Total wavenumber spectra (global)

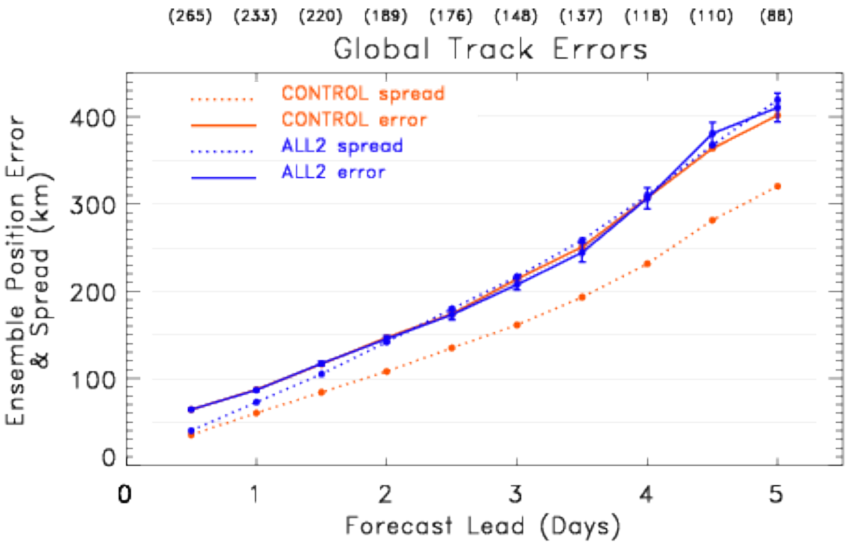
control vs SKEB+SPPT+SHUM



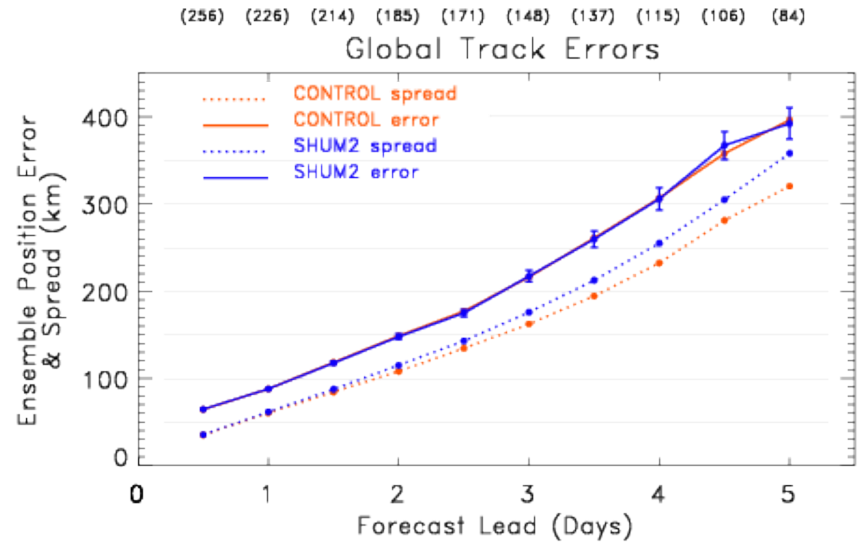
- *Well calibrated at larger scales in mass field.*
- *Still spread deficient at all scales for wind field.*

Track Errors

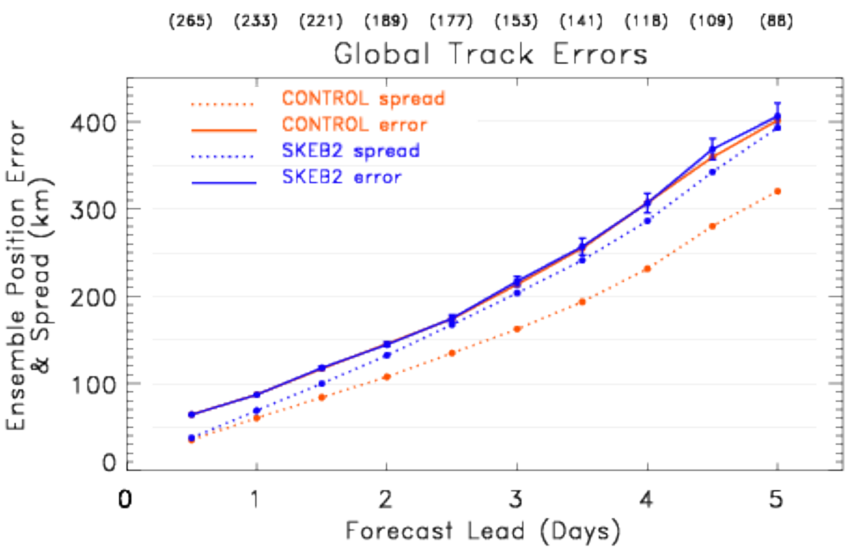
ALL



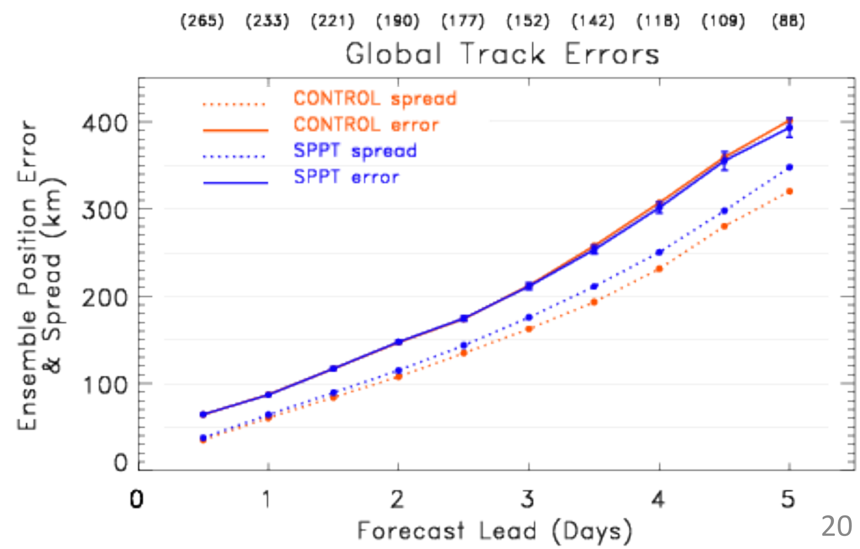
SHUM



SKEB



SPPT



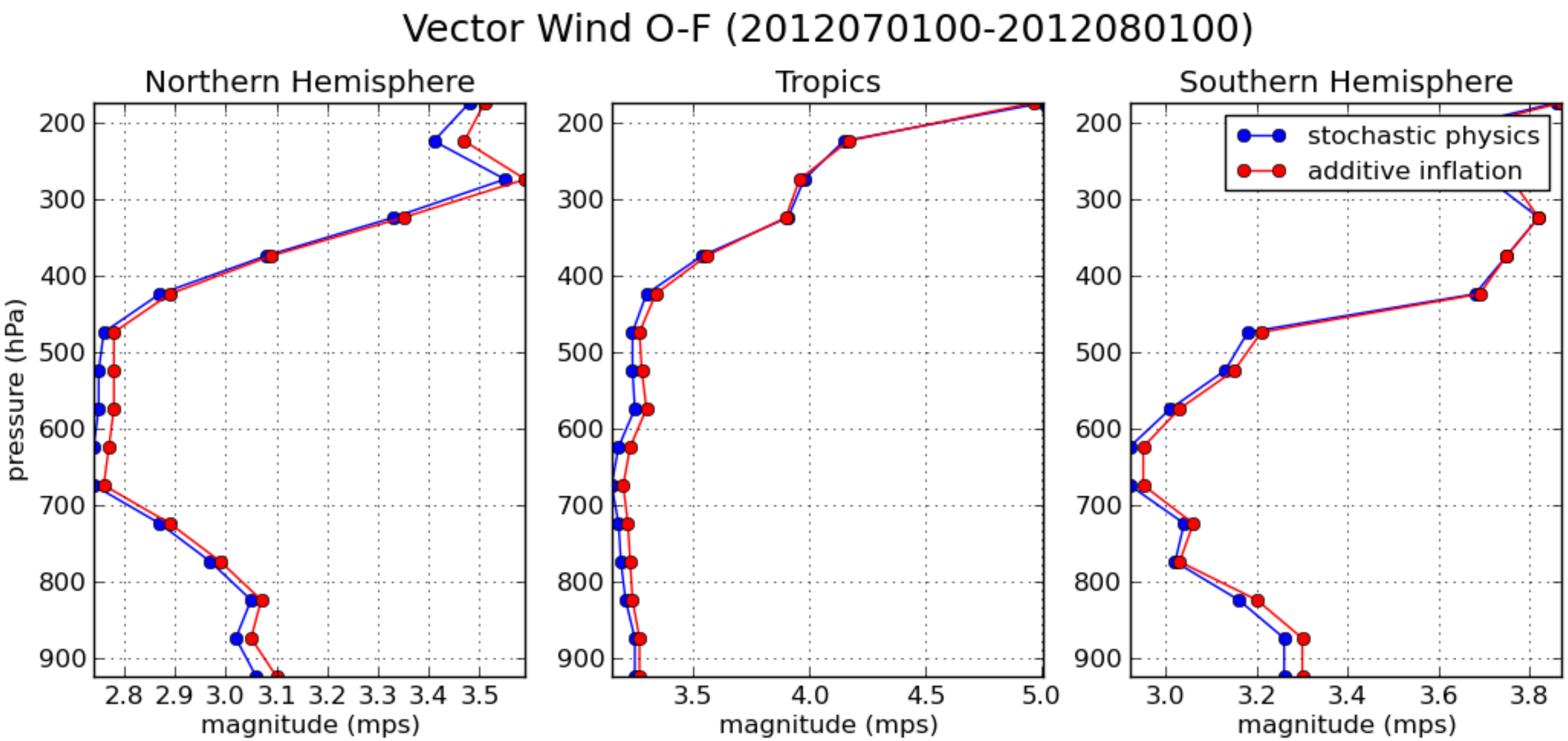
3d-ensemble Var DA expts

- Lower res version of ops (T254/T126 instead of T574/T254).
- Control with additive+multiplicative inflation (as in ops) and no stochastic physics.
- Expt with additive inflation replaced by stochastic physics (mult. Inflation unchanged).

Replacing additive inflation with stochastic physics

red: *control (with additive inflation)*

blue: *Turn off additive inflation, include stochastic physics in model (only in ensemble forecast)*.



Replacing additive inflation with stochastic physics

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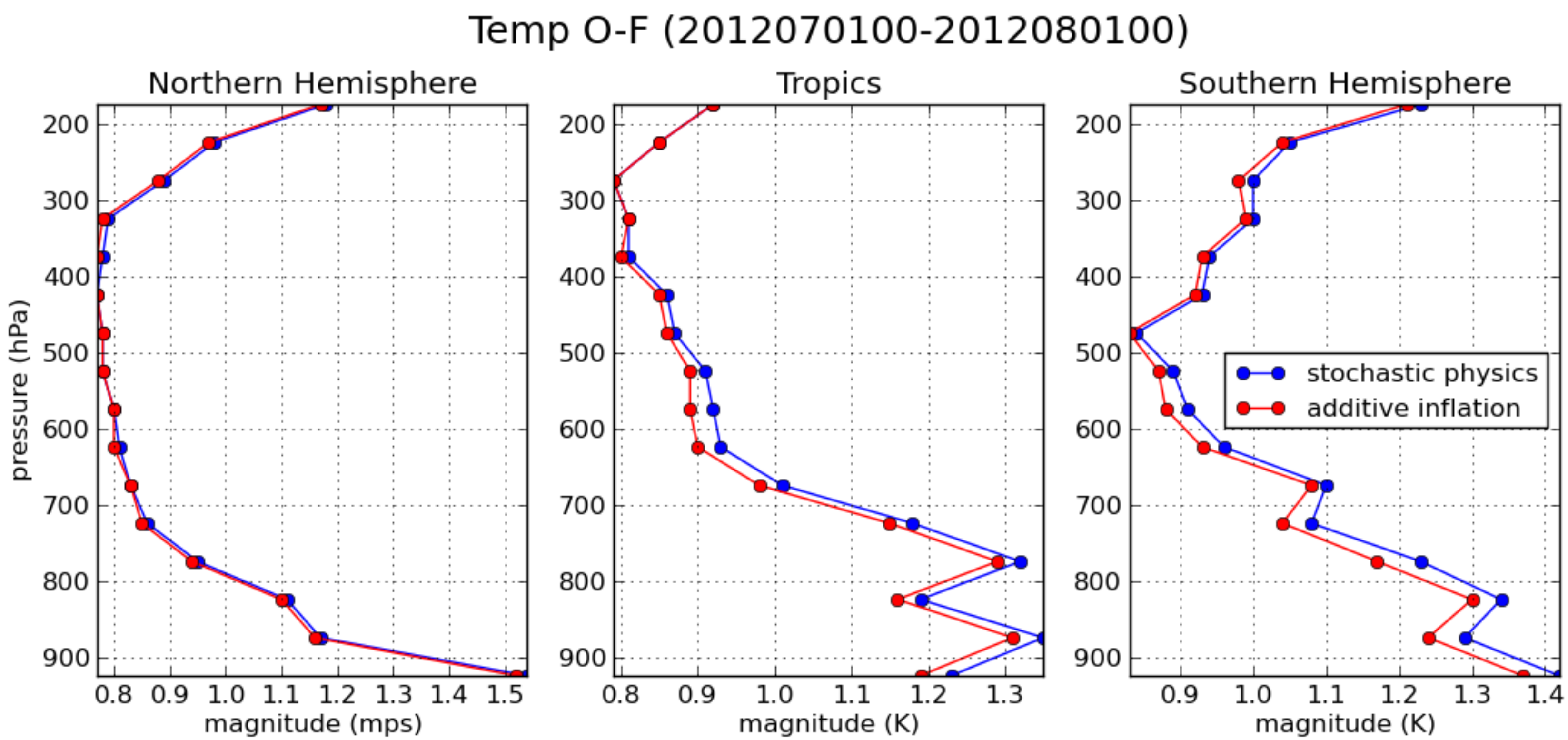

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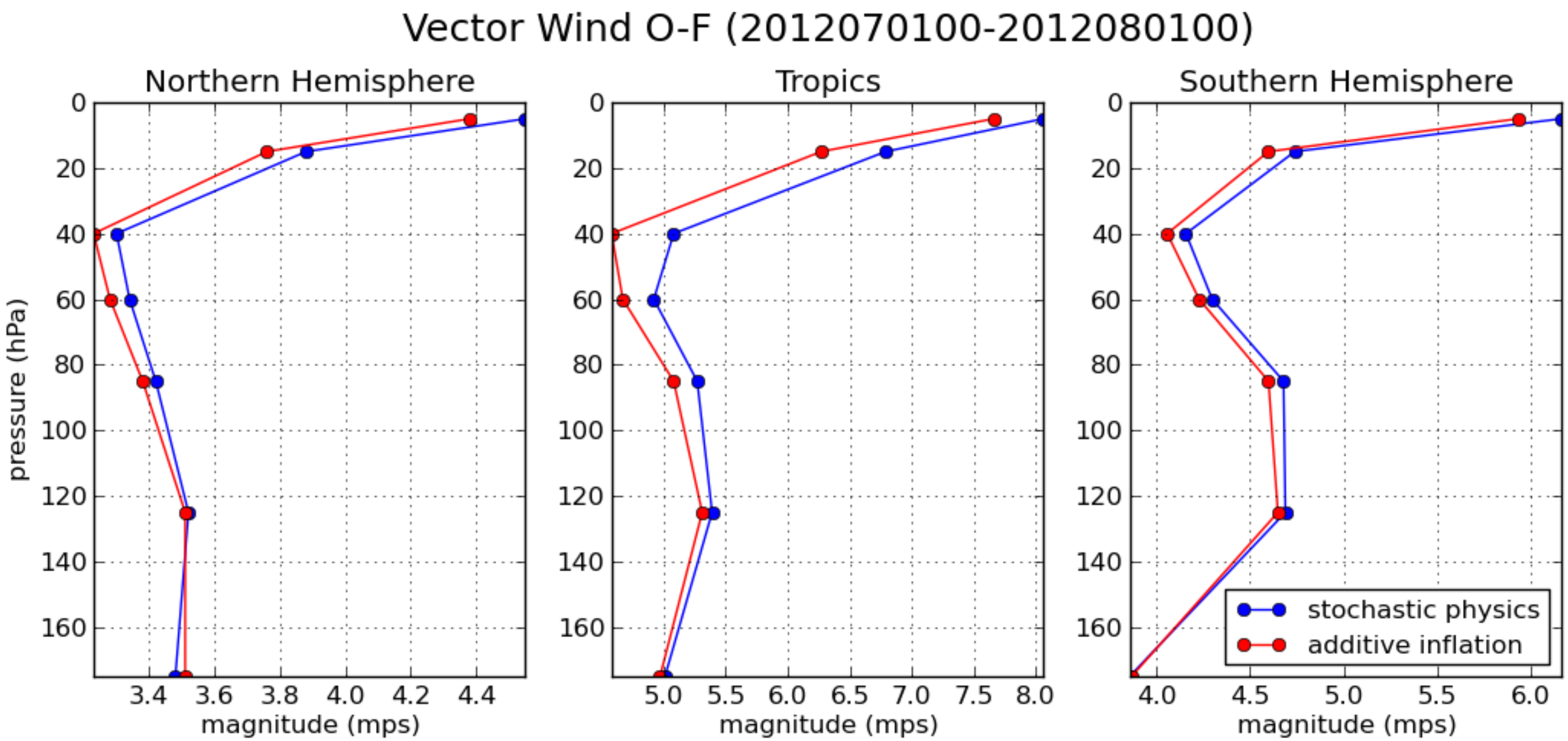
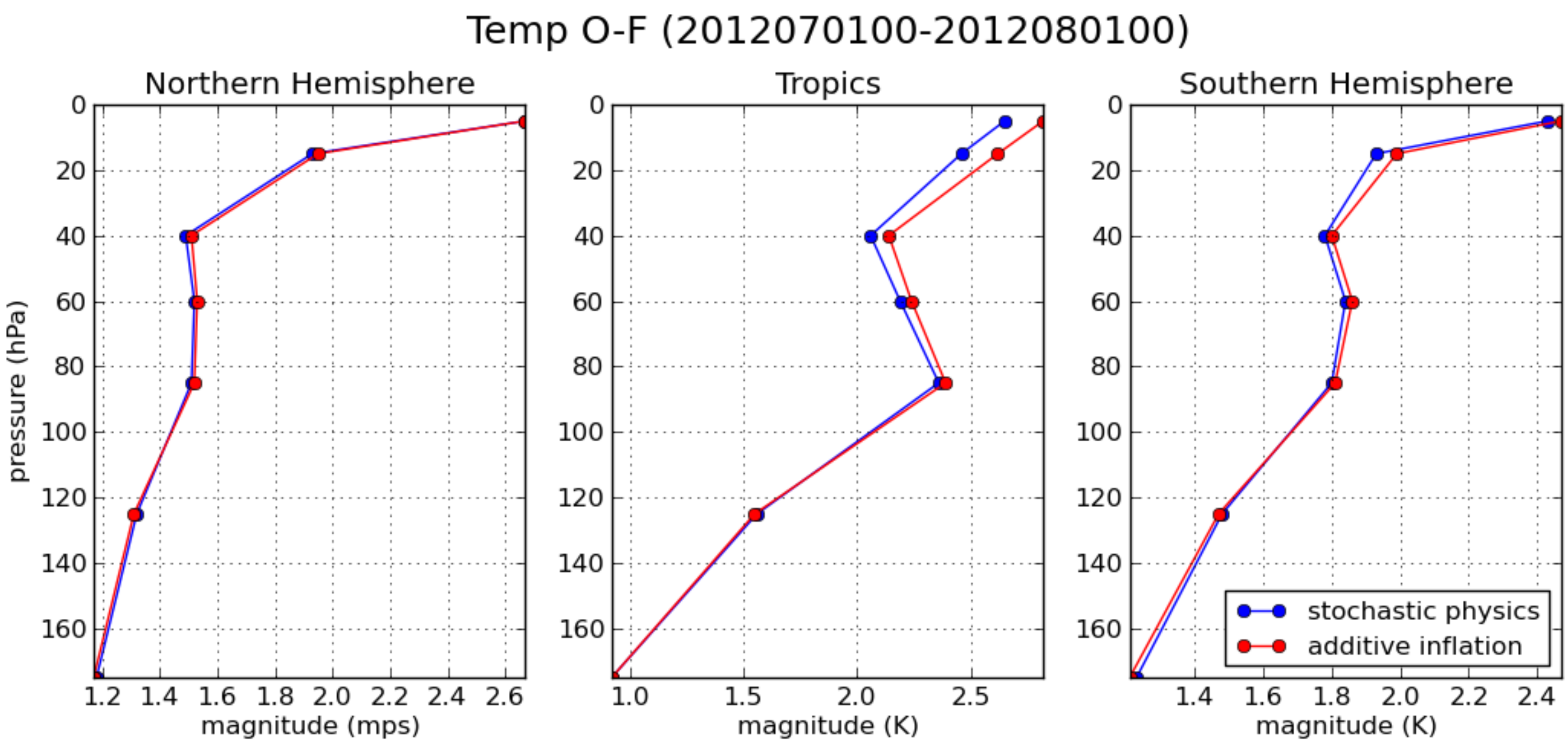


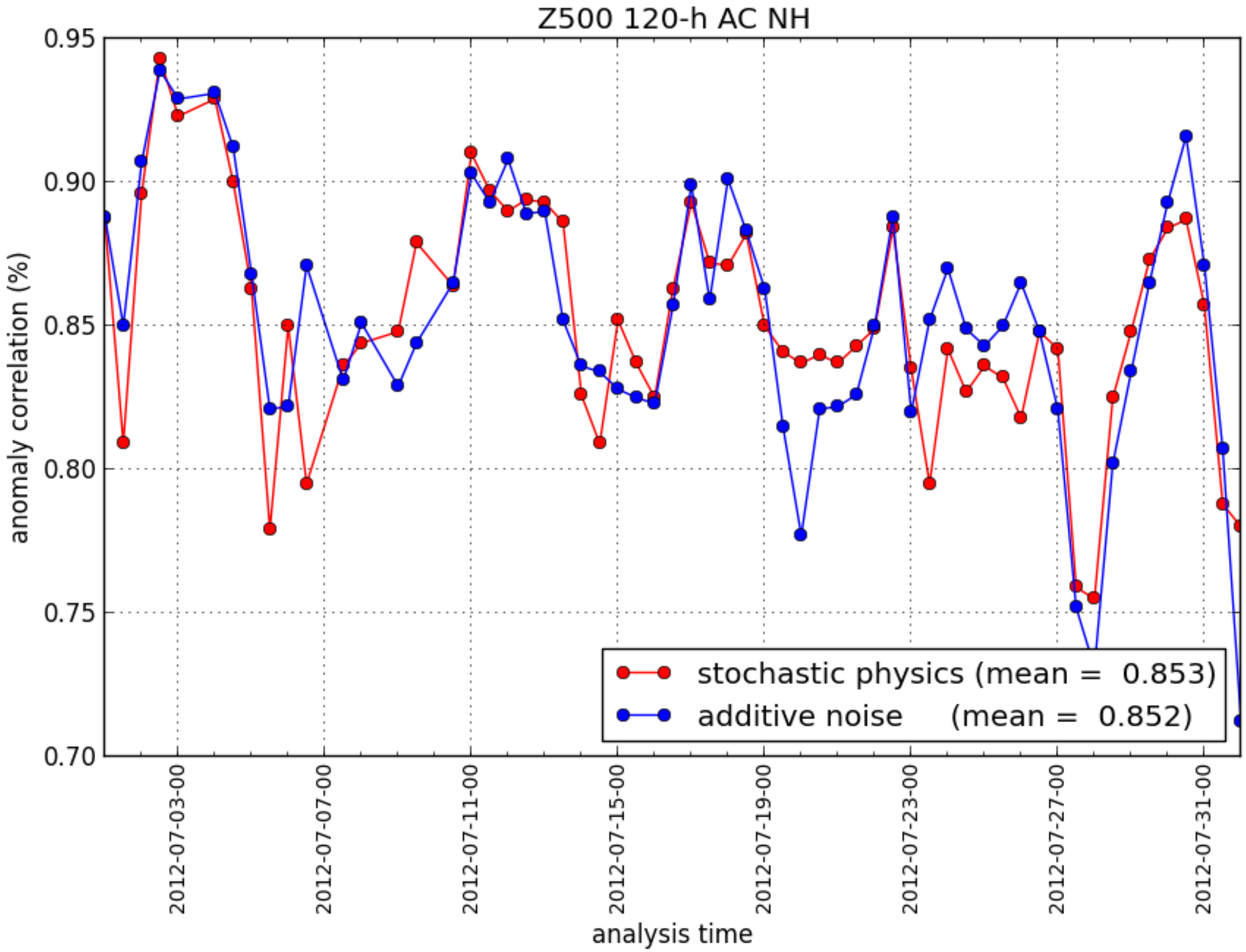
Replacing additive inflation with stochastic physics

red: *control (EnKF with additive inflation)*

blue: *Turn off additive inflation, include stochastic physics in model (only in ensemble forecast)*.

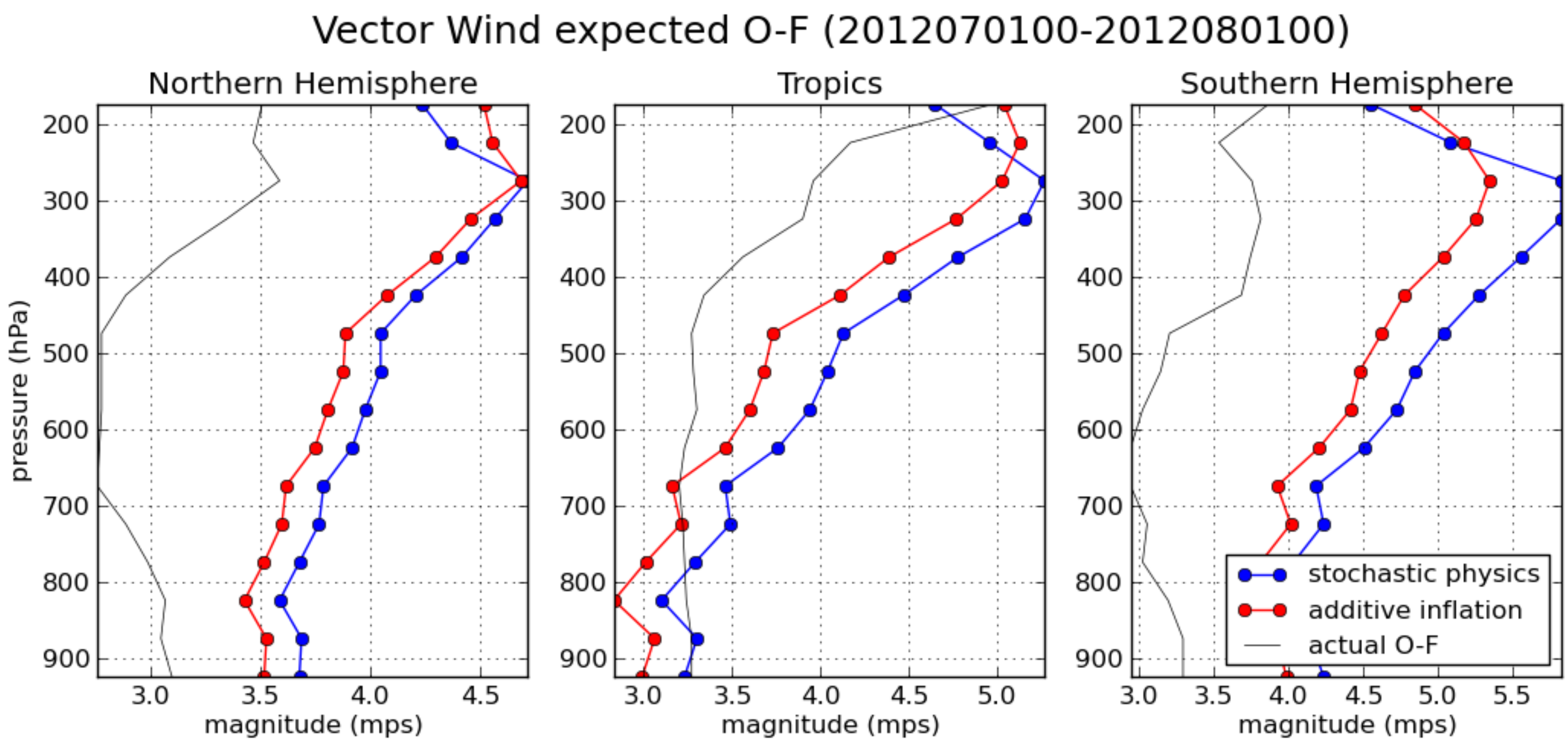


5-day control (T254) forecast skill

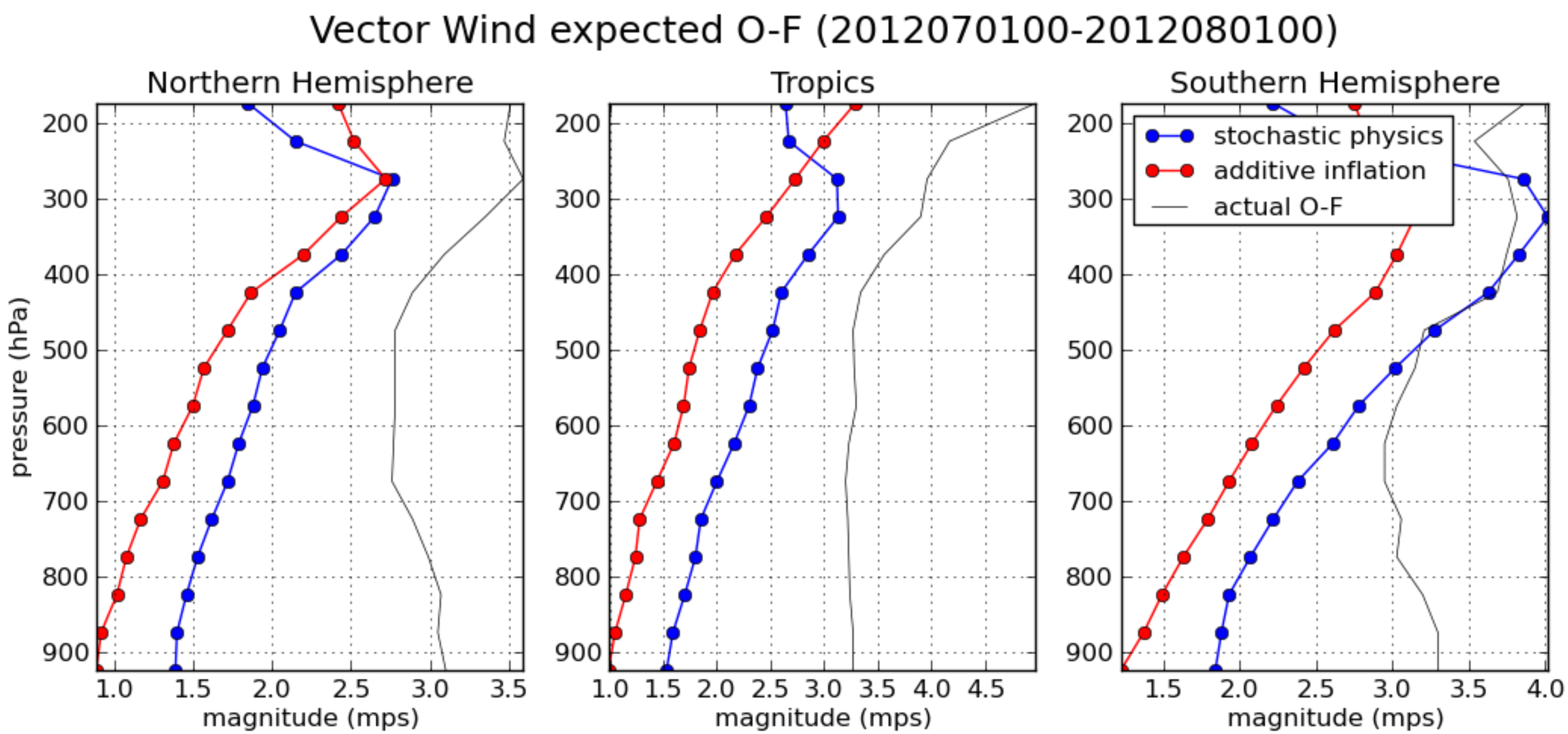


No significant difference in 5-day forecast skill

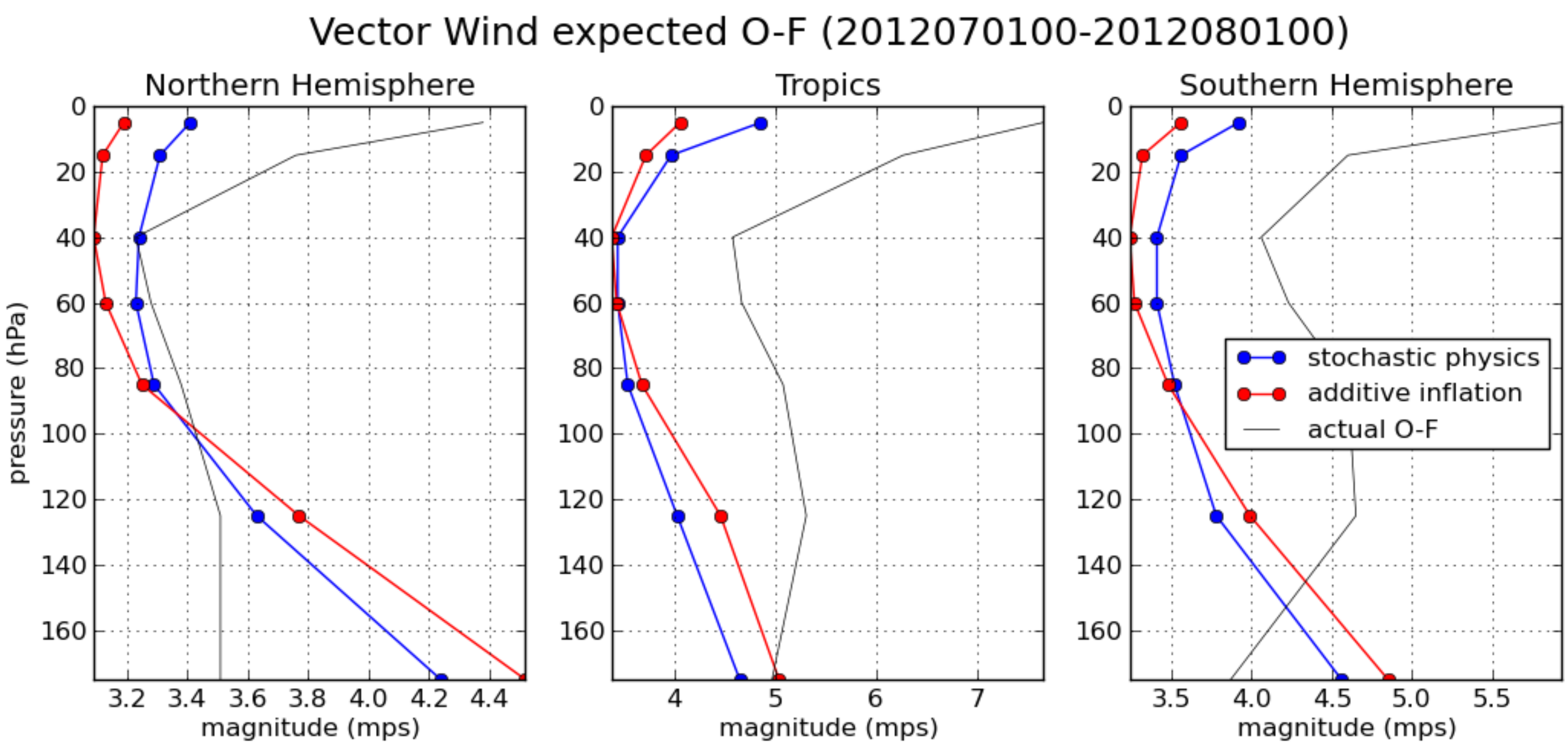
Expected vs Actual RMS ens mean innovations (tropospheric vector wind)



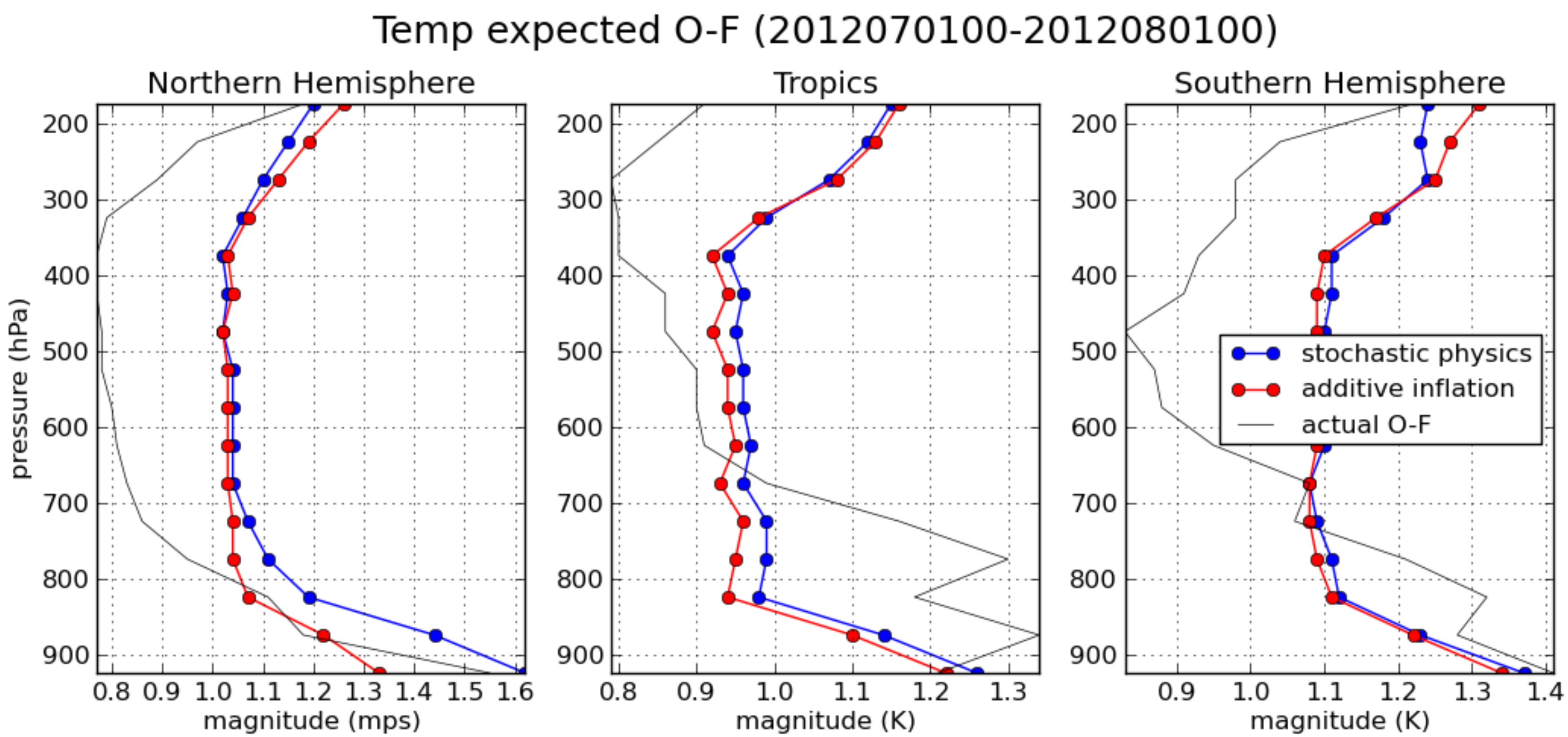
Ens Spread vs RMS ens mean innovations (tropospheric vector wind)



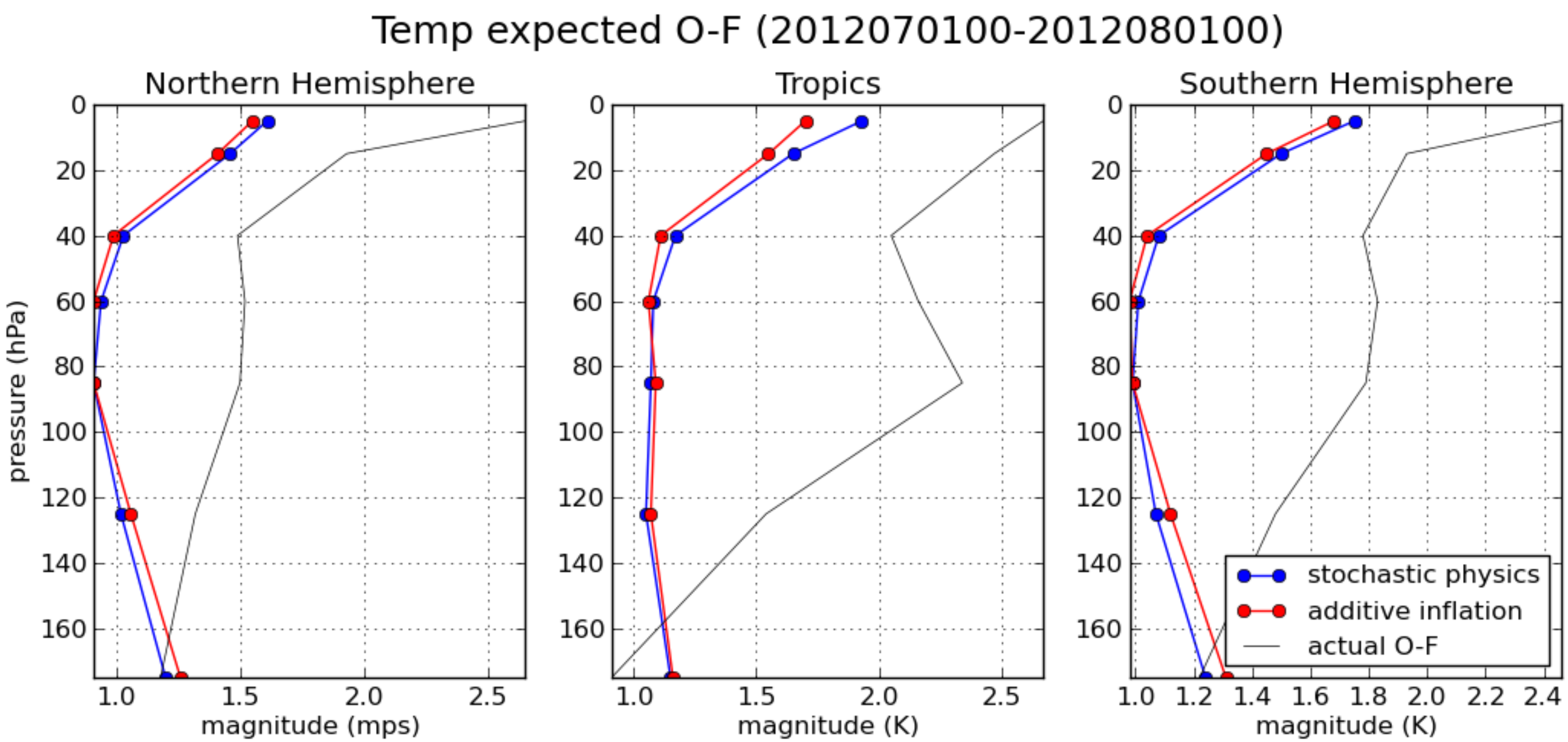
Expected vs Actual RMS ens mean innovations (stratospheric vector wind)



Expected vs Actual RMS ens mean innovations (tropospheric temperature)



Expected vs Actual RMS ens mean innovations (stratospheric temperature)



Conclusions

- Stochastic schemes added to GFS (branch EXP-stochphy, track ticket #58).
- A combination of SKEB+SHUM (and possibly SPPT) looks to be an improvement upon STTP along for medium range ensembles.
- It's hard to improve upon ad-hoc inflation for DA, but..
- Initial expts show impact of stochastic is slightly positive in trop, slightly negative for winds in strat. Multiplicative inflation still needed. Spread too large in trop. Should be able to replace additive inflation in DA cycle (with tuning).
- Stochastic physics should form a basis for further improvement (by treating model uncertainty the process level in each parameterization scheme).

Experiences with Env. Canada system

(Houtekamer, Mitchell and Deng, MWR July 2009)

- Operational EnKF tested with
  - Multiple parameterizations
  - SKEB (stochastic kinetic energy backscatter)
  - SPPT (stochastically perturbed physics tend)
  - Additive inflation (isotropic covariance structure)
  - Multi-physics plus additive inflation

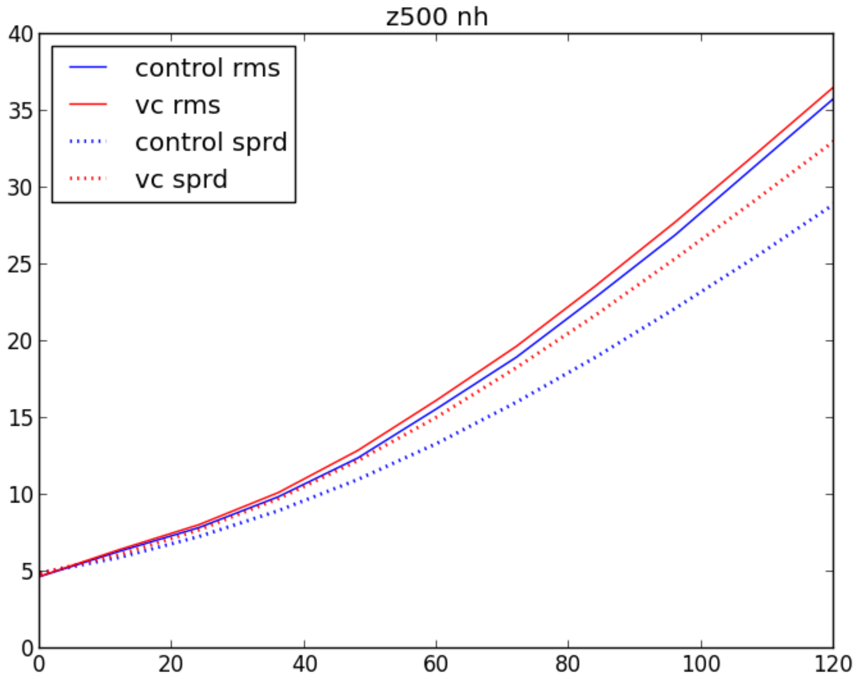
Experiences with Env. Canada system

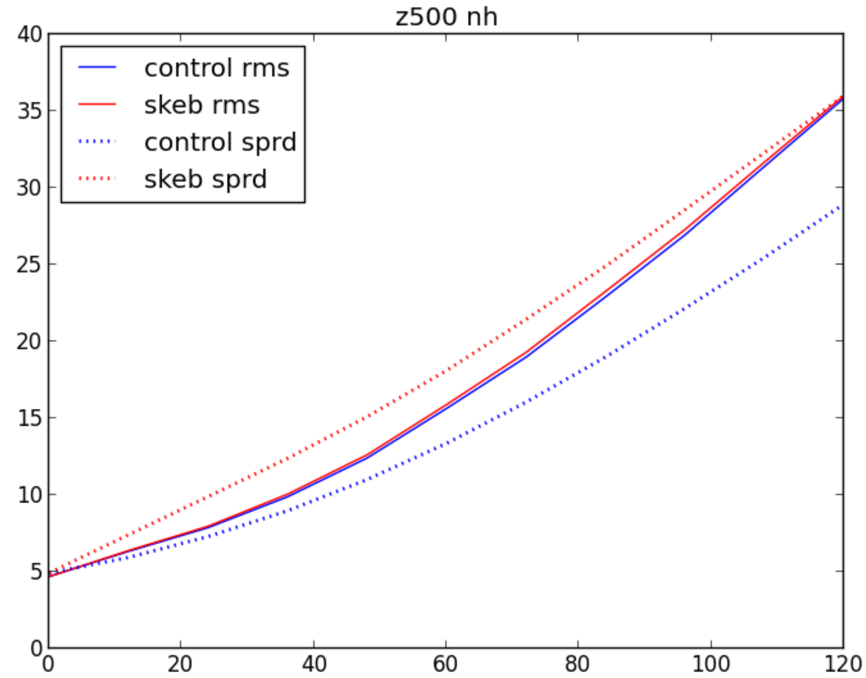
(Houtekamer, Mitchell and Deng, MWR July 2009)

configuration	O-F (energy norm)	Energy spread in ob space
Additive inflation	3.1388	2.0622
Multi-physics	3.2978	1.2773
SKEB	3.4348	1.2671
SPPT	3.3899	1.1670
Multi-physics + add. Infln.	3.0846	2.1335
SKEB + SPPT	3.3352	1.3608
SKEB+SPPT+Mult-physics +rescaled additive infln.	3.0940	2.1092

- Biggest impact from ad-hoc additive inflation.
- Addition of multi-physics improves assimilation slightly.
- SPPT and SKEB have less impact (tuned for EPS?, model error not dominant?)

SKEB vs VC

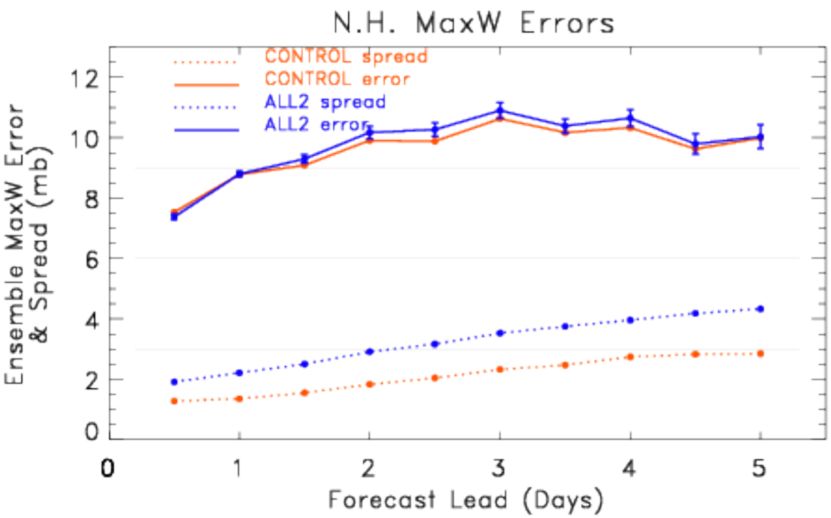




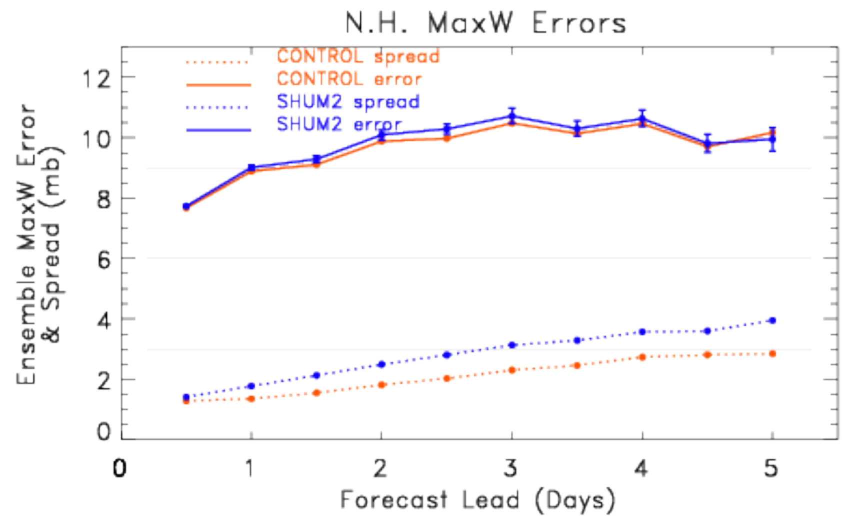
- *VC increases ensemble mean error.*
- *SKEB produces faster spread growth.*

Max Wind Errors

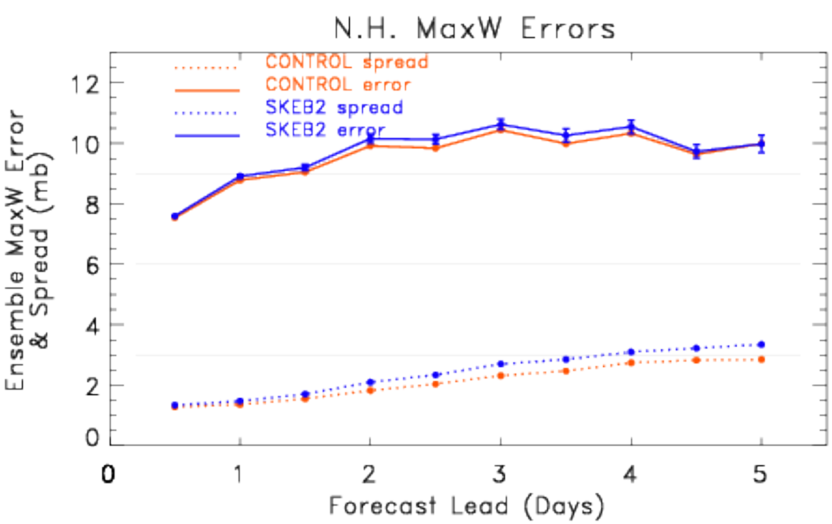
ALL



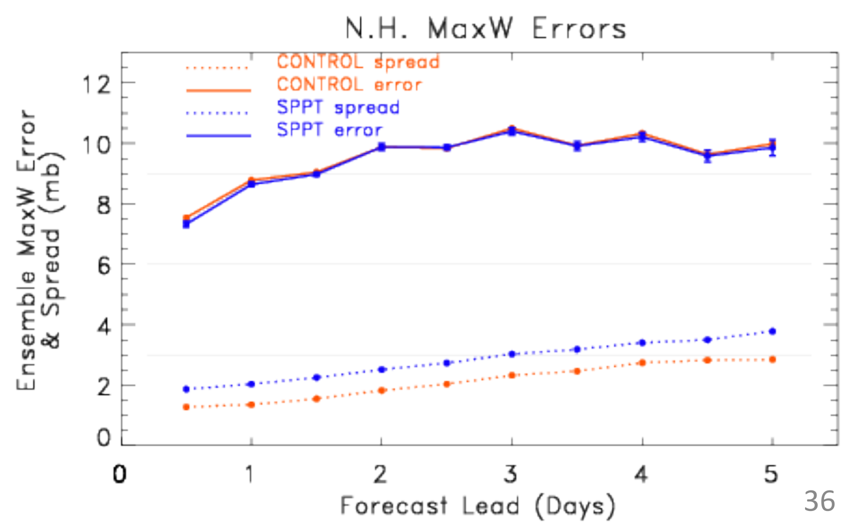
SHUM



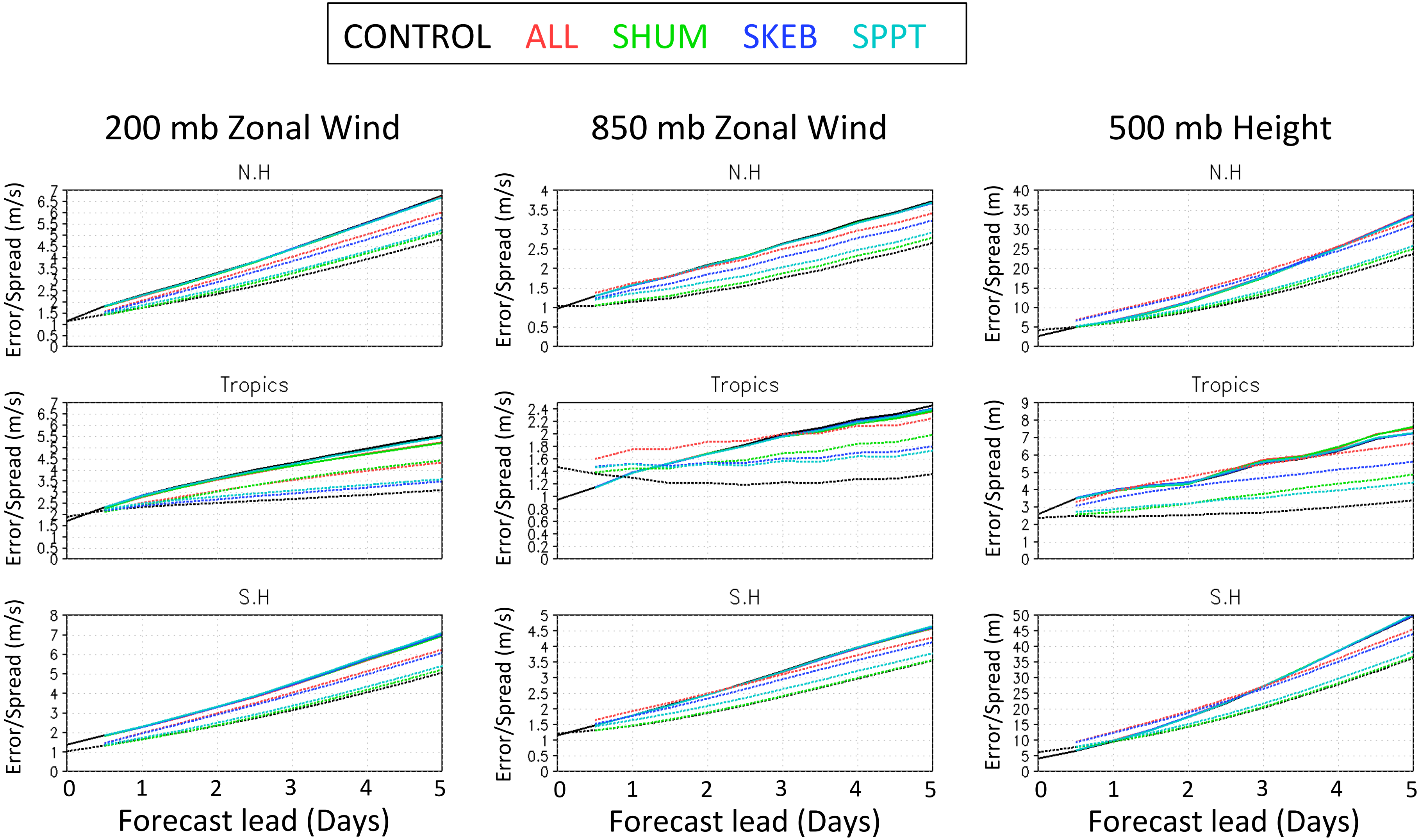
SKEB



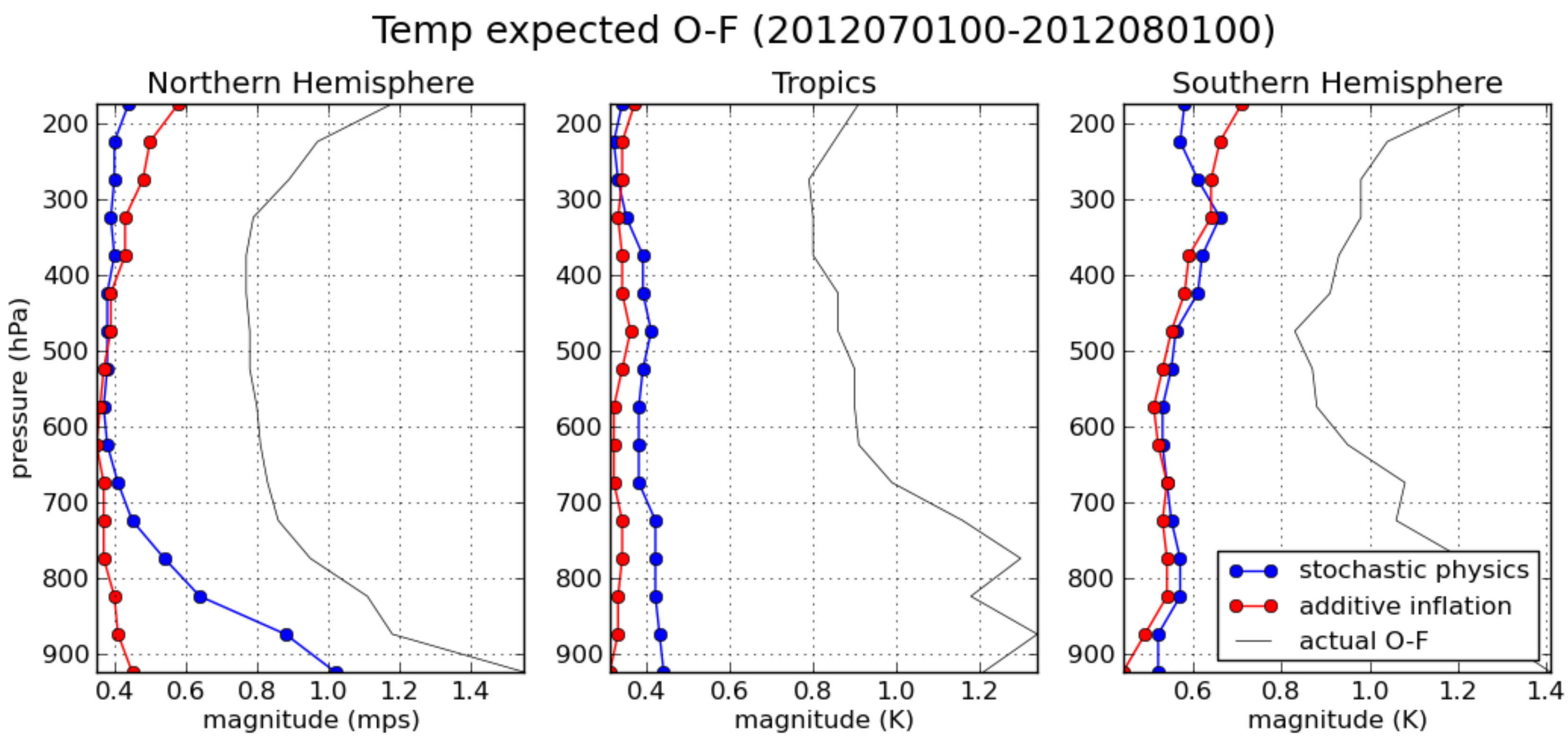
SPPT



Forecast Error and Ensemble Spread



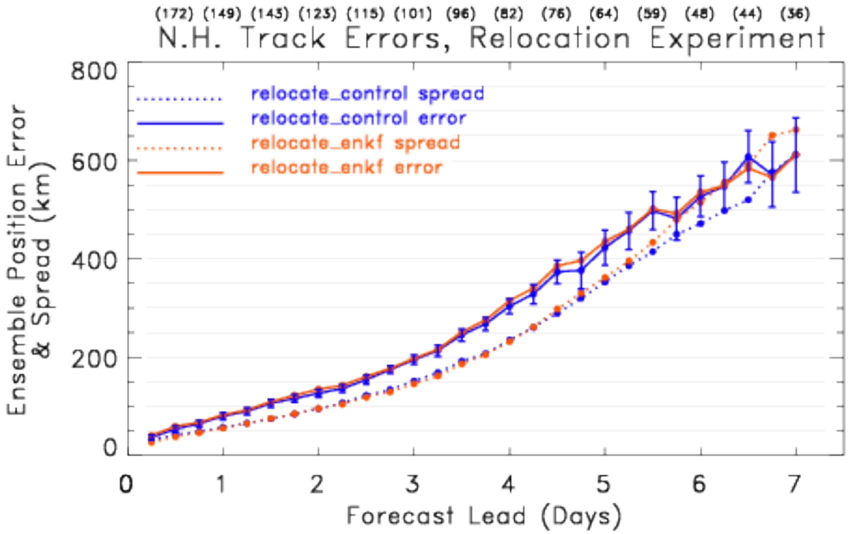
Ens. Spread vs RMS ens mean innovations (tropospheric temperature)



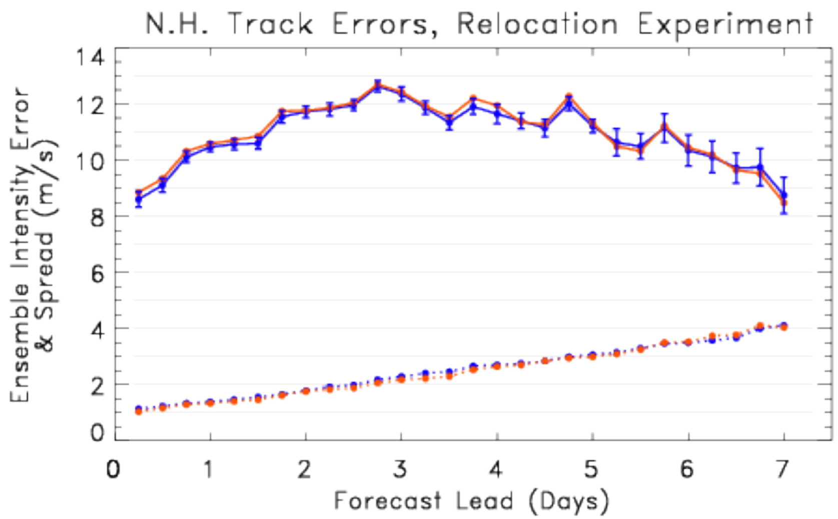
Relocation Experiment Track Errors (6-168 hrs)

20-member Ensemble

Track Error/Spread



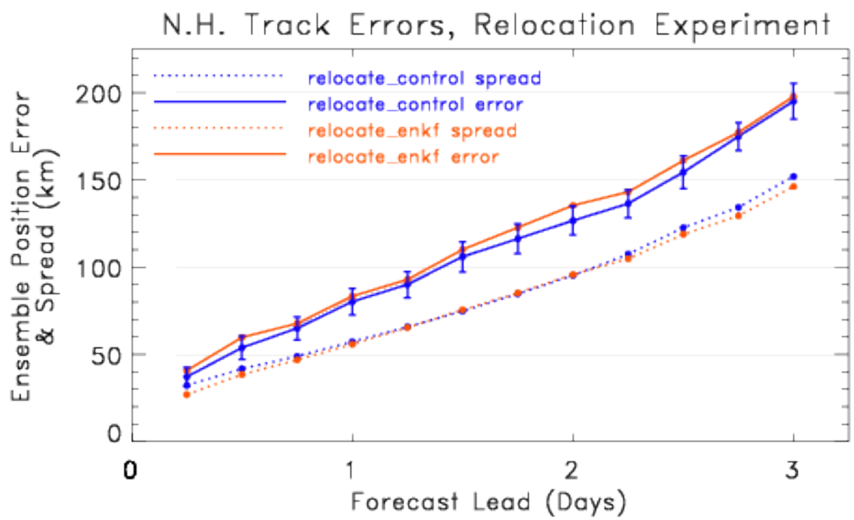
Max Winds Error/Spread



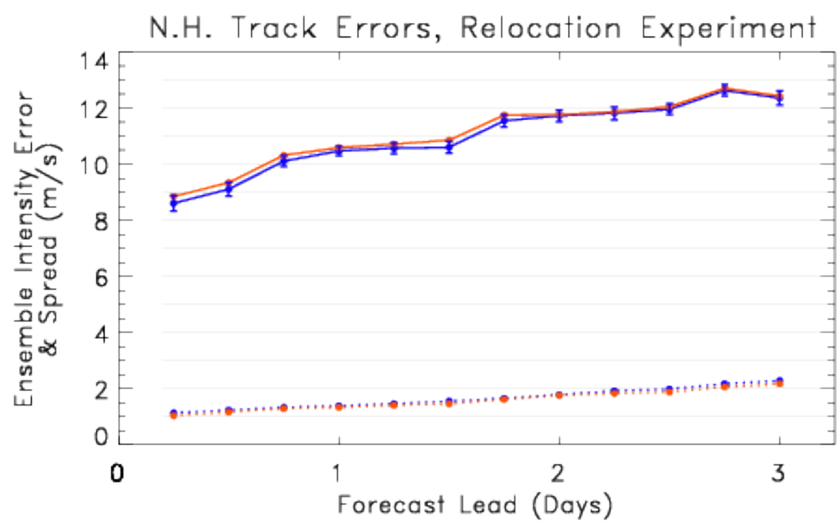
Relocation Experiment Track Errors (6-72 hrs)

20-member Ensemble

Track Error/Spread



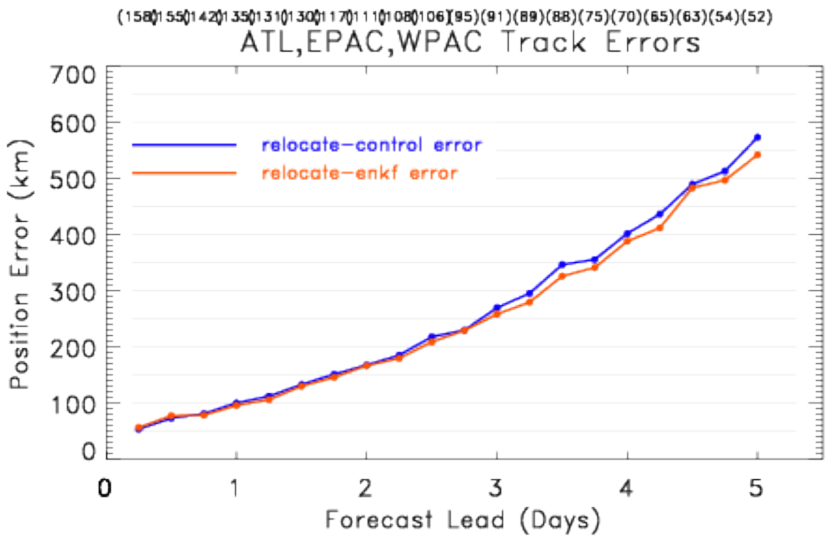
Max Winds Error/Spread



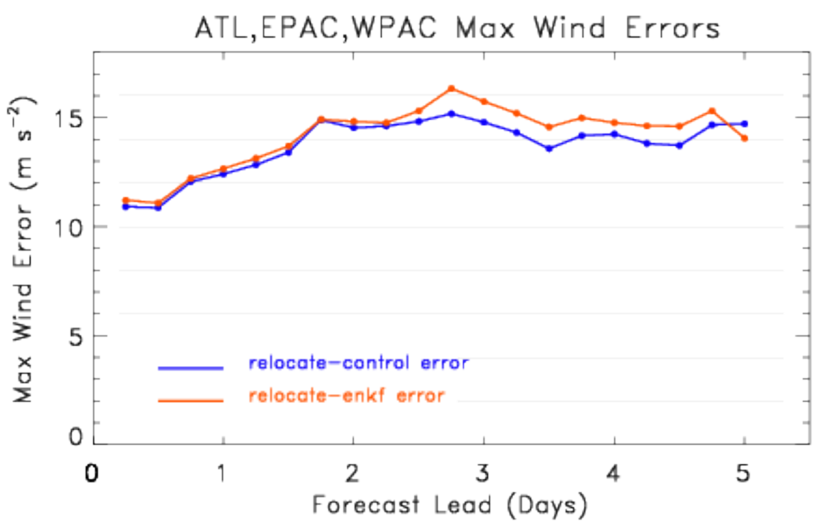
Relocation Experiment Track Errors (6-120 hrs)

T878 Determinist Forecast

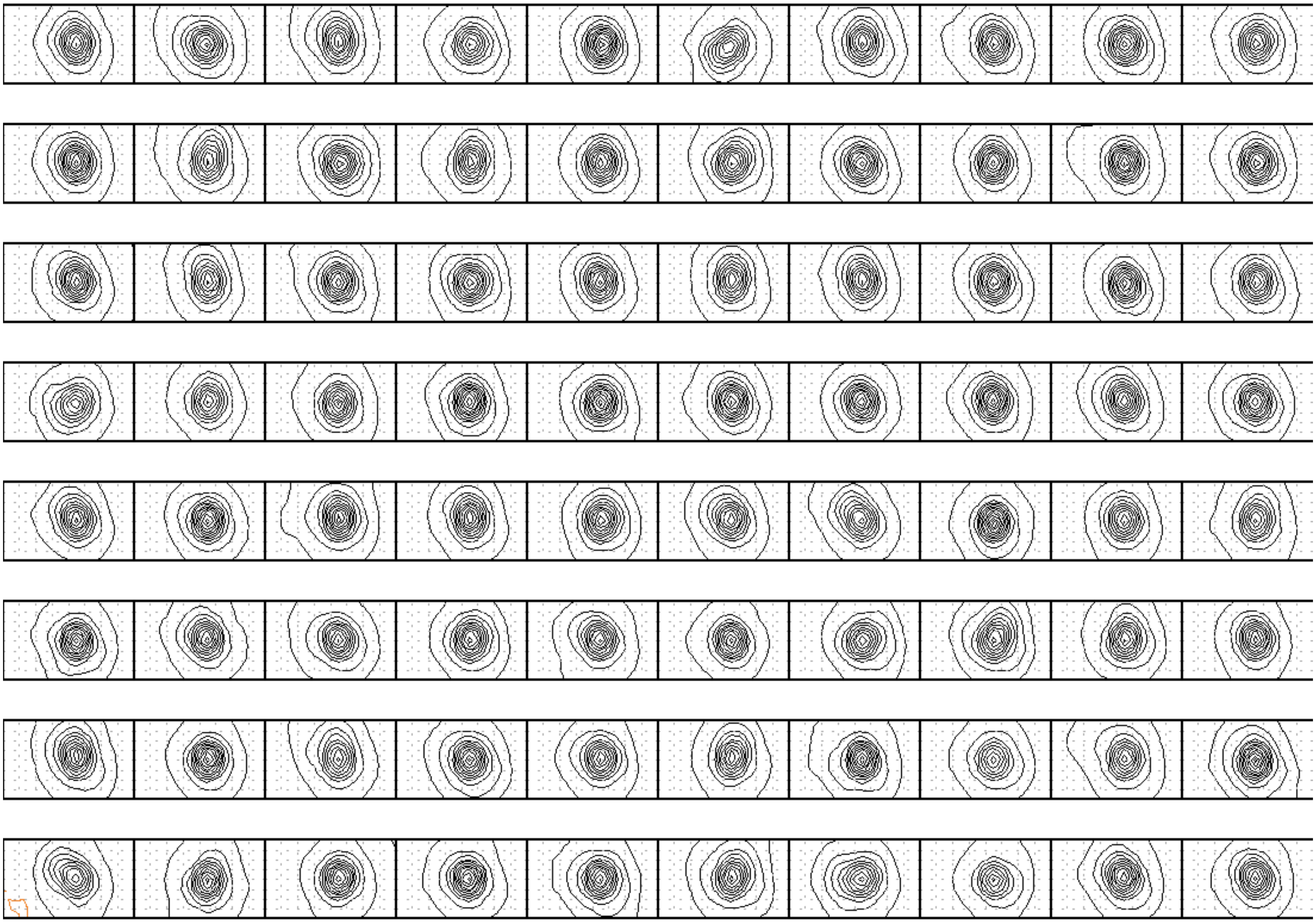
Track Error/Spread



Max Winds Error/Spread



18W: 00UTC Sep. 24 Analysis (relocate_control)



18W: 00UTC Sep. 24 Analysis (relocate_enkf)