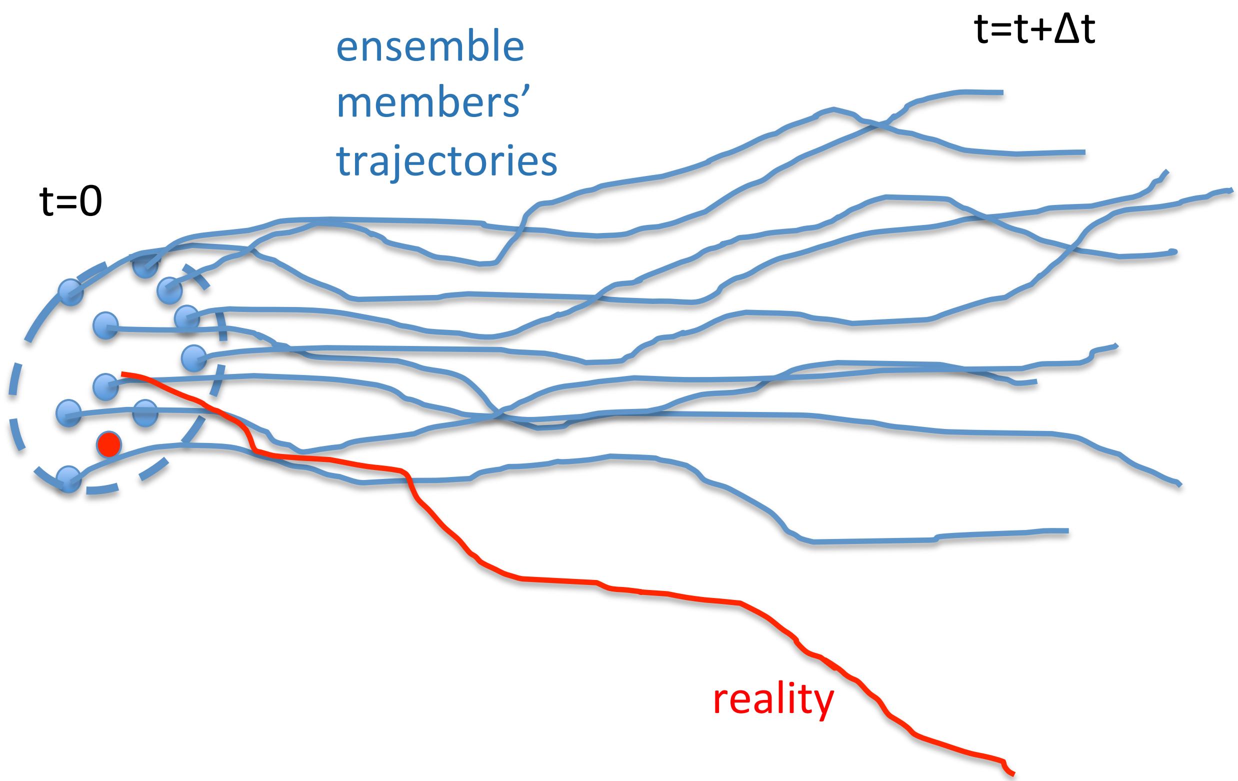
Tests of various schemes for representing model uncertainty in the GFS



Jeff Whitaker, Phil Pegion and Tom Hamill
(with help from Dingchen Hou)

Methods for representing model uncertainty in ensembles

- Multi-model ensembles
  - Pros
    - Everybody gets to keep working on their own model.
    - Seems to work well for seasonal predictions
  - Cons
    - Heavy maintenance burden – hard to keep all models equally skillful.
    - Addresses uncertainties in model formulation – but not the effects of sub-grid scale variability.

Methods for representing model uncertainty in ensembles

- Parameter perturbations
  - Pros
    - Relatively simple to create (no need to develop new schemes).
  - Cons
    - How to determine the sensitive parameters, what a reasonable parameter range is?
    - Nonlinear interactions between processes (radiation/convection/boundary layer). Easy to push model into an unrealistic regime.

Methods for representing model uncertainty in ensembles

- Stochastic parameterization
  - Pros
    - Potentially a more rigorous approach.
    - They have a deterministic limit – can maintain a single model for deterministic and ensemble prediction.
  - Cons
    - Hard to find observations to inform development (use LES simulations instead?)
    - Should be done from the ground-up, at the process level.

NCEP operational scheme (STTP)

Stochastic Total Tendency Perturbation

Scheme (*Hou, Toth and Zhu, 2006*)

NCEP operation – Feb. 2010

Formulation:

$$\frac{\partial X_i}{\partial t} = T_i(X_i;t) + \gamma \sum_{j=1,\ldots,N} w_{i,j} T_j(X_j;t)$$

Simplification: Use finite difference form for the stochastic term

Modify the model state every 6 hours:

$$X_i^{'} = X_i + \gamma \sum_{j=1}^{N} w_{i,j}(t)\{[(X_j)_t - (X_j)_{t-6h}] - [(X_0)_t - (X_0)_{t-6h}]\}$$

Where w is an evolving combination matrix, and γ is a rescaling factor.

random linear combinations of ensemble tendency perturbations added to state every 6-h (entire ensemble must be run concurrently).

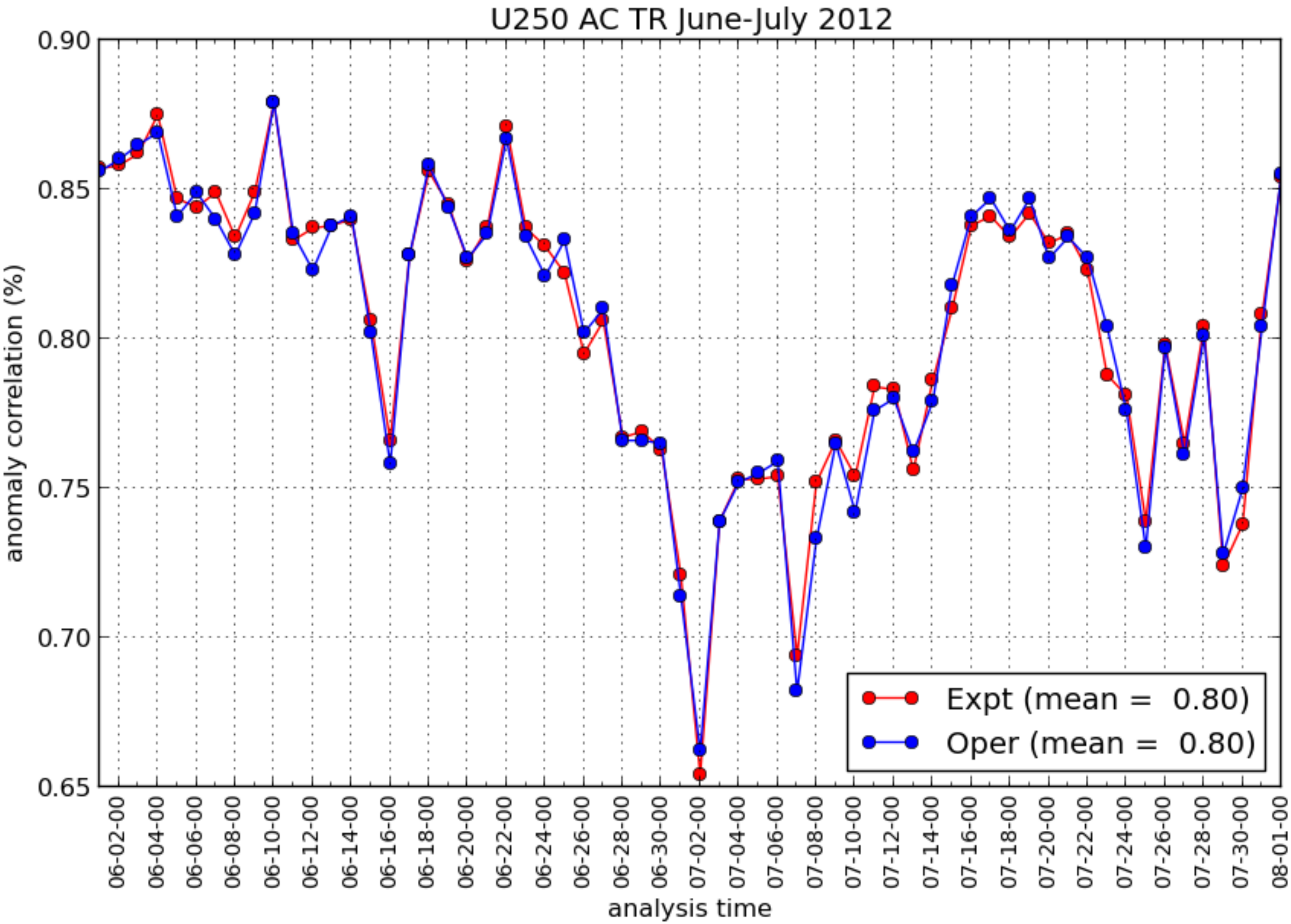
Schemes tested

- Stochastically-perturbed **physics** tendencies (SPPT) – operational ECMWF scheme.
- Vorticity confinement (VC) – under development at UKMET and ECMWF.
- Stochastically-peturbed boundary-layer humidity (SHUM).

Simplified version of GFS for prototyping

- GFS dycore modified to make it easier to prototype new schemes. Not a parallel development path!
  - No MPI (runs on a single node using openMP threading). Entire 3-D grids easily accessible. Code easier to modify.
  - On one 12-core jet node, runs twice as slow as opnl GFS on two nodes (same throughput per CPU).
- Differences with operational GFS
  - Uses two time-level semi-implicit RK3 (Kar, 2006), instead of three-time level semi-implicit leapfrog.
  - No reduced gaussian grid, NSST, surface cycling.
- gfs-dycore.googlecode.com (branches/stochastic)

Validation of simplified GFS (AC skill)



ECMWF method (SPPT)

Stochastically Perturbed Physics Tendency

- Perturbed Physics tendencies

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

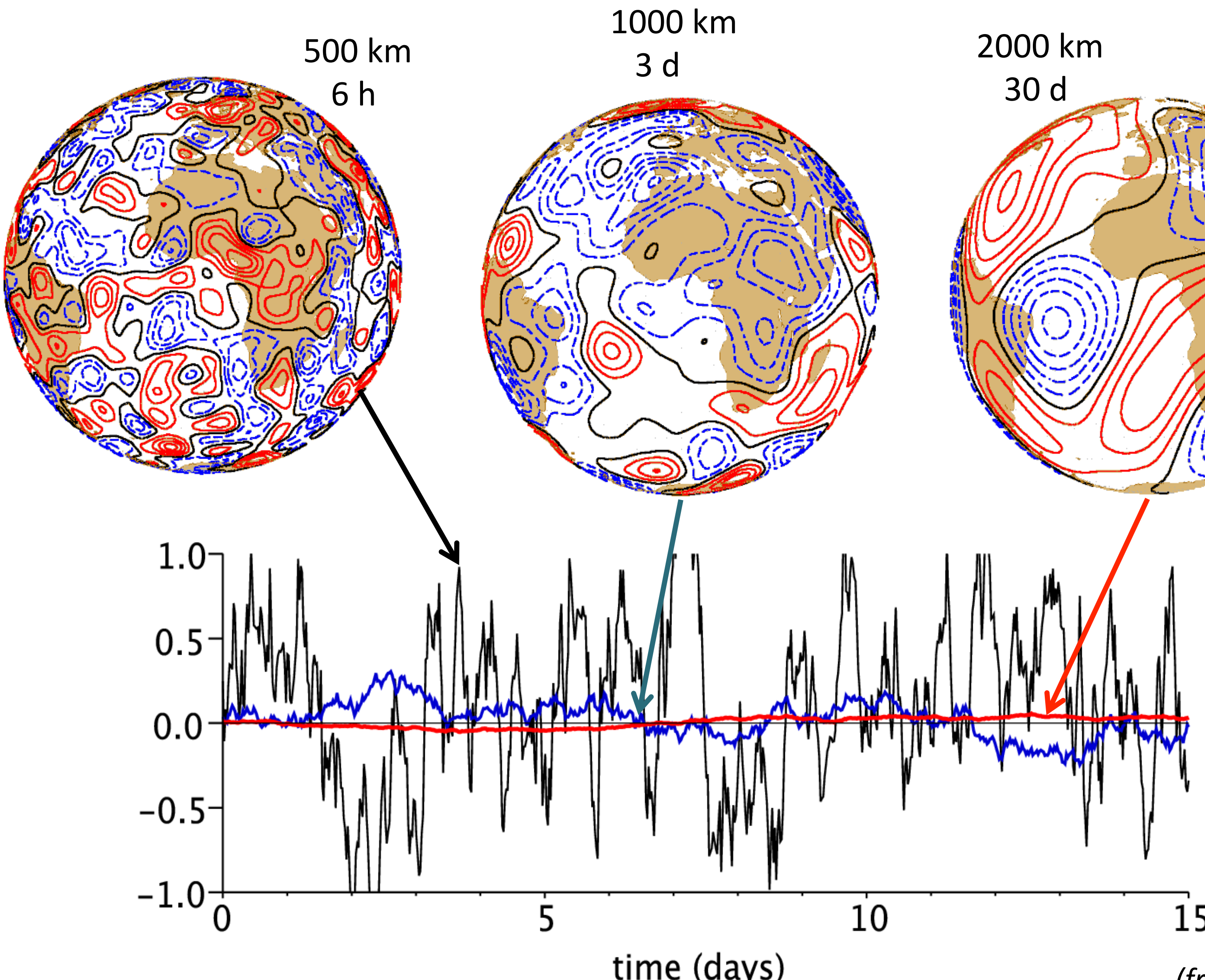
Original tendencies from gbphys

μ- vertical weight: 1.0 between surface and 100 hPa, decays to zero between 100 hPa and 50 hPa.

r- horizontal weights: ranges from -1.0 to 1.0, a red noise process with a

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

Examples of stochastic patterns



(from M Leutbecher)

Vorticity confinement

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

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

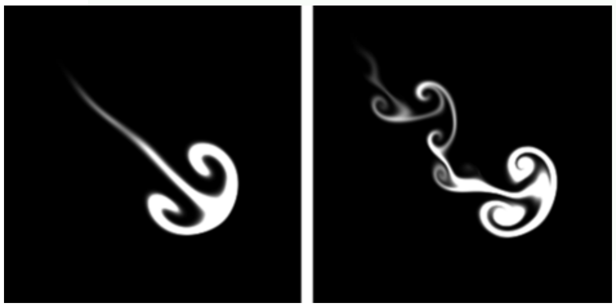
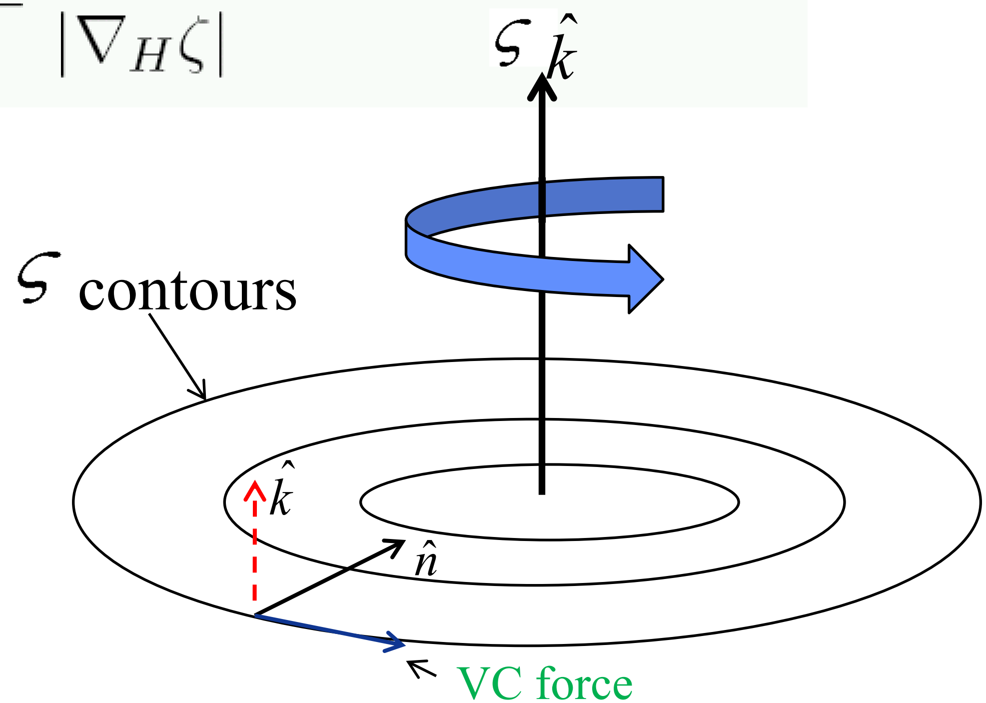


Figure 6: Two frames of animation from two mpeg movies created using `flowanim` and `mpeg2encode`. Both frames depict the 60th frame of the movie. The left animation is created without vorticity confinement, the one on the right with vorticity confinement and a *relatively* high force factor

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



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

ε=0.6 in our experiments

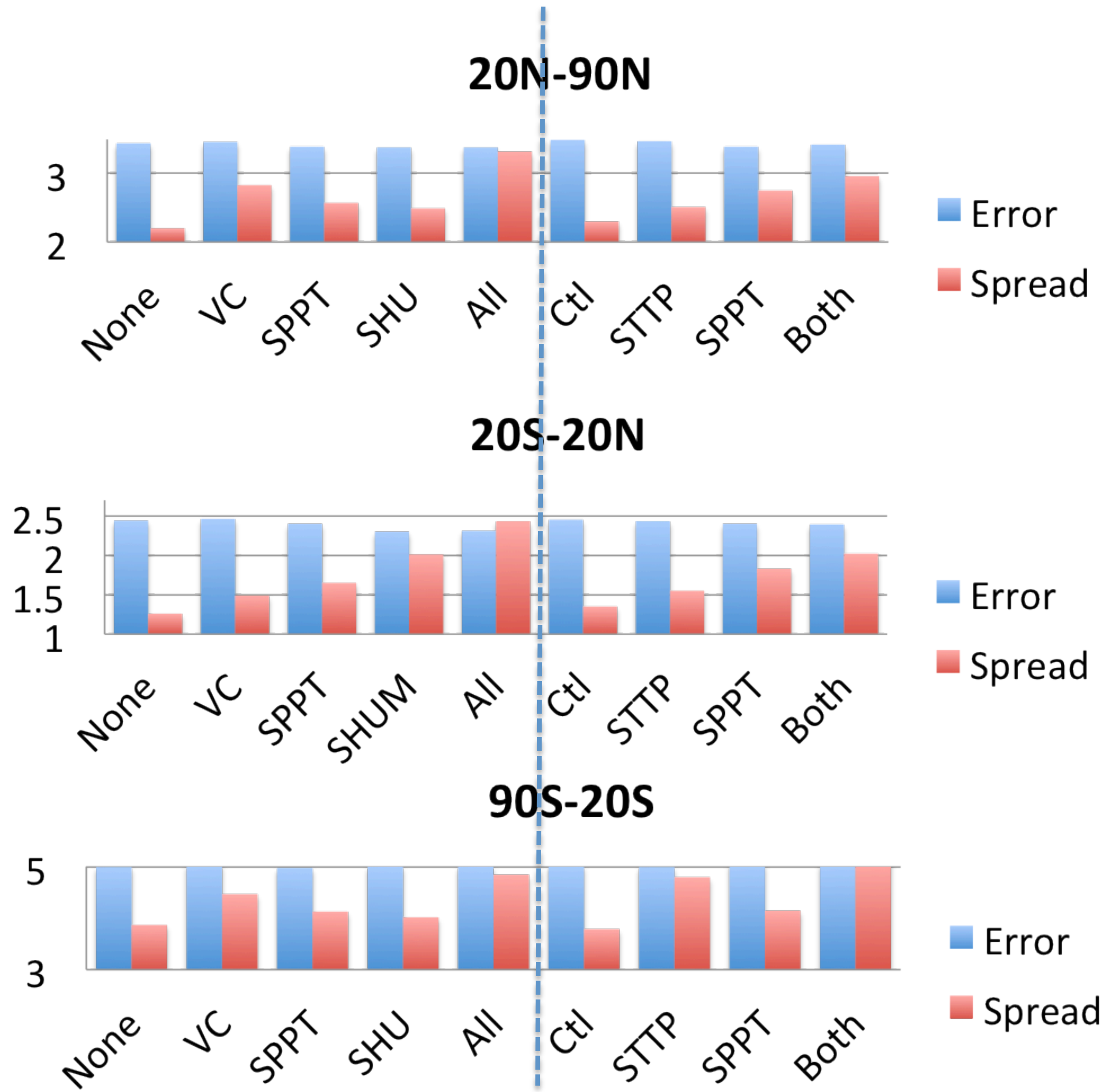
Stochastic boundary-layer humidity

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

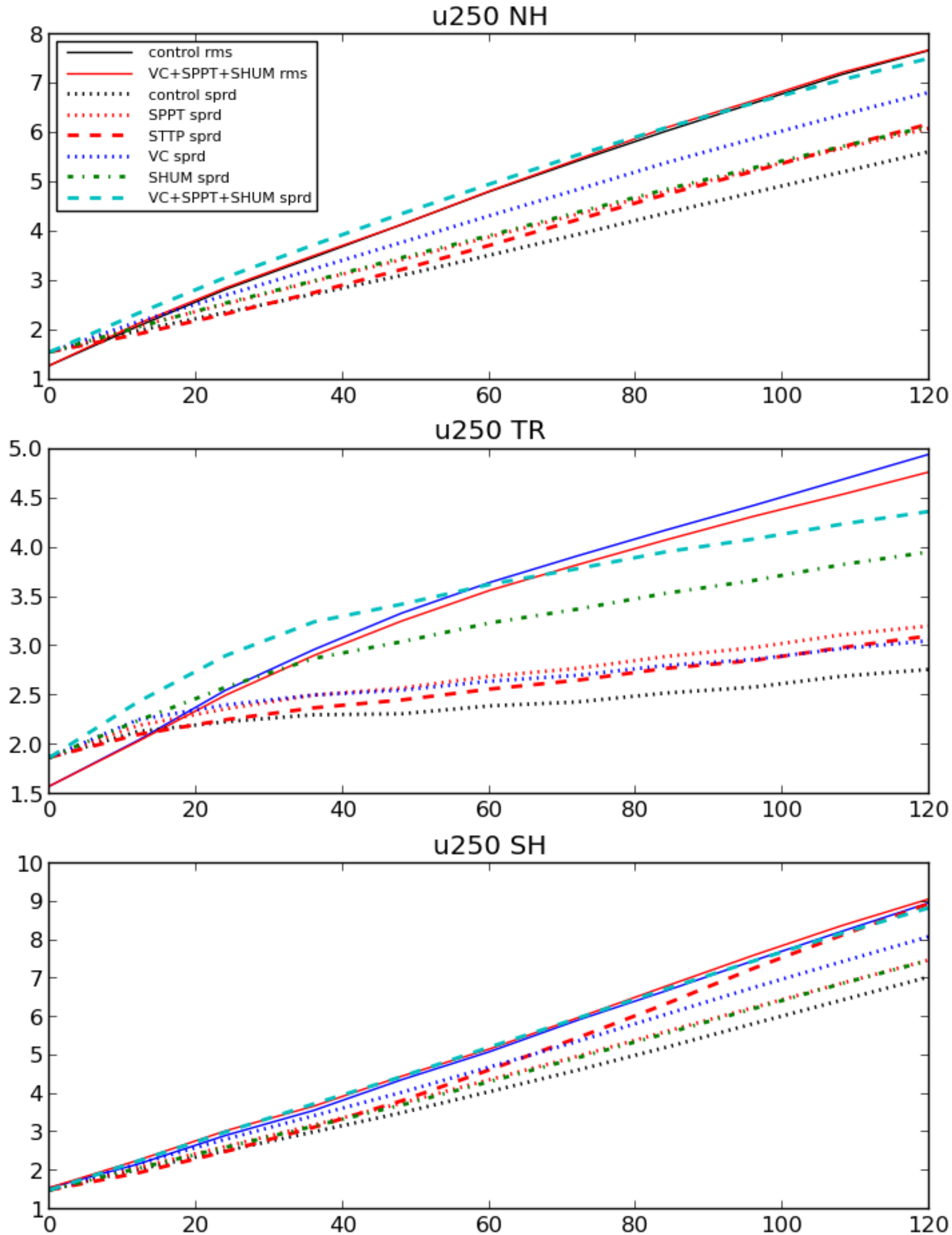
$$q_{perturbed} = (1 + r\mu)q$$

- Vertical weight **r** decays exponentially from surface. Added every time step after physics applied. Random pattern **μ** has a (very small) amplitude of 0.00375, horizontal/vertical scales (250 km, 3-h).

850 mb Zonal Wind forecast statistics



U250 spread/ error growth



VC+SPPT+SHUM
VC
SHUM
STTP
control

RMS error reduced
In tropics

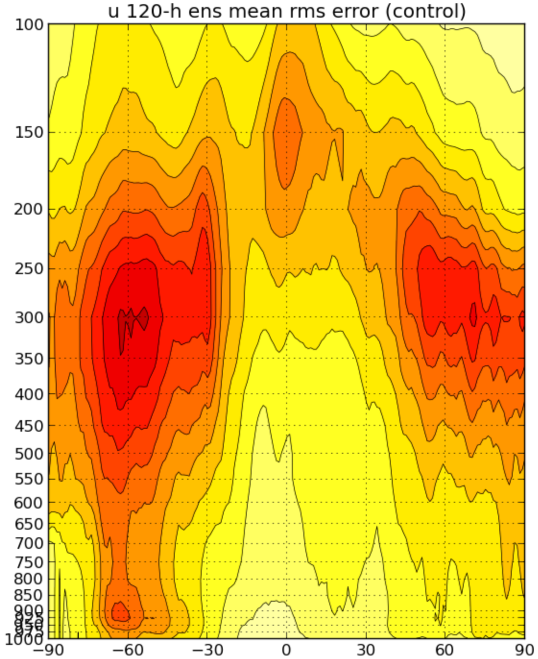
Much faster spread
growth with SHUM

VC+SPPT+SHUM
SHUM
SPPT
VC
STTP
control

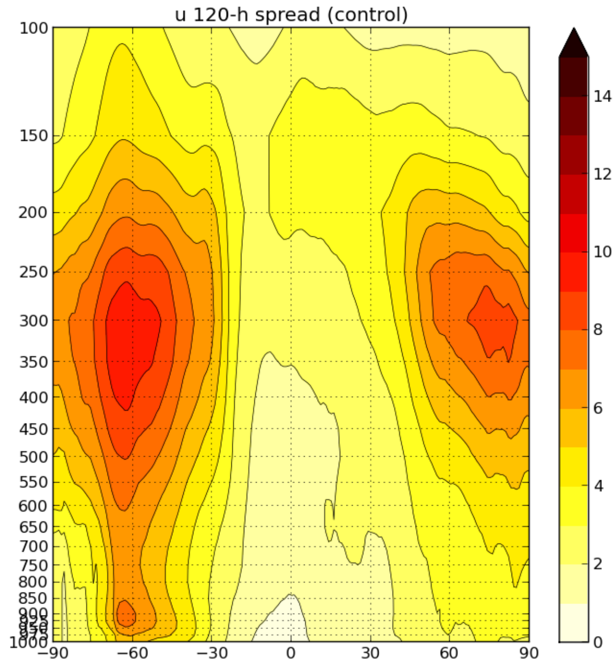
VC+SPPT+SHUM
STTP
VC
SHUM
SPPT
control

Zonal Wind Spread

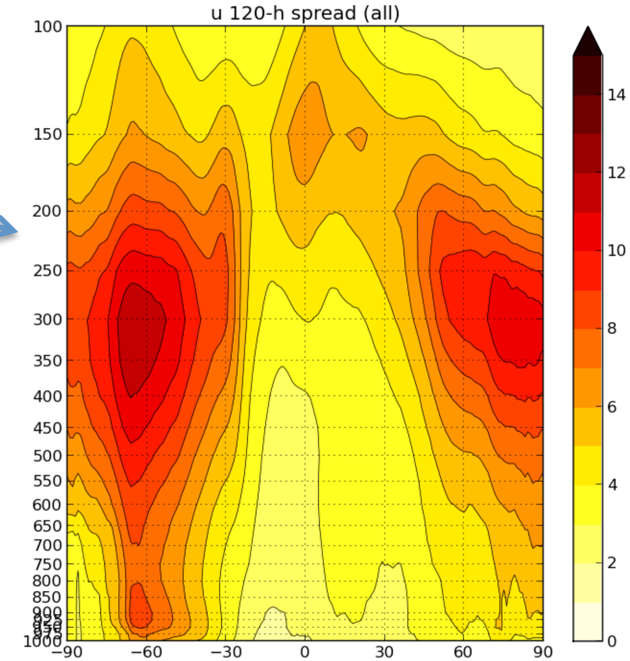
Ensemble Mean Error
(control)



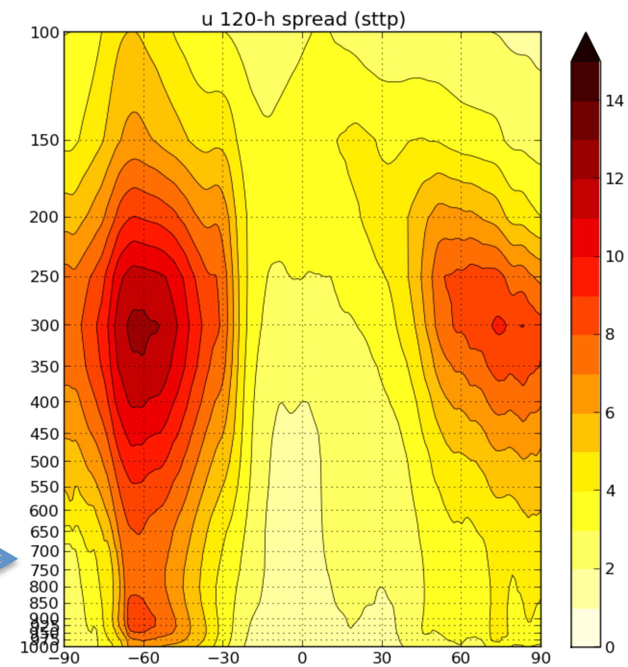
Ensemble Spread
(control)



Ensemble Spread
(SPPT+SHUM+VCl)

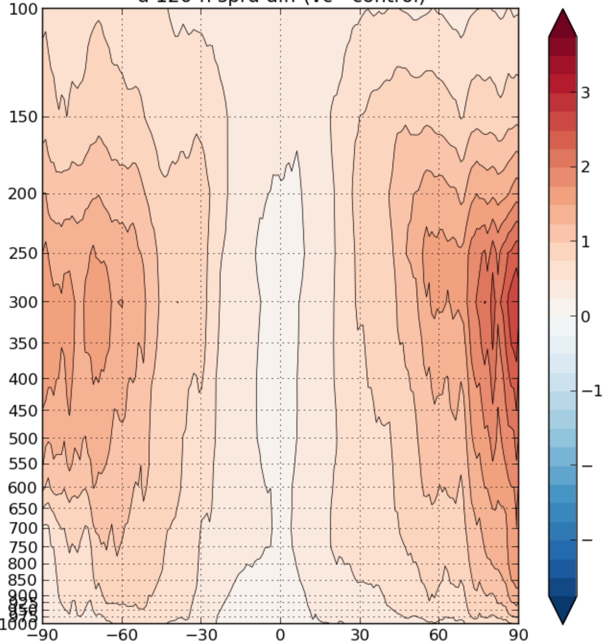


Ensemble Spread
(STTP)

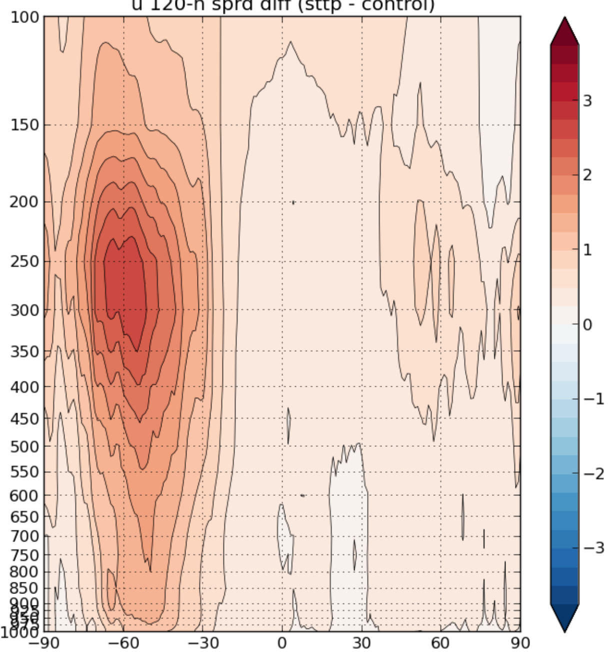


U spread differences

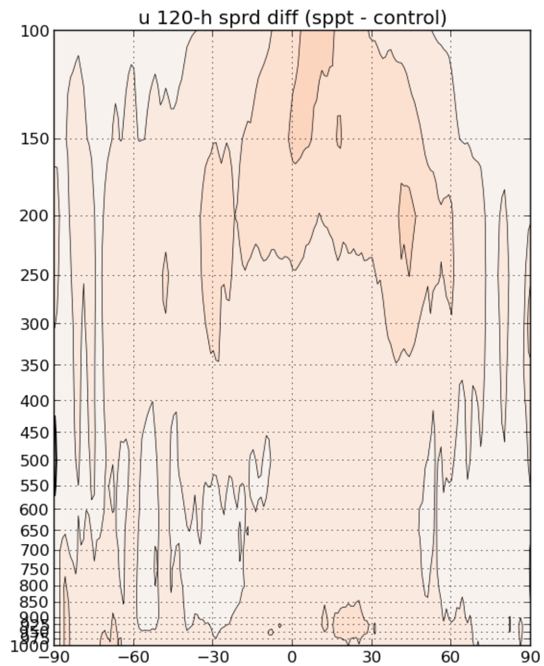
VC spread – control spread



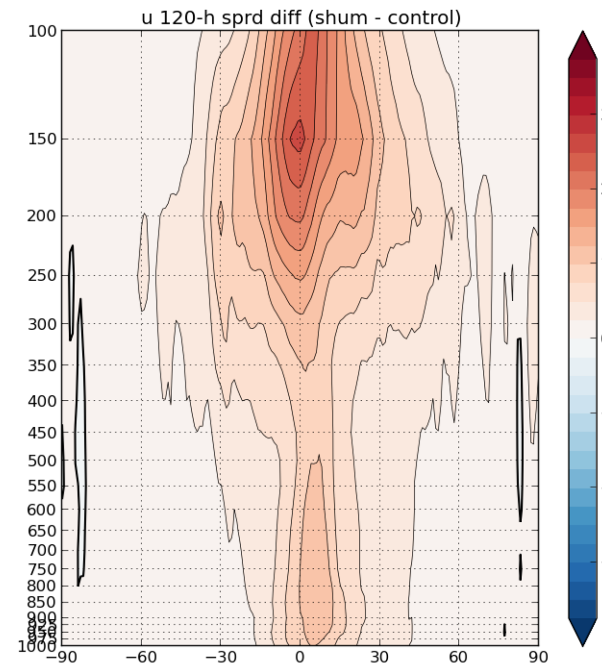
STTP spread – control spread



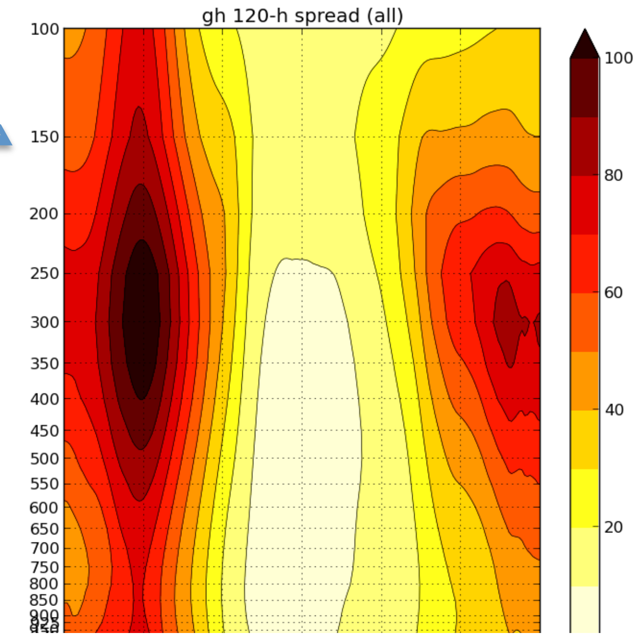
SPPT spread – control spread



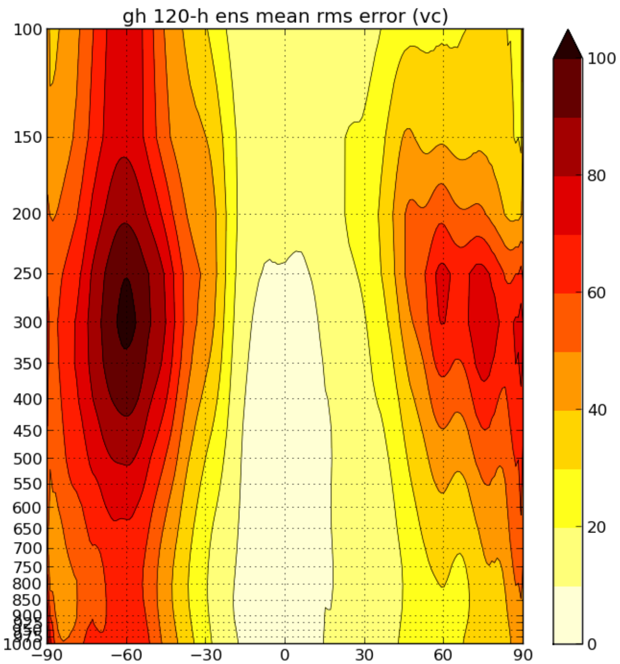
SHUM spread – control spread



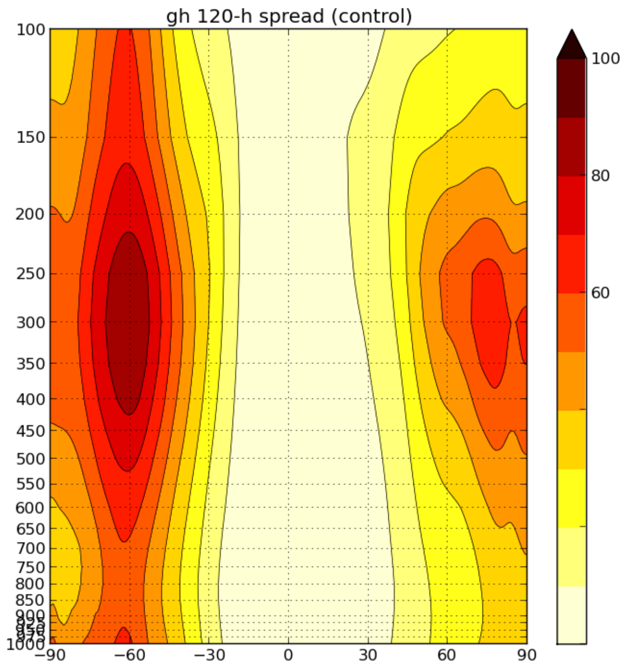
Ensemble Spread (SPPT+SHUM+VC)



Ensemble Mean Error (control)

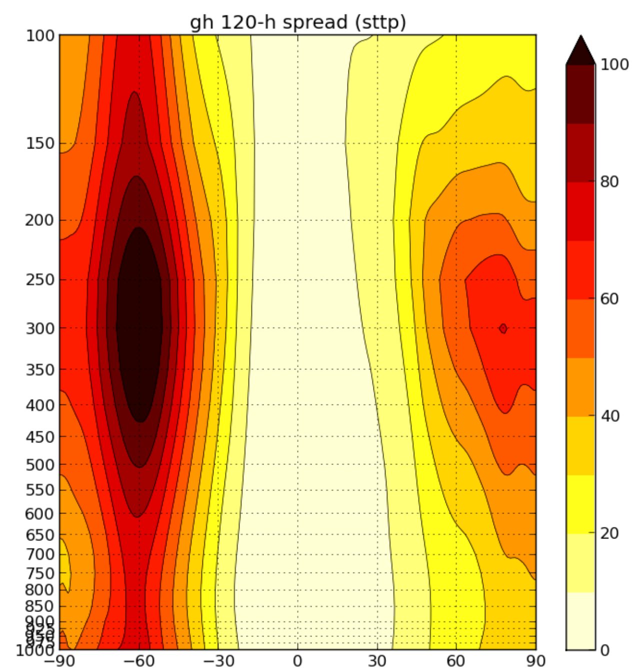


Ensemble Spread (control)



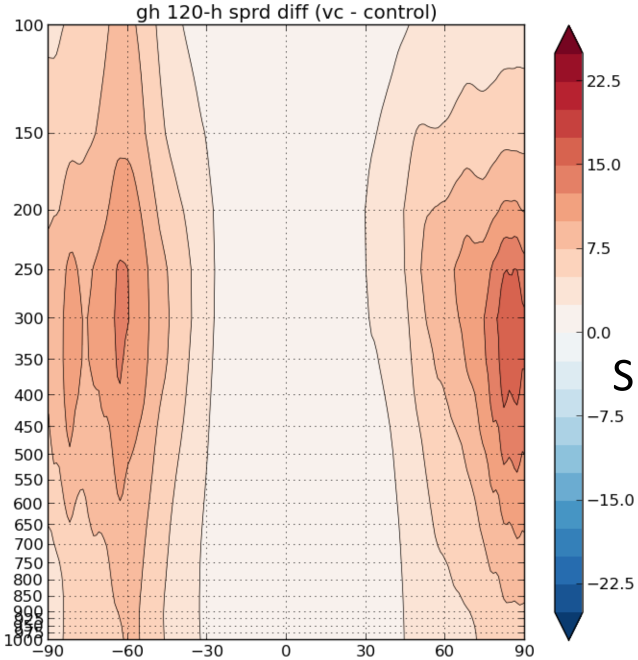
Geopotential Height Spread

Ensemble Spread (SPPTI)

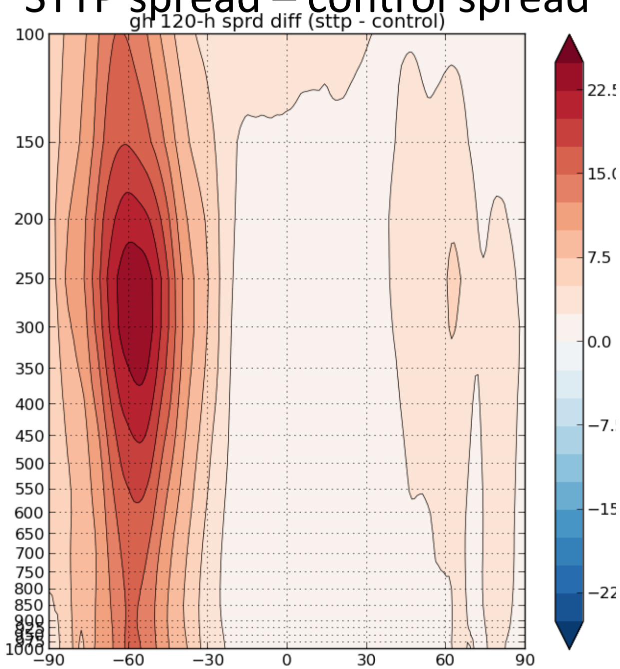


Z spread differences

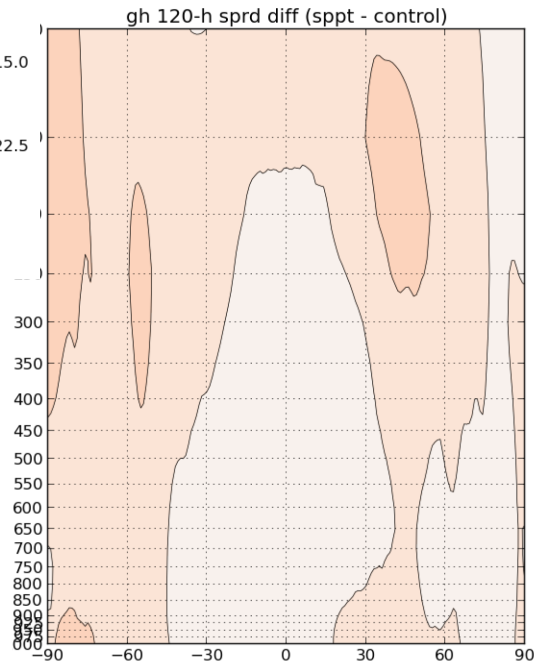
VC spread – control spread



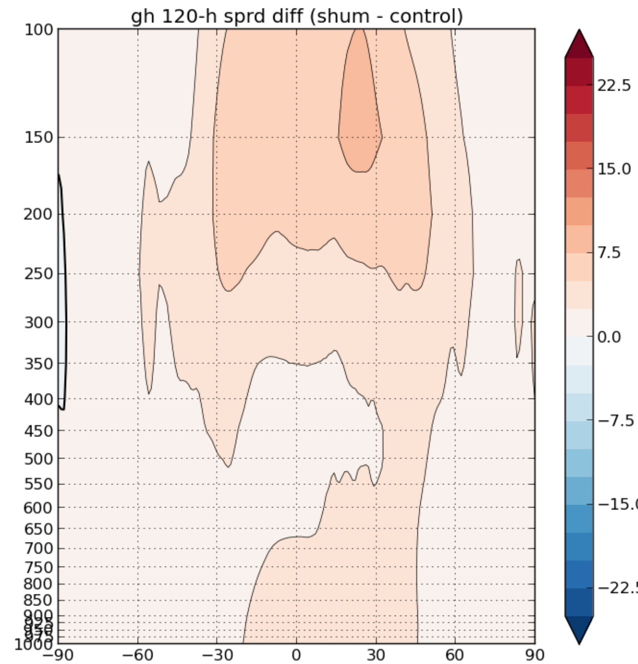
STTP spread – control spread



SPPT spread – control spread

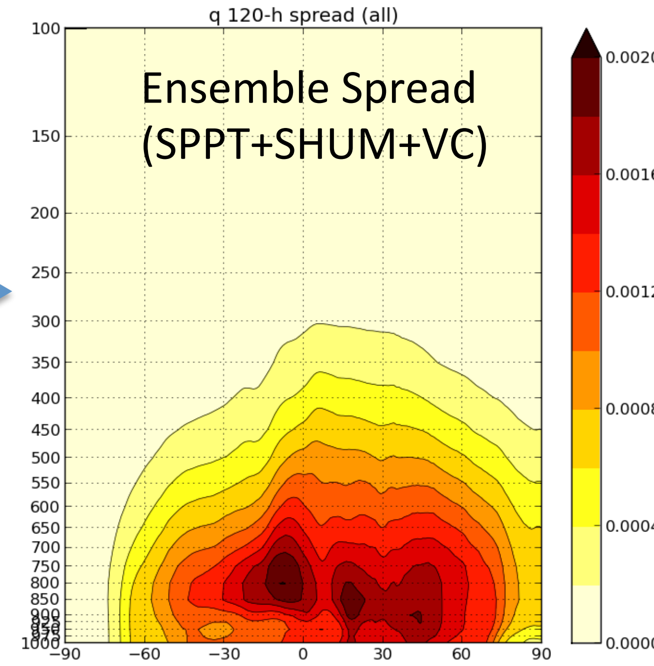


SHUMs pread – control spread

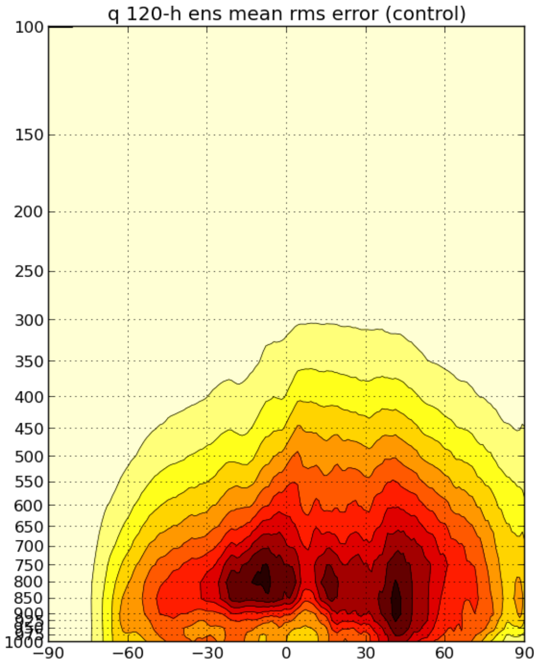


Specific Humidity Spread

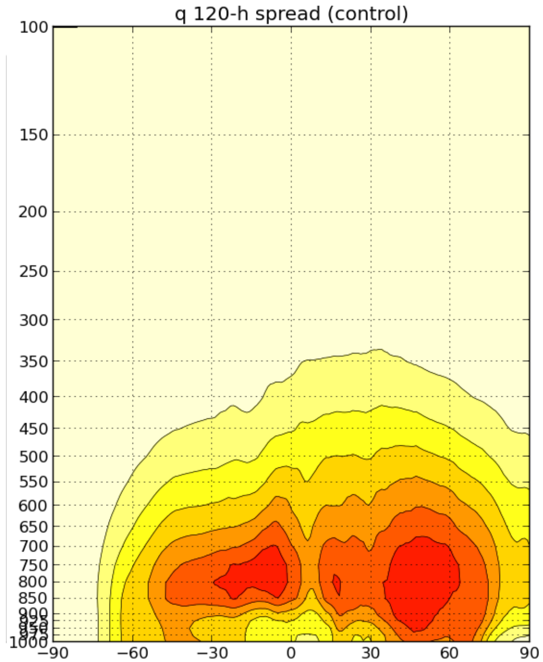
Almost all of the spread increase comes from SHUM →

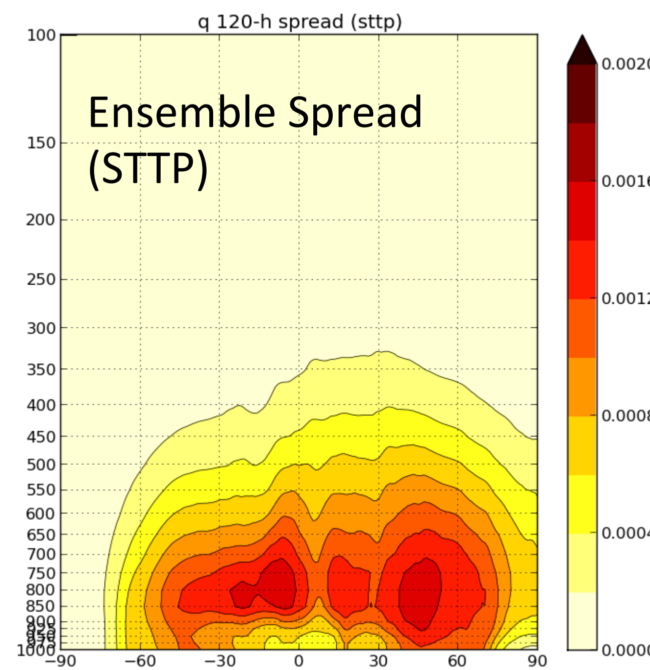


Ensemble Mean Error
(control)

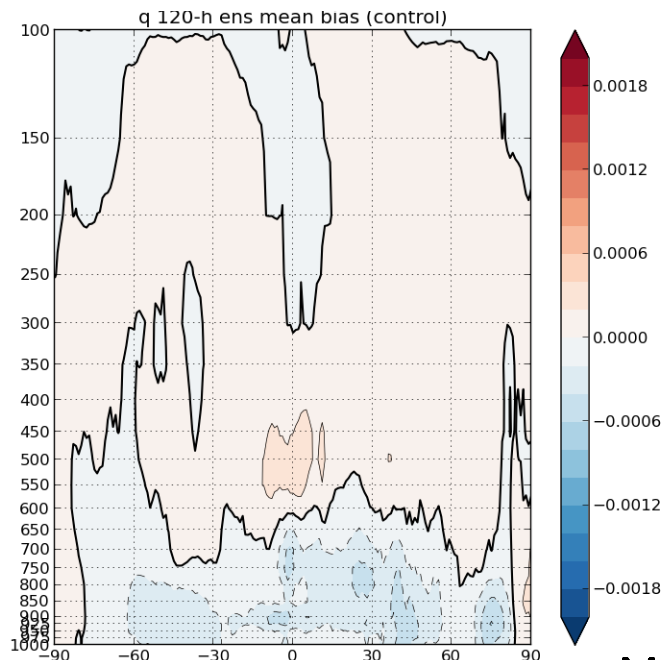


Ensemble Spread
(control)





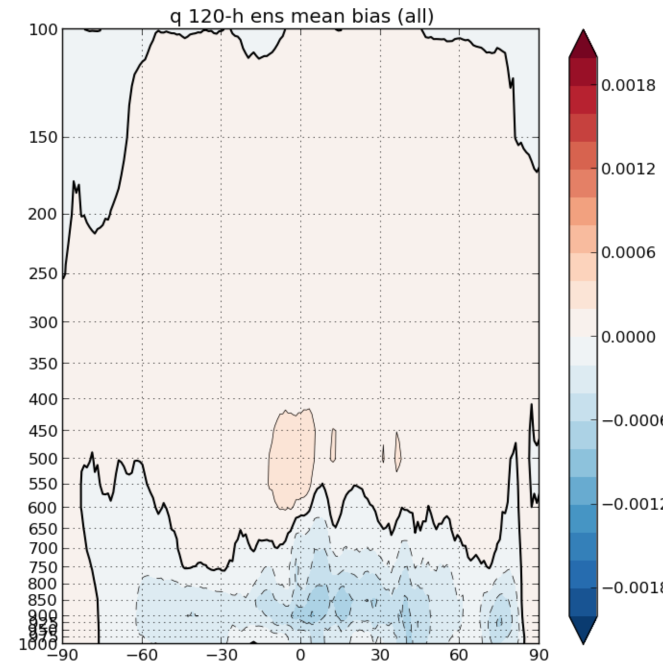
Bias

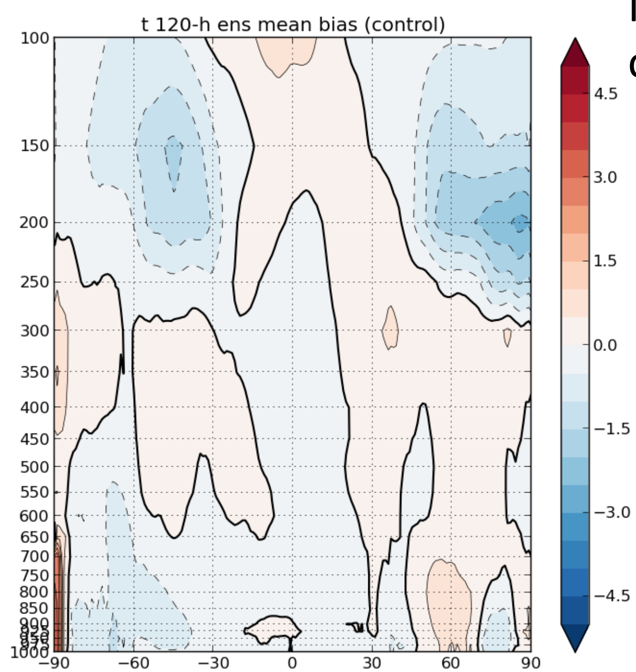


Humidity

← Control

ALL →



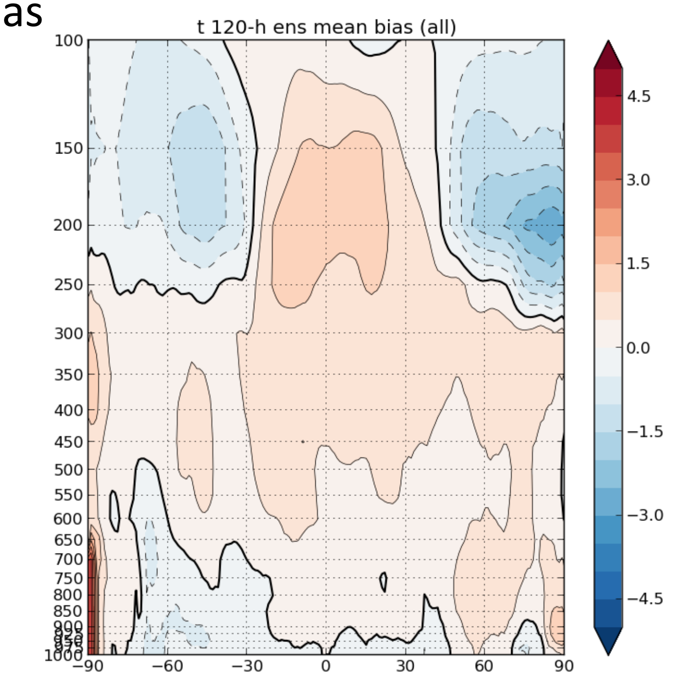


Most of additional bias comes from SHUM

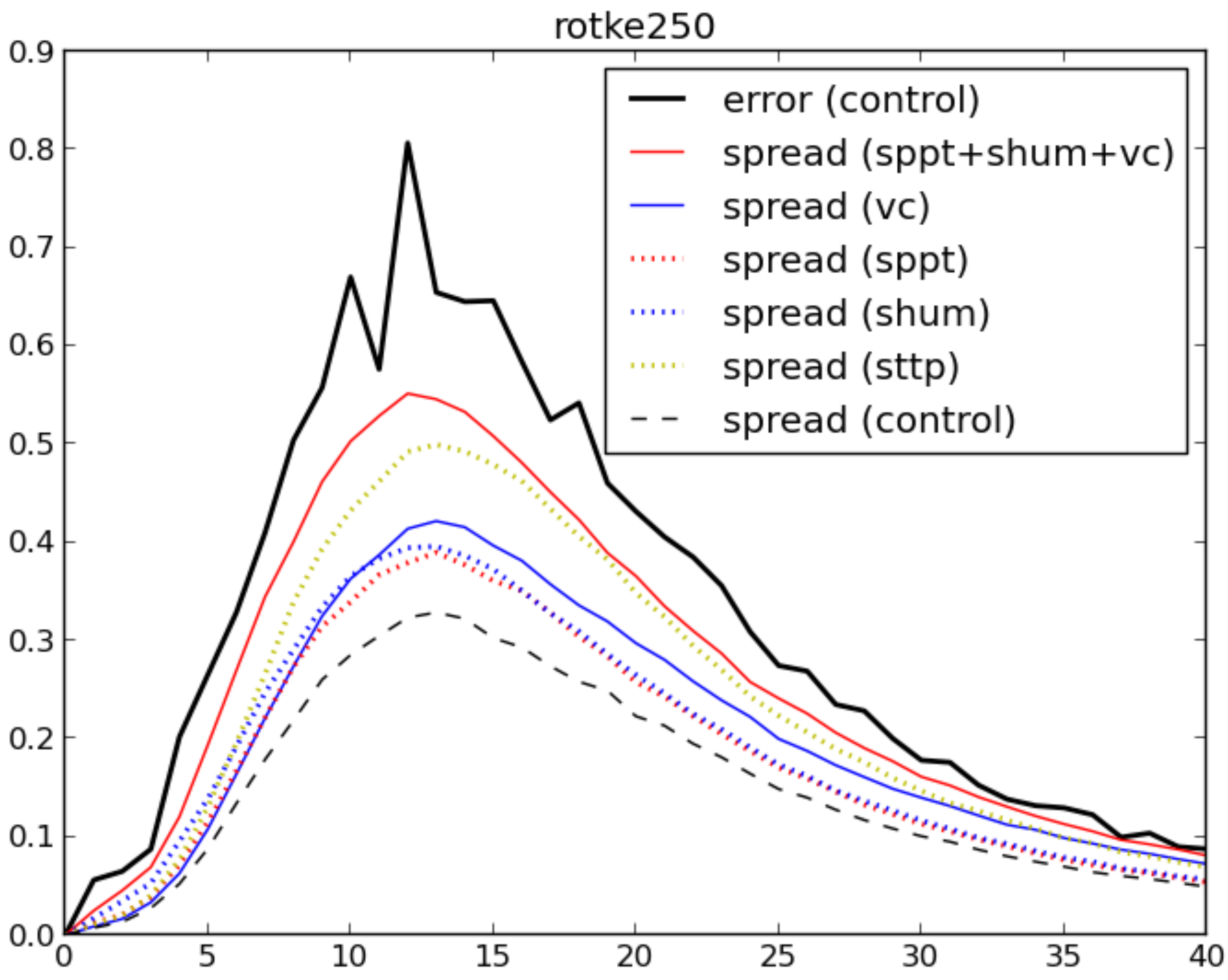
Temp

← Control

ALL →

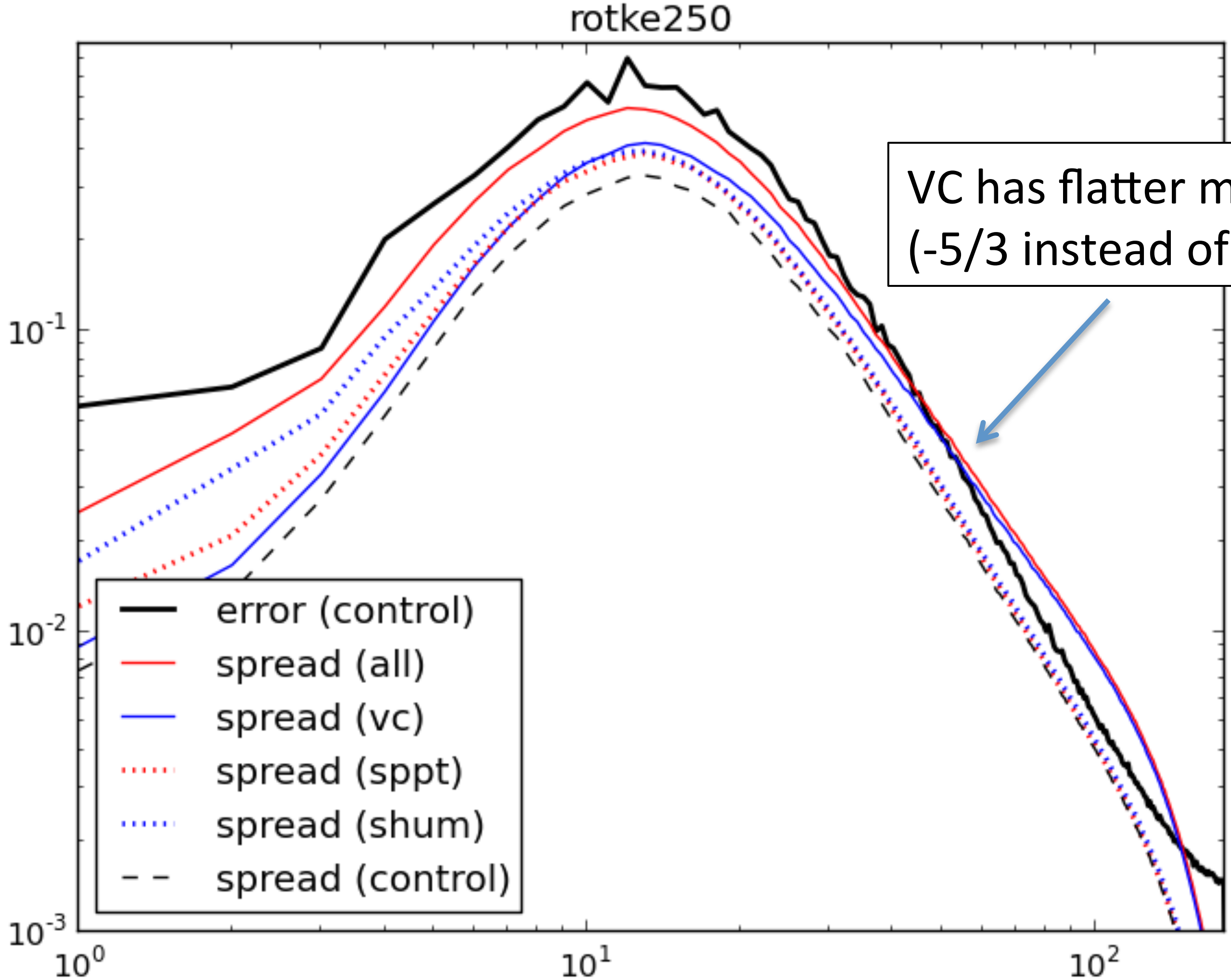


KE spectra



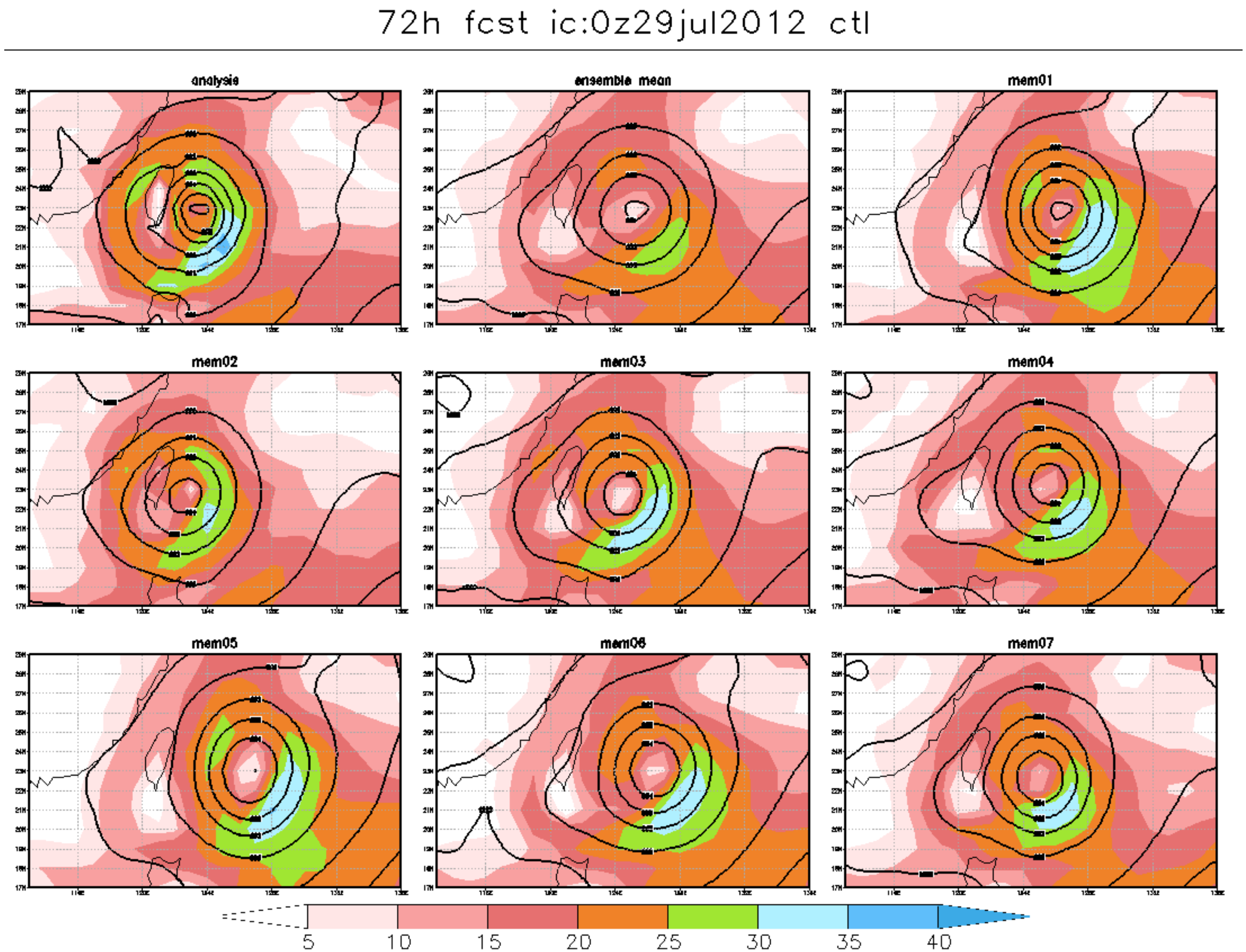
rotke250
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
error (control)
spread (sppt+shum+vc)
spread (vc)
spread (sppt)
spread (shum)
spread (sttp)
spread (control)

KE spectra (log-log)

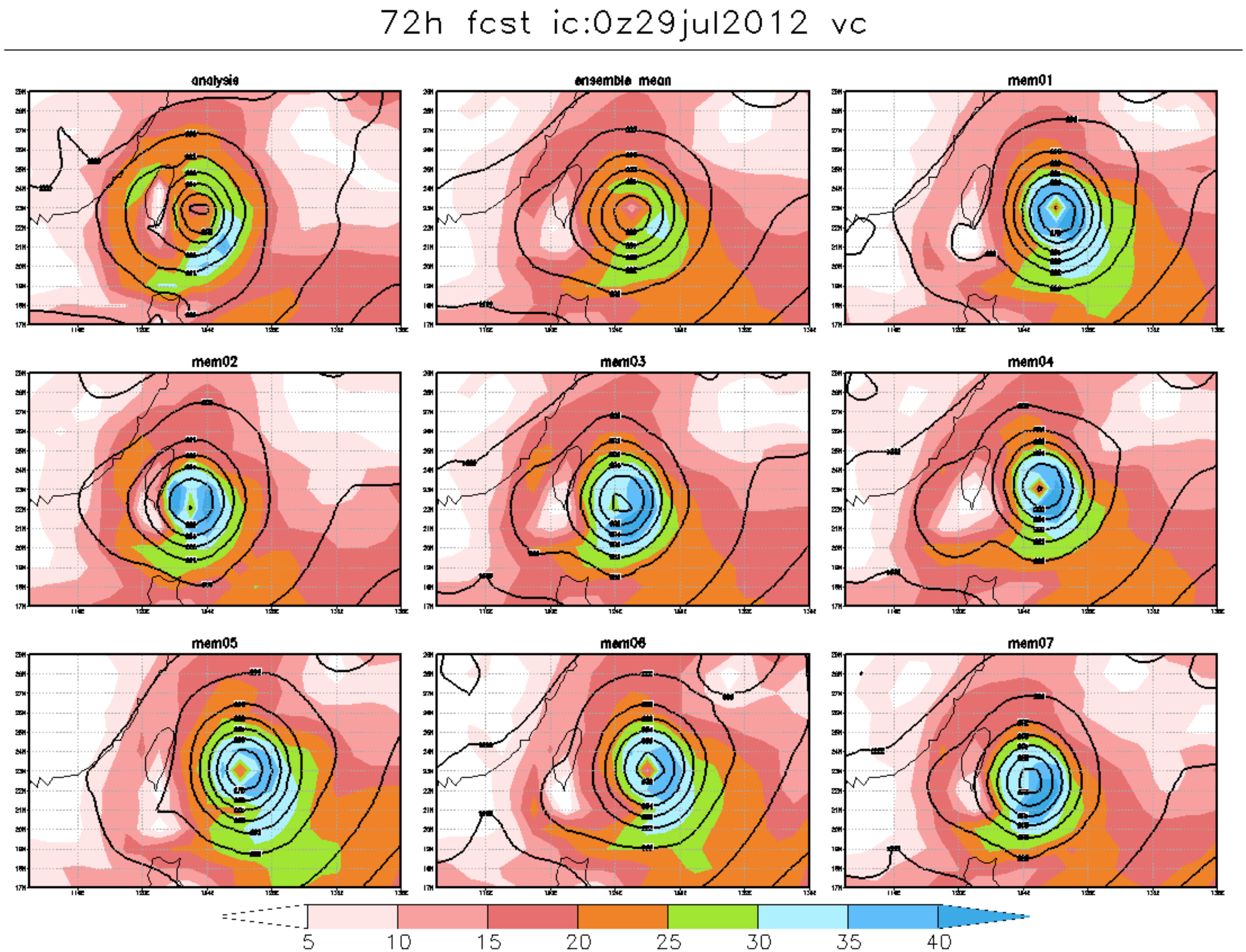


VC has flatter mesoscale spectrum
(-5/3 instead of -3?)

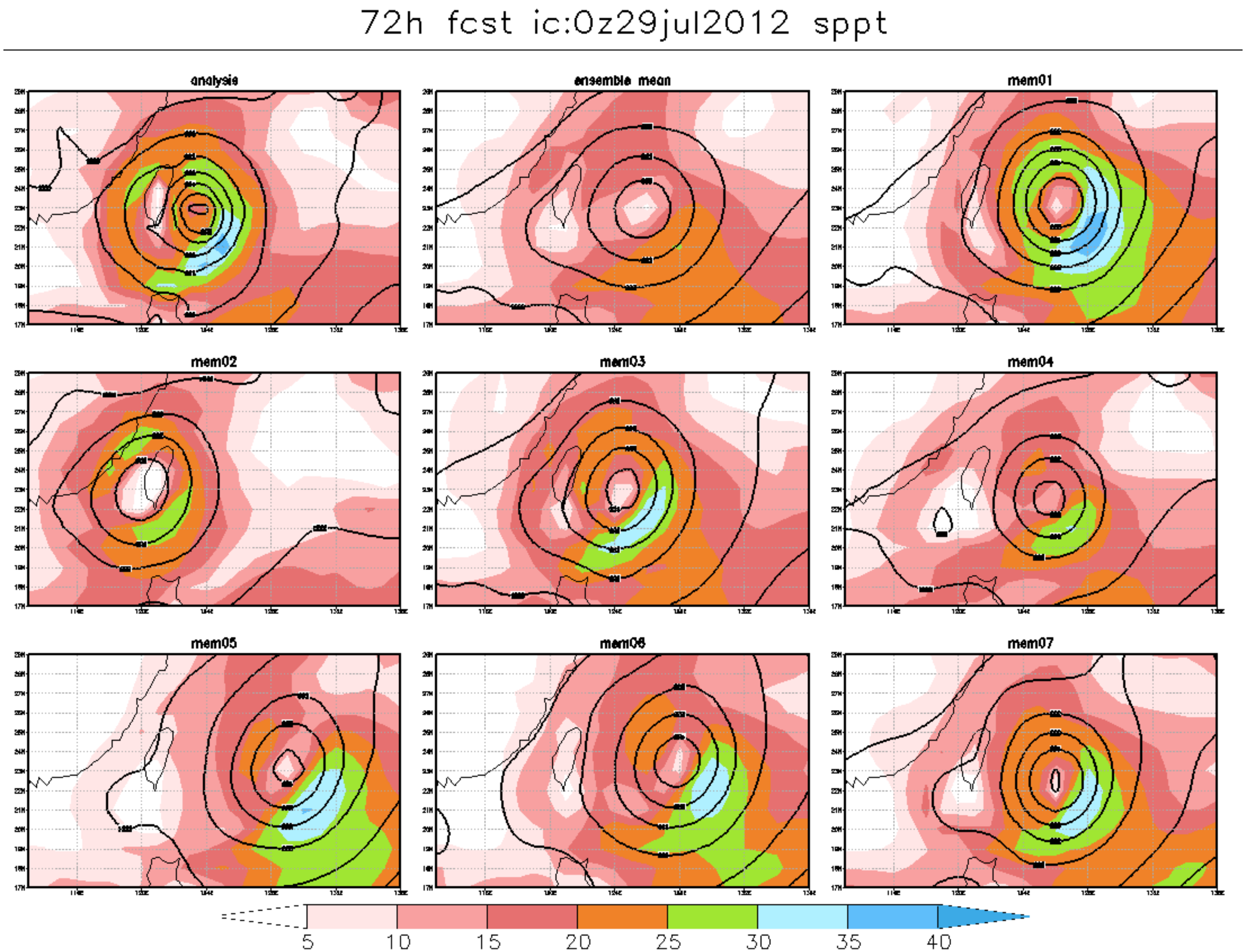
Typhoon Saola 0z1aug2012



Typhoon Saola 0z1aug2012



Typhoon Saola 0z1aug2012



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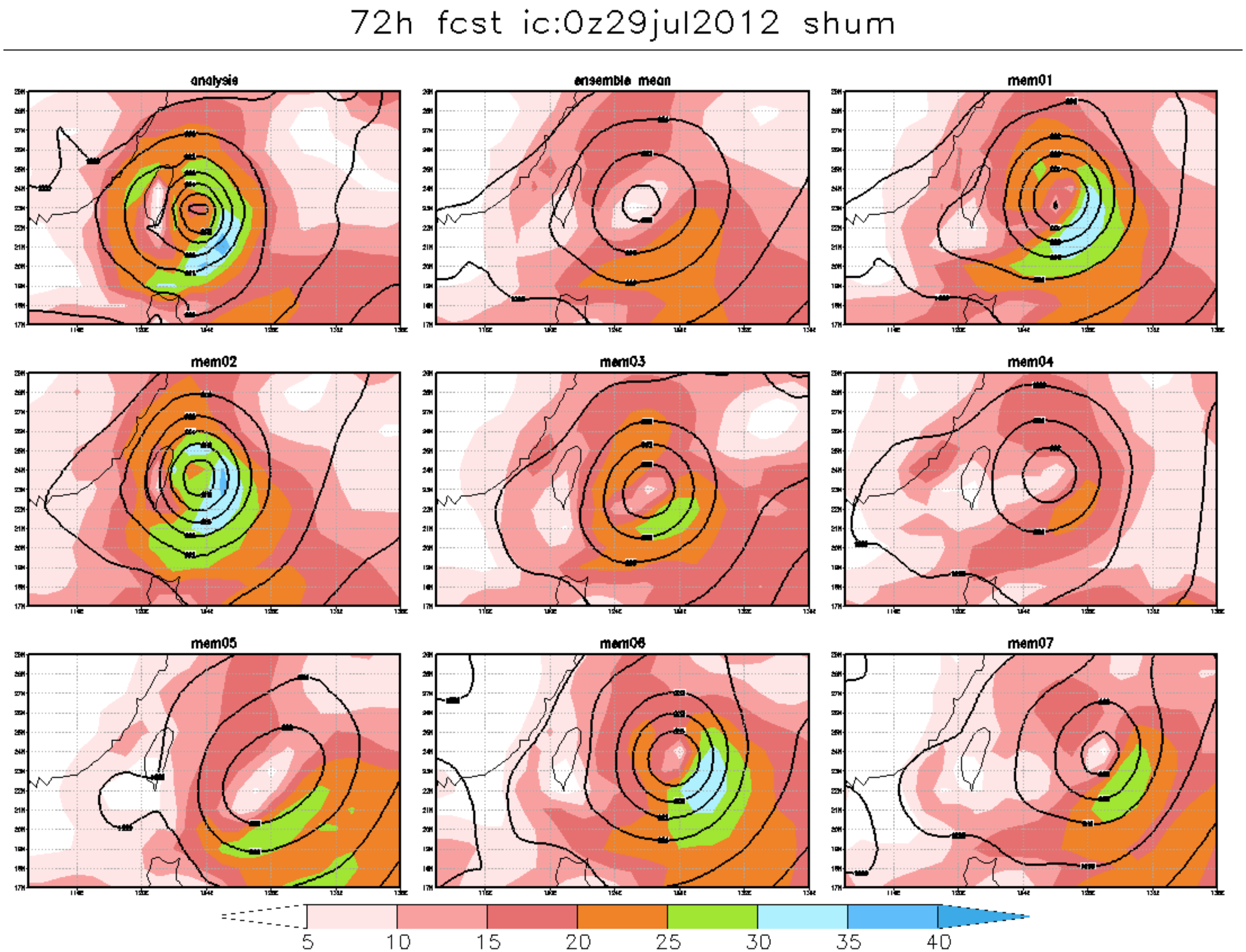
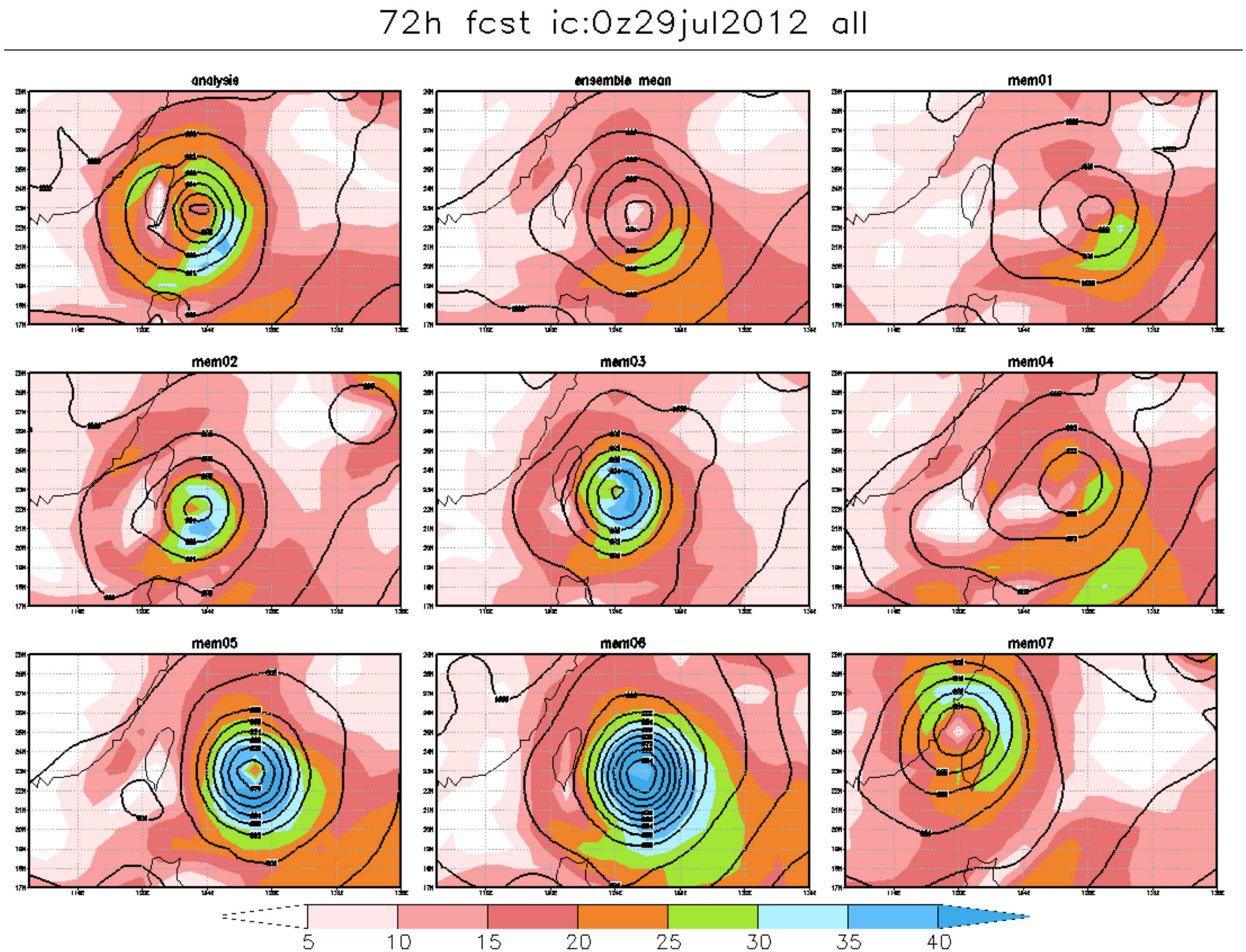
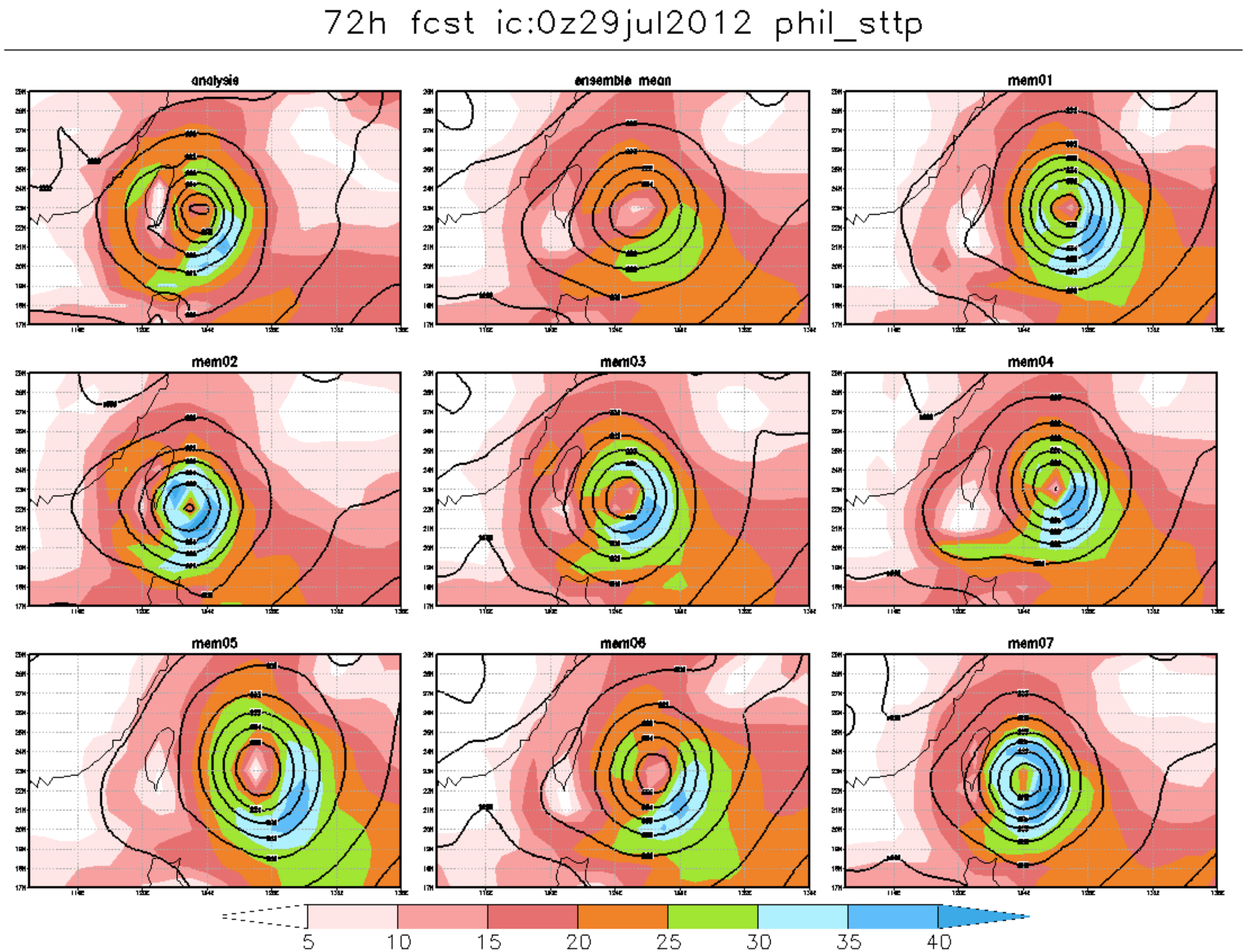


Typhoon Saola 0z1aug2012



Typhoon Saola 0z1aug2012



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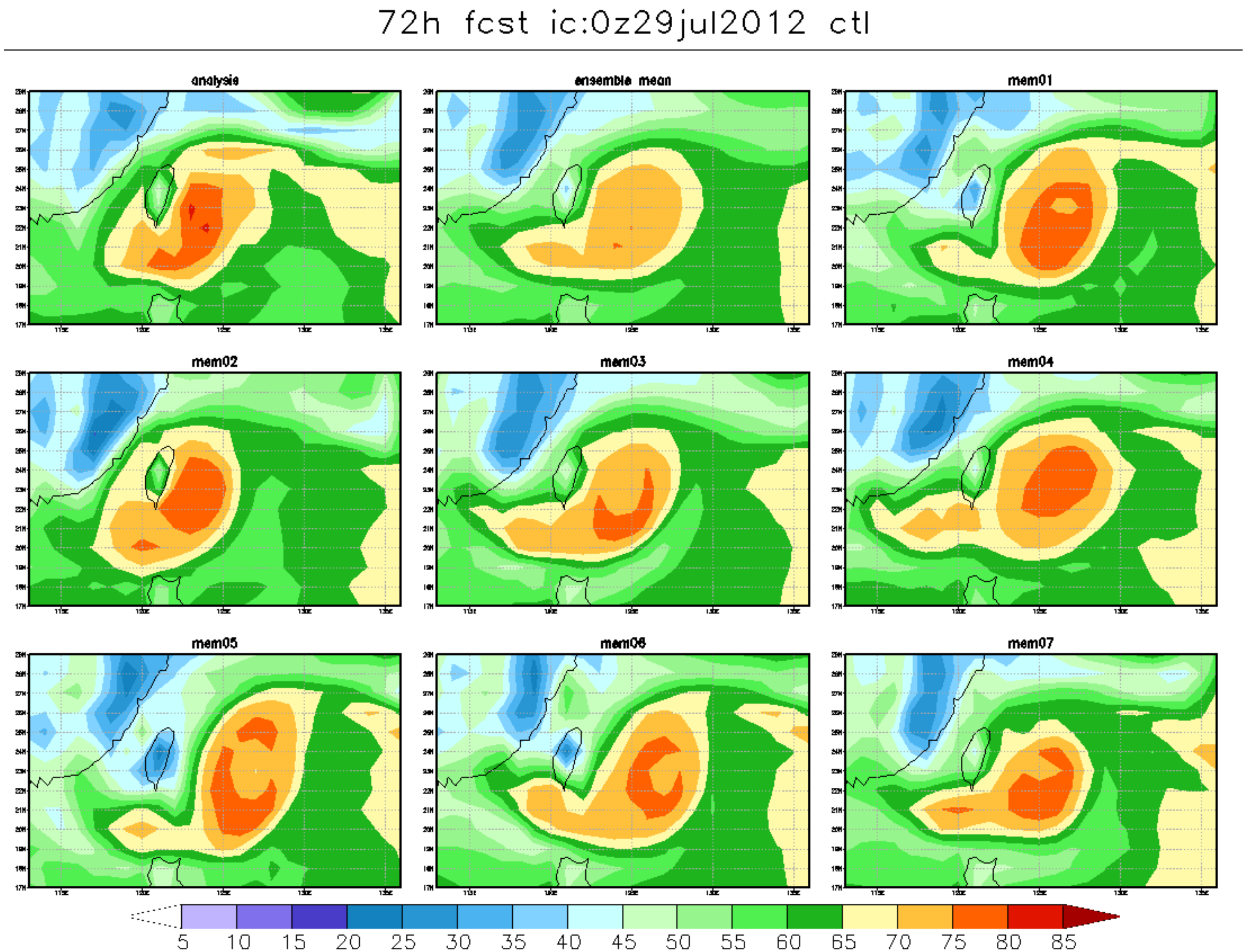

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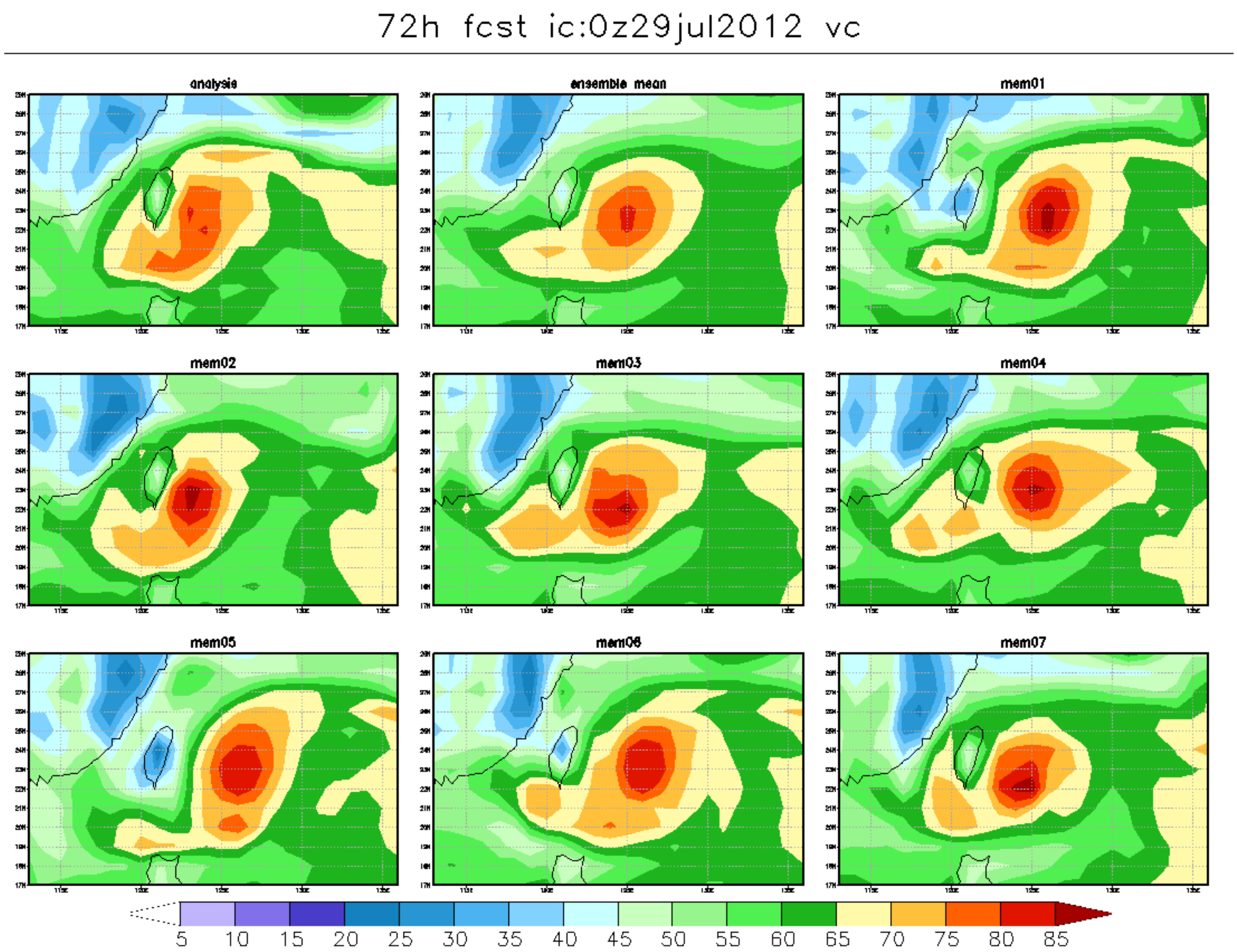
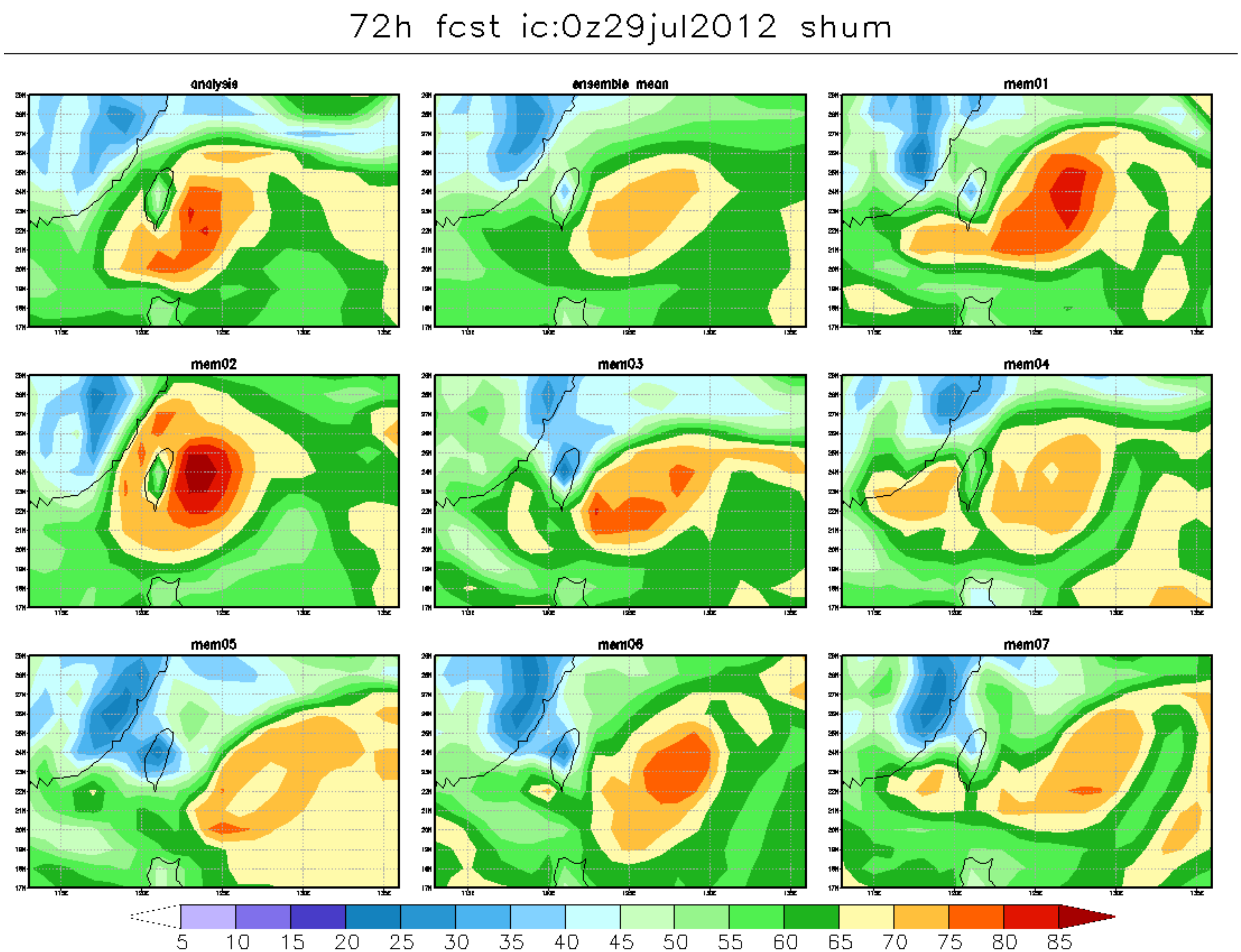


Typhoon Saola 0z1aug2012



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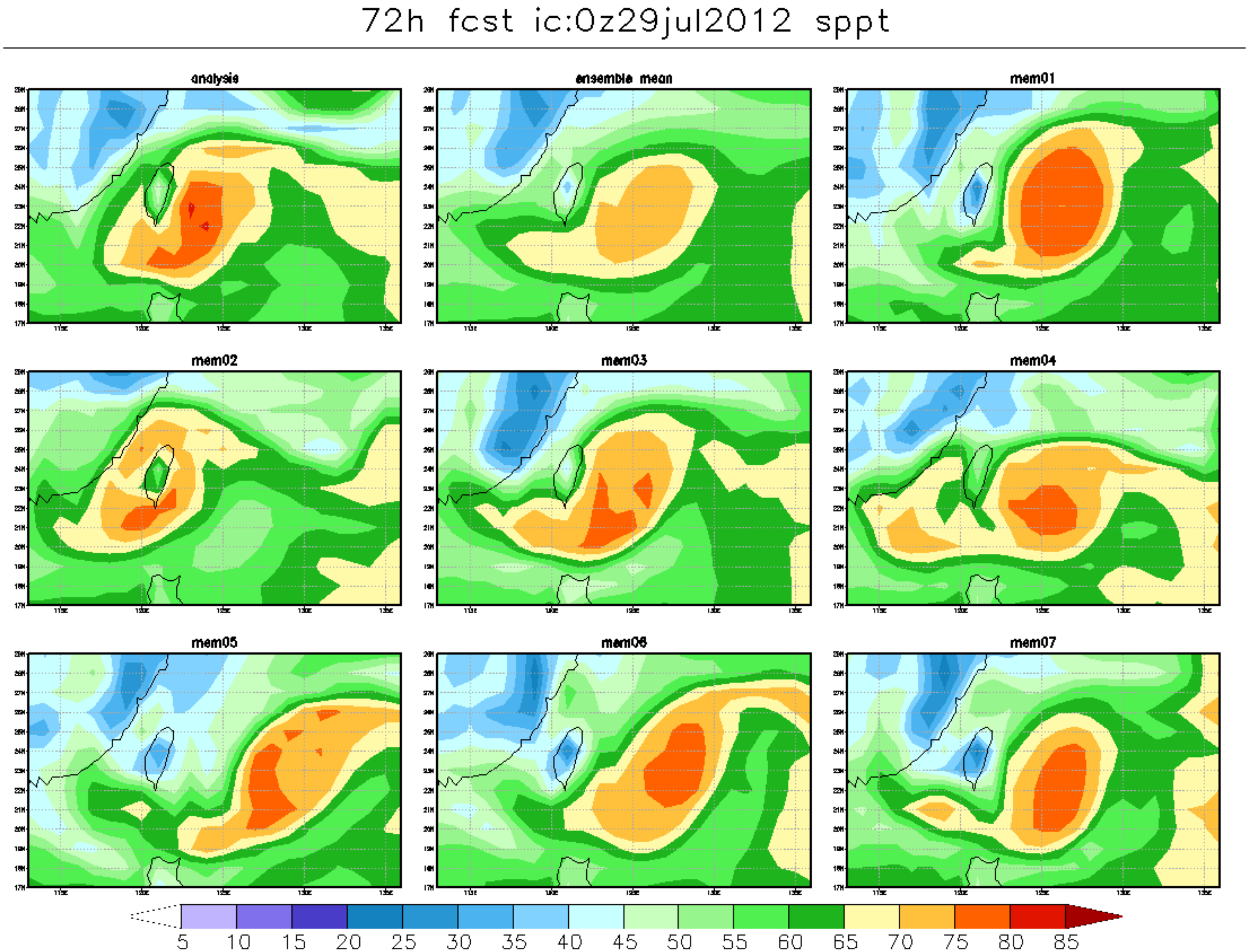

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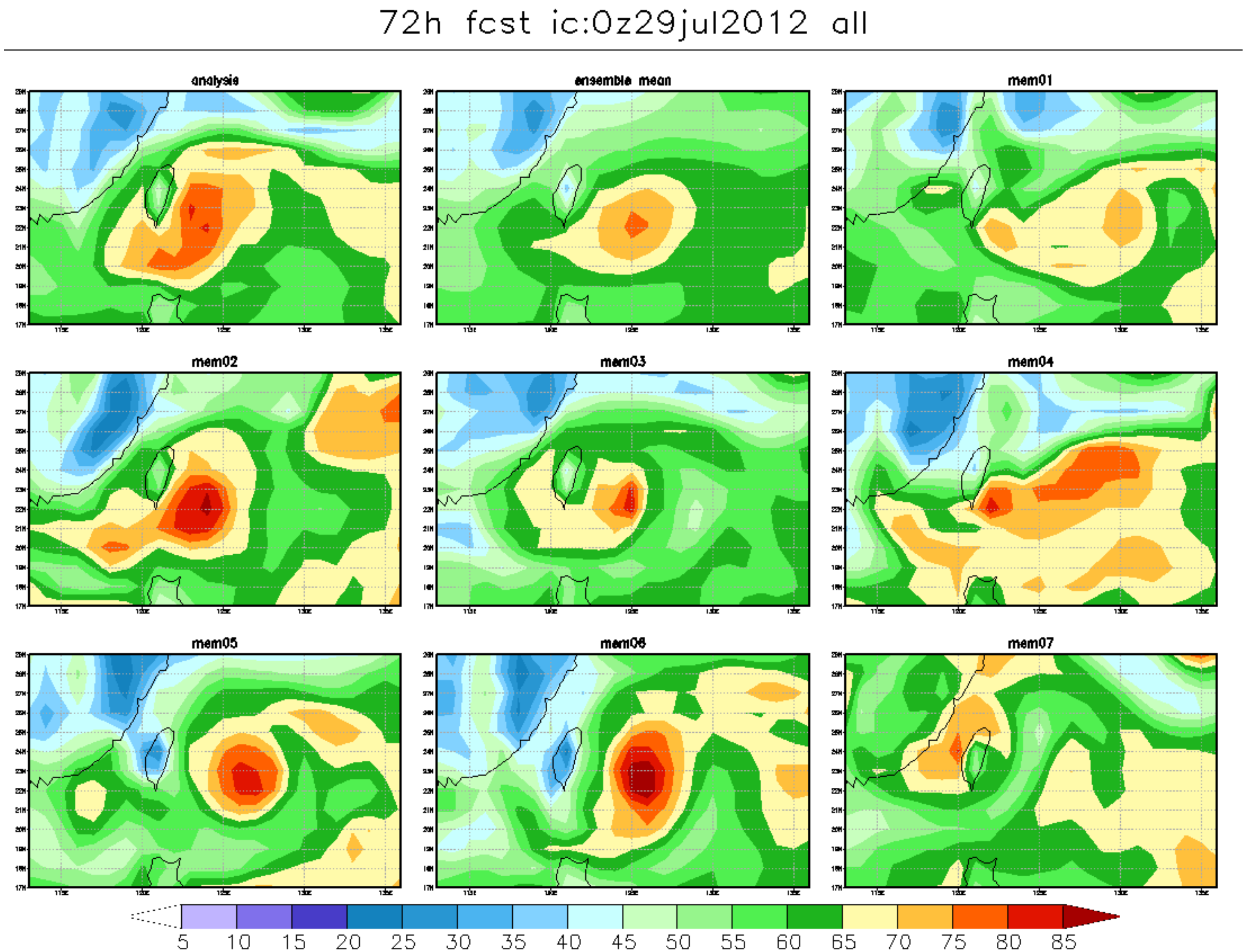

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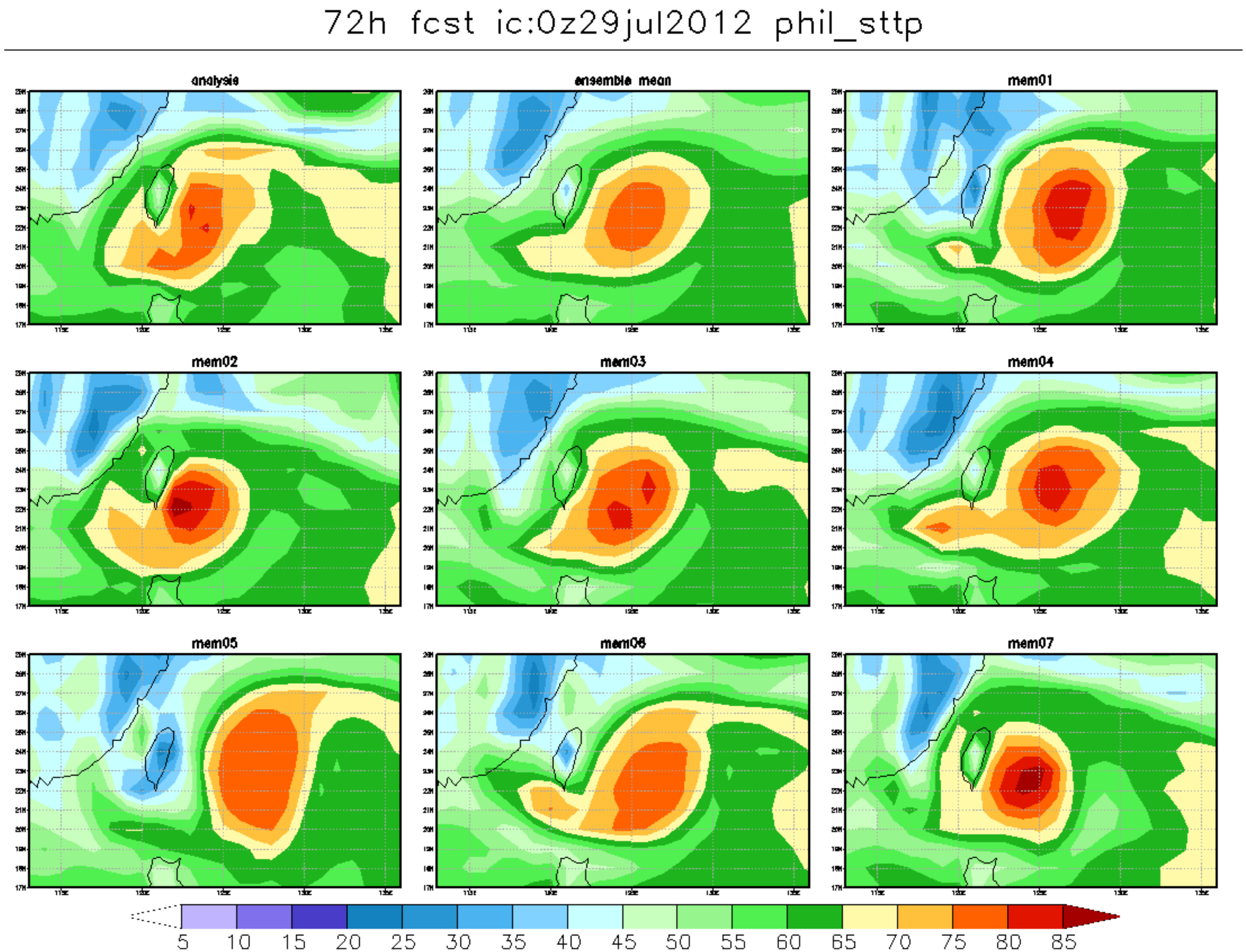
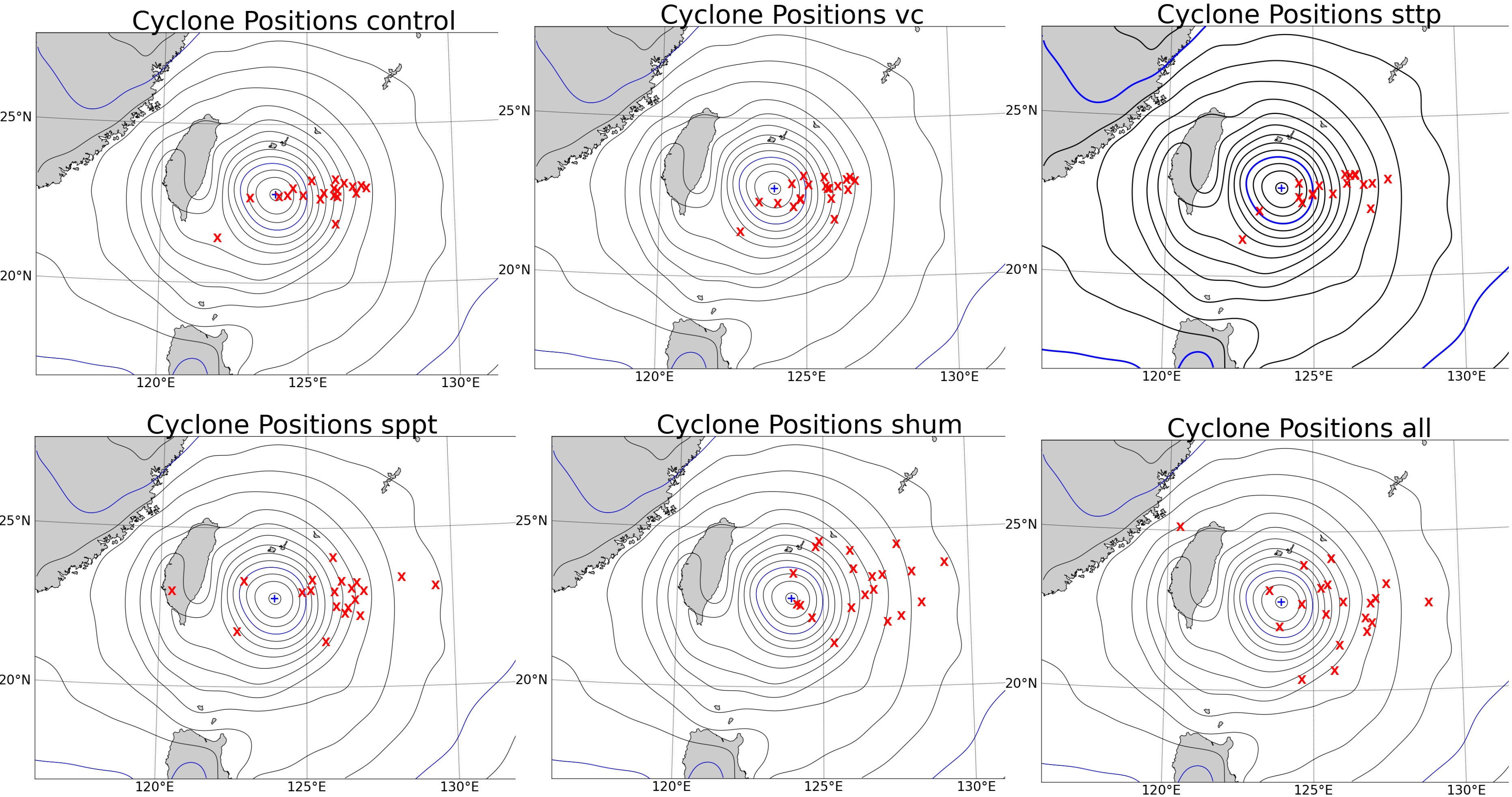


Effect on 3-d forecast TC position spread



Summary

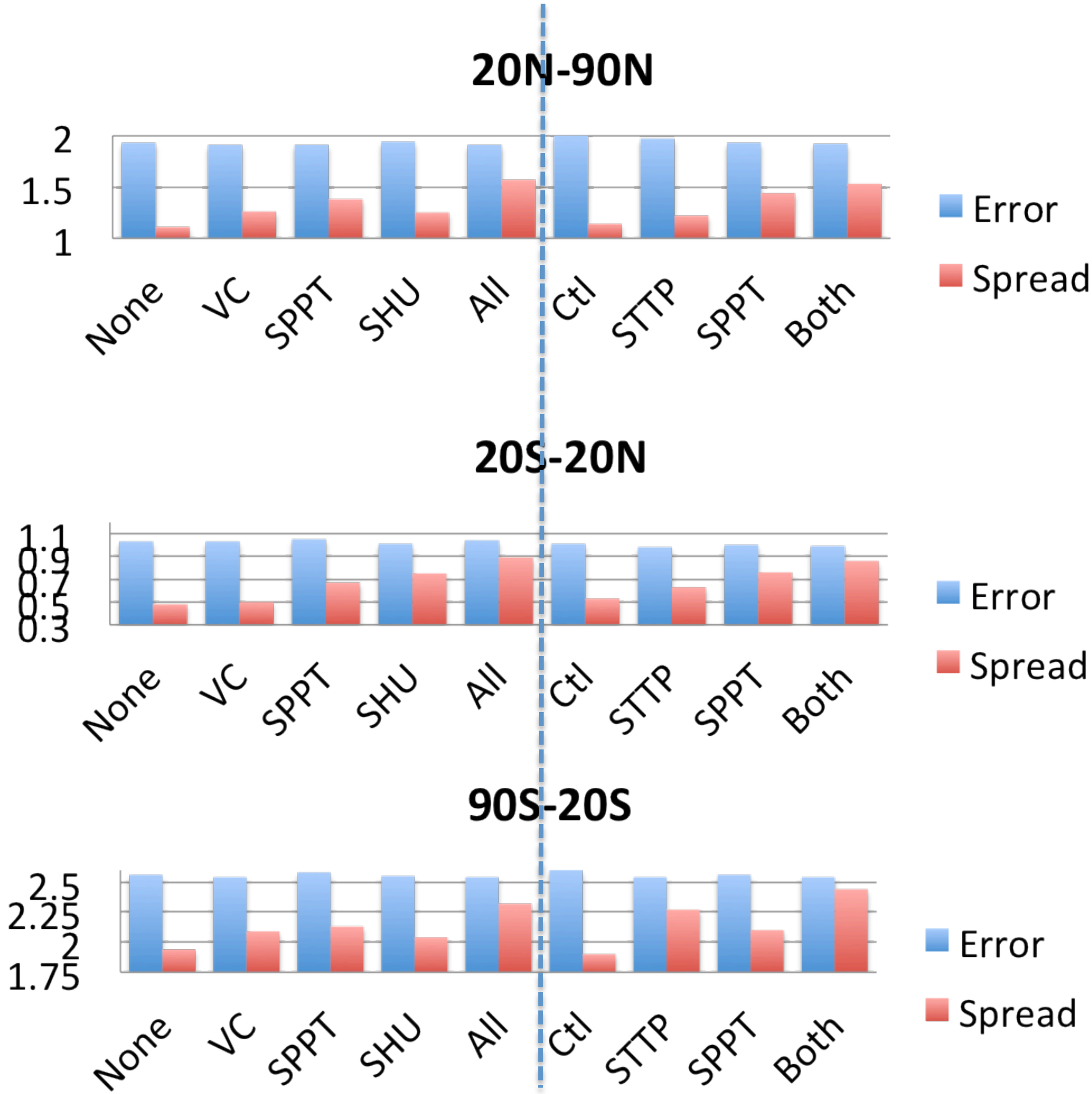
- NCEP's STTP scheme mostly affects the extra-tropics in the winter hemisphere where tendencies are largest.
- VC also is most active in extra-tropics, but more equally in winter and summer hemisphere.
  - Slight increase in mid-lat RMS error, strengthens tropical cyclones.
- SPPT and SHUM schemes have more of an impact in the tropics (including TCs) and the summer hemisphere.
  - Complement each other, since SPPT modules amplitude of existing convection while SHUM changes the location of convective precip.
- SHUM creates a warm (dry) bias in lower (upper) tropical troposphere.
  - Slightly increases (decreases) global mean precip (precipitable water).
- TC spread (track and intensity) increases dramatically with combination of VC/SPPT/SHUM. STTP has little impact on TC spread.

Next Steps

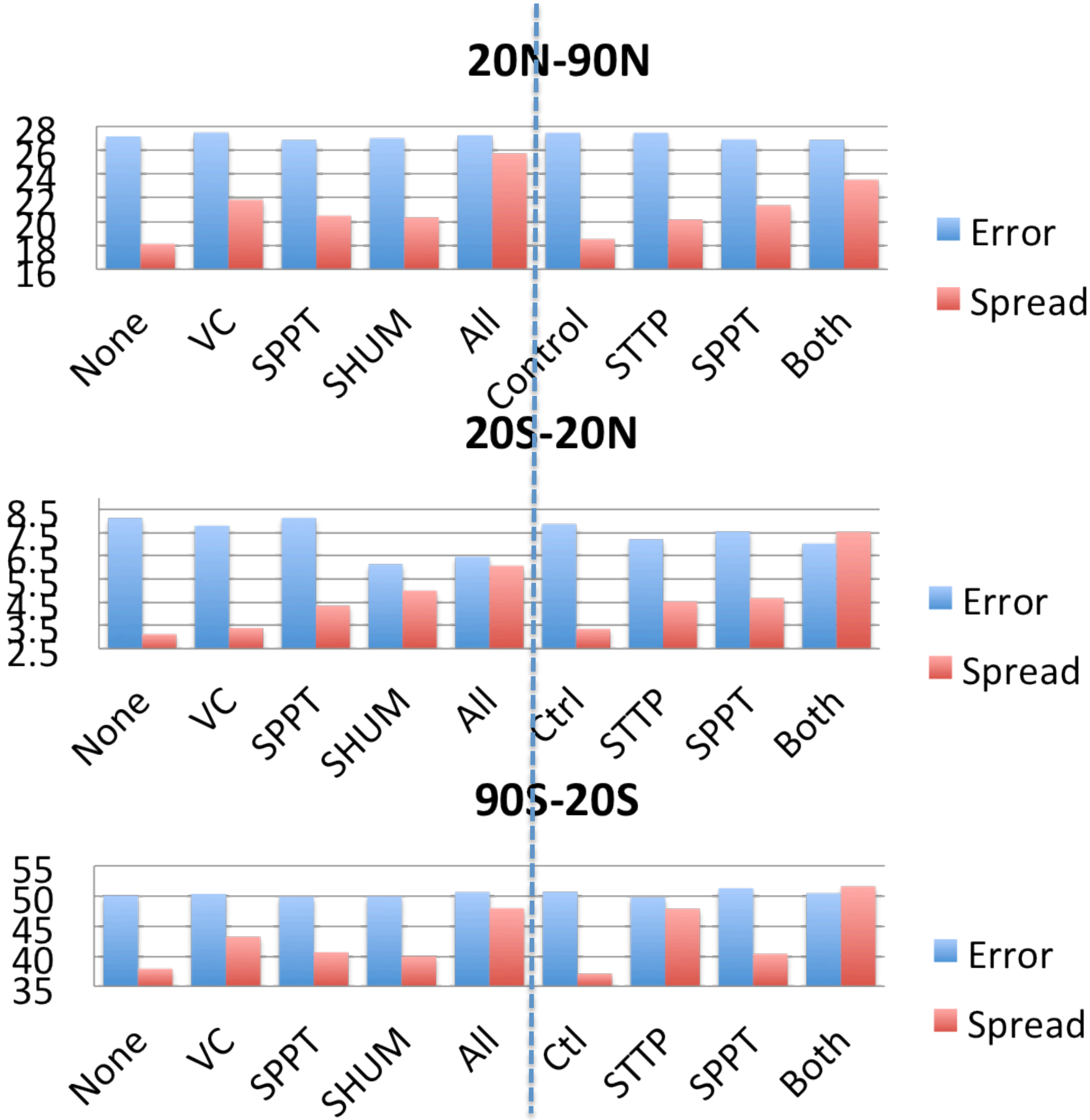
- Test in ensemble 3DVar DA cycle.
  - Can we decrease additive inflation?
  - Do background-error covariances improve?
- Investigate sources of bias in SHUM scheme.
- More extensive TC verifications.
- Port VC and SHUM to operational GFS codebase? (SPPT already done).

Extra slides

850 mb Temperature forecast statistics

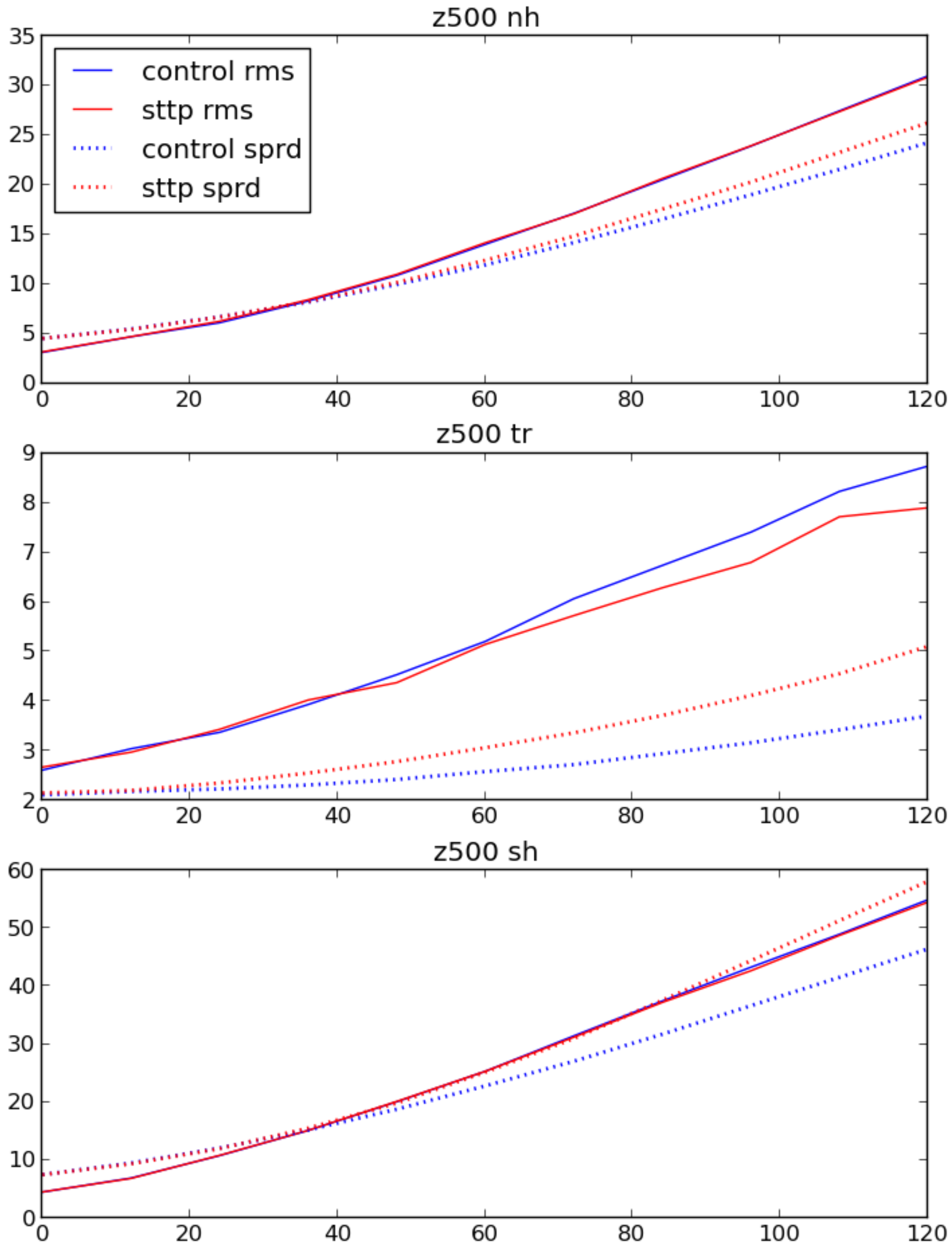


500 mb Height forecast statistics



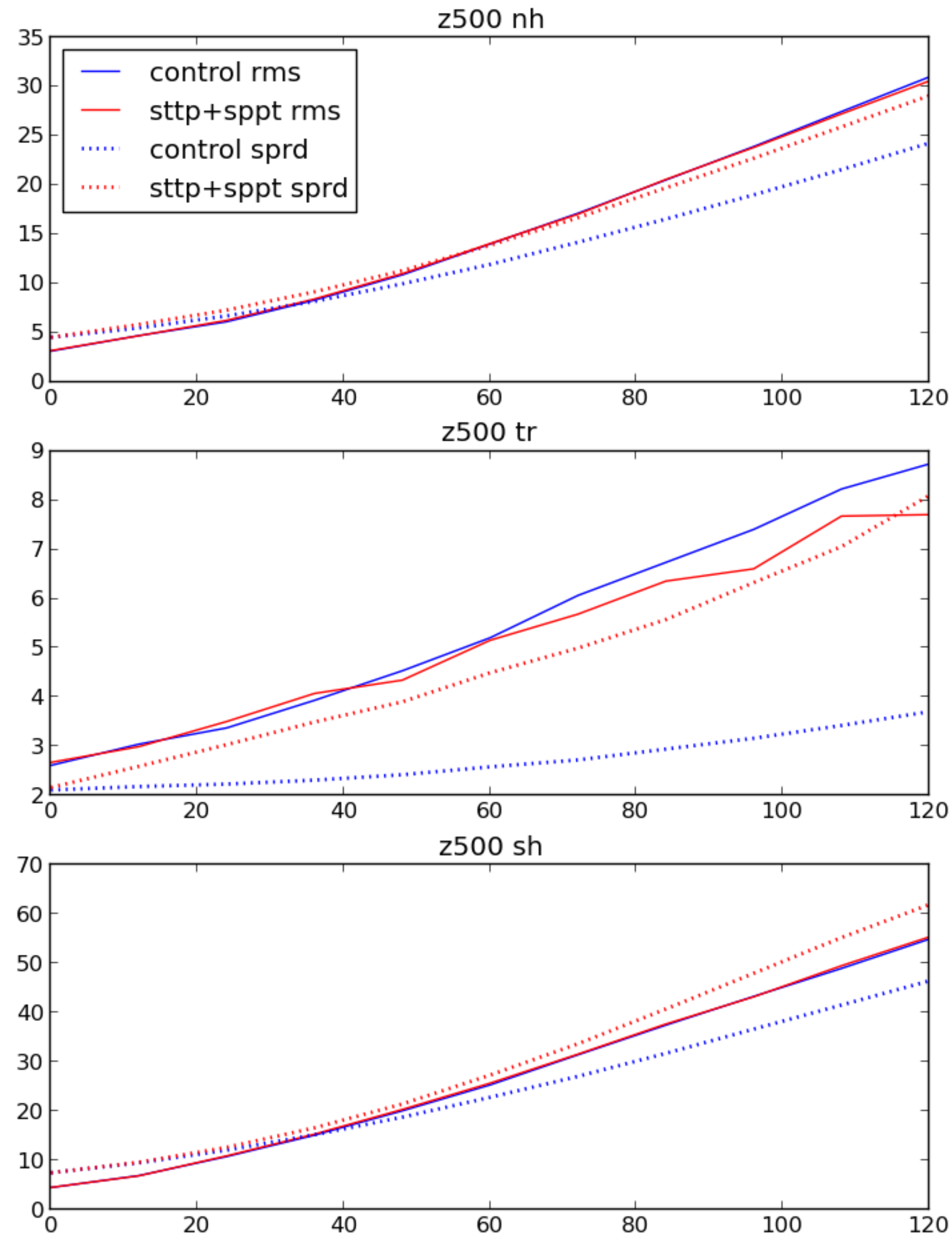
Z500 spread/ error growth

(control vs STTP)



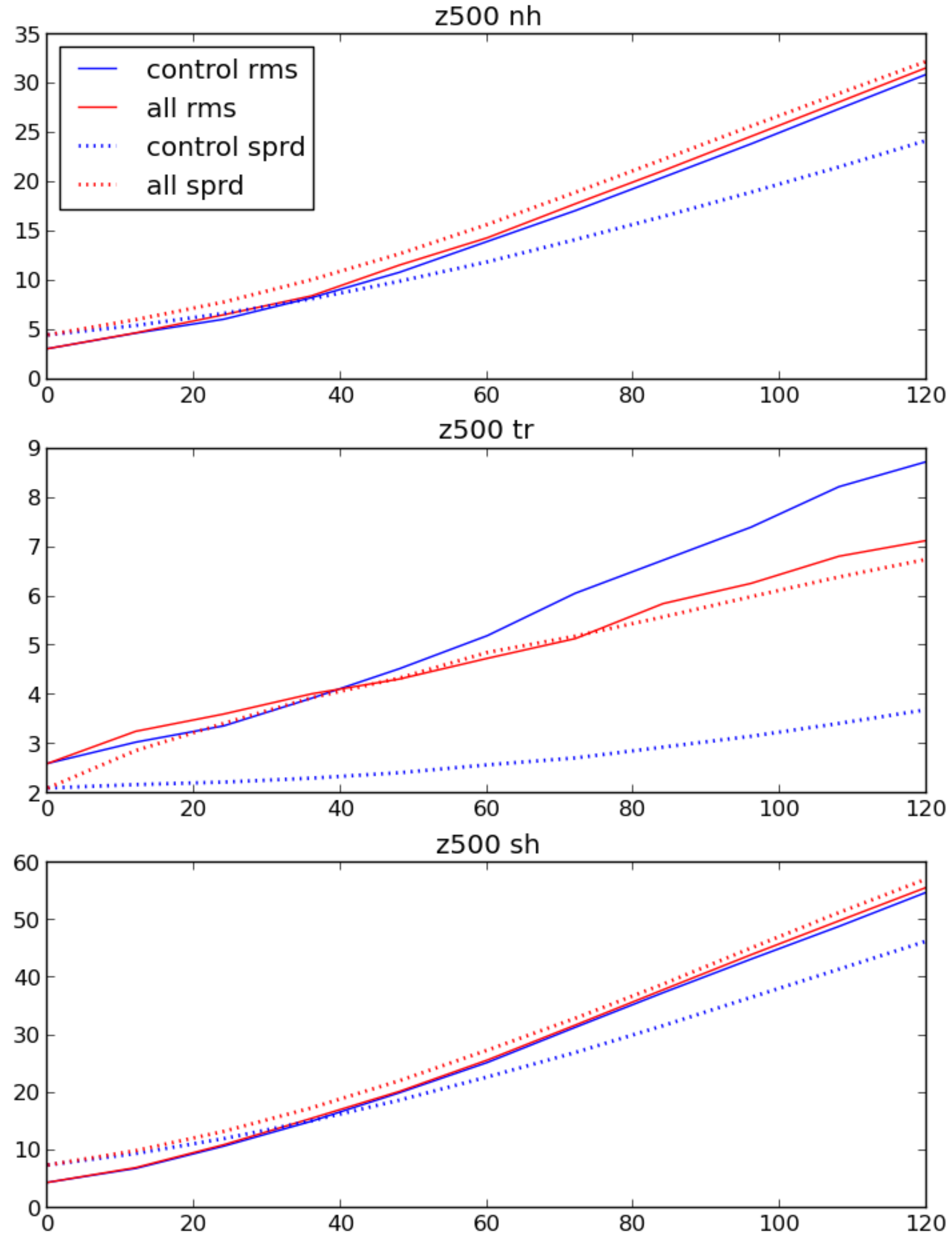
Z500 spread/ error growth

(control vs STTP+SPPT)



Z500 spread/ error growth

(control vs SPPT+SHUM +VC)



Z500 spread/ error growth

(all expts)