Stochastic parameterization development in the NOAA/NCEP Global Forecast System

Philip Pegion[*], Jeff Whitaker, Tom Hamill, Gary Bates[*], Maria Gehne[*]

NOAA/ESRL Boulder, CO and [*]CIRES University of Colorado, Boulder ,CO

Walter Kolczynski Jr.

IMSG & NOAA/NCEP College Park, MD

Motivation

- **Ensemble data assimilation**–
  - GFS analysis system is hybrid variational/EnKF system. Due to model uncertainty and a finite ensemble, additive inflation was used to increase the ensemble spread before running the background forecasts for the next cycle.
  - This additive inflation method provided no flow dependent information, and required a large data-base of forecasts to be available online at run-time.

- **Medium range forecast and beyond**—
  - Current operational scheme slaves the 21 ensemble members of the GEFS together which limits the possibility of large ensembles.
  - Operational scheme only injects spread where there is already spread.

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

- Schemes tested:
  - SPPT (stochastically perturbed physics tendencies – Palmer et al. 2009)
    - *Designed to represent the structural uncertainty of parameterized physics.*
  - SHUM (perturbed boundary layer humidity, inspired by 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 – Palmer et al. 2009)
  - 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.

Data Assimilation Cycling Experiments

Control:

- EnKF in NCEP operations (using additive inflation), but using semi-lagrangian GFS with T574 (~30km) 80-member ensemble.

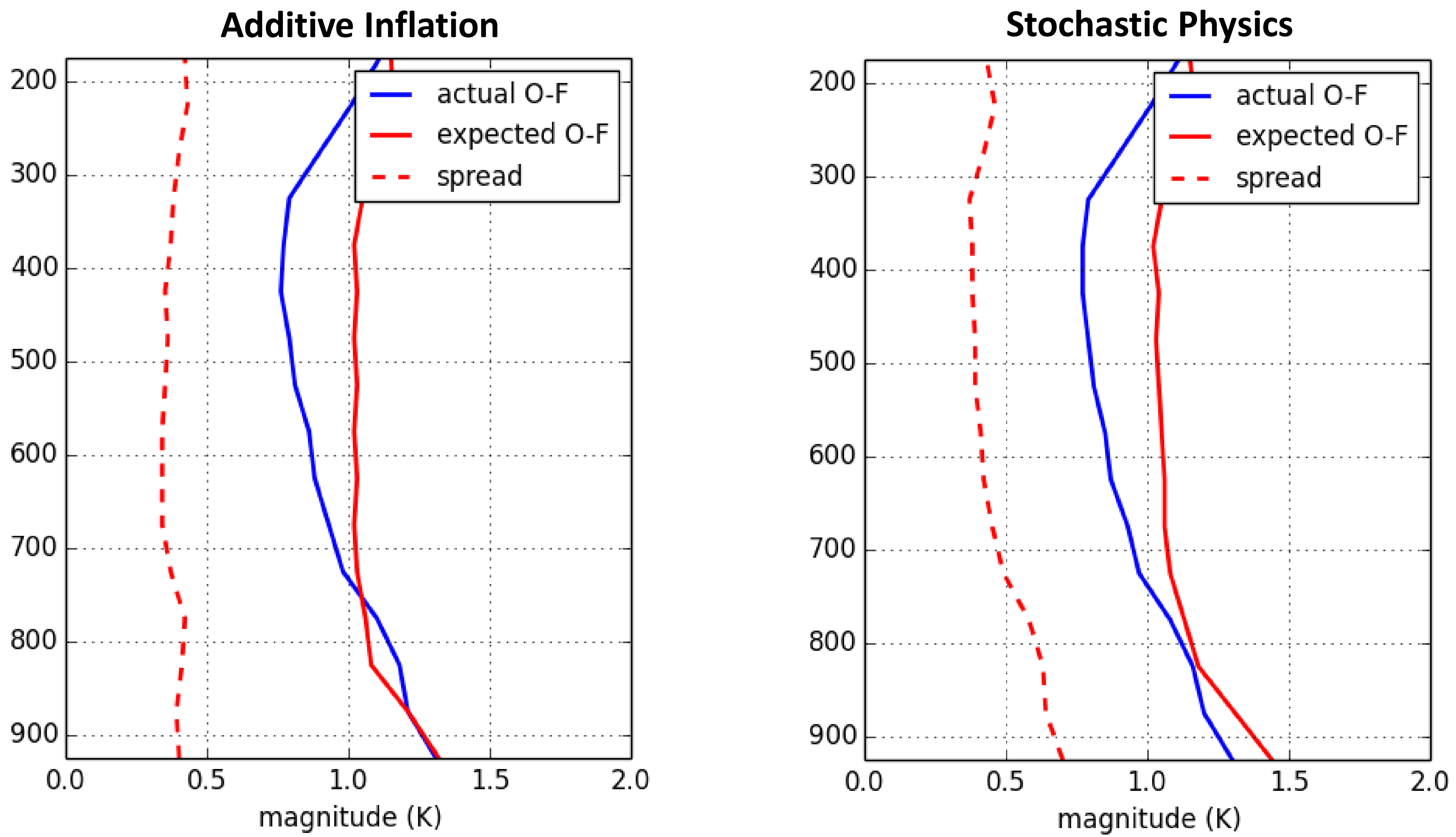
Expt:

- 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.

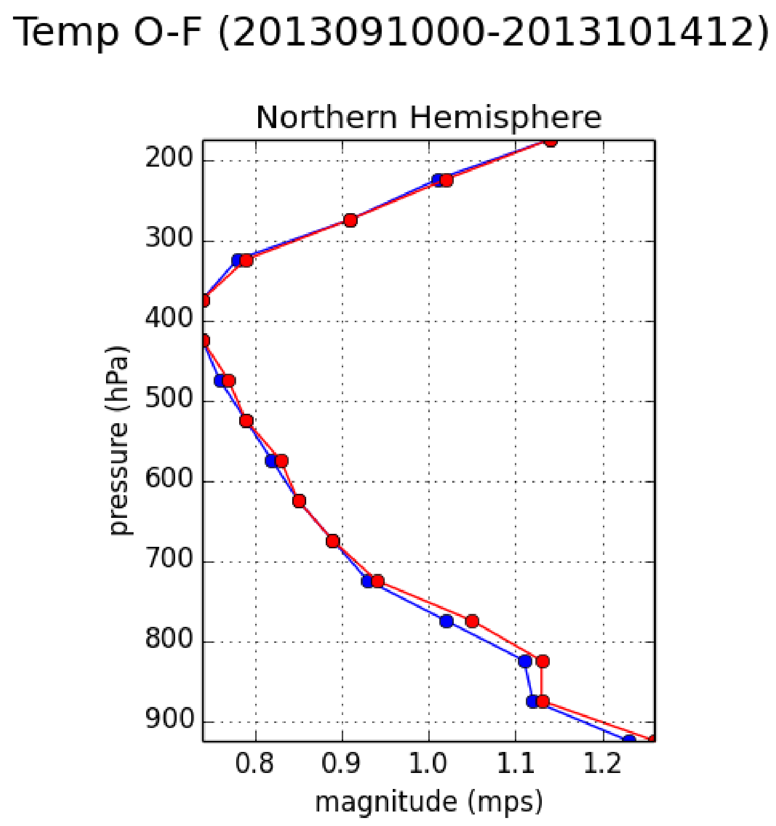
Period: Sept 1 to Oct 15 2013, after 7 day spin-up.

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

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



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



NCEP was satisfied with the changes, and these schemes went operational in January 2015.

What is different in the GFS implementation?

- Modifications to SPPT
  - Clipping of perturbations has potential of creating a bias, switch to a logit transform for random pattern
  - Allow SPPT to perturb the entire column, damping of perturbations below 850hPa in the GFS resulted in an anemic response to this scheme.
  - heating tendencies due to radiation interacting with clouds is perturbed, but clear sky is still unperturbed.
- Perturbed PBL scheme (SHUM)
  - we want to trigger convection in new places. SPPT only modifies tendencies in regional where convections is already active.
- SKEB
  - Energy dissipation does not include contribution from sub-grid-scale convection
- Vorticity confinement in addition to SKEB.
  - seems to operate at different time scales, SKEB perturbations grow quickly, VC has slower growth.
  - SKEB modifies Tropical Cyclone track spread
  - Vorticity confinement modifies Tropical Cyclone intensity

Medium range ensemble

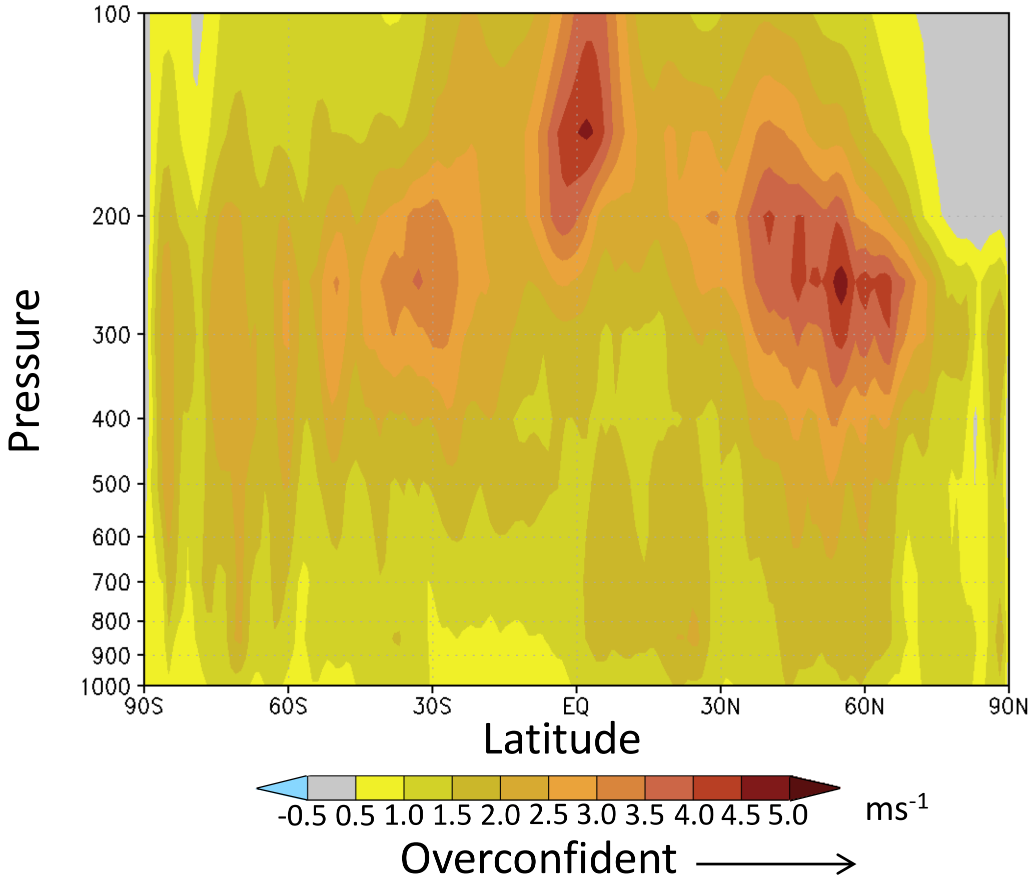
- Current scheme in the GFS (STTP) randomly adds differences in tendencies from linear combination of ensemble members to a given member.
    - In effect, this adds ensemble spread where there is already ensemble spread
    - Requires all of the ensemble members to run concurrently, preventing large ensembles

5-day forecast Zonal Wind RMS error – Spread

zonal average from 1 month of forecasts: August 2012

RMS error: ensemble mean error with respect to verifying analyses

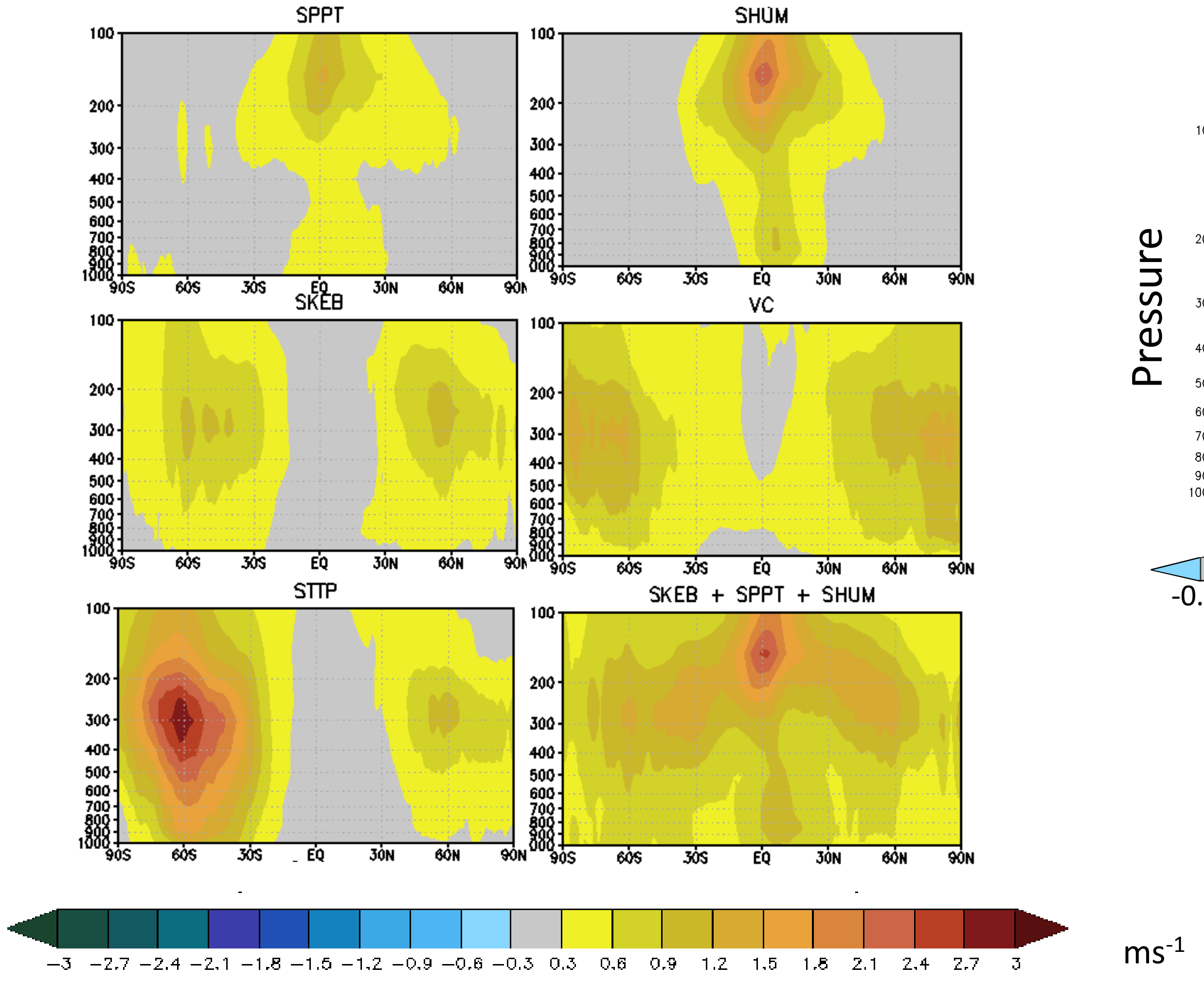
Spread: standard deviation among ensemble members



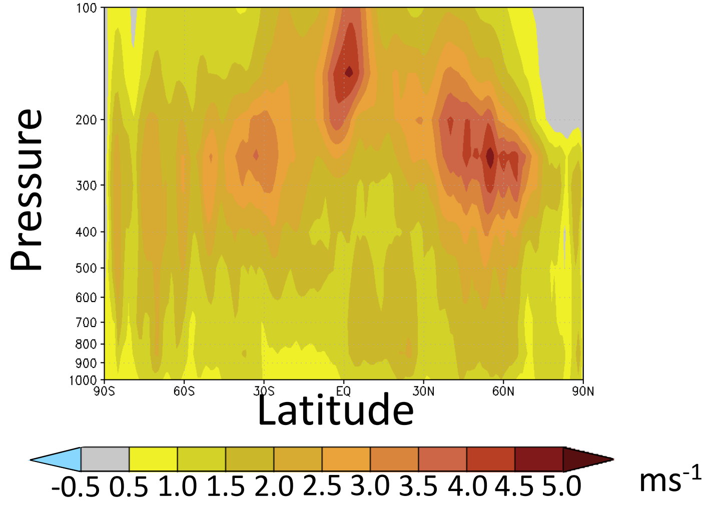
GFS ensemble, no treatment for model error "baseline"

Change in Ensemble Spread relative to Control Forecasts

Zonal Wind

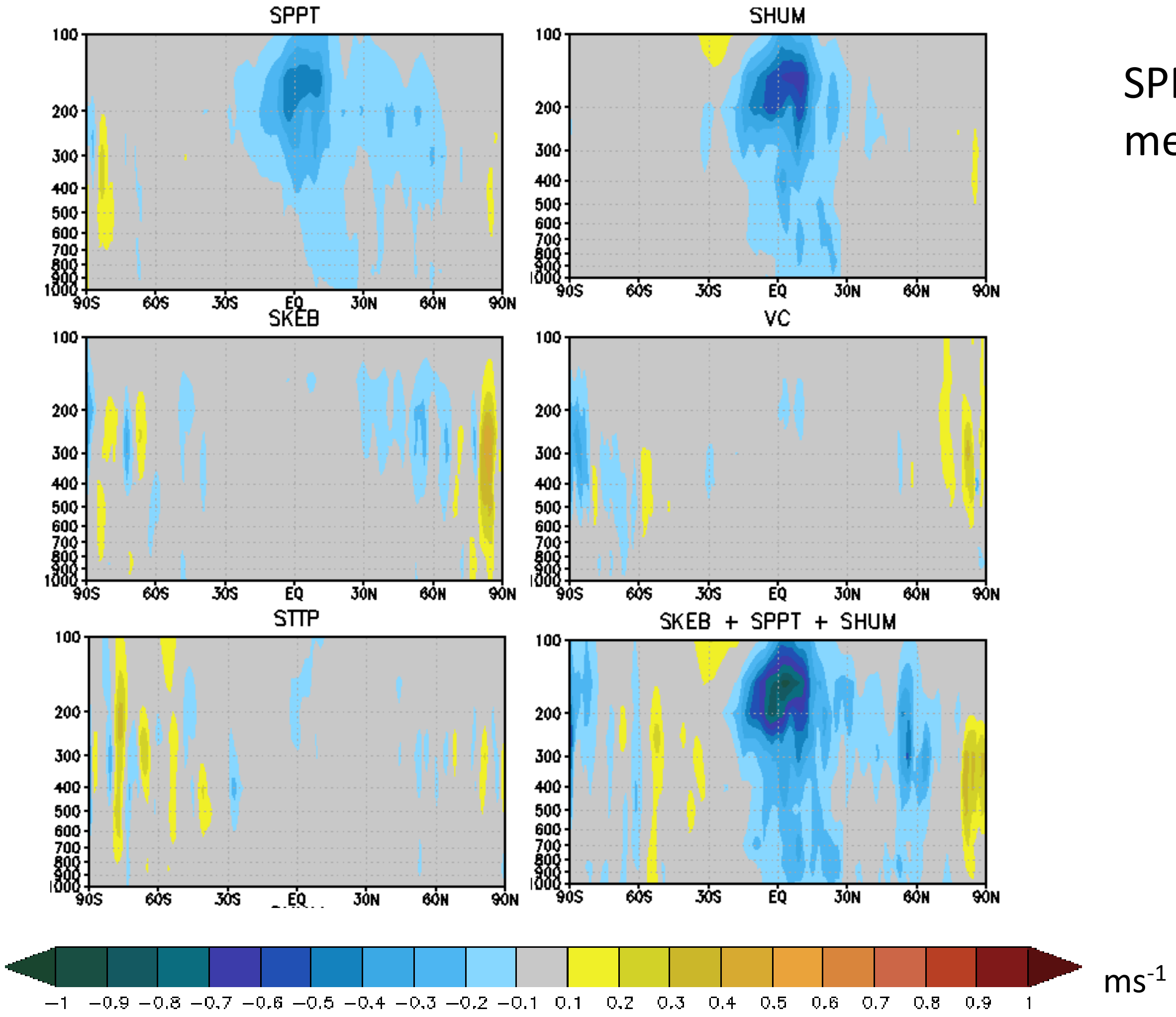


Control Ensemble
RMS error - Spread



Change in Ensemble Mean RMS Error relative to Control Forecasts

Zonal Wind

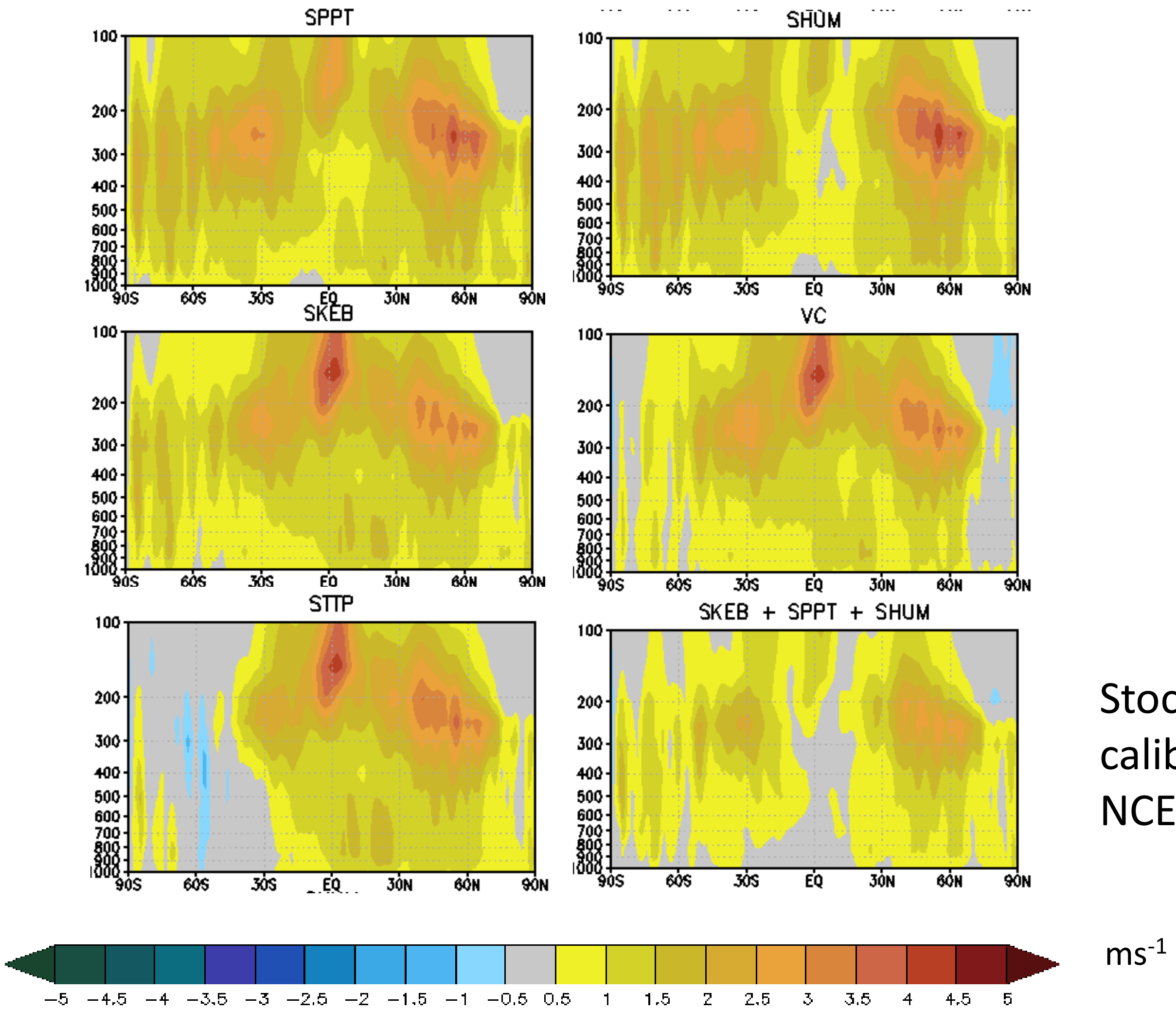


SPPT & SHUM improve ensemble mean forecasts in the tropics.

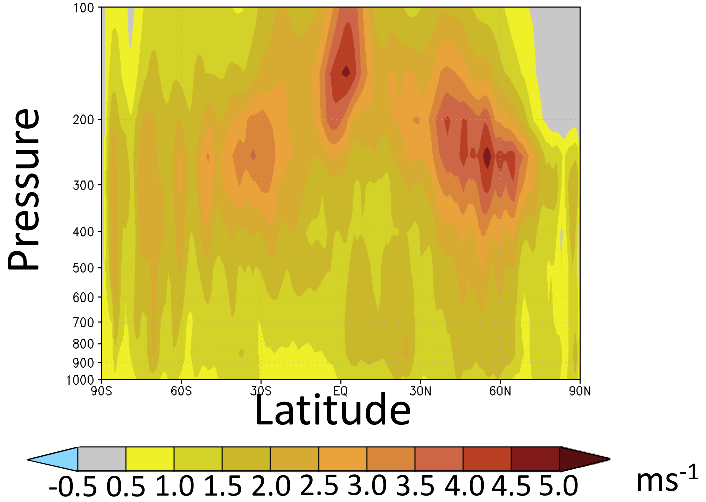
Note: contour interval 0.1ms^{-1}

RMS Error – Spread

Zonal Wind

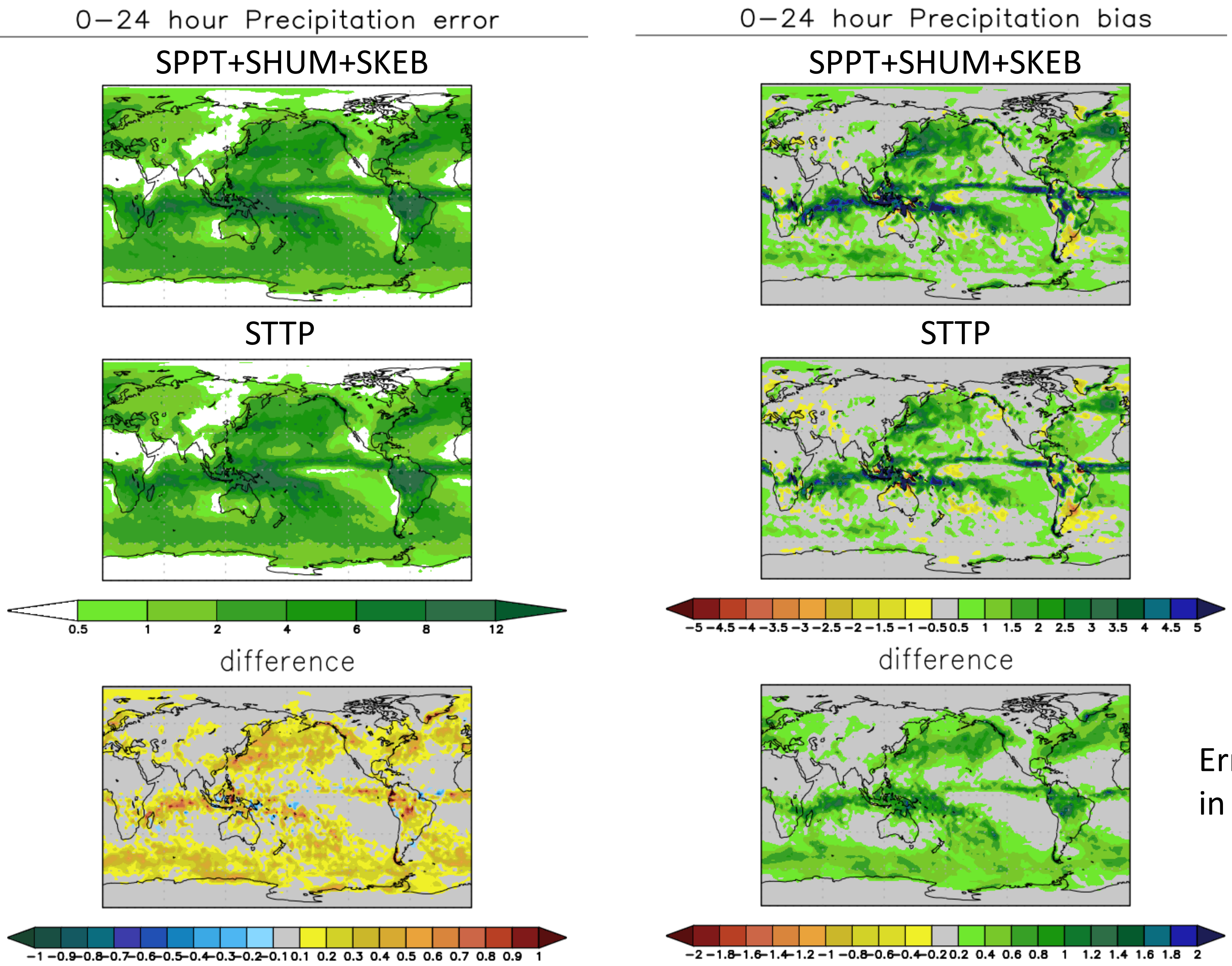


Control Ensemble
RMS error - Spread



Stochastic physics package provides a better calibrated system then STTP. At this point, NCEP began pre-implementation testing

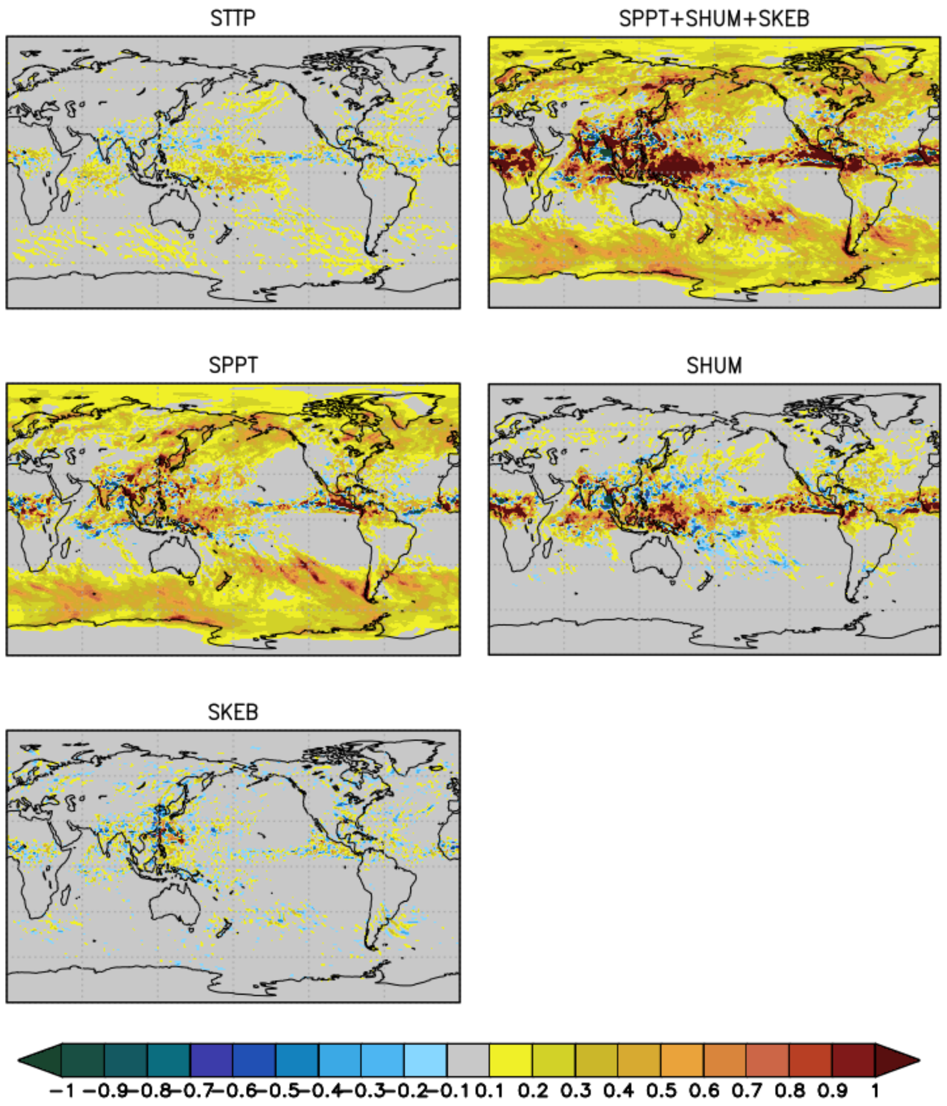
Jan-Mar 2014 Forecast validated again GPCP on 2.5-degree grid



Stochastic physics
Increases precipitation
error

Error is due to increase
in precipitation bias.

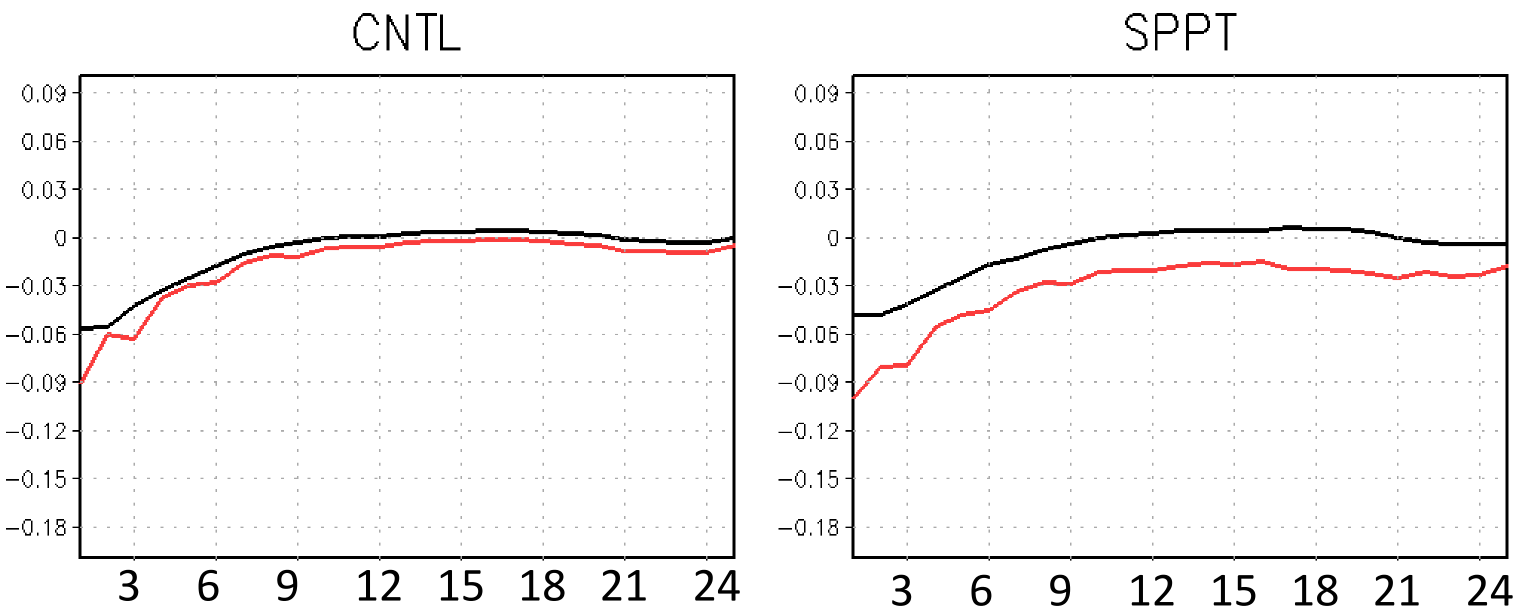
Precipitation Bias (wrt Control) 24-48 hours forecast : August 2012



Precipitation bias is because of SPPT, and occurs mainly
In large-scale condensation regimes.

Water Budget

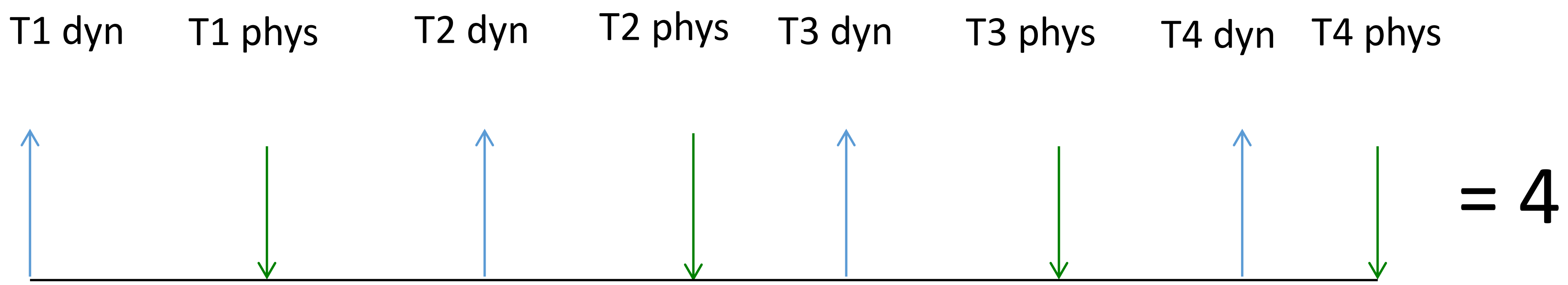
Hourly output from a 24-hour forecast



Hourly change in total precipitable water
Evaporation - Precipitation

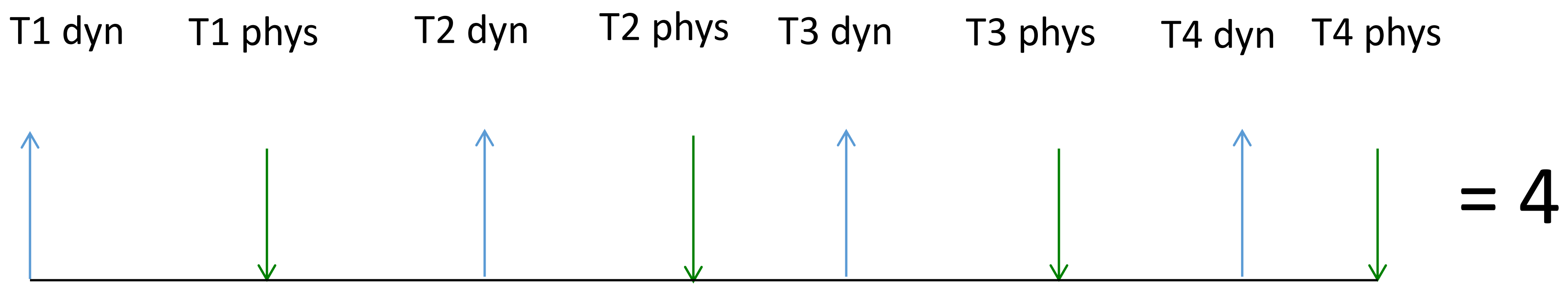
Cause of Precipitation Bias:
Idealized example

SPPT_WT = 1.0 – no perturbation

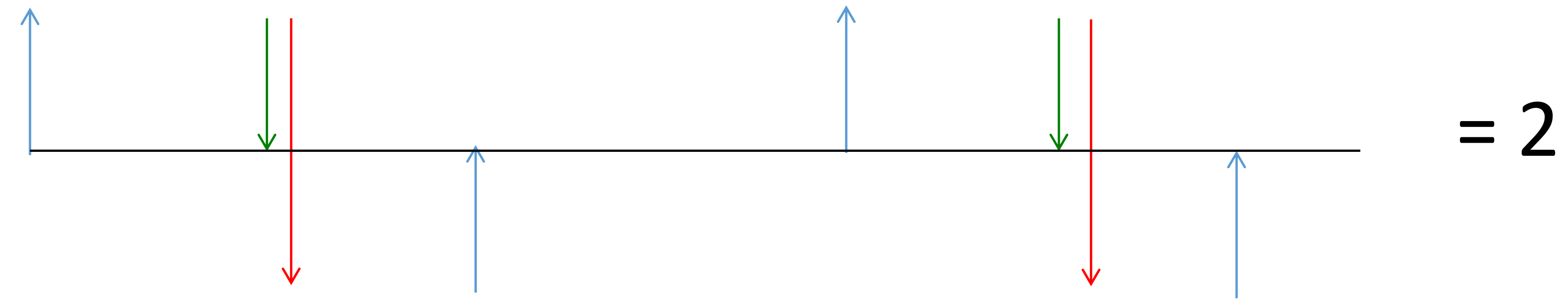


Idealized example

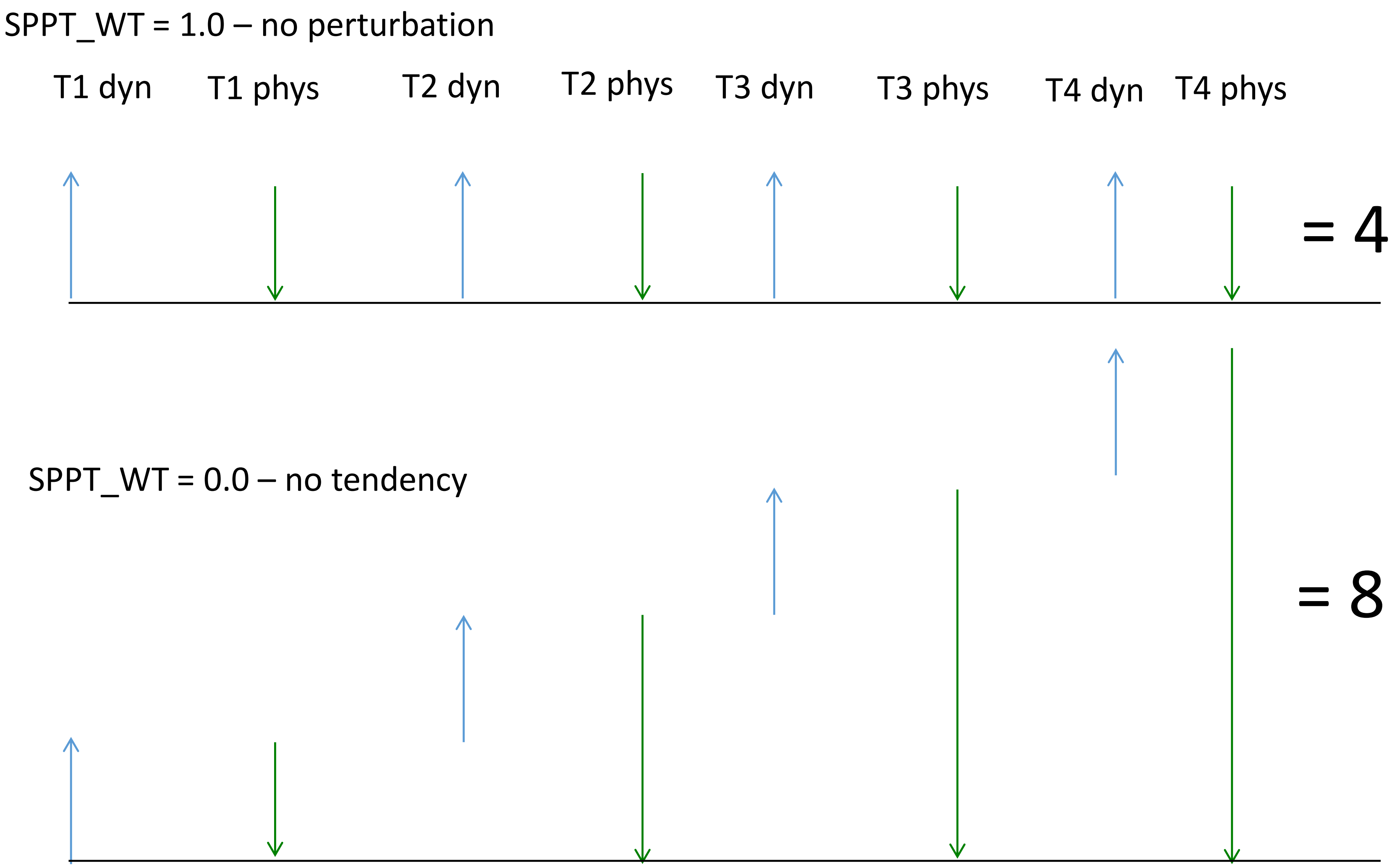
SPPT_WT = 1.0 – no perturbation



SPPT_WT = 2.0 – double tendency



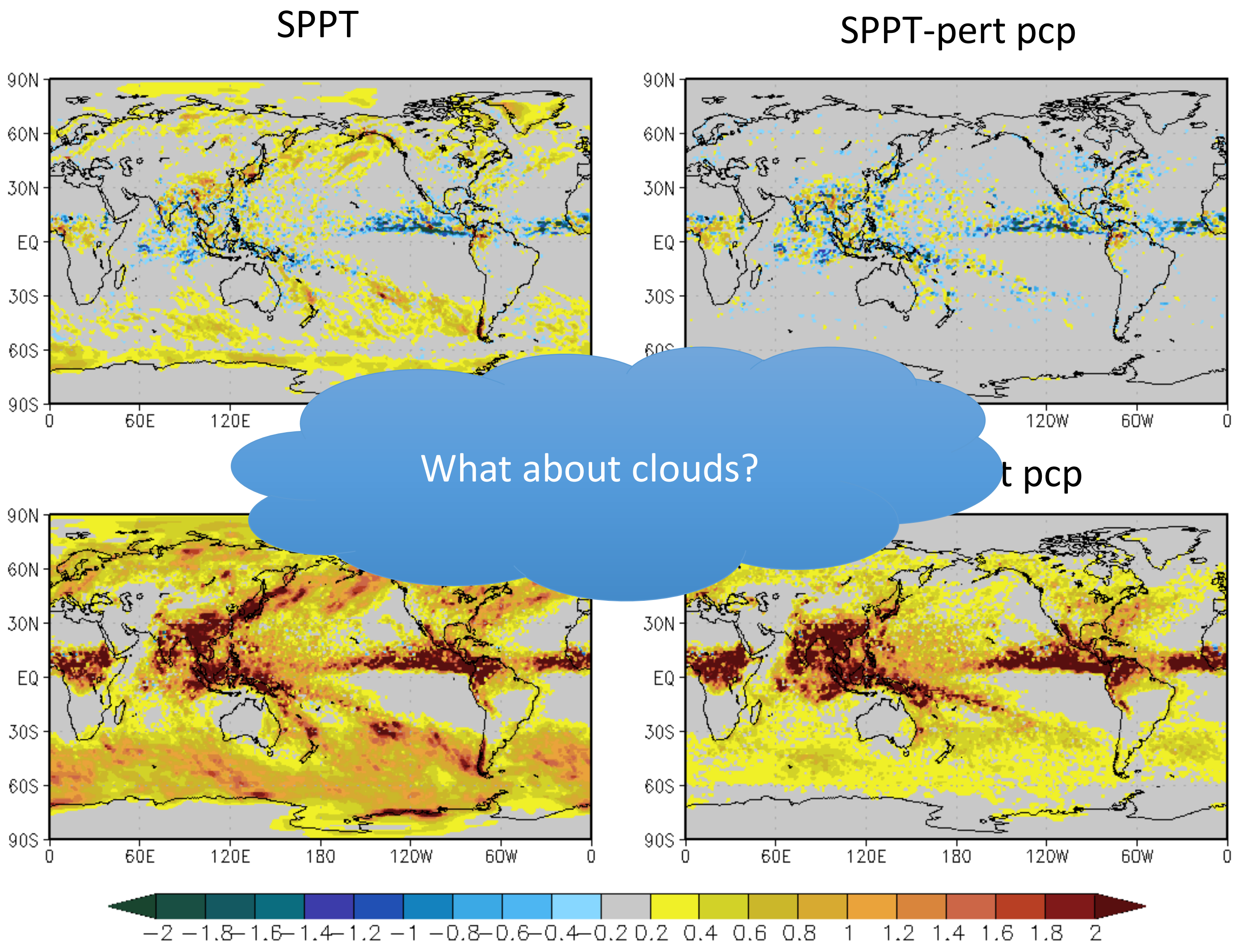
Idealized example



Precipitation Stats   August 2014

Change in Error

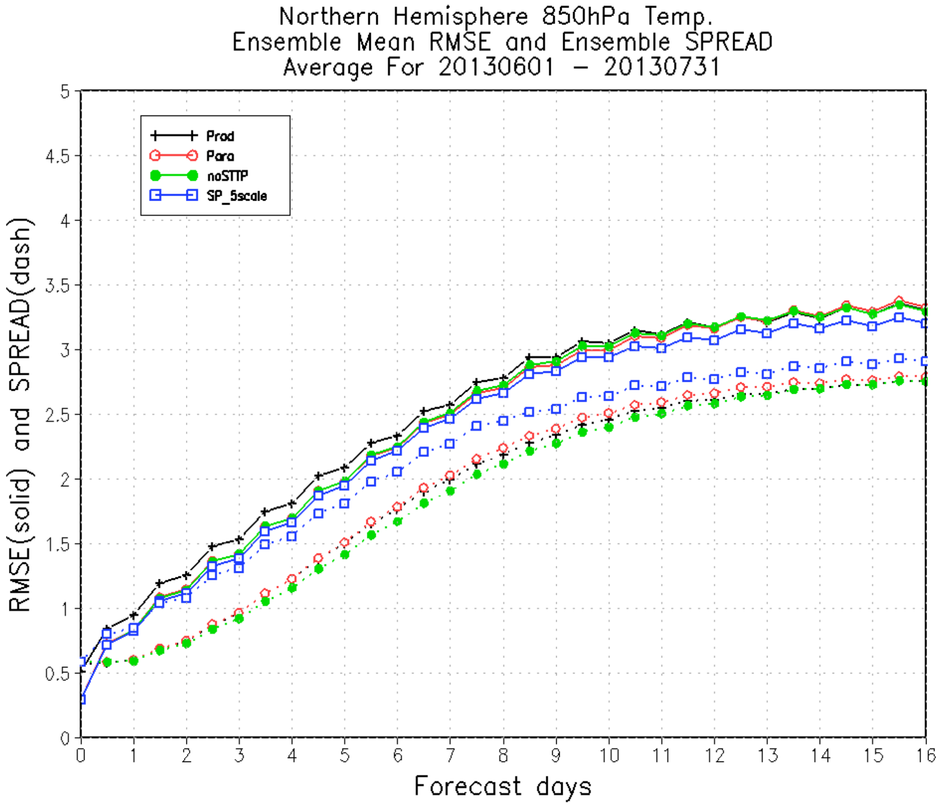
Change in Spread

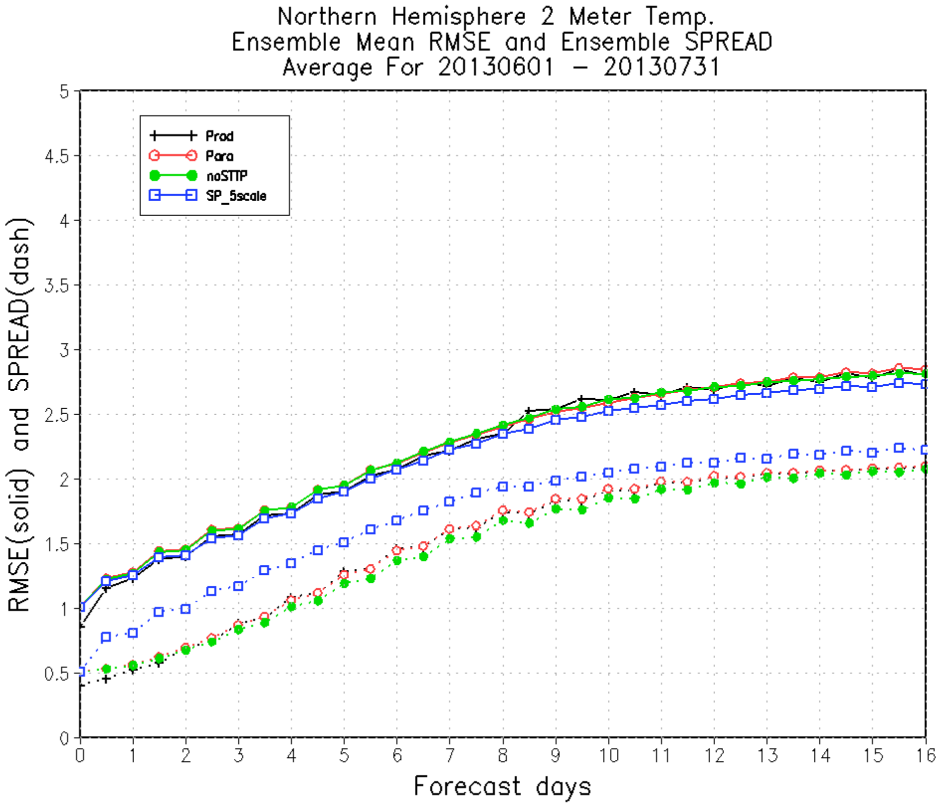


Stochastic physics effect on model’s climatology

- Running long AMIP style simulations to understand if these methods could be applied to coupled climate forecasts with the CFS.
- Initial results show that perturbing cloud water tendencies in addition to other physics tendencies is producing too much drying in atmosphere. Work is ongoing.

Surface quantities are still under-spread

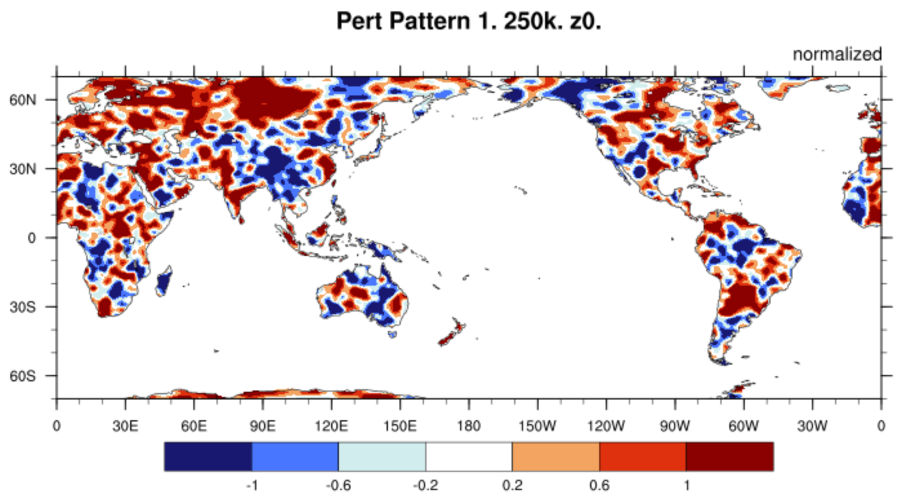




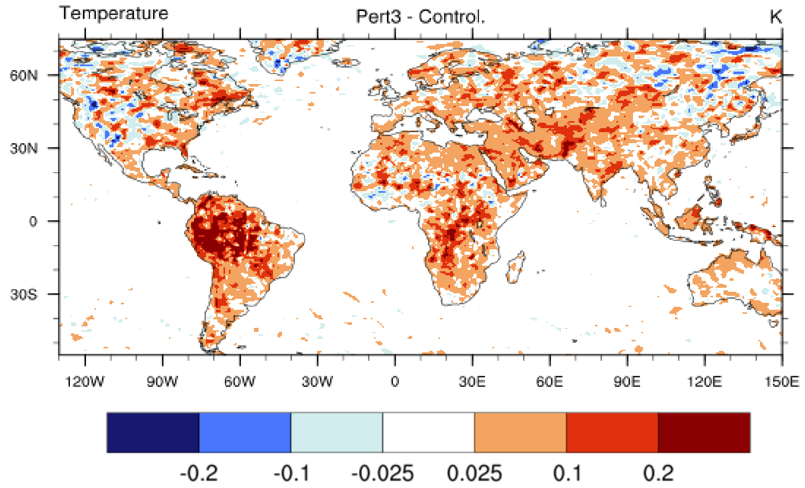
Surface Perturbations

- There are errors associated with the lower boundary conditions
  - in atmosphere only runs (GFS), SST anomalies are damped toward climatology during the forecast.
  - Errors associated with land surface model and initial conditions (not addressed here)

- Methods
  - Perturb SST with random pattern
  - Perturb surface momentum roughness length (Z0),thermal roughness length (zt) and soil hydraulic conductivity (SHC), and leaf area index (LAI)



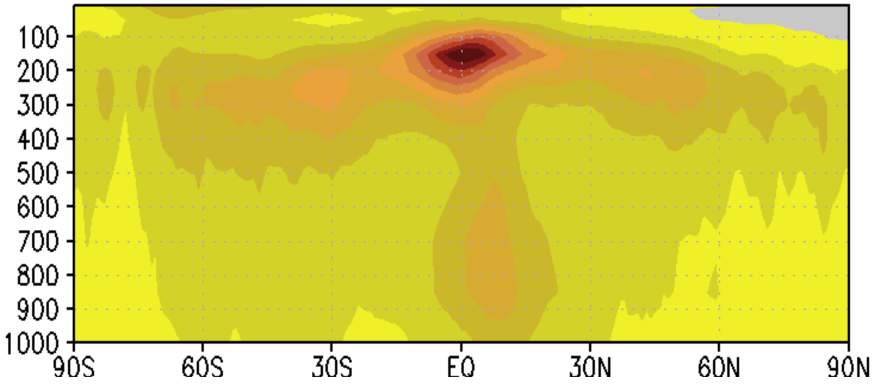
change of spread



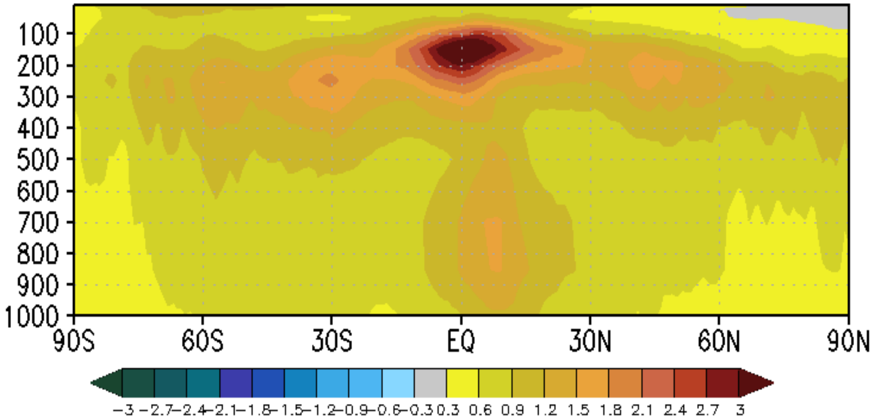
Change in Ensemble Spread

zonal average from 1 month of forecasts (August 2014)

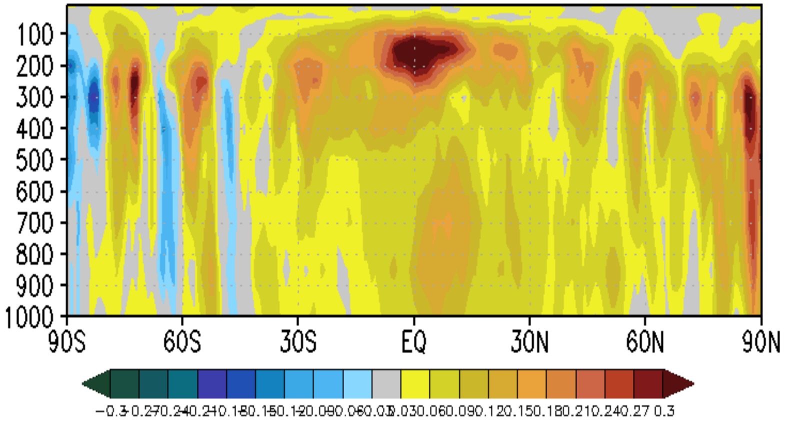
Atmosphere only stochastic parameterizations



Atmosphere & land stochastic parameterizations



Impact from surface perturbations



The addition of the surface (SST and land) perturbations provides a small increase in spread.

Future Work

- Continue to look at sensitivity to land surface, what other variables can we perturb?
- Need to address uncertainty in land surface initial conditions. Working on running land surface analysis off-line with different precipitation datasets to understand the sensitivity of initial state to observed forcing.
- Process level stochastic physics
  - There is a new PBL/shallow convective scheme scheme available to the GFS: SHOC (Simplified High Order Closure).
  - This scheme predicts the PDFs of sub-grid scale quantities. Our plan is to sample from these PDFs as input profiles to other physical parameterization such as deep convection.
  - SHOC also predicts sub-grid-scale TKE. We will test adding this to the gradient of convective mass flux used in stochastic convective backscatter (Shutts 2015).
- Looking to hire a post-doc this spring, announcement to come out soon