Stochastic parameterization development in the NOAA/NCEP Global Forecast System

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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 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)

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

Pressure

Latitude

ms$^{-1}$

ms$^{-1}$
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\(^{-1}\)
Stochastic physics package provides a better calibrated system than STTP. At this point, NCEP began pre-implementation testing.
### Jan-Mar 2014 Forecast validated again GPCP on 2.5-degree grid

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<thead>
<tr>
<th>0–24 hour Precipitation error</th>
<th>0–24 hour Precipitation bias</th>
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<tbody>
<tr>
<td><strong>SPPT+SHUM+SKEB</strong></td>
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**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

T1 dyn  T1 phys  T2 dyn  T2 phys  T3 dyn  T3 phys  T4 dyn  T4 phys

= 4
Idealized example

SPPT_WT = 1.0 – no perturbation

\[ T_{1 \, \text{dyn}} \quad T_{1 \, \text{phys}} \quad T_{2 \, \text{dyn}} \quad T_{2 \, \text{phys}} \quad T_{3 \, \text{dyn}} \quad T_{3 \, \text{phys}} \quad T_{4 \, \text{dyn}} \quad T_{4 \, \text{phys}} \]

= 4

SPPT_WT = 2.0 – double tendency

= 2
Idealized example

SPPT_WT = 1.0 – no perturbation

SPPT_WT = 0.0 – no tendency

= 4

= 8
Precipitation Stats  August 2014

Change in Error

Change in Spread

What about clouds?
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 ($Z_0$), thermal roughness length ($z_t$) and soil hydraulic conductivity (SHC), and leaf area index (LAI)
Change in Ensemble Spread
zonal average from 1 month of forecasts (August 2014)

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