Tests of various schemes for representing model uncertainty in the GFS

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(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:

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

Simplification: Use finite difference form for the stochastic term

Modify the model state every 6 hours:

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

Where \( w \) is an evolving combination matrix, and \( \gamma \) 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-perturbed 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

\[ X_p = (1 + r\mu)X_c \]

\( \mu \) - 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)

\[
\frac{DV_H}{Dt} + f k \times V_H + \nabla \phi = \mu \nabla^2 V_H + \epsilon \hat{n} \times |\zeta| \hat{k}
\]

\[
\hat{n} = \frac{\nabla_H \zeta}{|\nabla_H \zeta|}
\]

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

\[\epsilon \hat{n}\]
acts as an advective velocity

\[\epsilon = 0.6\] 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.

\[ q_{\text{perturbed}} = (1 + r \mu)q \]

• Vertical weight \( r \) decays exponentially from surface. Added every time step after physics applied. Random pattern \( \mu \) has a (very small) amplitude of 0.00375, horizontal/vertical scales (250 km, 3-h).
U250 spread/error growth

RMS error reduced in tropics

Much faster spread growth with SHUM

VC+SPPT+SHUM, VC, SHUM, STTP control
Zonal Wind Spread

Ensemble Mean Error (control)

Ensemble Spread (control)

Ensemble Spread (STTP)

Ensemble Spread (SPPT+SHUM+VCI)
Ensemble Mean Error (control)

Ensemble Spread (SPPT+SHUM+VC)

Geopotential Height Spread

Ensemble Spread (SPPTI)
VC spread – control spread
SPPT spread – control spread
STTP spread – control spread
SHUMs spread – control spread

Z spread differences
Specific Humidity Spread

Almost all of the spread increase comes from SHUM

Ensemble Mean Error (control)

Ensemble Spread (control)

Ensemble Spread (SPPT+SHUM+VC)

Ensemble Spread (STTP)
Bias

Humidity ← Control
ALL →

Most of additional bias comes from SHUM

Temp ← Control
ALL →
KE spectra

rotke250

- 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

72h fcst ic:0z29jul2012 ctl
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 vc
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 sppt
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 shum
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 all
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 phil_sttp
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 ctl
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 vc
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72h fcst ic:0z29jul2012 all
Typhoon Saola 0z1aug2012

72h fcst ic:0z29jul2012 phil_sttp
Effect on 3-d forecast TC position spread

Cyclone Positions control

Cyclone Positions vc

Cyclone Positions sttp

Cyclone Positions sppt

Cyclone Positions shum

Cyclone Positions all
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
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)