Advances in ensemble weather prediction, 2008-2009

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Highlights

• Improved stochastic treatments of model errors in ensemble predictions
• Growing maturity of ensemble Kalman filter for improved data assimilation, ensemble initialization.
• Convection-permitting ensembles
• Facilitation of research and model comparisons with new TIGGE data set
• Reforecasts and ensemble post-processing
(1) Improved stochastic treatments of model errors in ensemble predictions

SPPT: Stochastically Perturbed Physical Tendencies (ECMWF TM 598)

∀ \( X \in \{u,v,T,q\} \), \( X_p = (1 + r\mu)X_c \) \( \mu \in (0,1) \)

\( r \) is random number, \( \mu \) used for reducing the perturbation amplitude near surface and in stratosphere. Random numbers generated through spectral pattern generator of Berner et al. (2009).
SPPT, continued.

\[ \psi'(\phi, \lambda, t) = \sum_{n=0}^{N} \sum_{m=-n}^{n} \psi'^m(t) P^m_n (\cos \phi) e^{im\lambda} \]

\( \Psi' = \) streamfunction forcing; \( \lambda = \) longitude, \( \phi = \) latitude, \( t = \) time;
\( m = \) zonal wavenumber, \( n = \) total wavenumber,
\( \psi'^m_n(t) = \) the random perturbation for this wavenumber,
\( P^m_n = \) Legendre polynomial.

\[ \psi'^m(t + \Delta t) = (1 - \alpha) \psi'^m(t) + g_n \sqrt{\alpha} \varepsilon(t) \]

(1-\( \alpha \)) = linear autoregressive parameter, 0 < \( \alpha \) ≤ 1;
\( g_n = \) wavenumber-dependent noise amplitude,
\( \varepsilon(t) = \) Gaussian white-noise process with zero mean, variance \( \sigma_z^2 \)

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**SPPT: example of time series of r**

![Figure 1: Example of the pattern \( r \) used in the revised scheme; contour interval 0.25; red (blue) contours correspond to positive (negative) values.](image)

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SPPT: T850 RMS error, NH & tropics

- **NoTenPert**: No stochastic tendencies
- **SP**: Buizza, Miller, Palmer blocky stochastic tendencies
- **SP1M**: SPPT, 500 km, 6 h, o(r)=0.5
- **SP1L**: SPPT, 500 km, 6 h, o(r)=0.75
- **SP2**: Two independent r, planetary and synoptic scales

**Precipitation Brier scores**

(lower is better)

*Figure 6: Brier score for 24-hour precipitation accumulations for events of 5 mm day^{-1}. Left: Northern Extra-tropics (30°N–90°N), right: Tropics (30°S–30°N). The lead times at which the score differences (between an experiment and SP) are statistically significantly different from zero at the 10% level are marked with a dot. Verification against SYNOP data, joint sample of 40 cases.*
SPPT: incidence of heavy rain in old and new stochastic tendency schemes

old Buizza et al. scheme overpredicted heavy events; this much reduced.

Similar cautionary tale with stochastic convection

- Tompkins and Berner (2008) perturbed humidity inputs to convective parameterization scheme.

Since CP was tuned originally to give acceptable results, introduction of stochasticity produced a change in the distribution of precipitation forecasts, which in this case had undesirable consequences to the forecasts.

Ref: Tompkins and Berner, 2008, JGR, D18101
Spectral Stochastic Backscatter (SPBS)

- Total dissipation rate is computed on all model levels; 3 components:
  - Numerical dissipation, from bi-harmonic diffusion and interpolation error in the semi-Lagrangian scheme.
  - KE dissipation due to orographic gravity wave drag and flow blocking
  - Rate of kinetic energy export from sub-gridscale deep convection into the resolved flow.
- Found that must inject energy not just at truncation limit, but also at sub-synoptic scales of motion.
- Note: FURTHER DETAIL to be ADDED.

Backscatter comparison with perturbed physical tendencies

SP1M is perturbed physical tendency
SPBS is stochastic backscatter
NoTenPert is no tendency perturbations
(2) Maturity of ensemble Kalman filter for data assimilation, ensemble prediction

- Operational for last several years at Canadian Meteorological Centre.
  - Progress toward 4D-Var/EnKF hybrid.
- Used with high-resolution (T382) global models for NOAA’s Hurricane Forecast Improvement Project.
- Approximations:
  - LETKF used operationally at UK Met Office
  - ET (Ensemble Transform) used operationally at NCEP for medium-range ensemble
  - Experiments with parallel 4D-Vars & perturbed obs at ECMWF.

Key issues with EnKFs

- Treatment of model (system) errors in appropriate ways.
- Methods of stabilization/dealing with limited ensemble size introduces consequences.
  - Covariance localization in vertical ill-defined with non-point observations such as radiances.
  - As shown, additive noise to account for model error constrains forecast spread growth.
- Best way to hybridize with variational schemes
- Replicating variational QC.
Canonical EnKF equations

\[ x_i^a = x_i^b + K (y_i - Hx_i^b) \]

\[ K = P^b H^T (HP^b H^T + R)^{-1} \]

\[ P^b = \left\langle \left[ x_i^b(t) - \bar{x}_i^b(t) \right] \left[ x_i^b(t) - \bar{x}_i^b(t) \right]^T \right\rangle \]

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\[ x_i^b(t+1) = M x_i^a(t) + \eta_i, \quad \left\langle \eta_i, \eta_i^T \right\rangle = Q \]

how are we estimating the model-error?

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Model-error representations in CMC EnKF (Houtekamer et al. July 2009 MWR)

- operational = multimodel + SKEB + PTP
- isotropic = additive noise to streamfunction and unbalanced T
- SKEB = stochastic kinetic energy backscatter
- PTP = perturbed physical tendencies (like ECMWF’s SPPT)
- multi-model = 4 different CPs, 2 LSMS; 2 mixing length; 2 inverse Prandtl numbers
- basic = no model error simulation

isotropic additive noise dominates in EnKF.
A problem with isotropic additive noise

The standard additive noise results in a slow growth of spread in the early hours of the forecast. Introducing the additive noise earlier (here, 24 h earlier) and evolving it forward in time before using in the data assimilation improves the rate of growth of spread in the forecasts.


EnKF / 4D-Var hybrids?

Impact of CMC's 4D-Var using EnKF covariances relative to using static initial covariances. Impact measured in terms of reduction/increase in error standard deviation. Negative impact where contours are dashed.
NOAA EnKF vs. NCEP operational 3D-Var

EnKF at half the resolution fits temp. obs as well as operational 3DVar, but shows large improvement for winds.

TC position error and ensemble spread

FIM G8/EnKF vs NCEP GEFS/ET

FIM is NOAA/ESRL's experimental global icos grid model.
Error bars are 5th and 95th percentiles from paired block bootstrap.
Numbers in parentheses are the sample size at this lead.
TC position error and ensemble spread
FIM G8/EnKF vs UK Met Office

UK Met Office EPS vs. FIM G8/EnKF Track Error & Spread
20090715 to 20091009

TC position error and ensemble spread
FIM G8/EnKF vs ECMWF

ECMWF EPS vs. FIM G8/EnKF Track Error & Spread
20090715 to 20091009
Ensemble predictions for typhoon Morakot, 2009

WRF high-resolution regional model precipitation forecasts for Morakot

WRF/ARW, 4.5 km nested inside 13.5 km, initialized 2.5 days before landfall; GFS ensemble used for lateral boundary conditions.

from draft article by Fuqing Zhang et al., 2009
Ensemble precipitation forecasts for Morakot

(3) Convection-permitting limited-area ensembles

from 2007 NOAA/SPC “Spring Experiment”
(c/o Jack Kain, Steve Weiss)

“Spaghetti” Plot for Reflectivity > 40 dBZ
Exploring ensemble system characteristics with the TIGGE data set

from upcoming Bougeault et al. 2010 BAMS overview of TIGGE
Conclusions

• Substantial progress in 2008-2009 on:
  – Model error
  – Ensemble initialization through EnKF.
  – Convection-permitting applications.
  – Exploration of multi-model concepts via TIGGE.
  – Amelioration of systematic errors using reforecasts.
Intense vortices in forecasts, with ensembles of forecast positions relatively close to the observed position (red dot).

54-h ensembles from T382 GFS & EnKF initial conditions.

54-h ensembles from experimental T382 GFS & GSI / ET perturbations (operational).

Note that this GFS model resolution is much greater than current operational, T126 GSI-ET initialized ensemble produces less intense vortices, and forecasts are slow in moving typhoon west.