Stochastic Parametrization of Deep Convection in a Regional Ensemble Prediction System

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Rationale for stochastic parametrizations

- Stochastically Perturbed Parametrization Tendencies scheme (SPPT; Buizza et al. 1999, Charron et al. 2010) is a very efficient method to represent model error but rather unsatisfactory from a more fundamental perspective.

- In the long-term, SPPT should be ideally replaced by more physically based approaches to error simulation – inherently stochastic schemes.

- At RPN-A/CMC, we are currently working on a stochastic deep convection scheme and investigating its application in the REPS.
Stochastic deep convection scheme at RPN/CMC

- **Approach is based on the Plant-Craig (PC) stochastic deep convection scheme** (Plant and Craig, 2008).

- **Plume model adopted from Bechtold scheme** (Bechtold, 2001):
  - A bulk mass-flux parametrization very similar to Kain-Fritsch (KF; used in the original PC scheme)
  - CAPE-type closure – based on the assumption that 90% of CAPE is removed within a specified adjustment period $\sim 60$ min
  - The plume model used with this scheme, however, differ to some extent from KF (e.g., triggering mechanism, conservation of enthalpy and mixing ratio).

- **Rationale for the use of Bechtold scheme**:
  - Modular structure
  - Consistent deep and shallow convection representation – possible extension to shallow convection.
Stochastic deep convection scheme at RPN/CMC

- **Deterministic version of the Bechtold scheme**: A single plume represents the mean properties of the entire subgrid-scale population of clouds.

- **Stochastic version**: in a given grid cell a cluster of convective activity with different intensities and sizes occurs.
  - Multiple plumes are randomly drawn from the radius distribution
  - Population size scaled by the closure assumptions.

![Graph showing updraft radius at the LCL vs. count (in 40^-4)](image)

![Realization 1 and Realization 2 diagrams](image)
The clouds are generated based on the **Plume sampling function** – on average $<N>$ plumes is generated during the specified cloud life time $T$ (45 min in our case):

$$p(r)dr = \langle N \rangle \frac{\Delta t}{T} \frac{2r}{\langle r^2 \rangle} \exp \left( -\frac{r^2}{\langle r^2 \rangle} \right)$$

where $\langle N \rangle$ is the expected number of plumes generated over time $T$:

$$\langle N \rangle = \frac{\langle M \rangle}{\langle m \rangle}$$

$\langle M \rangle$ is obtained from CAPE closure assumptions in the deep-convection scheme. In other words $<N>$ number of clouds act to remove 90% of the CAPE in time $T$. This is equivalent to as having one single plume in the given area but with mass flux $M$.

$\langle N \rangle$ can be changed by the tuneable $\langle m \rangle$ but if $\langle m \rangle$ is reduced the scheme becomes more costly. Therefore, larger grid areas could be problematic.
Preliminary results

- Case of REPS forecast for 0000Z 10 July 2014
- REPS domain zoomed over the US (24-hr forecast valid 0000Z 11 July)
Preliminary results

- Impact of various perturbations on **00-24h pcp accumulation** (valid 0000Z 11 July 2014)
- One source of perturbations at a time.

bit pattern  SPPT  Stoch. Deep Conv.
Preliminary results

- Impact of various perturbations on **24h screen-level temperature** (valid 0000Z 11 July 2014)
- One source of perturbations at a time.

**bit pattern**

**SPPT**

**Stoch. Deep Conv.**
Preliminary results

- Impact of various perturbations on 72h screen-level temperature (valid 0000Z 13 July 2014)
- One source of perturbations at a time.
Preliminary results

- Impact of various perturbations on **24h GZ 500 hPa** (valid 0000Z 11 July 2014)
- One source of perturbations at a time.

**bit pattern**

**SPPT**

**Stoch. Deep Conv.**
Preliminary results

Impact of various perturbations on 72h GZ 500 hPa (valid 0000Z 13 July 2014)

One source of perturbations at a time.
Scale analysis of regional REPS error

- EPS field: \( x = x_m(i, j, k, t, \tau) \)
  \( i, j \) and \( k \) are horizontal and vertical grid indices, \( m \) ensemble member, \( t \) forecast issue time and \( \tau \) lead time.

- Analysis: \( y = y(i, j, k, t + \tau) \).

- Model error \( \varepsilon_m \equiv x_m - y \) is decomposed as

  \[
  \langle \varepsilon \rangle = \langle x \rangle - y \\
  \varepsilon_m^* = x_m - \langle x \rangle,
  \]

  where

  \[
  \langle x \rangle = \frac{1}{N_m} \sum_{m=1}^{N_m} x_m.
  \]

  is the ensemble mean.
Scale analysis of REPS error

Using the Discrete Cosine Transform (Denis et al. 2002), the spatial variance of model error $\varepsilon$ can be decomposed into contributions from different spatial scales $\lambda$ :

$$
\sigma_{\varepsilon\varepsilon}^2(k, m, t, \tau) \equiv (\varepsilon - \bar{\varepsilon})^2 = \sum_{q=1}^{N_q} \delta_{\varepsilon\varepsilon}(\lambda_q, k, m, t, \tau)
$$

where

$$
\overline{(\cdot)} = \frac{1}{N_i N_j} \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} (\cdot)
$$

is the spatial average.

It can be shown that the expectation of the error variance over the ensemble is additive in terms of error components :

$$
\langle \hat{\sigma}_{\varepsilon\varepsilon}^2 \rangle = \hat{\sigma}_{\varepsilon}^2 \langle \varepsilon \rangle \langle \varepsilon \rangle + \langle \hat{\sigma}_{\varepsilon*\varepsilon*}^2 \rangle
$$
Error variance components

The two error variance components can be conveniently expressed in the form of the law of cosines:

\[ \hat{\sigma}^2_{\langle \varepsilon \rangle \langle \varepsilon \rangle} = \hat{\sigma}^2_{yy} \left( 1 + (\hat{\gamma} \hat{\rho})^2 - 2 (\hat{\gamma} \hat{\rho}) \hat{r} \right) \]  

(1)

\[ \langle \hat{\sigma}_{\varepsilon^* \varepsilon^*}^2 \rangle = \hat{\sigma}^2_{yy} \left( \hat{\gamma}^2 (1 - \hat{\rho}^2) \right) \]  

(2)

Here \( \hat{\gamma} \) represents the spectral ratio of variances, \( \hat{\rho} \) is the inter-member coherence and \( \hat{r} \) is the coherence between the ensemble mean and analyses:

\[ \hat{\gamma}^2 \equiv \frac{\langle \hat{\sigma}^2_{xx} \rangle}{\hat{\sigma}^2_{yy}}, \quad \hat{\rho}^2 \equiv \frac{\hat{\sigma}^2_{\langle x \rangle \langle x \rangle}}{\langle \hat{\sigma}^2_{xx} \rangle}, \quad \hat{r} \equiv \frac{\hat{\sigma}^2_{\langle x \rangle y}}{\left( \hat{\sigma}^2_{\langle x \rangle \langle x \rangle} \hat{\sigma}^2_{yy} \right)^{1/2}}. \]

The role of \( \hat{\rho} \) is twofold – it represents:

1. Smoothing effect of averaging in the ensemble mean (Eq. 1)
2. Ensemble spread (Eq. 2)
Modern-Era Retrospective analysis for Research and Applications (MERRA)

DA System
- Goddard Earth Observing System Model version 5 (GEOS-5) atmospheric DA system.
- Integrates a AGCM with grid-point statistical interpolation.
- 1/2° x 1/3° horizontal grid, 72 levels.

Dataset
- Fields: GZ, UU, VV, TT @ 500 and 250 hPa.
- Three-hourly time series (instantaneous values).
- Lat-lon grid 0.5° x 0.625° interpolated to the REPS grid (0.1375°).

Verification period
- Summer: July 01 – 31, 2014.
Variance Ratio and Reproducibility, EKIN 200 hPa, summer

\[ \hat{\gamma} \equiv \left( \frac{\langle \hat{\sigma}^2_{xx} \rangle}{\sigma^2_{yy}} \right)^{1/2}, \]

\[ \hat{\rho} \equiv \left( \frac{\hat{\sigma}^2_{x} \langle x \rangle}{\langle \hat{\sigma}^2_{xx} \rangle} \right)^{1/2} \]
Members of a perfect EPS and perfect analyses would be statistically indistinguishable. Hence:

\[ \langle \varepsilon \rangle = \langle x \rangle - y \sim \langle x \rangle - x = \varepsilon^* \]

which yields

\[ \hat{\sigma}^2_{\langle \varepsilon \rangle \langle \varepsilon \rangle} = \langle \hat{\sigma}^2_{\varepsilon^* \varepsilon^*} \rangle \]

or

\[ 1 + (\hat{\gamma}\hat{\rho})^2 - 2(\hat{\gamma}\hat{\rho})\hat{\gamma} = \hat{\gamma}^2(1 - \hat{\rho}^2). \]

In the spectral range in which we have confidence in the analyses we require:

\[ \hat{\gamma} \approx 1 \]

which yields the following necessary condition for an EPS to be balanced:

\[ \hat{\rho} \approx \hat{\gamma}. \]
Coherence vs. Reproducibility Ratio, EKIN 200 hPa, summer

\[ \hat{\rho} \equiv \frac{\hat{\sigma}_y^2}{\left( \hat{\sigma}_x^2 \langle \langle x \rangle \rangle \hat{\sigma}_{yy} \right)^{1/2}} \]

\[ \hat{\rho} \equiv \left( \frac{\hat{\sigma}_y^2}{\langle \hat{\sigma}_{xx}^2 \rangle} \right)^{1/2} \]
Error-to-Spread Ratio, EKIN 200 hPa, summer

\[ \left( \frac{\widehat{\sigma}_\varepsilon^2 \langle \varepsilon \rangle \langle \varepsilon \rangle}{\langle \widehat{\sigma}_\varepsilon^2 \varepsilon \varepsilon^* \rangle} \right)^{1/2} \]
Error-to-Spread Ratio, EKIN 200 hPa, winter

\[ \left( \frac{\hat{\sigma}^2 \langle \varepsilon \rangle \langle \varepsilon \rangle}{\langle \hat{\sigma}^2 \varepsilon^* \varepsilon^* \rangle} \right)^{1/2} \]

![Graph showing error-to-spread ratio for KK 200 in winter](image-url)
Error-to-Spread Ratio, TT 200 hPa, summer

\[
\left( \frac{\hat{\sigma}^2 \langle \varepsilon \rangle \langle \varepsilon \rangle / \langle \hat{\sigma}^2 \varepsilon^* \varepsilon^* \rangle}{2} \right)^{1/2}
\]
Applications of the scale analysis method

- **Study the contribution of different sources of perturbations**
  - Use to study the impact of perturbations in initial and lateral boundary conditions, SPPT
  - Contribution of stochastic parametrizations to the spread.

- **Uncertainty in the reanalyses**
  - Use other reanalyses (ERA-Interim, NARR - higher spatial resolution (35 km), 3-hourly
  - Use CMC analyses.

- **Apply to the Global EPS**
  - The method can be easily adapted to allow spectral transformations on the sphere
  - More degrees of freedom for PTP and stochastic parametrizations than in the REPS.
Conclusions and Future Work

**Expectations from the stochastic deep convection scheme:**
- Contribute to ensemble spread in weather situations with **weak large-scale forcing** – convection driven with the diurnal cycle.
- Increase the spread at scales **below 1000 km** in the **early** stages of the forecast.
- Hasten the **upscale propagation** of the inter-memember differences.
- It is not expected to have a large impact in situations with strong large-scale forcing.

**Future work:**
- Scheme adds fine-scale variability (grainy precipitation patterns) – how this impacts the quality of the forecasts?
- A systematic evaluation of the scheme in REPS and proper scoring.
- Introducing stochasticity in other schemes (e.g., shallow convection, PBL vertical diffusion, gravity wave drag).