Stochastic Physics Perturbations
For Ensemble Forecast

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Dingchen Hou and Xiaqiong Zhou

Special thanks to IITM and Dr. Mukmopadhyay
Highlights

• Introduction
• Current status of global ensemble
• Testing of stochastic physics
• Next NCEP GEFS
• Where to go from here?
Uncertainties & disagreements

Ensemble forecast is widely used in daily weather forecast
Introduction (2)

2017 was 25\textsuperscript{th} anniversary of both NCEP and ECMWF global ensemble forecasts into operational implementation
Introduction (3)

**Description of the ECMWF, MSC and NCEP systems**

Each ensemble member evolution is given by integrating the following equation

\[ e_j(T) = e_j(0) + \frac{de_j(0)}{dt} + \int_{t=0}^{T} [P_j(e_j,t) + dP_j(e_j,t) + A_j(e_j,t)] \, dt \]

where \( e_j(0) \) is the initial condition, \( P_j(e_j,t) \) represents the model tendency component due to parameterized physical processes (model uncertainty), \( dP_j(e_j,t) \) represents random model errors (e.g. due to parameterized physical processes or sub-grid scale processes – stochastic perturbation) and \( A_j(e_j,t) \) is the remaining tendency component (different physical parameterization or multi-model).


Reference: - first global ensemble review paper


One year statistics of three ensembles:
NCEP, CMC and ECMWF

Northern Hemisphere 500hPa Height
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20130901 – 20140831

Common measurement for perfect ensemble (bias free), without considering analysis uncertainty

NH 500hPa height
RMS error (solid) vs Spread (dash)

One year statistics of three ensembles:
NCEP, CMC and ECMWF
<table>
<thead>
<tr>
<th>Version</th>
<th>Implementation</th>
<th>Initial uncertainty</th>
<th>TS relocation</th>
<th>Model uncertainty</th>
<th>Resolution</th>
<th>Forecast length</th>
<th>Ensemble members</th>
<th>Daily frequency</th>
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Introduction (5)

- An ensemble forecasting system should provide information on how much we can trust the forecast.
- This comes in the form of ensemble spread, which ideally would be close to the average error of the forecasts.
- Initial perturbed single modeling ensemble systems (e.g. NCEP and ECMWF) are generally over confident (under dispersion) on their forecasts.
Introduction (5)

• An ensemble forecasting system should provide information on how much we can trust the forecast.
• This comes in the form of ensemble spread, which ideally would be close to the average error of the forecasts.
• Initial perturbed single modeling ensemble systems (e.g. NCEP and ECMWF) are generally over confident (under dispersion) on their forecasts.
• Stochastic Physics could improve this relationship.
Stochastic Representation of Physical Uncertainty

Today

\[ T = D + (1 + e) \sum_{i=1}^{N} P_i \]

Future

\[ T = D + \sum_{i=1}^{N} (1 + e_i) P_i \]

\[ T = D + \sum_{i=1}^{N} P_i (r_j (1 + e_{i,j}), j = 1, m) \]

\[ T = D + \sum_{i=1}^{N} P_i (r_j (1 + e_{i,j}), j = 1, m) \]

Major physical schemes:
- Convection (shallow and deep)
- Clouds
- Radiation
- Gravity wave drag
- PBL
- Land-surface
- Others ?

\( T \) – total tendency
\( D \) – dynamical tendency
\( P \) – physical tendency
\( e \) – random pattern (4-d)
\( r \) – physical parameter
Model uncertainty in the operational GEFS

• Stochastic Total Tendency Perturbations (STTP)

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

– Random linear combinations of 6-hour tendency perturbations from the ensembles are applied to a given member during the model integration

– Reference:
  • Hou and et al, 2008

  – STTP has less impact to tropical area
Changes of NCEP Ensemble Spread (STTP)

Then

Average 00Z Ensemble Spread (Mar 2007 - Mar 2009)
168-h Forecasts of 500-mb Geopotential Height (n=745)

Now

Average 00Z Ensemble Spread (Mar 2012 - Mar 2013)
168-h Forecasts of 500-mb Geopotential Height (n=360)

Courtesy of Dr. Alcott Trevor
Model uncertainty in the GFS DA (EnKF) cycle

• **Dynamics:** Due to the model’s finite resolution, energy at non-resolved scales cannot cascade to larger scales.
  - Approach: Estimate energy lost each time step, and inject this energy in the resolved scales. a.k.a stochastic energy backscatter (SKEB; Berner et al. 2009)

• **Physics:** Subgrid variability in physical processes, along with errors in the parameterizations result in an under spread and biased model.
  - Approach: perturb the results from the physical parameterizations, and boundary layer humidity (Palmer et al. 2009), and inspired by Tompkins and Berner 2008, we call it SPPT and SHUM

• Above schemes has been tested for current operational GEFS (spectrum model) with positive response – plan to replace STTP for next implementation

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See next slide for the example of random pattern
Examples of stochastic patterns

500 km / 6 h  1000 km / 3 d  2000 km / 30 d

(adapted from M. Leutbecher)
Current Status of Global Ensembles

Spring 2016 – NH 500hPa height

Northern Hemisphere 500hPa Height
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20160301 – 20160531

RMS error – solid line
Spread – dash line

Against own analysis

Upper atmosphere:

• Apply stochastic schemes and/or multi-physics
• All ensemble forecasts have reasonable spread compared to the errors

Spring 2016 – NH 2-m temperature

Northern Hemisphere 2 Meter Temp.
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20160301 – 20160531

RMS error – solid line
Spread – dash line

48-hour forecast
Assume analysis is a true reference
NCEP and EC forecasts are 1:2 (spread: error)
CMC forecast is 1:1.25 (spread: error)

Surface elements:

• Does not apply stochastic schemes
• All ensemble forecasts have more/less under dispersion (over confident)
Precipitation Forecast (1 year; 12-36hr; >5mm/24hr)

Reliability Diagram

fhr 12–36 For 20150301 - 20160229

- Observed frequency (%)
- Forecast probability (% >5.00mm)

RAW: RELI=0.008  BSS=0.361
CAL: RELI=0.005  BSS=0.399

80%

42%
Spread-Error relationship

2015 TC track AL/CP/EP/WP

- ERROR-T254
- ERROR-T574
- SPREAD-T254
- SPREAD-T574

T254 – Operation (ETR cycling)
T574 – Retrosp. runs (EnKF from 3DEnVar)

Less spread from EnKF (3D) did not appear for 2015 summer season
Stochastic Schemes for Atmosphere - Testing for GEFS

• **Stochastic Kinetic Energy Backscatter (SKEB)**
  – Represents process absent from model
  – Stream function is randomly perturbed to represent upscale kinetic energy transfer (Berner et al., 2009)

• **Stochastic Perturbed Physics Tendencies (SPPT)** – (ECWMF tech memo 598)
  – Designed to represent the structural uncertainty (or random errors) of parameterized physics
  – Multiplicative noise used to perturb the total parameterized tendencies (Palmer et al., 2009)
  – Biggest impact on tropic

• **Stochastically-perturbed boundary layer HUMidity (SHUM)**
  – The same formula as SPPT
  – Designed to represent influence of sub-grid scale humidity variability on the triggering of convection (Tompkins and Berner 2008)
  – Biggest impact on tropic
Characteristics of one summer month test

STTP $\rightarrow$ strong at winter hemisphere
SKEB $\rightarrow$ similar to STTP, but for large scale
SPPT $\rightarrow$ big impact is tropical, not mid-latitude
SHUM – big impact is tropical, duplicate to SPPT
VC – big impact is high latitude
Change of ensemble spread from introducing new stochastic physics

New STTP at 120 h
500-hPa U spread-skill

112 forecasts
Ensemble Std Dev
m/s

112 forecasts
RMSE of Ens Mean
m/s

112 forecasts
% Diff from Ideal Spread-Skill Ratio
%

Sto_Phy at 120 h
500-hPa U spread-skill

112 forecasts
Ensemble Std Dev
m/s

112 forecasts
RMSE of Ens Mean
m/s

112 forecasts
% Diff from Ideal Spread-Skill Ratio
%

500hPa U

% diff from spread: error ratio

V11 (STTP)

V11 (with new stochastic)
Impact to temperature

North American 850-hPa Temperature
RMSE (solid) and Spread (dashed)

GEFSv11 – opr
GEFSv11 – w. SPs

GEFSv11 – opr
GEFSv11 – w. SPs
Precipitation reliability for 36-60hr and greater than 5mm/day

Summer-Fall 2013
Four months
Typical example of over-confident for precipitation forecast

Precipitation reliability for 36-60hr and greater than 5mm/day

10% <-> 14%
90% <-> 70%
e.g. when we predict 10% chance of 5+ mm, it happens 13% of the time
ECMWF has run SPPT

Hurricane Matthew
Initial: 2016092900

Top left – GEFS operation forecast (V11)

Top right – GEFS legacy forecast (V10)

Bottom left – ECMWF forecast
GEFS (opr)

Spread is too small?

GEFS (Legacy)

ECMWF

Spread is too large?

+ SPs

It helps spread

Not sure the mean error
GEFS week 3&4 forecasts (un-coupled)

Period: May 2014 – May 2016
Higher resolution (~50km) for week 3&4 with different SPs

MJO skill: RMM1+RMM2
20140501-20160526 for STTP&SPs

Extend 4-5 days of MJO skill

AC

Lead day

STTP
SPs
GEFS week 3&4 forecasts (un-coupled)

MJO skill: RMM1+RMM2
20140501-20160526 for STTP&SPs

Extend another 2 days of MJO skill

Period: May 2014 – May 2016
Higher resolution (~50km) for week 3&4 with different SPs
GEFS week 3&4 forecasts (un-coupled)

MJO skill: RMM1+RMM2
20140501-20160526 for STTP&SPs

- STTP
- SPs
- SPs+CFSBC
- CFSv2

How about MJO skill of coupling model ?

Period: May 2014 – May 2016
Higher resolution (~50km) for week 3&4 with different SPs
Tropical 850hPa U.
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20150501 - 20151221

850hPa tropical zonal wind

With stochastic perturbations:
Error is reduced
Spread is increased

Tropical 250hPa U.
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20150501 - 20151221

250hPa tropical zonal wind

With stochastic perturbations:
Error is reduced
Spread is increased
Under development – test uncertainties for land model

- **Stochastic Perturbed Tendencies of Land (SPTL) - EMC**
  - Designed to represent the uncertainty (and/or random errors) of land surface parameterization
  - Perturbed soil temperature/moisture directly

- **Perturb parameters of land model – PSD/ESRL**
  - Roughness, surface albedo and soil hydraulic conductivity

- **Initial perturbations of soil temperature/moisture – PSD/ESRL**
  - EOF analysis of the difference of NOAH and climate
EMC’s investigations

• Early investigation – GEFSv9
  – EMC visitor from CMA (Dr. Deng) in 2010
  – Initial Soil temperature/soil moisture perturbations

• Current investigation – based on GEFSv11
  – Not initial perturbations, but stochastic physics perturbations.
  – The same stochastic pattern as SPPT
  – Soil temperature – all four layers (1\textsuperscript{st} try)
  – Both soil temperature/moisture
Model Lower Level Temperature

Temperature       SP_Baseline std dev          K

Temperature       SP_soilTM_20x_logit std dev          K

Temperature       Difference                   K

2 Meter Temperature

Temperature       SP_Baseline std dev          K

Temperature       SP_soilTM_20x_logit std dev          K

Temperature       Difference                   K
North American 2 Meter Temp.
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20130801 - 20130807

Summary:
- Stochastic of atmosphere could help to increase spread
- Stochastic perturbations of soil temperature/moisture could help another additional

Large under-dispersion
ESRL/PSD’s Investigations

• In land model, perturb surface momentum roughness length ($Z_0$), thermal roughness length ($Z_t$) and soil hydraulic conductivity (SHC)

• Test sensitivity of surface albedo

• Parameter values are perturbed using spatially and temporally correlated random patterns, as in SPPT and SHUM.

• Only a slight increase (0.1 K or less) in spread, even when combining SHC and roughness perturbations. Perturbing albedo has a larger effect, but still only ~0.25 K for the largest perturbation.
Sensitivity test for albedo perturbations

2-m Temperature Spread (Land Only)

Northern Hemisphere

Tropics

Sensitivity test for albedo perturbations

Courtesy of Dr. Maria Gehne
Next GEFS (version 12)

- Introduce new dynamic core – FV3
- Integrate current/improved physics
- C384L63 (25km) for day 1-8
- C192L63 (50km) for day 8-35
- 21-31 members per cycle, 4 times per day
- Initial perturbations – EnKF f06
- Model uncertainties
  - Stochastic perturbations for atmosphere
  - Stochastic perturbations for land
- Ocean boundary – SST
  - Introduce bias corrected coupled predictive SST
  - NSST to assimilate diurnal variation of SST
- Reanalysis and reforecast to support downstream application
Where to go from here?
Towards physically based stochastic parameterization - NGGPS

• Direction of future model physics development
  – Physically based stochastic parameterization
  – Not deterministic solution, but full representation of model uncertainty
  – Generates ensemble realizations of tendencies including realistic space-time correlations.
  – From tunable to functional

• Closed coordination (or work together) between model physics and ensemble development.
  – Connection through NGGPS CCPP (Common Community Physics Package)
  – Verify new stochastic parameterization in terms of ensemble metric (GMTB - Global Modeling Testbed)

• Identify (and/or understand) source of uncertainty, the key parameters to produce model errors (for different scales?), such as:
  – Convective trigger?
  – Rate of entrainment (updraft)/Detrainment (downdraft)?
  – Turbulence and convection parametrizations? - EDMF
  – Parameters in the microphysics?
  – Many others???

• Physically based scheme should be appropriate for all scales (scale aware), not only one/two schemes.
Towards physically based stochastic parameterization - NGGPS

• Should we?
  – Avoid to spend major resources on:
    • Multi-model or multi-physics approach?
    • Ad-hoc stochastic physics process?
  – Pay attention to:
    • Land surface process (important to improve surface elements of forecast)
    • Ocean surface (SST) (important to extend forecast, week 2, 3, &4)
    • HIW, such as tropical storm forecast
Model error at mesoscale: 
Example: cloud microphysical processes

**Conversion processes**, like snow to graupel conversion by riming, are very difficult to parameterize but very important in convective clouds.

Especially for snow and graupel the particle properties like **particle density** and **fall speeds** are important parameters. The assumption of a constant particle density is questionable.

**Aggregation processes** assume certain collision and sticking efficiencies, which are not well known.

Most schemes do not include **hail processes** like wet growth, partial melting or shedding (or only very simple parameterizations).

The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood.

from Axel Seifert presentation to NCAR ASP summer colloquium
Stochastic Deep convection

The Plant-Craig stochastic convection scheme

1. Closure assumption scales a pdf of cloud radii

2. Draw clouds randomly from this pdf
Figure: Schematic diagram showing an air parcel path when raised along B-C-E compared to the surrounding air mass Temperature (T) and humidity (Tw)

Stochastic Parameterization

“Convective trigger”

Convective Trigger function in most cumulus parameterization scheme (SAS: Simplified Arakawa-Schubert)

\[ P_{LSC} - P_{LFC} \leq DP(w) \]

Convection is triggered,

\[ P_{LCS} - P_{LFC} > DP(w) \]

No sub-grid convection

LSC – Level of Start Convection

LCL – Lifted Condensation Level

LFC – Level of Free Convection

CIN – Convective Instability

CAPE – Convective Available Potential Energy

EL – Equilibrium Level

W – Vertical Motion

DP(w) – SAS trigger function (delta pressure)

R(N) – Random function (small delta pressure)
Extra slides – may be for discussion?
Towards physically based stochastic physics/parameterization

- **ECMWF**: New scheme, SPP: Stochastically Perturbed Parameterizations (starting with cloud/radiation interaction)
- **Enviro Canada**: In development: Plant-Craig stochastic deep convection, cloud model is adopted from the Bechtold scheme (closure is still deterministic, plume generation is stochastic)
- **UK Met** is testing random parameters in physics schemes. Parameters include droplet number in microphysics, entrainment rate, turbulent mixing rates.
SKEB - Spectral Kinetic Energy Backscatter

- **Rationale:** A fraction of the dissipated energy is backscattered upscale and acts as streamfunction forcing for the resolved-scale flow (Shutts and Palmer 2004, Shutts 2005, Berner et al. 2009)

- **Streamfunction forcing is given by:**

\[ F_{\Psi}(\lambda, \mu, \eta, t) = \sqrt{b_R D_{tot} F(\lambda, \mu, \eta, t)} \]

- **Figure 6 from Berner et al. (2009)**

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**Rotational Component**

- **No SKEB**
- **With SKEB**

**Divergent Component**

- **Total dissipation rate**
- **Backscatter ratio**
- **Pattern generator**

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**Power Spectrum**

- **Total Wavenumber n**
Schematic of the Madden-Julian Oscillation - cross-section along equator

- Upper level divergence
- Enhanced evaporation
- Low level convergence
- Mean westerly wind
- Increased shortwave flux

Cold to warm transition over approximately 60° of longitude or ~30 days
What other global centers are doing?

- ECMWF
  - Operational: SPPT and SKEB in the medium/extended range, Ensemble DA only uses SPPT
  - In development: Modifications to SPPT (SPPTi and work on ensuring global integral of tendency perturbations is zero)
  - New scheme, SPP: Stochastically Perturbed Parameterizations (starting with cloud/radiation interaction)
What other global centers are doing?

• Environment Canada:
  – Operational: PTP (similar to SPPT), SKEB and multi-physics
  – In development: Plant-Craig stochastic deep convection, cloud model is adopted from the Bechtold scheme (closure is still deterministic, plume generation is stochastic)
What other global centers are doing?

- UK Met is testing random parameters in physics schemes similar to the land surface perturbations that Maria and Gary are working on.
- Parameters include droplet number in microphysics, entrainment rate, turbulent mixing rates.

Increase in spread is small, and ensemble is still under-spread in near surface wind and temperature, but improves fog forecasts. They are also perusing land surface perturbations.
Physically-based Stochastic Perturbations (PSP)

Implementation in COSMO model (2.8 km grid length)
- Add random increments to model variables
- Amplitude scaled using turbulence theory
- Rescaled to account for averaging over effective horizontal resolution
- Perturbations are coherent in height and over 10 min in time

\[
\left( \frac{\partial \Phi}{\partial t} \right)_{sh}^{stoch} = \frac{\partial \Phi}{\partial t} + \alpha_{sh} \cdot \eta_{sh} \cdot \langle \Phi^2 \rangle^{1/2}
\]

\[
\frac{\partial \Phi}{\partial t} : \text{tendency of } \Phi \text{ of all physical parameterizations}
\]

\[
\Phi : \text{resolved variable (T, w, q)}
\]

\[
\alpha_{sh} : \text{scaling factor}
\]

\[
\eta_{sh} : \text{Gaussian random perturbation}
\]

\[
\langle \Phi^2 \rangle : \text{variances from turbulence parameterization}
\]

\[
\alpha_{sh} = \alpha_{sh,\Phi} \cdot \frac{\ell_\infty}{5 \cdot dx} \cdot \frac{1}{dt}
\]

\[
dt : \text{temporal resolution of model}
\]

\[
\ell_\infty : \text{asymptotic mixing length}
\]

\[
dx : \text{horizontal resolution of model grid}
\]

\[
\alpha_{sh,\Phi} : \text{scaling factor}
\]

(Kober and Craig 2016)
Where to go from here?

- Need closed coordination (or work together) between model physics and ensemble development.
- Identify (and or understand) the key parameters to produce model errors (for different scales?)
- Develop physics based stochastic parameterization schemes
- Physically based scheme is appropriate for all time scales (scale aware - hourly to seasonal) and spatial resolutions (less Km to ???)
- Multi-model or multi-physics approach????
- Land surface needs more attention
- Ocean surface needs more attention
- Tropical storm needs to investigate (could be related issue, not only for stochastic, but also initial perturbation)
Contribution of Variables

**U200**

- STTP
- SPS
- GEFS_v10
- SPS+CFSBC+NSST
- SPS+CFSBC
- CFSv2

**U850**

- STTP
- SPS
- GEFS_v10
- SPS+CFSBC+NSST
- SPS+CFSBC
- CFSv2

**OLR**

- STTP
- SPS
- GEFS_v10
- SPS+CFSBC+NSST
- SPS+CFSBC
- CFSv2