Representing Model Related Uncertainty with Stochastic Formulation: NOAA THORPEX Contributions

Dingchen Hou
Environmental Modeling Center/NCEP/NOAA
5200 Auth Road, Camp Springs, MD 20746, USA

Jian-Wen Bao
NOAA/ESRL/Physical Sciences Division, Boulder, CO, USA

Acknowledgements:
NOAA THORPEX Program: Roger Pierce, Zoltan Toth and Tom Hamill
EMC/NCEP: Yuejian Zhu, Steve Lord, Bill Lapenta, Hua-Lu Pan, Jun Du
EMC/NCEP: Zoltan Toth, Weiyu Yang, Richard Wobus
PSD/ESRL: Evelyn Grell

5th NAEFS Workshop, Juitepec, Mexico,17-19 May 2010

Outline

- Two approaches in representing model-related uncertainty
- Two types of stochastic formulations
- Stochastic Perturbation Scheme (SPS)
- SPS contributions to 2010 GEFS upgrade
- Physics Based Ensemble Generation by ESRL
- Plan for next stage: Stochastic Physics Parameterizations

Two approaches in representing model uncertainty

Why do we need ensemble forecasting

To represent forecast uncertainty.

Sources of Forecast Uncertainty

INITIAL CONDITIONS

MODEL

Approaches to Representing Model Related Uncertainties

a) Multiple Model

To describe systematic errors. No truncation related error included.

Multi-version of a single model (*e.g. Houtekamer et al. 1996; Stensrud et al. 2000)*

Multi-model, Multi-version (*e.g. MSC global ensemble; SREF, Du and Tracton 2001*)

Multi-model, Multi-center (*e.g. Richardson, 2001; NAEFS, Toth et al, 2006*)

b) Stochastic Model Formulation (imposing stochastic terms to the tendency)

See next slide.

Two Types of Stochastic Formulation

Stochastic Model Formulation (imposing stochastic terms to the tendency)

(1) Imposing stochastic perturbations on tendencies calculated for individual physical processes

To describe truncation related errors associated with a particular physical process

Buizza et al. 1999: ECMWF, Stochastic Physical Parmeterzation (SPP)

Shutts, 2004: Stochastic Kinetic Energy Backscatter (SKEB).

Teixeira and Reynolds, 2008: Stochastic Convection Parameterization (SCP)

Mylne et al, 2005: Stochastic Convective Vorticity (SCV) and Random Parameters (RP).

(2) Imposing stochastic perturbations on TOTAL tendency of model equations

To capture total random errors in a lump-sum approach,

subgrid scale errors

grid-scale model errors: temporal and spatial truncation, design of computational algorithms (Vannitsem and Toth, 2002).

Stochastic (tendency) Perturbation Scheme, developed and implemented in this study

Extension (to the stochastic world) of Toth and Kalnay (1995), who Inflated the ensemble perturbations

A Stochastic Perturbation Scheme
General Strategy (*Hou, Toth and Zhu, 2006*)

General Expression: $$\frac{\partial X_i}{\partial t} = T(X_i;t) + S_i(t)$$ **for each ensemble member i**

T=Conventional Tendency, S=Stochastic Tendency

Strategy: Use $P_i = T_i - T_0$ vectors as the basis for stochastic forcing S

Formulation of S vectors: $$S_i \sim \sum_j w_{i,j} P_j$$

Generate the S terms from (random) linear combinations of the conventional perturbation tendencies, similar to ET but applied to ensemble perturbation tendencies successively

Required Properties of S vectors:

- Applied to all state variables (Yes)
- Orthogonal (See next slide)
- Flow dependent (Yes)
- Spatial and cross-variable correlation (Automatically available)

A Stochastic Perturbation Scheme: Formulation

(*Hou, Toth, Zhu, 2006*)

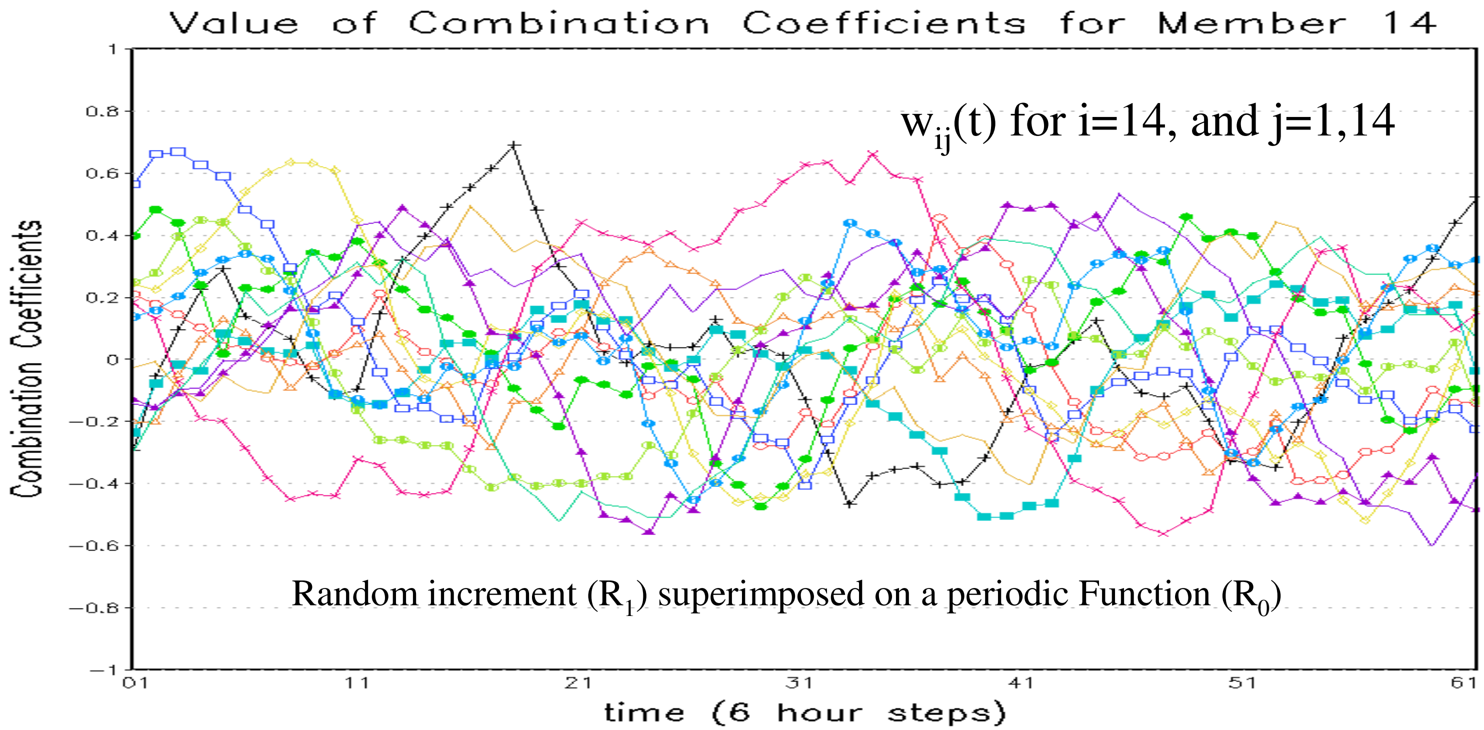
Generation of combination coefficients:

- **Matrix Notation** (N forecasts at M points)

  S (t) = P(t) W(t)

  MxN MxN NxN

- As P is quasi orthogonal, an orthonormal matrix W ensures orthogonality for S.
- **Generation of W matrix:** (**Methodology and software provided by James Purser**).
  - a) Start with a random but orthonormalized matrix W(t=0);
  - b) $W(t)=W(t-1)\ R_0\ R_1(t)$
- R_0, R(t) represent random but slight rotation in N-Dimensional space



A Stochastic Perturbation Scheme Computational Implementation

1. Use finite difference form for the stochastic term (a "full" version)

Modify the model state every 6 hours (Hou et al. 2008)

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

Where γ is a rescaling factor.

$$\gamma = \gamma_0 \gamma_1$$

$\gamma = \gamma_0$ (t)={ 0.1 if t < 120h; 0.1-(0.1-0.02)(t-120h)/(384h-120h) if t > 120h

$$\gamma_1 = 1.0 + A \sin(\theta) \sin \frac{2\pi(d-91)}{364}$$

Θ=Latitude, d=Julian Day

A=0.2

2. A simplified version: (Hou, Toth, Zhu, 2006)

Use a single perturbation tendency instead of a combination

$$S_i \sim T_j - T_0$$

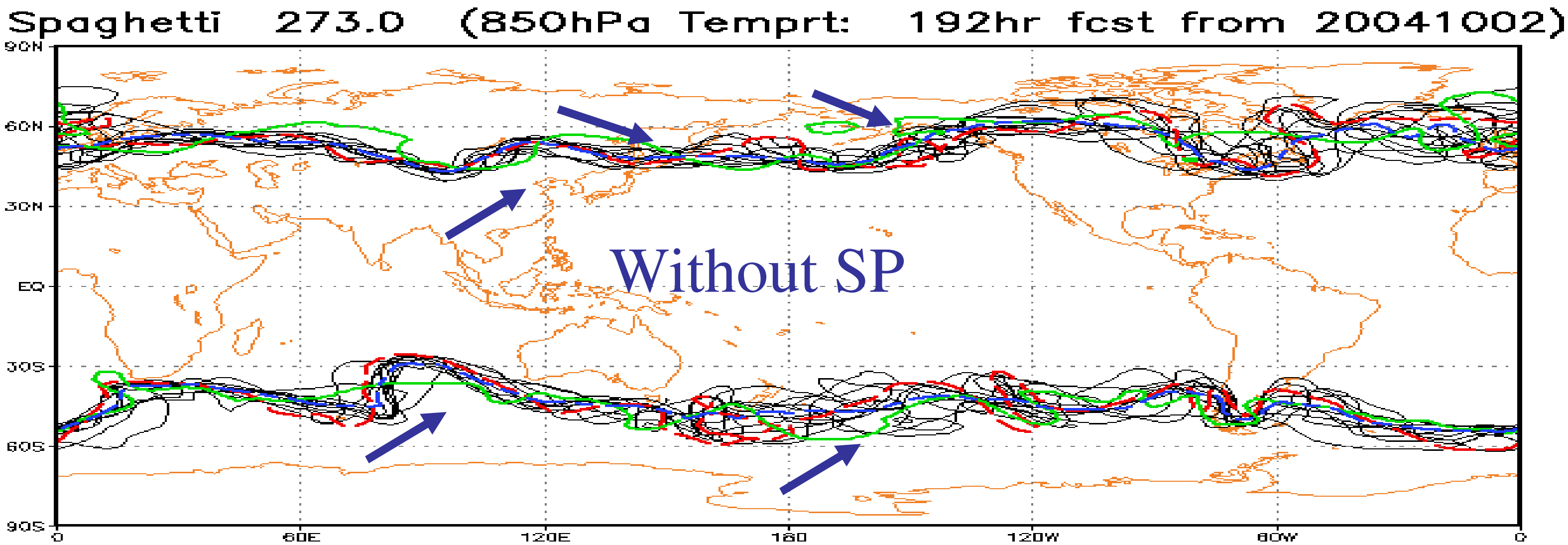
I =/= j and Random match between i and j

$$\dot{X} = T_i + \alpha_i (T_j - T_0)$$

W reduces to diagonal matrix with $w_{i,i} = \alpha_i$

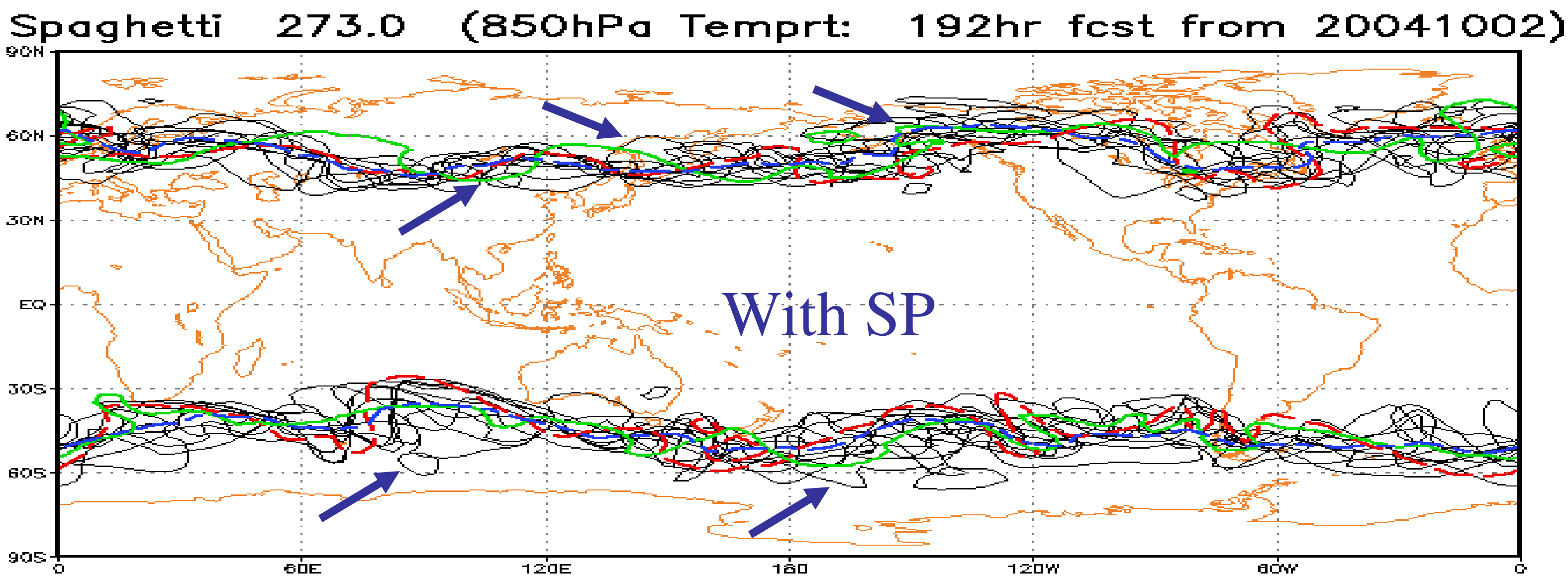
$$X_i' = X_i + \alpha_i \{ [(X_j)_t - (X_j)_{t-6h}] - [(X_0)_t - (X_0)_{t-6h}] \}$$

Spaghetti Diagrams



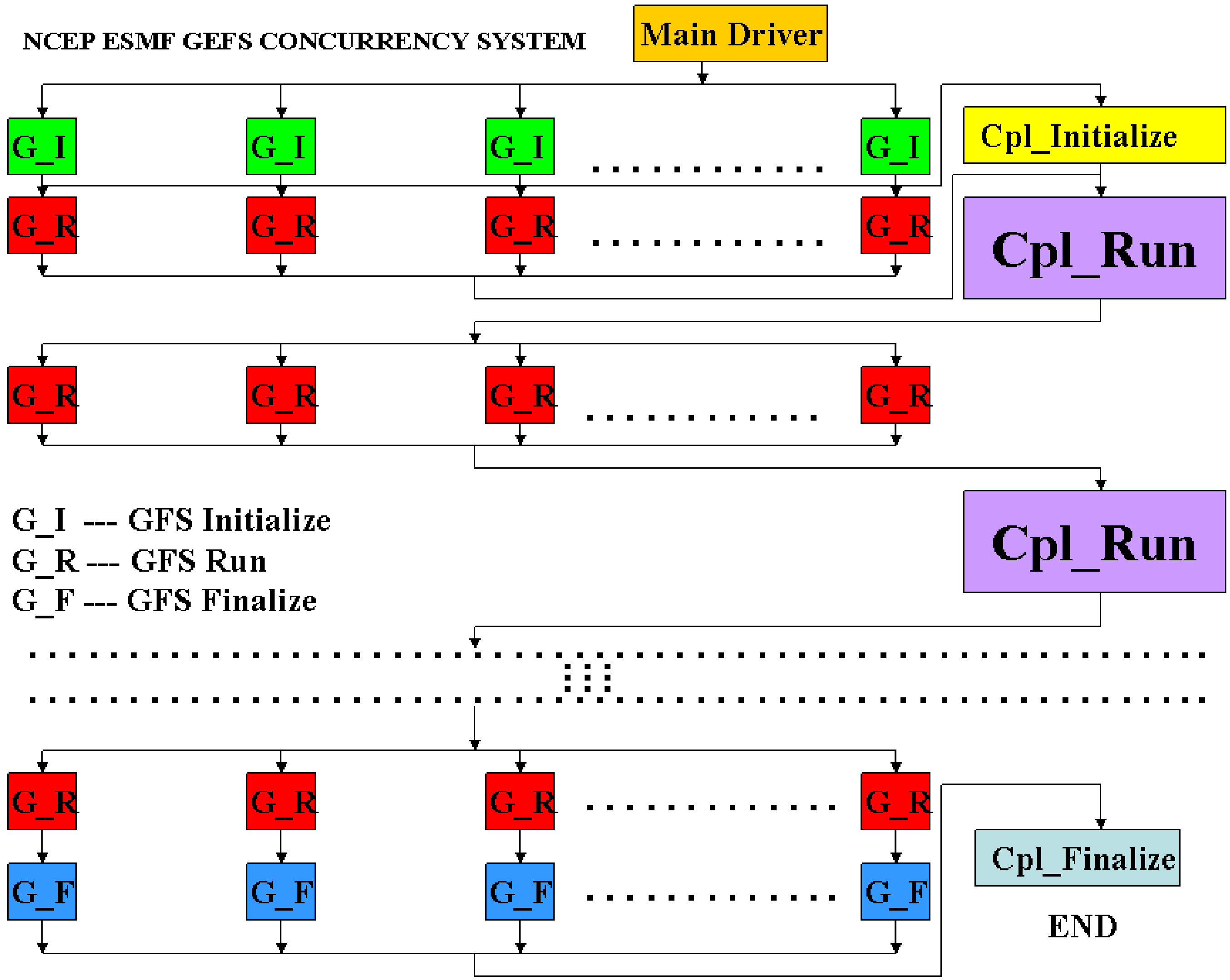
Without SP, the analysis is out of the range of ensemble in these areas.

When SP is applied, ensemble range is increased to embrace analysis.



Implementation of the Full Version of SPS Under ESMF environment

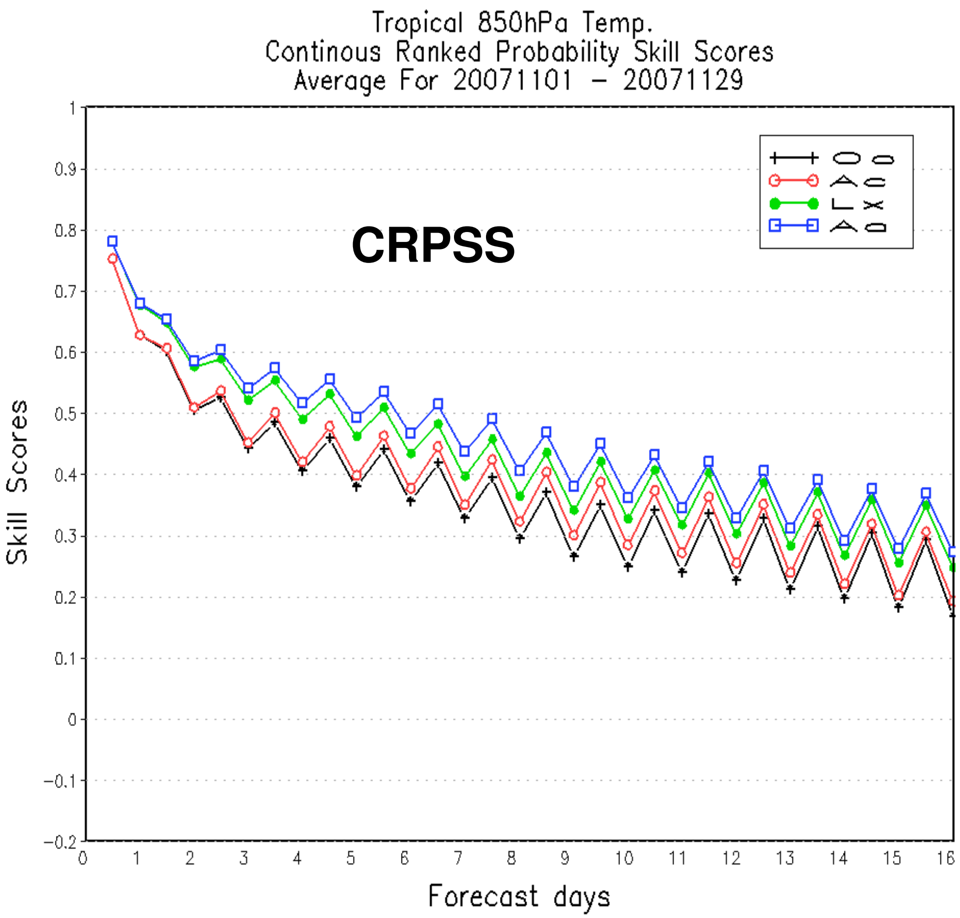
(ESMF=Earth System Modeling Framework)

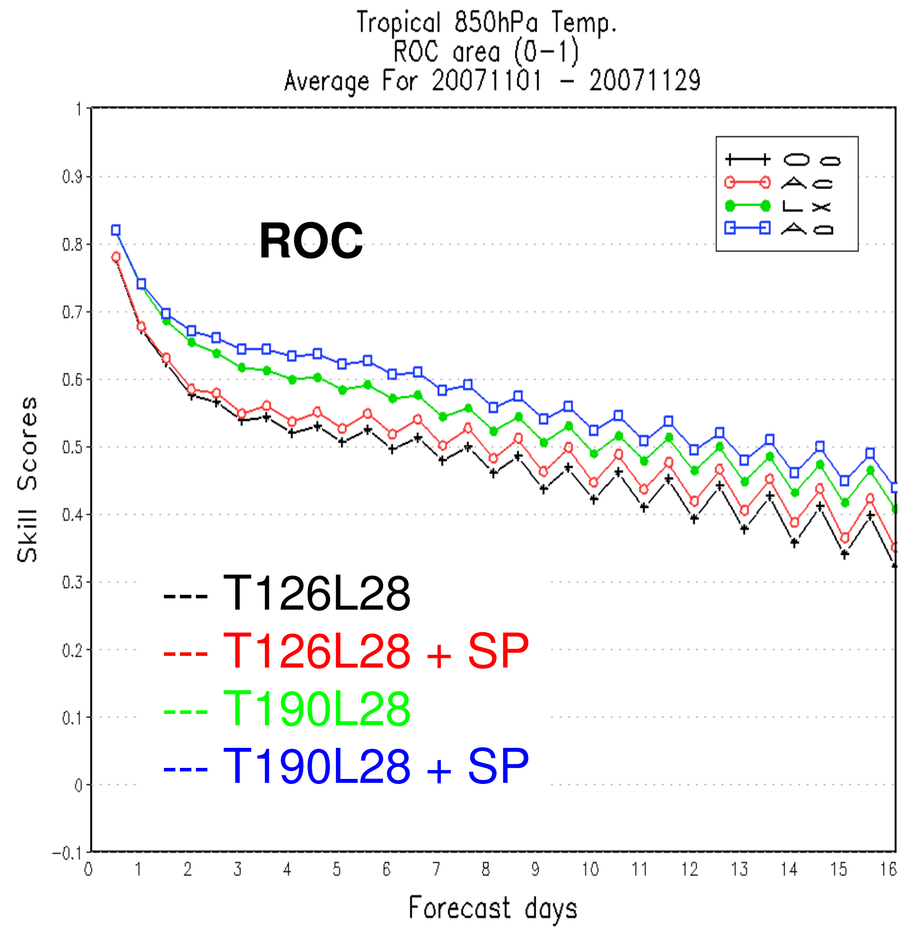


Experiments for 2009 Operational Implementation

T126L28 vs. T190L28 resolution, Nov. 2007 Cases

SPS works with both resolutions





Physics Based Ensemble Generation (Bao of ESRL?NOAA) Implementation and Testing of in NCEP's GFS Model

(Slide From Bao et al, 2010)

Model Framework

The NOAA/ESRL experimental ensemble Kalman Filter (EnKF) data assimilation system, based on the GFS model and developed by Whitaker et al. (2008).

Experiment Design

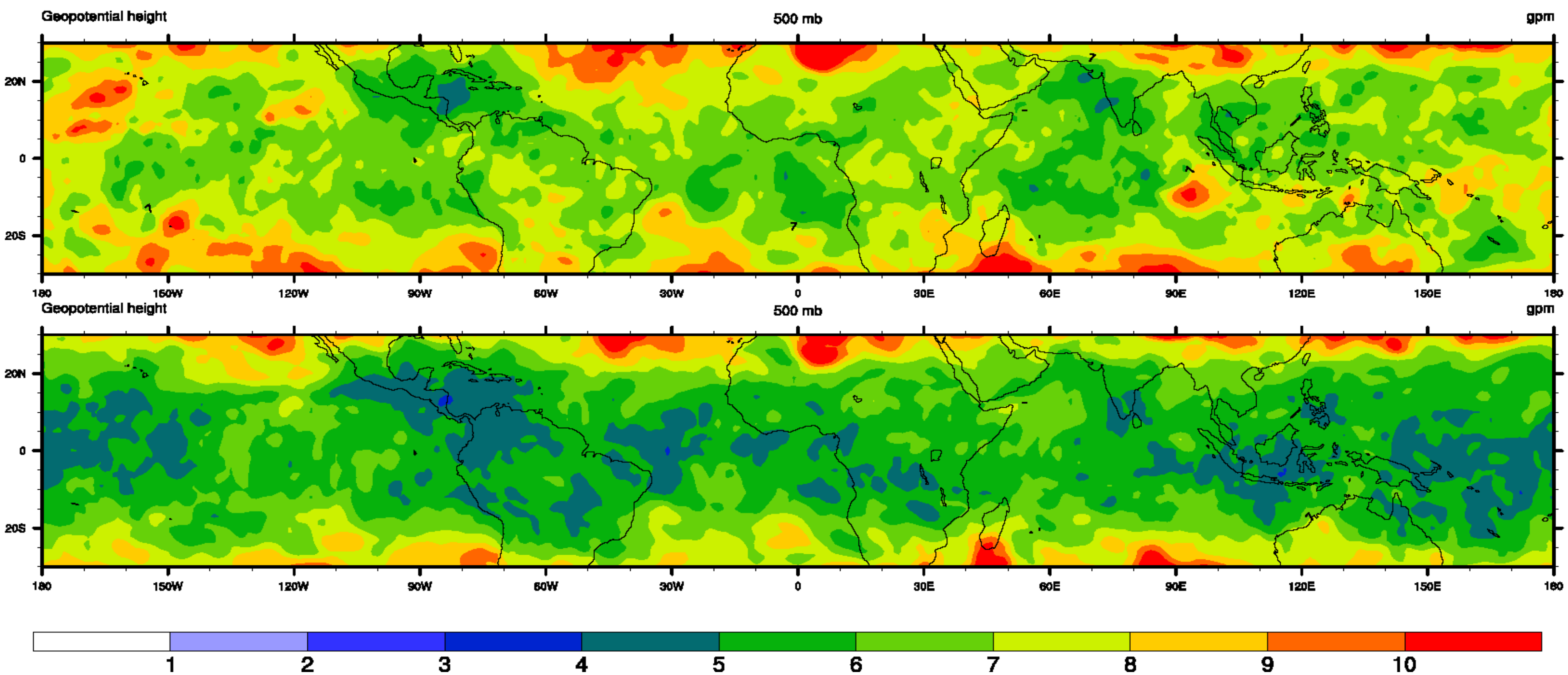
The data assimilation system is run at the resolution of T126 for the period of one month (Dec 2007). A 64-member ensemble of 9-h forecasts are updated at 6 h with observations.

An ensemble square root filter (EnKF) (Whitaker and Hamill, 2002) is applied to generate an ensemble of analyses every 6h.

Preliminary Results

(Slide From Bao et al, 2010)

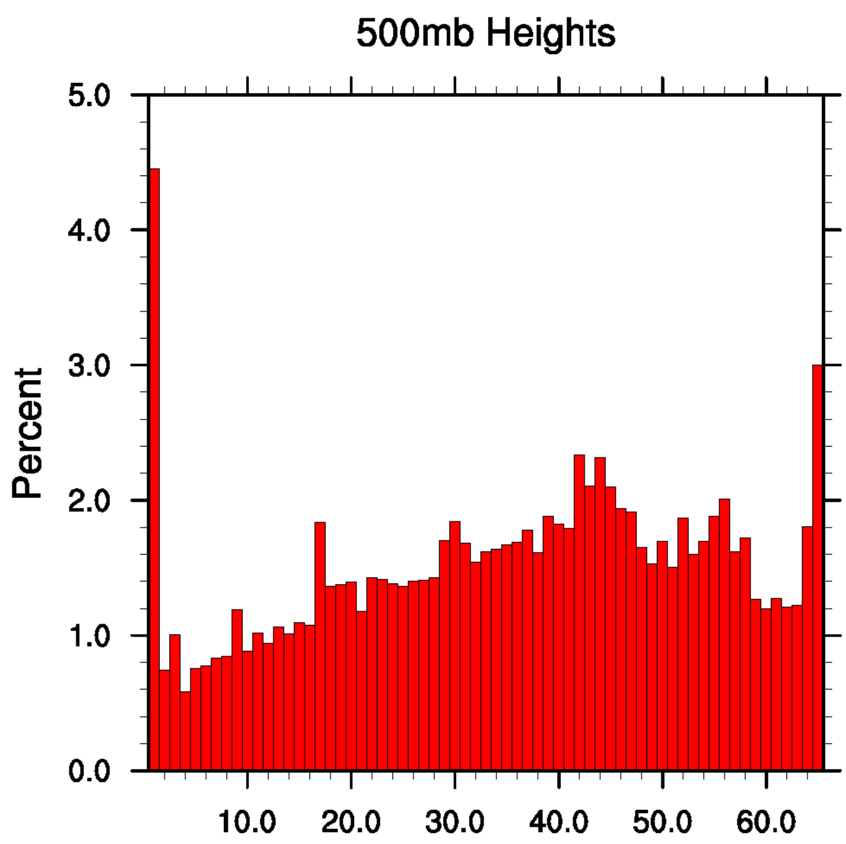
Ensemble spread of the 500mb geopotential height for the ensemble generated by the stochastic scheme with EnKF (top) and by the EnKF only (bottom).

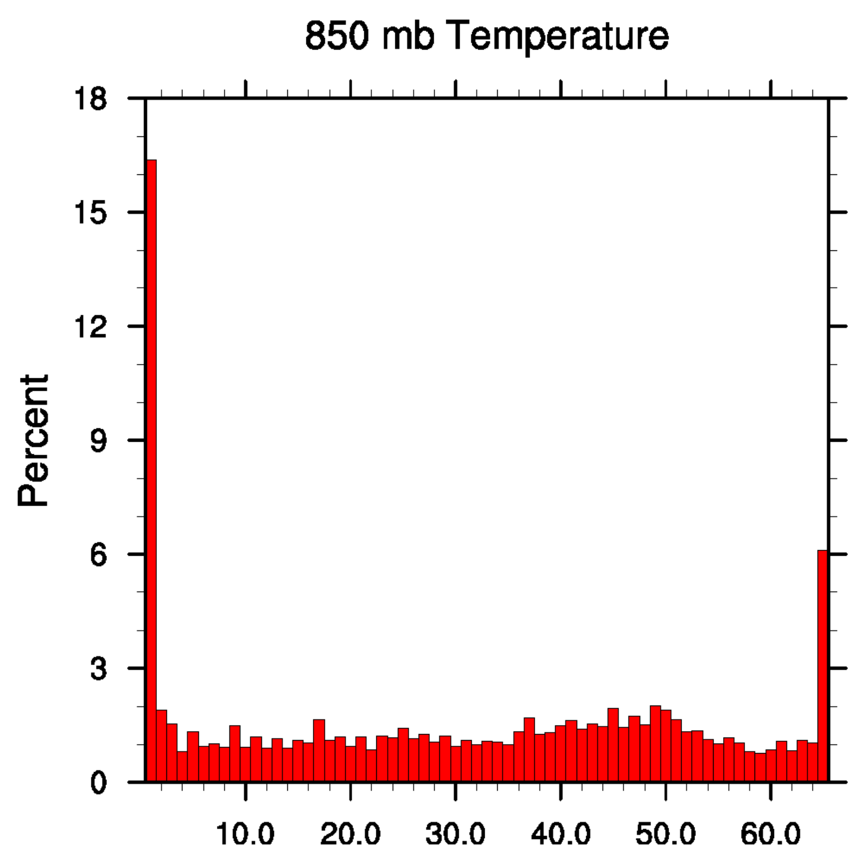


Preliminary Results (cont'd.)

(Slide From Bao et al, 2010)

Talagrand diagrams for 500mb heights (left) and 850mb temperatures (right) in the tropics (20N-20S) for a 24h ensemble simulation in which all initial conditions were identical.





Plan: Stochastic Physics Parameterization

- Thanks to THORPEX for continued support
- Closer collaboration with Jian-Wen Bao (ESRL)
- Expansion of Stochastic Formulation
- Focus on Physics Parameterization
- Operational GEFS (SPS implemented) as benchmark
- Coordinate with SPS parameters
- Starting with cumulus convection
- To be continued with other physical processes

Proposed Work

- Test Physics Based Ensemble Generation (PBEG) with a revised version of Grell-Devenyi (2002) convection scheme (Grell et al. 2009)
- Test Stochastic Convection Parameterization (SCP, Teixeira and Reynolds, 2008)
- Separate or combined implementation and quasi-real time experiments
- Optimizing the configuration of PBEG, SCP and SPS
- Implementation of the optimized configuration to NCEP production
- Algorithm to perturb radiation calculated using Monte Carlo integration of the Independent Column Approximation (McICA)
- Extent PBEG method to micro physics, ABL physics and other processes (ESRL)
- Work towards a strategy and algorithms to include perturbations in various physical processes

Concluding remarks

- A Stochastic Perturbation Scheme (SPS) was developed at NCEP and upgraded through NOAA THORPEX supported research program;
- The Stochastic Perturbation Scheme (SPS) was implemented in Feb. 2010 in NCEP’s production suite, under ESMF environment.
- With this full implementation, SPS improves the forecast by increasing ensemble spread, reducing systematic error and generating better ensemble pdf, measured by CRPS scores.
- Under THORPEX support, Physics Based Ensemble Generation (PBGE) is developed and test at ESRL/NOAA.
- It is expected that the stochastic physics parameterizations, based on PBGE and other methodology, will further improve the current operational GEFS.