NCEP Global Ensemble Forecast System (GEFS) - Review

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Highlights

- Familiar to EMC ensemble team and collaborators.
- Why do we need ensemble?
- NCEP ensemble (GEFS) milestones
- Ensemble initialization and cycling
- Tropical storm relocation
- Stochastic total tendency perturbation (STTP)
- Multi-model ensemble application – NAEFS
- Future plan
Team members

• Yuejian Zhu
  – Lead and over all planning
• Dingchen Hou
  – GEFS implementation
  – Model STTP (THORPEX proposal)
  – Post processing
  – River ensembles
• Mozheng Wei
  – Ensemble initialization
  – HVEDS (THORPEX proposal)
  – HFIP high resolution demonstration
• Richard Wobus
  – Code manager
  – GEFS implementation
  – TIGGE and NAEFS data exchange
• Malaquias Pena
  – Intraseasonal forecast calibration
  – Coupling GEFS and CFS ensembles (CTB proposal)
• Yucheng Song
  – WSR (winter storm reconnessass)
  – Targeting observation (THORPEX proposal)
• Bo Cui
  – Ensemble post processing (THORPEX proposal)
  – NAEFS/UNOPC and GEFS post process implementation
  – Forecast evaluations
• Yan Luo
  – Precipitation forecast calibration (THORPEX/HYDRO proposal)
  – Precipitation analysis (CCPA)
• Jiayi Peng
  – HFIP post processing
  – Track verifications, TIGGE cxml track data exchanges

• Juhui (Jessie) Ma
  – PhD student
  – Ensemble initialization and configuration
• Jun Du
  – SREF code manager
  – SREF leading implementation
• Bo Yang
  – SREF post processing
  – SREF initialization (ETR)

• Yuqiu (Julia) Zhu
  – Ensemble RFCs
  – Real time experiments setting up and run
• Zhan Zhang
  – HFIP high resolution demonstration
  – HWRF ensembles
• Weiyu Yang
  – ESMF for ensembles
  – MOM4 for GFS/CFS coupling
• George Vandenberghe
  – HFIP high resolution demonstration
  – NOAA HPC - research
• Mary Hart
  – Ensemble web master
• Shrinivas Moorthi
  – GFS model consulting
Collaborators

• International:
  – NAEFS
    • Meteorological Service of Canada (MSC)
    • National Meteorological Service of Mexico
  – ECMWF/UKMet
    • Ensemble development and application
  – CMA/KMA/JMA/Roshydromet
    • WMO/RDP – Beijing Olympic demonstration project
    • Exchange visitors for ensemble development

• National
  – THORPEX - Earth System Research Lab (ESRL)
  – NUOPC
    • FNMOC and NRL
    • AFWA
  – THORPEX-HYDRO - OHD
  – Ensemble post processing – OST/MDL
  – NCEP service centers
    • SPC – storm probabilistic guidance
    • OPC – wave probabilistic guidance
    • TPC – hurricane probabilistic guidance
    • HPC – 1-7 days probabilistic guidance
    • CPC – week-2 forecast (precipitation and temperature)

• Universities
Scientific Needs – Ensemble forecast System
Describe Forecast Uncertainty Arising Due To Chaos

ORIGIN OF FORECAST UNCERTAINTY

1) The atmosphere is a **deterministic system and** has at least one direction in which **perturbations grow**

2) **Initial** state (and model) has **error** in it $$\Rightarrow$$

*Chaotic system + Initial error = (Loss of) Predictability*

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**Buizza 2002**

- **90% Fcst probability**
- **Climate mean**
- **90% Climate probability**
- **Initial time**
- **Day 5** Large uncertainty
- **Day 12** Almost all predictability is lost – full nonlinear saturation

- **Ocean/Atm coupled system**
- **5 months**
- **12 months**
Schematic of Stochastic Prediction: The initial probability PDF(D) represents the initial uncertainties. From the best estimate of the initial state a single deterministic forecast (blue solid curve) is performed. This single deterministic forecast fails to predict correctly the future state (red dotted curve). An ensemble of perturbed forecasts (thin blue solid curves) starting from perturbed initial conditions designed to sample the initial uncertainties can be used to estimate the probability PDF(D+n) at future time, D+n.
NWS Seamless Suite of Forecast Products Spanning Climate and Weather

NCEP Model Perspective

Forecast Lead Time

- Outlook
- Guidance
- Threats Assessments
- Forecasts
- Watches
- Warnings & Alert Coordination

Forecast Uncertainty

Climate/Weather Linkage

- Climate Forecast System*

Global Ensemble Forecast System

- Global Forecast System
- Short-Range Ensemble Forecast
- North American Forecast
- Rapid Update Cycle for Aviation
- Dispersion Models for DHS

Benefits

- Life & Property
- Aviation
- Maritime
- Space Operations
- Fire Weather
- Emergency Mgmt
- Commerce
- Energy Planning
- Hydropower
- Reservoir Control
- Agriculture
- Recreation
- Ecosystem
- Health
- Environment

- snel - GFDL
- WRF
Milestones of GEFS development

• 1992 – GEFS was in NCEP operation
  – 00UTC only, T62 (220km), 2+1 members, out to 12 days

• 1994 – GEFS run twice per day
  – 00UTC 10+1 members, 12UTC 4+1 members
  – Out to 16 days

• 2000 – GEFS increased resolution
  – T126L28 (110km) for first 60 hours

• 2004 – GEFS run four times per day
  – 00UTC, 06UTC, 12UTC and 18UTC; 40+4 members

• 2005 – Introduced TS relocation (TSR)

• 2006 – ETR replaced BV, 6-h cycling instead of 24-h

• 2007 – Full size GEFS, 80+4 members per day
  – 20 perturbed ensembles plus control

• 2010 – introduced STTP, increased resolution (70km)
  – T190L28 resolution

• 2012 – Increasing resolution (~50km)
  – T254L42 resolution, tuning TSR, ETR and STTP
Ensemble initializations and cycling
LYAPUNOV, SINGULAR, AND BRED VECTORS

• **LYAPUNOV VECTORS (LLV):**
  - Linear perturbation evolution
  - Fast growth
  - Sustainable
  - Norm independent
  - Spectrum of LLVs
  \[ \lambda_i = \lim_{t \to \infty} \frac{1}{t} \log \left( \frac{p_i(t)}{p_i(t_0)} \right) \]

• **SINGULAR VECTORS (SV):**
  - Linear perturbation evolution
  - Fastest growth
  - Transitional (optimized)
  - Norm dependent
  - Spectrum of SVs
  \[ \| x(t) \|^2 = \langle \hat{L} E L x_0; x_0 \rangle \]

• **BRED VECTORS (BV):**
  - Nonlinear perturbation evolution
  - Fast growth
  - Sustainable
  - Norm independent
  - Can orthogonal (Boffeta et al)
  \[ \frac{dv}{dt} = av (1 - v) \]

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Courtesy of Zoltan Toth
ESTIMATING AND SAMPLING INITIAL ERRORS: THE BREEDING METHOD - 1992

- **DATA ASSIM:** Growing errors due to cycling through NWP forecasts
- **BREEDING:** - Simulate effect of obs by rescaling nonlinear perturbations
  - Sample subspace of most rapidly growing analysis errors
    - Extension of linear concept of Lyapunov Vectors into nonlinear environment
    - Fastest growing nonlinear perturbations
    - Not optimized for future growth –
      - Norm independent
      - Is non-modal behavior important?

References
1. Toth and Kalnay: 1993 BAMS
2. Tracton and Kalnay: 1993 WAF

Courtesy of Zoltan Toth
24-hour breeding cycle

2004

6-hour breeding cycle

2004
6 hours breeding cycle

2006, 2007

Re-scaling

Next T00Z

Up to 16-d

ETR

T00Z

56m

6hrs

T06Z

56m

T12Z

56m

T18Z

56m

Re-scaling

Re-scaling

Re-scaling

Re-scaling

6 hours breeding cycle

ETR

T00Z

80m

6hrs

T06Z

80m

T12Z

80m

T18Z

80m

Re-scaling

Re-scaling

Re-scaling

Re-scaling

Up to 16-d

Up to 16-d

Up to 16-d

Up to 16-d

2006, 2007
P#, N# are the pairs of positive and negative
P1 and P2 are independent vectors
Simple scaling down (no direction change)

P1, P2, P3, P4 are orthogonal vectors
No pairs any more
To centralize all perturbed vectors (sum of all vectors are equal to zero)
Scaling down by applying mask,
The direction of vectors will be tuned by ET.

References:
1. Wei and et al: 2006 Tellus
2. Wei and et al: 2008 Tellus
How do we tune ETR initial perturbations?

Northern Hemisphere 500hPa Height
Ensemble Mean RMSE and Ensemble SPREAD
Average For 20091202 – 20100201

Rescaling mask and factors

Schematic of tuning initial perturbations

Current operation

Future

500hPa NH

850hPa NH

1000hPa NH

20% more

1.0 factor

1.2 factor

Top

same

Linear

Reference mask

same

Surface

20% more

Current operation

Future
Ensemble tropical storm relocation
GFS TS relocation

Hurricane Track Plots (case 1)

Frances (08/28)

Without relocation

Reduced initial spread

With relocation

Large initial spread
Hurricane Tracks Plots (case 2)

Ivan (09/14)

Without relocation

With relocation
Track errors and spreads
2004 Atlantic Basin (8/23-10/1)

From Timothy Marchok (GFDL)

Reduced mean track errors and spreads
Ensemble Stochastic Total Tendency Perturbation (STTP) Scheme
Ensemble Stochastic Total Tendency Perturbation (STTP) Scheme (Hou, Toth and Zhu, 2006)

NCEP operation – Feb. 2010

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

Simplification: Use finite difference form for the stochastic term

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

Where \(w\) is an evolving combination matrix, and \(\gamma\) is a rescaling factor.

Reference:
2. Hou and et al: 2010 in review of Tellus
Stochastic Total Tendency Perturbation (STTP) Scheme Application

Generation of Stochastic combination coefficients:

- **Matrix Notation** (N forecasts at M points)
  \[ S(t) = P(t) W(t) \]
  \[ M \times N \quad M \times N \quad N \times N \]

- 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

Value of Combination Coefficients for Member 14

\[ w_{ij}(t) \text{ for } i=14, \text{ and } j=1,14 \]

Random walk \( (R_1) \) superimposed on a periodic Function \( (R_0) \)
Experiments for 2009 Operational Implementation

**T126L28 vs. T190L28 resolution**, Nov. 2007 Cases

SPS works with both resolutions

--- T126L28
--- T126L28 + SP
--- T190L28
--- T190L28 + SP

Tropical 850hPa Temp.
Continous Ranked Probability Skill Scores
Average For 20071101 - 20071129

CRPSS

ROC area (0-1)
Average For 20071101 - 20071129

Skill Scores
Next GEFS implementation (Q4FY2011)

• Model and initialization
  – Using GFS V9.01 instead of GFS V8.00
  – Improved Ensemble Transform with Rescaling (ETR) initialization
  – Improved Stochastic Total Tendency Perturbation (STTP)

• Configurations
  – T254 (55km) horizontal resolution for 0-192 hours (from T190 – 70km)
  – T190 (70km horizontal resolution for 192-384 hours (same as current opr)
  – L42 vertical levels for 0-384 hours (from L28)

• Part of products will be delayed by approximately 20 minutes
  – Due to limit CCS resources
  – 40 nodes for 70 minutes (start +4:35 end: +5:45)

• Unchanged:
  – 20+1 members per cycle, 4 cycles per day
  – pgrb file output at 1*1 degree every 6 hours
  – GEFS and NAEFS post process output data format

• Why do we make this configurations?
  – Considering the limited resources
  – Resolution makes difference (example of T126 .vs T190)

• What do we expect from this implementation?
  – Preliminary results (NH 500hPa and SH 500hPa height and tracks)
Winter 2 months

Anomaly Correlation

NH 500hPa height

SH 500hPa height

NH 850hPa temperature

SH 850hPa temperature

GFS V8.0 vs V9.0
**Anomaly Correlation**

**Summer 2 months**

### Northern Hemisphere 500hPa Height
- **NH 500hPa height**
- Anomaly Correlation
  - GFS V8.0 vs V9.01
  - Forecast days
- **Skillful line**
- 9.75d
- 9.5d

### Southern Hemisphere 500hPa Height
- SH 500hPa height
- Anomaly Correlation
- Forecast days

### Northern Hemisphere 850hPa Temperature
- **NH 850hPa temperature**
- Anomaly Correlation
  - GFS V8.0 vs V9.01
  - Forecast days
- T190L28, T254L42

### Southern Hemisphere 850hPa Temperature
- **SH 850hPa temperature**
- Anomaly Correlation
- Forecast days
- T190L28, T254L42
Tropical Storm Tracks (Aug. – Sep. 2010, for AL, EP and WP)
NAEFS and post process

Multi-model ensembles
NAEFS & THORPEX

- Expands international collaboration
  - Mexico joined in November 2004
  - FNMOC to join in 2009
  - UK Met Office may join in 2009

- Provides framework for transitioning research into operations
  - Prototype for ensemble component of THORPEX legacy forecast system: Global Interactive Forecast System (GIFS)

Articulates operational needs
Transfers New methods
Current NCEP/EMC Statistical Post-Processing System

- Bias corrected NCEP/CMC GEFS and GFS forecast (up to 180 hrs), same bias correction algorithm
  - Combine bias corrected GFS and NCEP GEFS ensemble forecasts
  - Dual resolution ensemble approach for short lead time
  - GFS has higher weights at short lead time
- NAEFS products
  - Combine NCEP/GEFS (20m) and CMC/GEFS (20m), FNMOC ens. will be in soon
  - Produce Ensemble mean, spread, mode, 10% 50%(median) and 90% probability forecast at 1*1 degree resolution
  - Climate anomaly (percentile) forecasts also generated for ens. mean
- Statistical downscaling
  - Use RTMA as reference - NDGD resolution (5km), CONUS only
  - Generate mean, mode, 10%, 50%(median) and 90% probability forecasts
NCEP/GEFS raw forecast

4+ days gain from NAEFS

NAEFS final products

From Bias correction (NCEP, CMC)
Dual-resolution (NCEP only)
Down-scaling (NCEP, CMC)
Combination of NCEP and CMC
From Bias correction (NCEP, CMC) Dual-resolution (NCEP only) Down-scaling (NCEP, CMC) Combination of NCEP and CMC

NAEFS final products

NCEP/GEFS raw forecast

8+ days gain
Alaska NAEFS Wind Speed MAE
July-October 2010

50th (median) and mean are best
Track forecast error for 2009 season (AL+EP+WP)

NAEFS is combined NCEP (NCEPbc) and CMC’s (CMCbc) bias corrected ensemble and bias corrected GFS

Contributed by Dr. Jiayi Peng (EMC/NCEP)
Track forecast error for 2009 season (AL+EP+WP)

NAEFS is combined NCEP (NCEPbc) and CMC’s (CMCbc) bias corrected ensemble and bias corrected GFS

Contributed by Dr. Jiayi Peng (EMC/NCEP)
Future plans
Flow Chart for Hybrid Variation and Ensemble Data Assimilation System (HVEDAS) - concept

Lower resolution

Ensemble fcst (1)
\[ t = j-1 \rightarrow j \]

EnKF assimilation
\[ t = j \]

Ensemble fcst
\[ t = j, \rightarrow j+1 \]

EnKF assimilation
\[ t = j+1 \]

Ensemble initialization

Ensemble fcst (2)
\[ t = j \rightarrow 16 \text{ days} \]

Estimated Background Error Covariance from Ensemble Forecast (6 hours)

Replace Ensemble Mean

Hybrid Analysis?

Higher resolution

GSI/3DVAR
\[ t = j \]

GSI/3DVAR
\[ t = j+1 \]

Two-way hybrid

Estimated Background Error Covariance from Ensemble Forecast (6 hours)
NCEP/GEFS will plan for T254L42 (2010 GFS version) resolution with tuned ETR initial perturbations and adjusted STTP scheme for 21 ensemble members, forecast out to 16 days and 4 cycles per day. Extended to 45 days at T126L28/42 resolution, 00UTC only (coupling is still an issue?) NAEFS will include FNMOC ensemble in 2011, with improving post process which include bias correction, dual resolution and down scaling.

Main event:
MJO

Main products:
- ENSO predictions???
- Seasonal forecast???

Main products:
1. Probabilistic forecasts for every 6-hr out to 16 days, 4 times per day: 10%, 50%, 90%, ensemble mean, mode and spread.
2. D6-10, week-2 temperature and precipitation probabilistic mean forecasts for above, below normal and normal forecast
3. MJO forecast (week 3 & 4 … )

Next Operational CFS will plan to be implemented by Q2FY2011 with T126L64 atmospheric model resolution (CFSv2, 2010 version) which is fully coupled with land, ocean and atmosphere (GFS+MOM4+NOAH), 4 members per day (using CFS reanalysis as initial conditions, one day older?), integrate out to 9 months.

Future: initial perturbed CFS
ENSEMBLES AND THE RESEARCH COMMUNITY
LINKED THROUGH THORPEX – MAJOR INTERNATIONAL RESEARCH PROGRAM
GOAL: Accelerate improvements of high impact weather forecasts

- Adaptive Collection & Use of Observations
- Integrated Data Assimilation & Forecasting

Global Operational System

Observing System

Probabilistic Forecast Procedures

Forecast Error Covariance Matrix

Initial State + Error Estimate

Data Assimilation

Targeted Forecast Requirements

User Controllable Probabilistic Forecasts

Model Errors & High Impact Modeling

Weather-Climate Link

Global Interactive Forecast System (GIFS)

Global Operational Test Center

NWS Operations

Global Operational

Days 15-60

Climate Forecasting / CTB