The Development and operational implementation of GRAPES Global ensemble predication system at CMA

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Outline

• SV-based initial perturbations
• Representations of model uncertainties
• The performances of GRAPES-GEPS
• Summary and future work
The GRAPES Global Singular Vectors

- **Global/Regional Assimilation Prediction System (GRAPES) at CMA**
- **GRAPES** global SVs with the Euclidean vector $\hat{X}_i(t_0)$ are calculated as follows:
  \[
  \left( E^{-\frac{1}{2}} L^T P^T E P L E^{-\frac{1}{2}} \right) \hat{X}_i(t_0) = \lambda_i^2 \hat{X}_i(t_0) \\
  X_i(t_0) = E^{-\frac{1}{2}} \hat{X}_i(t_0)
  \]
  - $L$ : Tangent linear model (TLM)
  - $L^T$ : Adjoint model (ADM)
  - $P$ : Projection operator
  - $E$ : Total energy norm

- Total energy norm $E$ is based on variables of GRAPES TLM

\[
\iint_V \left( \frac{\rho_r \cos \phi}{2} (u')^2 + \frac{\rho_r \cos \phi}{2} (v')^2 + \frac{\rho_r \cos \phi c_P T_r}{(\theta_r)^2} ((\theta')')^2 + \frac{\rho_r \cos \phi c_P T_r}{(\Pi_r)^2} ((\Pi')')^2 \right) dV
\]

- $u'$ : the perturbations of $u$
- $v'$ : the perturbations of $v$
- $((\theta')')$ : the perturbations of perturbed potential temperature $\theta'$
- $((\Pi')')$ : perturbations of perturbed Exner pressure $\Pi'$
GRAPES Singular Vectors (Version 1)

- 48h optimization time interval (OTI)
- 2.5 degree horizontal resolution and 36 vertical levels
- **Localized regions**: Northern Hemisphere extra-tropics (30°–80°N); Southern Hemisphere extra-tropics (30°–80°S)
- **TLM and ADM (version 1)**: dynamical core of GRAPES_GFS without Linearized physics schemes
- The trajectory of TLM is from forecast of dynamical core of GRAPES_GFS
- Iteration times of Lanczos Algorithm is 50, and 30 SVs are obtained approximately

the shallow unreasonable fast-growing structures in the lower level of model near surface was observed in evolved SVs.
Typical total-energy SVs

• The typical structures of SV based on total-energy norm
  Buizza and Palmer (1994); Lawrence et al (2009); Leutbecher (2012)

• At initial time:
  – the energy maximum of SVs is located in the middle troposphere, and potential energy is dominant
  – westward tilt with height at initial time

• At final time
  – the upward energy transfer to higher troposphere and downward energy transfer toward lower troposphere, the kinetic energy of SVs is dominant at final time
  – upscale energy transfer with a pronounced final-time energy spectral
Localized regions: Northern Hemisphere extra-tropics (30°–80°N); Southern Hemisphere extra-tropics (30°–80°S)

TLM and ADM (version 2) with Linearized PBL scheme

The trajectory of TLM is from forecast of GRAPES_GFS

- Typical energy vertical profile observed in GRAPES SVs at initial time and final time.
- The energy spectrum of GRAPES SVs shows upscale energy transfer at final time
Typical *westward tilt* structure is observed in GRAPES SVs at initial time, and barotropic structure without obvious tilt is shown at final time.
Besides the *westward tilt* structure SVs at initial time, and *Upward energy transfer* and *downward energy transfer* (kinetic energy) are observed at final time.
Improving computational efficiency of GRAPES SVs

- The computation of ADM in SV calculation is most time consuming part
- The computation of the ADM are improved greatly by two aspects:
  - optimize the use of GCR in the ADM
  - increase the computation nodes
- The optimization reduces the computation time from 73 minutes to 55 min on IBM Flex P460

**SVs calculation time for each iteration**

- 37 minutes on new HPC “PI-Sugon” at CMA (2018)
SV-based Initial Perturbations for GRAPES ensemble

The initial perturbations are obtained from the singular vectors via a multivariate Gaussian sampling technique (Leutbcher, 2008)

Main steps:

(1) Calculating the rescale factors for the SVs based on standard deviation of analysis error: \( \beta_j \)

\[
f_j^2 = \sum_{i=1}^{N} \left( \frac{u_i'}{e_u} \right)^2 + \left( \frac{v_i'}{e_v} \right)^2 + \left( \frac{\theta_i'}{e_\theta} \right)^2 + \left( \frac{\Pi_i'}{e_\Pi} \right)^2
\]

\[
\beta_j = \gamma / \bar{f}_j
\]

The GRAPES SVs: \( \hat{X}(j) = (u', v', (\theta')', ((\Pi')') \)

\( e_u, e_v, e_\theta, e_\Pi \): estimated magnitude of standard deviations of analysis errors

\( \gamma \): The empirical parameter to generate adequate ensemble spread

(2) Using coefficients from random vector with Gaussian distribution to make linear combinations of rescaled SVs to get linearly sampled perturbations

\[
P_i = \sum_{j=1}^{N} \alpha_{i,j} \beta_j \hat{X}(j) \quad i = 1, 2, \ldots, M
\]

the coefficients \( \alpha_{i,j} \) are random number with distribution of \( N(0,1) \)
SV-based initial perturbations for GRAPES-GEPS

(3) The SV-based initial perturbations with the component of evolved SVs

Evolved SVs provided an easy way to include more stable and large-scale directions in generation of EPS initial perturbation (Barkmeijer et. al, 1998)

\[ Pert_i = (1 - a)P_i(d, 0) + a EP_i(d - 2, +2d) \]

(4) Adding and subtracting linearly combined SVs from analysis (from GRAPES 3Dvar/4Dvar) to construct perturbed initial conditions for GRAPES global ensemble

\[ X_i = X_A \pm Pert_i \]
The Structure of Initial Perturbations

500 hPa geopotential height, temperature perturbation (shaded); wind vector perturbation (arrows)

20 May, 2013, 00UTC
### Ensemble Experiments based on Initial Perturbations

- **Exp. INISV**: Initial perturbations generated from initial SVs
- **Exp. EVOSV**: Initial perturbations generated from initial SVs and evolved SVs, coefficient $a$ is 0.1

#### Configuration of GRAPES-GEPS

<table>
<thead>
<tr>
<th>Experiment period</th>
<th>May 1-31, 2013; 31 days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TLM/ADM model for SVs</strong></td>
<td></td>
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<tr>
<td></td>
<td>Horizontal resolution: $2.5^\circ \times 2.5^\circ$; Vertical level: 60</td>
</tr>
<tr>
<td><strong>Linear physics in TLM/ADM model</strong></td>
<td>Linear PBL scheme</td>
</tr>
<tr>
<td><strong>SVs computation area</strong></td>
<td>NH: $30^\circ$ N~$80^\circ$ N; SH: $80^\circ$ S~$30^\circ$ S</td>
</tr>
<tr>
<td><strong>OTI of SVs computation</strong></td>
<td>48h</td>
</tr>
<tr>
<td><strong>Ensemble size</strong></td>
<td>41 (40 perturbed member + control)</td>
</tr>
<tr>
<td><strong>Forecast length of EPS</strong></td>
<td>10 days</td>
</tr>
<tr>
<td><strong>Initial analysis</strong></td>
<td>GRAPES-3DVar ($0.5^\circ \times 0.5^\circ$; 60 levels)</td>
</tr>
<tr>
<td><strong>resolution of GRAPES_GEPS</strong></td>
<td>Horizontal resolution: $0.5^\circ \times 0.5^\circ$; Vertical level: 60</td>
</tr>
</tbody>
</table>
RMS ERROR AND ENSEMBLE SPREAD

- RMSE of ensemble mean is smaller than that of Cntl, indicating the improvement of EPS
- The relationship between ensemble mean error and ensemble spread is reliable
Larger ensemble spread in EVOSV experiment at different lead times

- Ensemble Spread difference (EVOSV-INISV)

- Larger ensemble spread in EVOSV experiment at different lead times
SVs for tropical cyclones (TCSV) and initial perturbations

**Up to six targeted area for tropical cyclone**

- **SVs-based Initial perturbation with TCSVs included**

\[ Pert_i = (1 - a) P_i(d, 0) + a EP_i(d - 2, +2d) + b TCP_i(d, 0) \]

- Lanczos iteration times: 20
- Linearized PBL, and LSC scheme

**TCSVs targeted areas**

- **INISV**
- **EVOSV**
- **TCSV**
Tropical cyclone tracks from GRAPES-GEPS

6 TC cases in 2017

RMSE/SPREAD of TC track

With TCSV

No TCSV

Ensemble Tracks of TC (1712)
120 h forecast based on 2017081212 UTC
tracks: OBS = black  CTRL = red  MEAN = green  EPS members = blue

With TCSV

No TCSV
• SV-based initial perturbation
• Representations of model uncertainties
• The performance of GRAPES-GEPS
• Summary and future work
Stochastic Physics (1)-SPPT
Stochastically perturbed physics tendencies (SPPT) scheme

\[ \delta X_p = \psi(\lambda, \phi, t) \delta X \]

- Random perturbed Physical tendency
- Random pattern
- Physical tendency

\[ \psi(\lambda, \phi, t) = \mu + \sum_{l=1}^{L} \sum_{m=-l}^{l} \alpha_{l,m}(t) Y_{l,m}(\lambda, \phi) \]

\[ \alpha_{l,m}(t + \Delta t) = e^{-\Delta t/\tau} \alpha_{l,m}(t) + \sqrt{\frac{4\pi \sigma^2 (1 - e^{-2\Delta t/\tau})}{L(L+2)}} R_{l,m}(t) \]

- Random pattern
  - following **Gaussian distribution**
  - temporal decorrelation scales: 6h
  - the lower and upper limit of random values: [0.5, 1.5]

- Applying stochastic perturbation to model variables (u, v, T, q)

First-order auto-regressive process
Structure of random pattern used in SPPT

(a) the horizontal distribution;
(b) time series of the random number value at an arbitrary model grid
The ensemble experiments with SPPT

**Talagrand Histogram**

(a) GZ500 over NH at Day 4

GZ500 over NH at Day 8

**RMSE Spread skill**

RMSE/SPD T850 over TR

RMSE/SPD UV850 over TR

exp1: INISVS
exp2: INISVS+SPPT
**Stochastic Physics (2) - SKEB**

Stochastic kinetic energy backscatter (SKEB) scheme

✓ SKEB introduces horizontal wind \((u,v)\) stochastically forcing terms through an added tendency terms:

(Charron et. al. 2010)

\[
\left( \frac{\partial u}{\partial t} \right)_{\text{SKEB}} = S_u
\]

\[
\left( \frac{\partial v}{\partial t} \right)_{\text{SKEB}} = S_v
\]

\[
S_u = -\frac{1}{a} \frac{\partial F_\psi}{\partial \phi}
\]

\[
S_v = \frac{1}{a \cos \phi} \frac{\partial F_\psi}{\partial \lambda}
\]

Stream-function forcing

\[
F_\Psi = \frac{\alpha \Delta x}{\Delta t} \Psi(\lambda, \phi, t) \sqrt{\Delta t \hat{D}(\lambda, \phi, \eta, t)}
\]

3D random field  
Dissipation rate

Random field (same random generator as SPPT with specified parameters)

from explicit horizontal diffusion

\[
D_{\text{num}} = \sqrt{(u \times du)^2 + (v \times dv)^2}
\]
Structure of $u, v$ wind forcing of SKEB

12 h forecast at model level 30 (initialized at 00 UTC 13 May, 2013)
The GRAPES-GEPS with SKEB

— SV

— SV+SKEB
• SV-based initial perturbation
• The model uncertainties
• The performance of GRAPES-GEPS
• Summary and future work
**Operational GRAPES-GEPS (since Dec. 2018)**

- **GRAPES-GEPS** has been operationally running at CMA since 26 Dec 2018, replacing previous operational T639-GEPS

<table>
<thead>
<tr>
<th>Forecast Model</th>
<th>GRAPES GFS</th>
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<tbody>
<tr>
<td>Resolution</td>
<td>0.5° × 0.5° ; 60 layer top at 3hPa</td>
</tr>
<tr>
<td>Initial Perturbation</td>
<td>SVs-based</td>
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<tr>
<td>Model perturbation</td>
<td>SPPT; SKEB</td>
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<tr>
<td>Ensemble Size</td>
<td>31 (30 perturbed members + control)</td>
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<tr>
<td>Forecast length</td>
<td>15 days</td>
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<thead>
<tr>
<th>Forecast Model</th>
<th>T639L60</th>
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<tbody>
<tr>
<td>Resolution</td>
<td>0.28° ; 60 layer top at 0.1hPa</td>
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<tr>
<td>Initial Perturbation</td>
<td>Breeding Vector-based</td>
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<tr>
<td>Model perturbation</td>
<td>SPPT</td>
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<tr>
<td>Ensemble Size</td>
<td>15 (14 perturbed members + control)</td>
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<td>Forecast length</td>
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</tbody>
</table>
Performance of GRAPES-GEPS compared with T639-GEPS (1)

- **GRAPES-GEPS**
- **T639-GEPS**

ACC, 500hpa 位勢高度場 “北半球地區”
2016101512-2018043012

0.3 day gain

ACC, 500hpa 位勢高度場 “南半球地區”
2016101512-2018043012

0.8 day gain
Performance of GRAPES-GEPS compared with T639-GEPS (2)

RMSE & Spread, 500hpa 位势高度场“北半球地区”
2017120112-2017123112

NH Z500 RMSE/SPD

Outlier, 500hpa 位势高度场“北半球地区”
2017120112-2017123112

NH Z500 Outlier

CRPS (dgm): HGT P500 GE/NH 12Z, 20171201-20171221

NH Z500 CRPS

SH Z500 CRPS

Difference w.r.t. T639

AC differences outside of outline bars are significant at the 95% confidence level

Forecast Hour
Overall, GRAPES-GEPS has better performance than T639-GEPS

Score cards (CRPS; Ens Mean RMSE)

<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter</th>
<th>Level</th>
<th>CRPS</th>
<th>RMSE</th>
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<tbody>
<tr>
<td>East Asia</td>
<td>UWND</td>
<td>250</td>
<td>Better</td>
<td>Better</td>
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<td></td>
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<td>850</td>
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<td></td>
<td>EGT</td>
<td>500</td>
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<tr>
<td>NH Extratropics</td>
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△: Better
▼: Worse
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Overall, GRAPES-GEPS has better performance than T639-GEPS.
Performance of operational GRAPES-GEPS (201901-201905)

RMSE/SPD

ACC of GZ500 at Day 7

GZ500 over NH grids of GRAPES_GEPS at 7 day
Forecast of blocking high at middle range

Example: 00 UTC 5 Feb. 2019

The development Ural blocking high before breakout of cold wave

GRAPES_GEPS is able to give the useful information for the development of the Ural blocking high 7-10 days earlier

500hPa Spaghetti (5360, 5680, 5880)

500hPa Ensemble mean /ensemble spread
Forecast for onset of South China Sea Monsoon 2019

- The monsoon index

• Monitor Area of South China Sea monsoon 850hpa (10°-20°N, 110°-120°E)

• 850hpa Zonal wind and pseudo-equivalent potential temperature are used as index of onset of monsoon (by National Climate Center of CMA)

The onset of Monsoon on 6th-7th May

Dot line - Obs
Solid lines – forecasts at 1d, 5d, 7d, 10d, and 14d
Summary and future work

• SV-based initial perturbation contribute the major performance of GRAPES-GEPS: ensemble spread and forecast skills

• The empirical parameters in the generation of SV-based initial perturbation will be tuned when GRAPES model is upgraded

• The improvement for TC SVs will be focused on the improvement of linearized moist physics

• The model uncertainty of GRAPES-GEPS will be focused on the improvement of existed SPPT and SKEB