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

- **G**lobal/**R**egional **A**ssimilation **Pre**diction **S**ystem (**GRAPES**) at CMA
- **GRAPES** global SVs with the Euclidean vector $\hat{X}_i(t_0)$ are calculated as follows:

$$\left(\boldsymbol{E}^{\frac{-1}{2}}\boldsymbol{L}^{T}P^{T}\boldsymbol{E}P\boldsymbol{L}\boldsymbol{E}^{\frac{-1}{2}}\right)\hat{X}_i(t_0) = \lambda_i^2\hat{X}_i(t_0)$$

$$X_i(t_0) = \boldsymbol{E}^{-\frac{1}{2}}\hat{X}_i(t_0)$$

$$X = (u', v', (\theta')', (\Pi')')^T$$

  - ***L*** : Tangent linear model (TLM)
  - ***L^T*** : Adjoint model (ADM)
  - ***P*:** Projection operator
  - ***E*:** Total energy norm

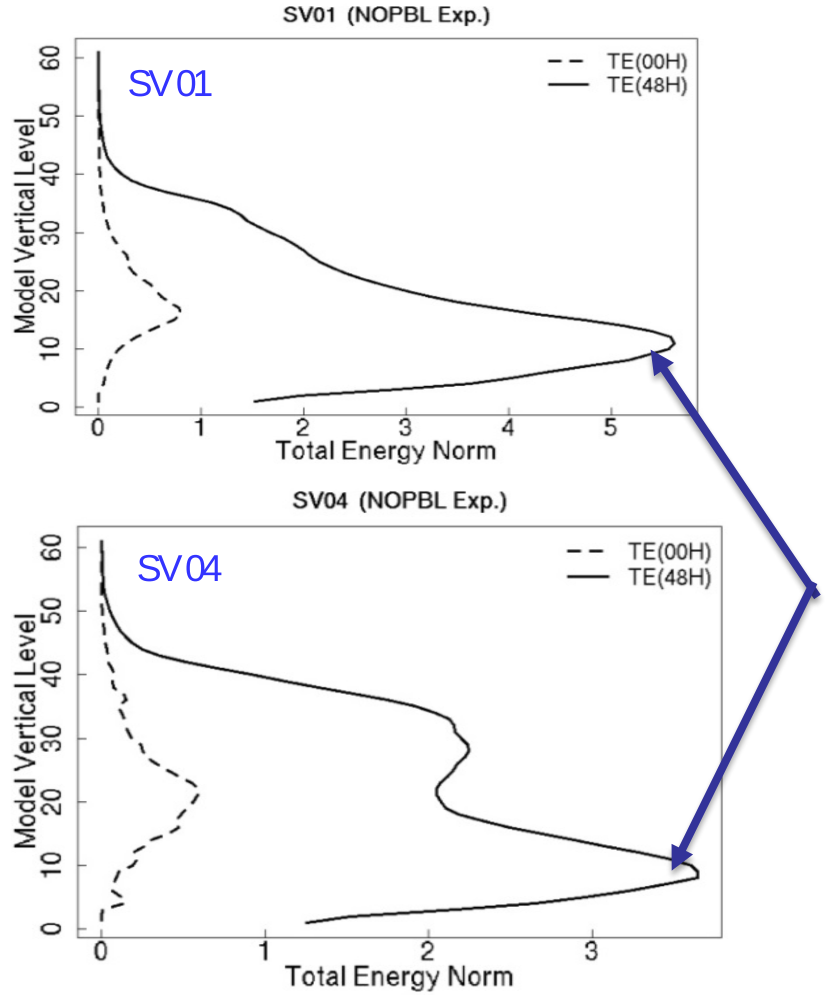
- Total energy norm **E** is based on variables of GRAPES TLM

$$\iiint_V \left(\frac{\rho_r cos\varphi}{2}(u')^2 + \frac{\rho_r cos\varphi}{2}(v')^2 + \frac{\rho_r cos\varphi C_P T_r}{(\theta_r)^2}((\theta')')^2 + \frac{\rho_r cos\varphi C_P T_r}{(\Pi_r)^2}((\Pi')')^2\right) d\boldsymbol{V}$$

u': the perturbations of u
v': the perturbations of v
$((\theta')'$: the perturbations of perturbed potential temperature θ'
$((\Pi')'$: perturbations of perturbed Exner pressure Π'

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



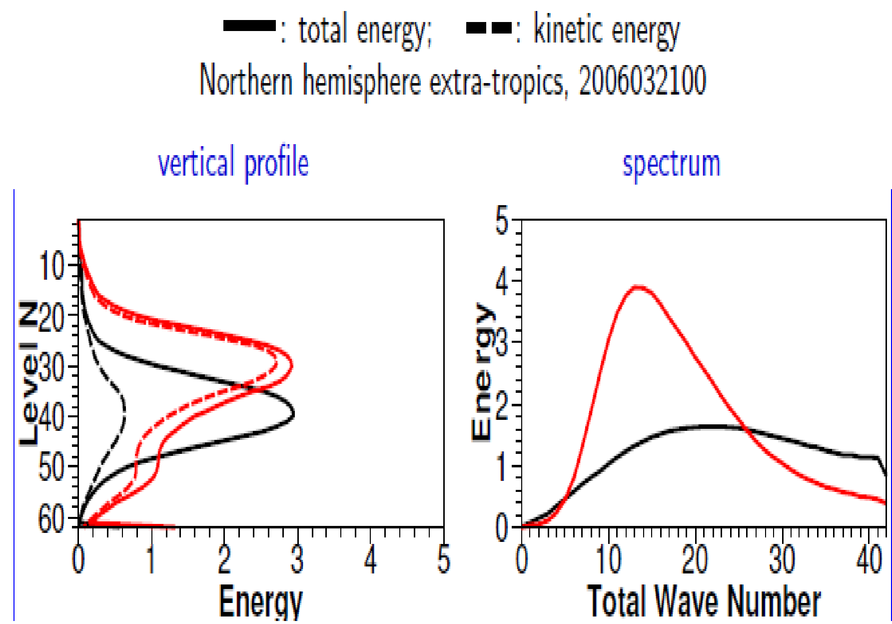
the shallow unreasonable fast-growing structures in the lower level of model near surface was observed in evolved SVs.

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



200 hPa ↔ level 20	300 hPa ↔ level 27
500 hPa ↔ level 35	700 hPa ↔ level 42
850 hPa ↔ level 48	925 hPa ↔ level 52

wave number	wave length
5	8000 km
10	4000 km
20	2000 km
40	1000 km

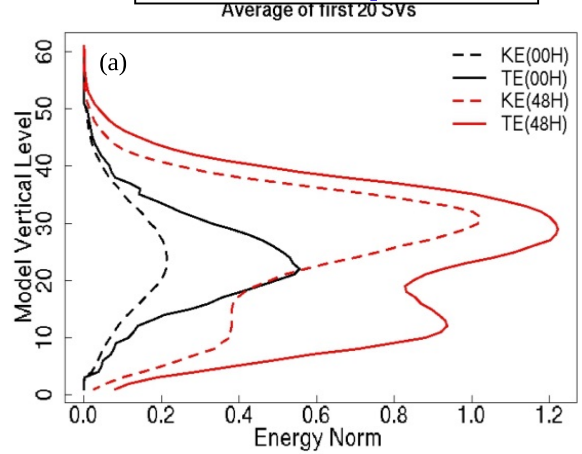
Leutbecher (2012)

ECMWF Initial Uncertainties in the EPS (I) Training Course 2012 30 / 51

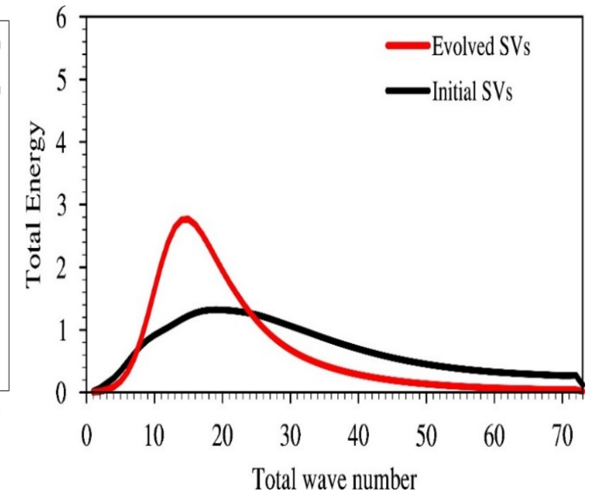
Improved GRAPES SVs （Version 2）

- **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**

vertical profile

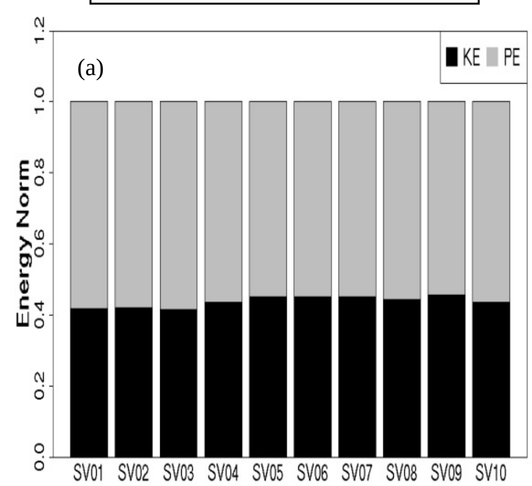


spectrum

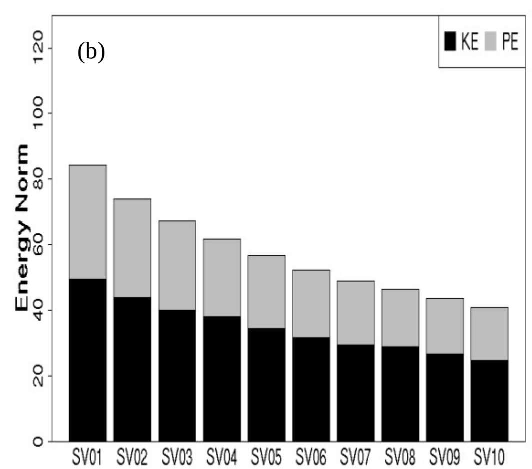


- ✓ Typical *energy vertical profile* observed in GRAPES SVs at initial time and final time.
- ✓ The energy spectrum of GRAPES SVs shows upscale energy transfer at final time

Energy partition at Initial time



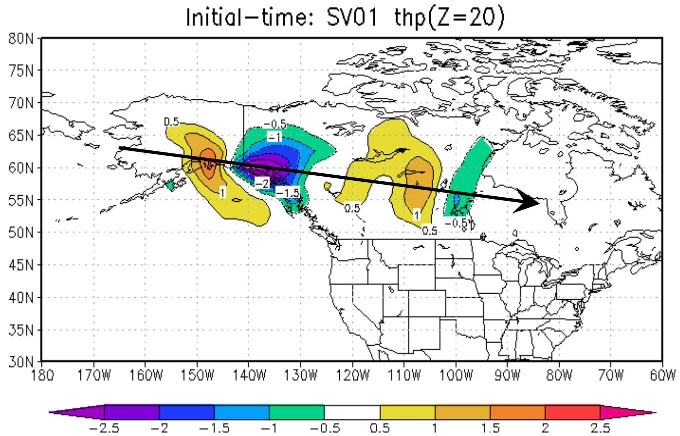
Energy partition at final time

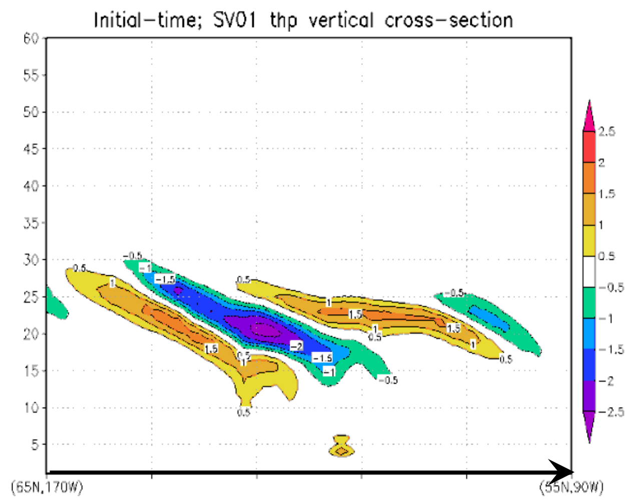


The distribution of improved GRAPES NH SVs (1)

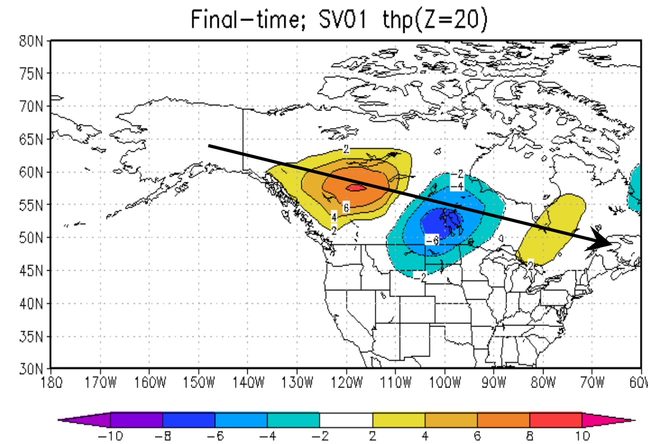
SV01- potential temperature perturbation (*1000), 8 May 2013,00UTC

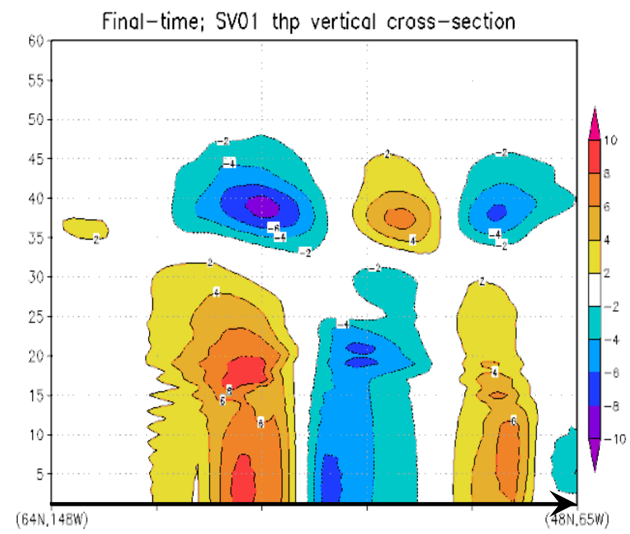
Initial time





Final time





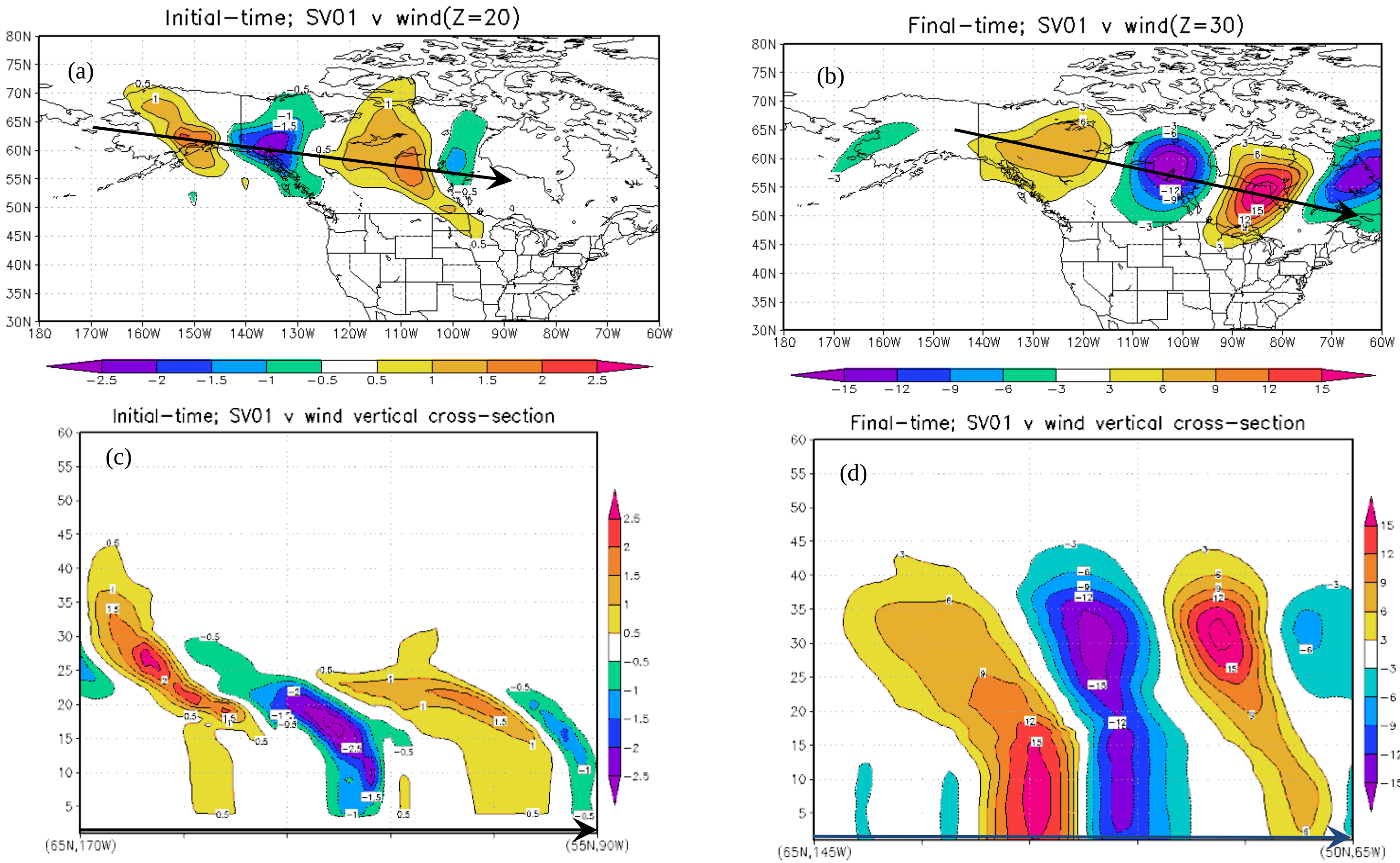
Typical *westward tilt* structure is observed in GRAPES SVs at initial time, and barotropic structure without obvious tilt is shown at final time

The distribution of improved GRAPES NH SVs (2)

SV01- u wind perturbation (*1000) , 8, May, 2013,00UTC

Initial time

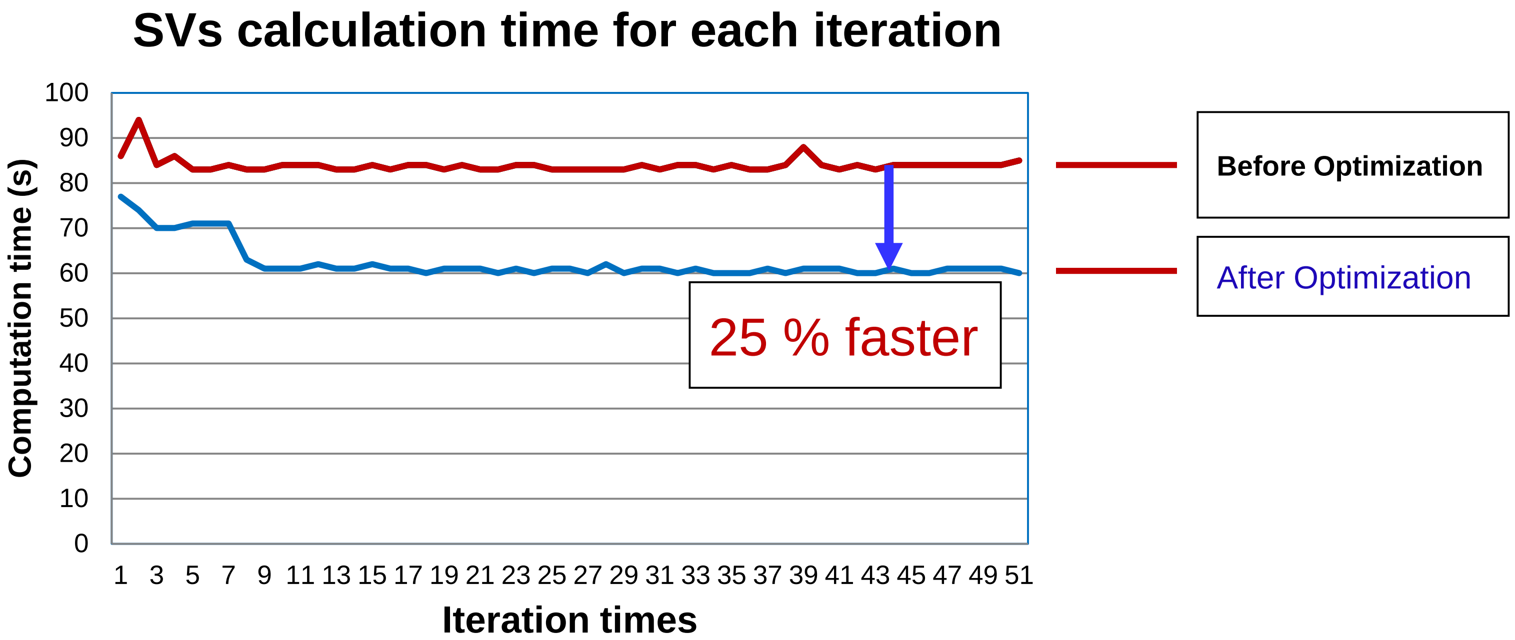
Final time



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



\- 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: β_j

$$f_j{}^2 = \sum_{i=1}^{N}(u_i{}'/e_u)^2 + (v_i{}'/e_v)^2 + ((\theta_i{}')'/e_\theta)^2 + ((\Pi_i{}')'/e_\Pi)^2$$

$$\beta_j = \gamma/\overline{f_j}$$

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

e_u ,e_v ,e_θ,e_Π : estimated magnitude of standard deviations of analysis errors

γ : 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

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

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*)

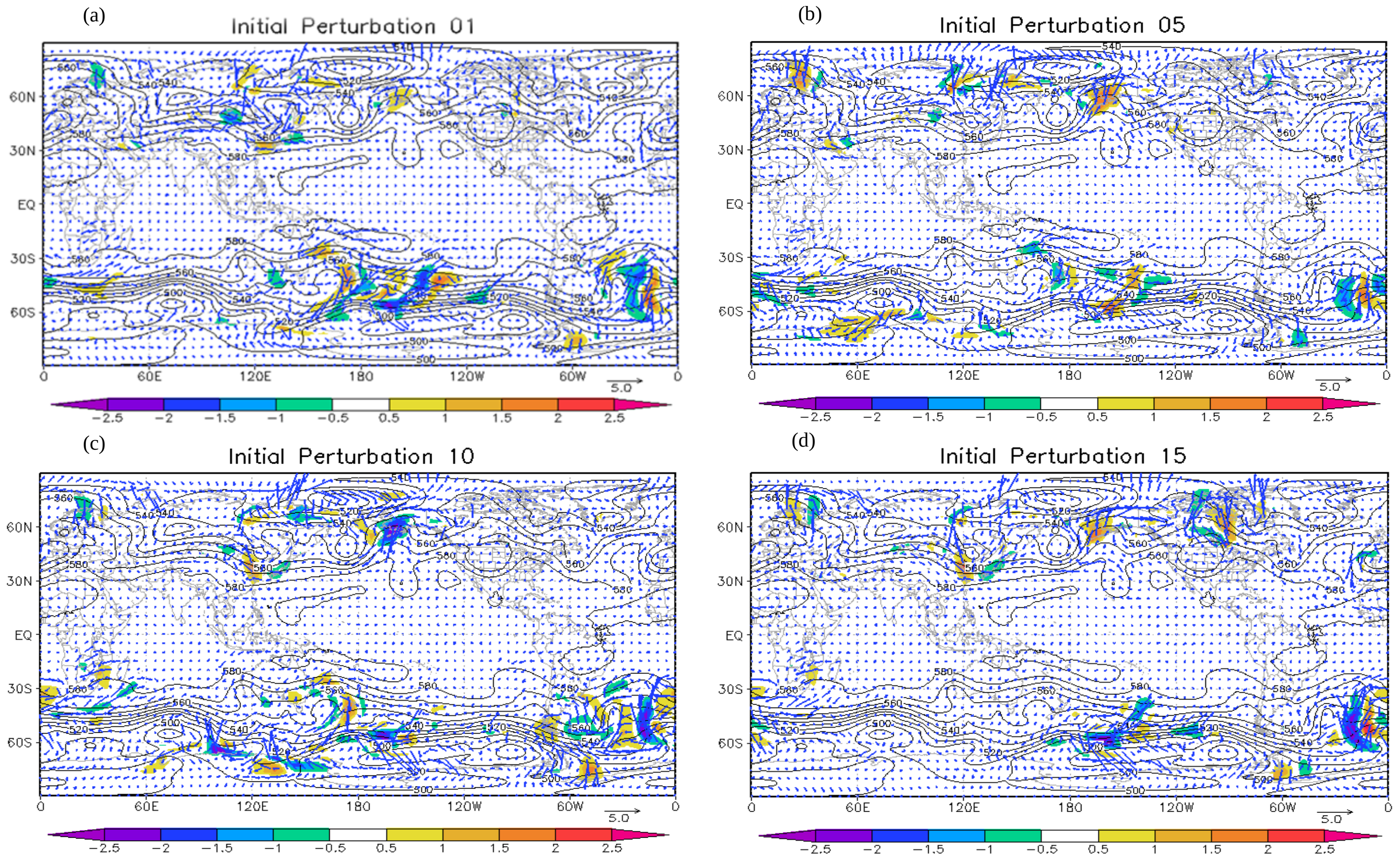
$$Pert_i = \underbrace{(1-a)\boldsymbol{P}_i(d,0)}_{\text{INISV}} + \underbrace{a\,\boldsymbol{EP}_i(d-2,+2d)}_{\text{EVOSV}}$$

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

$$\mathrm{X}_i = \mathrm{X}_A \pm Pert_i$$

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

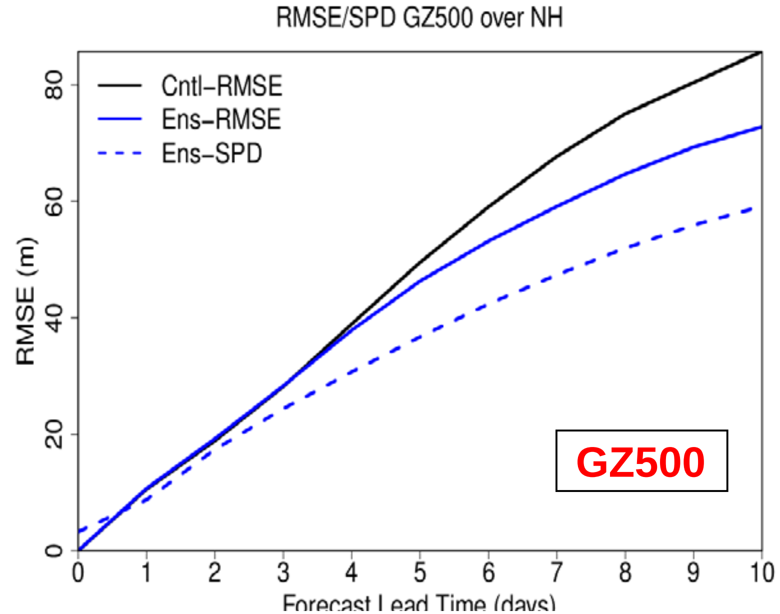
- Exp. INISV: Initial perturbations generated from initial SVs
- Exp. EVOSV : initial perturbations generated from initial SVs and evolved SVs ,coefficient a is 0.1)

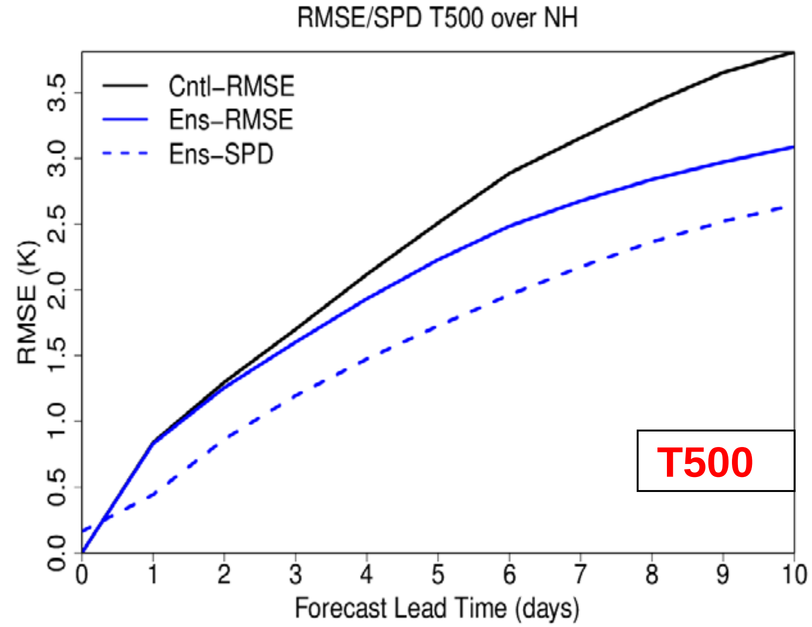
Configuration of GRAPES-GEPS

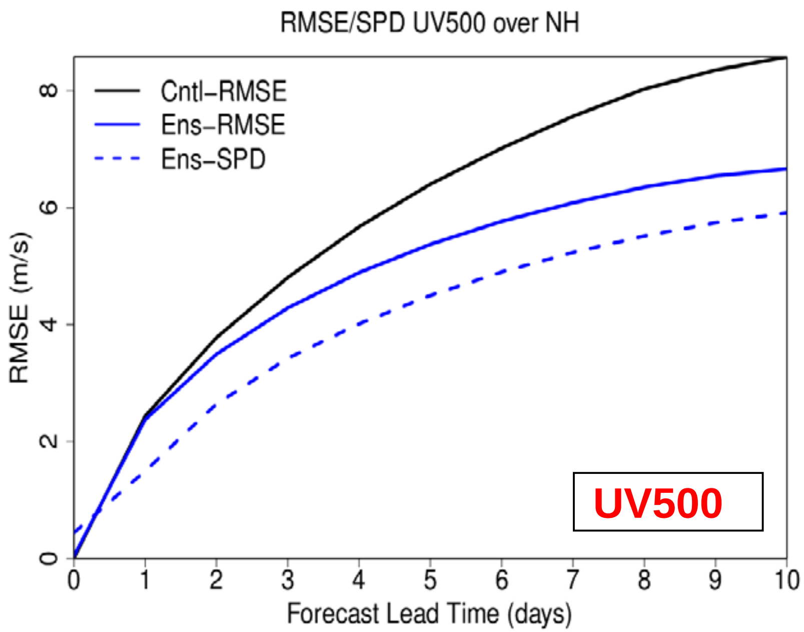
Experiment period	**May 1- 31, 2013 ; 31days**
TLM/ ADM model for SVs	Horizontal resolution: 2.5° ×2.5° ； Vertical level: 60
Linear physics in TLM/ADM model	Linear PBL scheme
SVs computation area	NH :30° N~80° N ; SH : 80° S~30° S
OTI of SVs computation	48h
Ensemble size	41 (40 perturbed member + control)
Forecast length of EPS	10 days
Initial analysis	GRAPES-3DVar (0.5° ×0.5° ; 60 levels)
resolution of GRAPES_GEPS	Horizontal resolution: 0.5° ×0.5° ； Vertical level: 60

Exp :INISV

RMS ERROR AND ENSEMBLE SPREAD

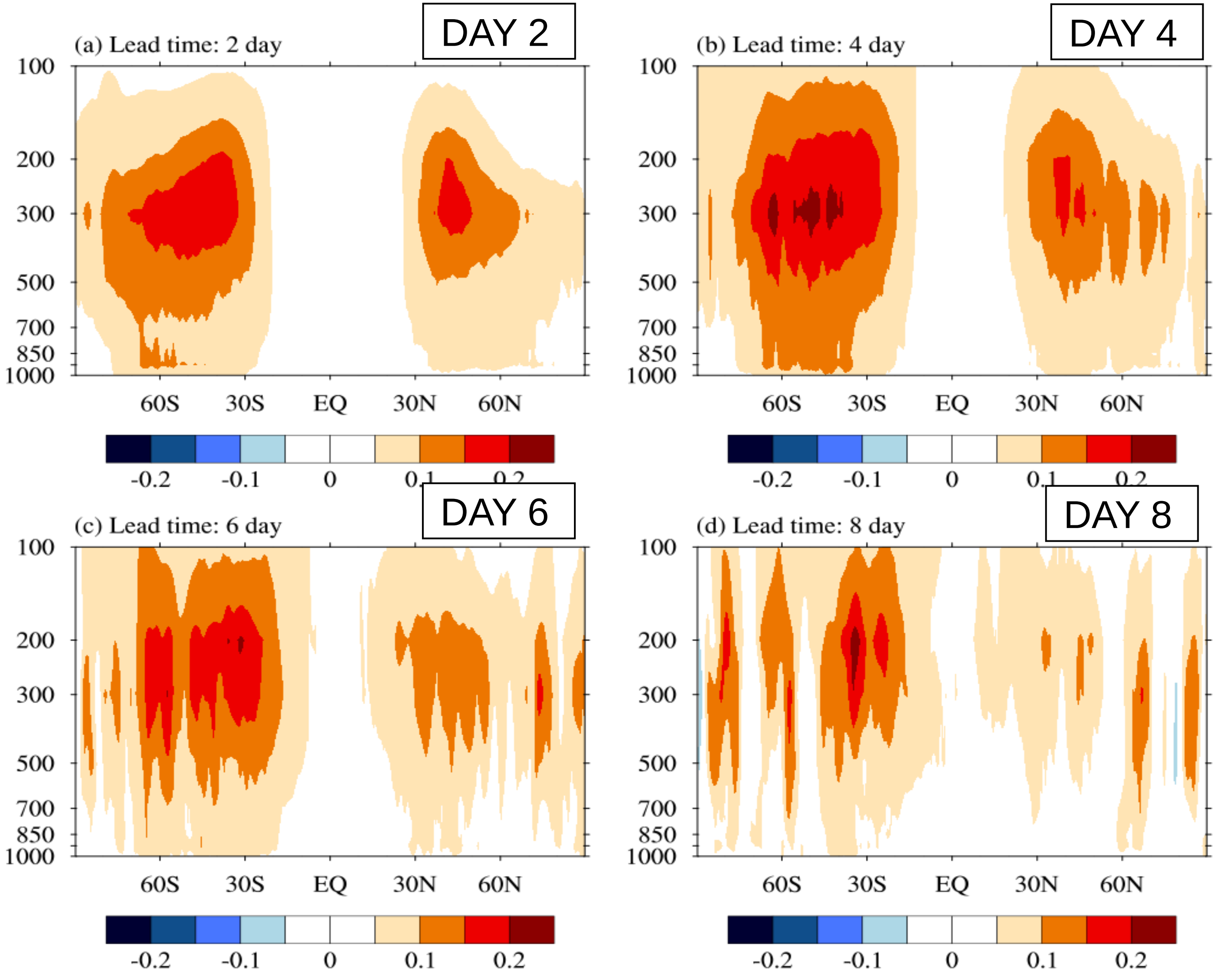






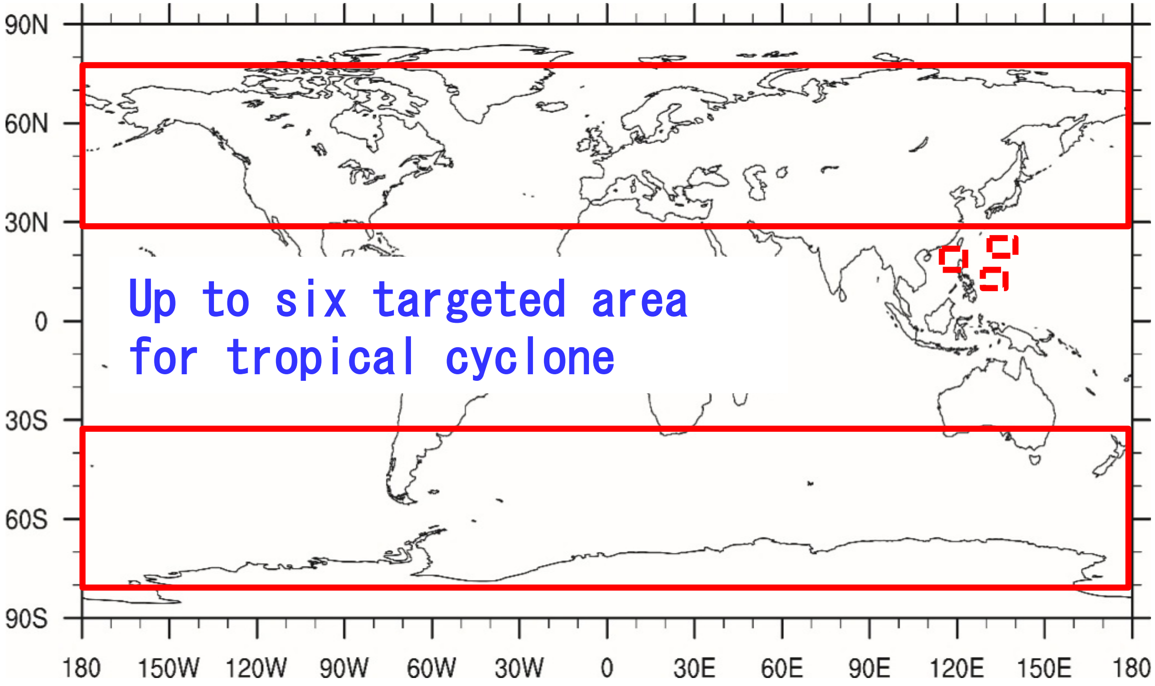
- RMSE of ensemble mean is smaller than that of Cntl, indicating the improvement of EPS
- The relationship between ensemble mean error and ensemble spread is reliable

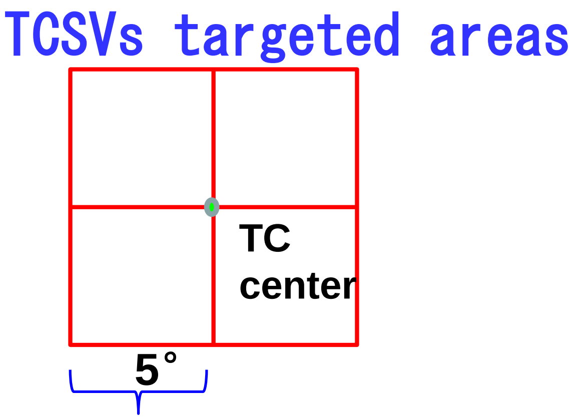
Ensemble Spread difference (EVOSV-INISV)



- Larger ensemble spread in EVOSV experiment at different lead times

SVs for tropical cyclones (TCSV) and initial perturbations





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

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

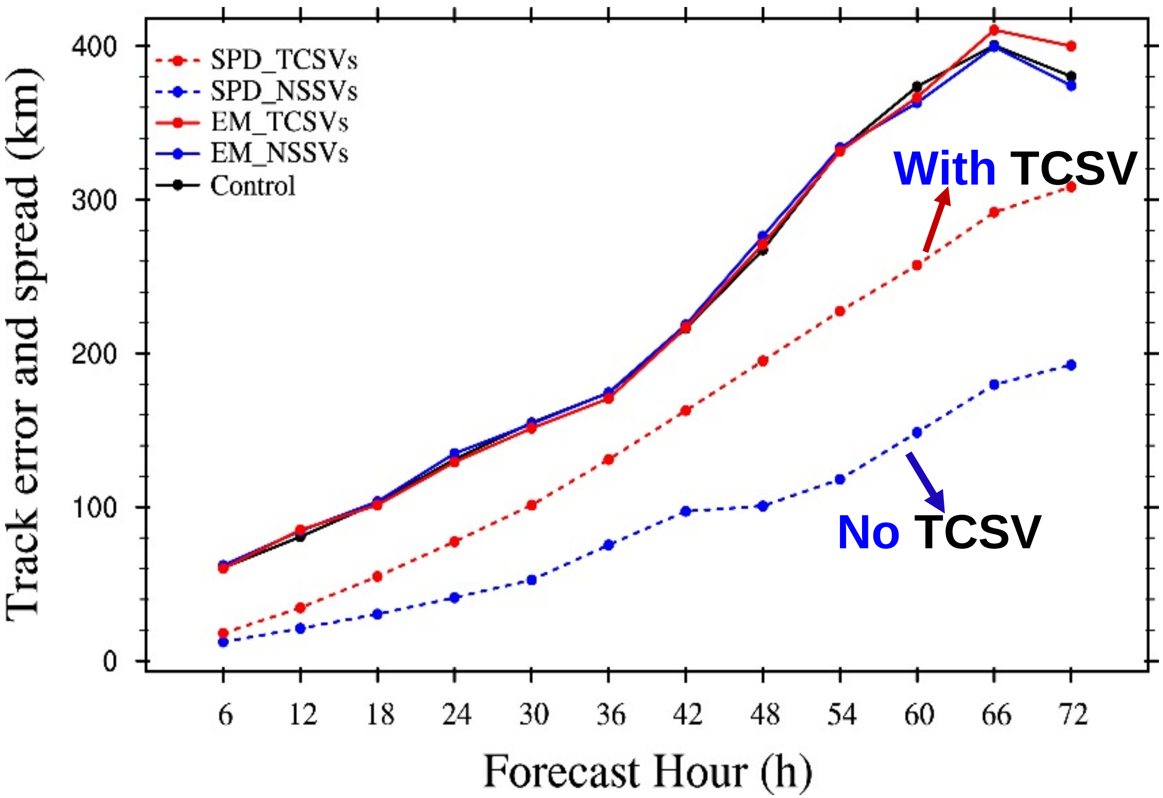
$$Pert_i = (1-a)\,\boldsymbol{P}_i(d,0) + a\,\boldsymbol{EP}_i(d-2,+2d) + b\,\boldsymbol{TCP}_i(d,0)$$

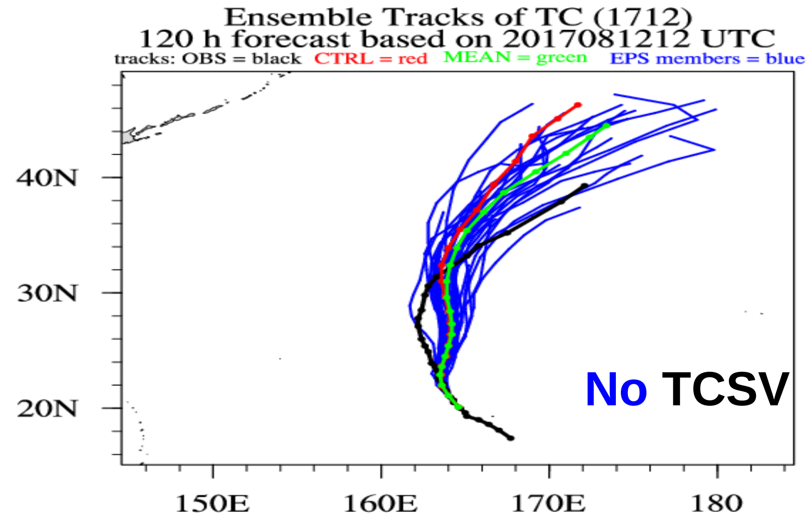
INISV **EVOSV** **TCSV**

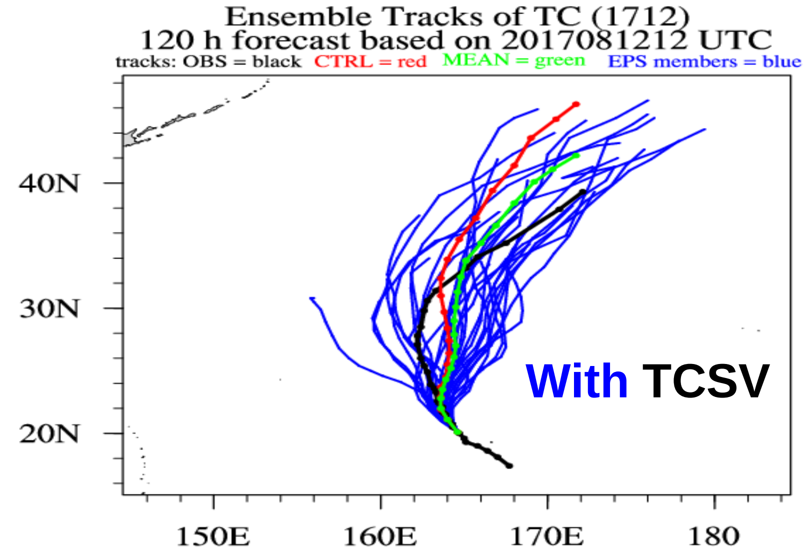
Tropical cyclone tracks from GRAPES-GEPS

6 TC cases in 2017

RMSE/SPREAD of TC track







- 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

$$\delta X_p = \psi(\lambda, \varphi, t) \quad \delta X$$

Random perturbed Physical tendency	Random pattern	Phyiscal tendency

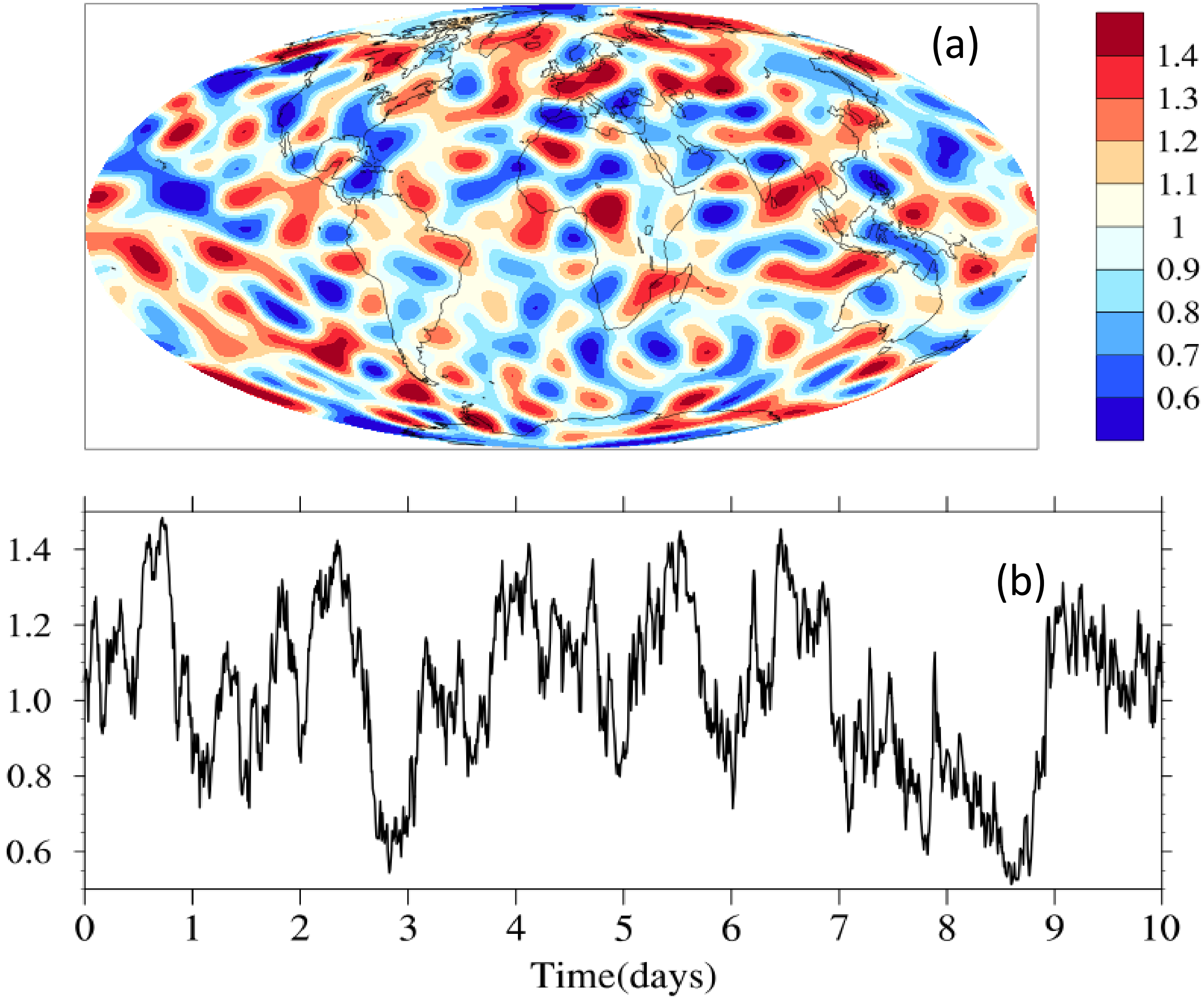
$$\psi(\lambda, \phi, t) = \mu + \sum_{l=1}^{L} \sum_{m=-l}^{l} \alpha_{l,m}(t) Y_{l,m}(\lambda, \phi)$$

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

⇨ First-order auto-regressive process

- 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)**

Structure of random pattern used in SPPT



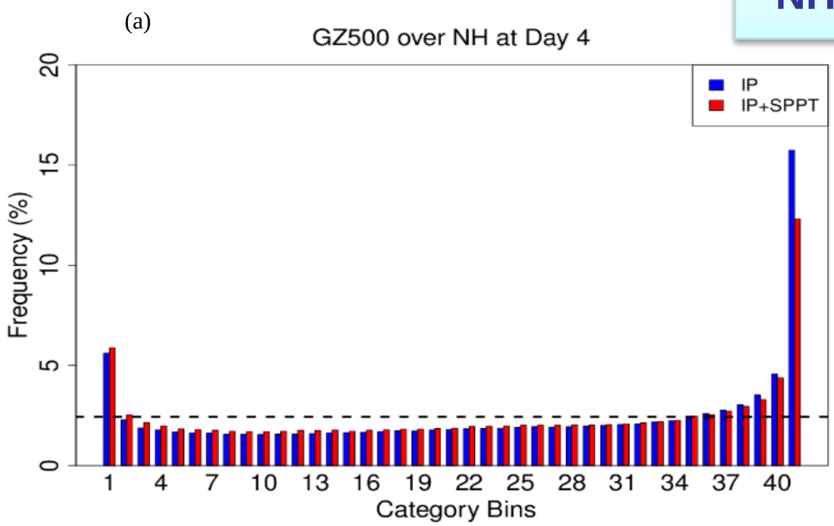
(a) the horizontal distribution;
(b) time series of the random number value at an arbitrary model grid

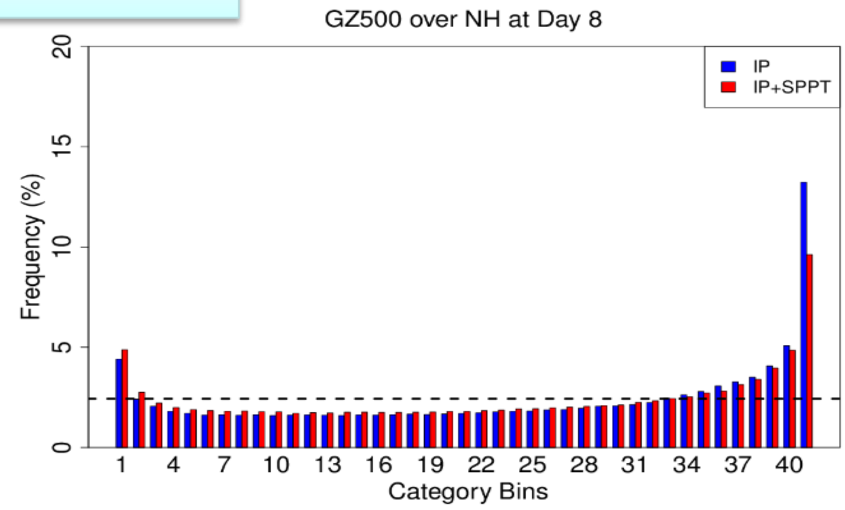
The ensemble experiments with SPPT

exp1： INISVS
exp2： INISVS+SPPT

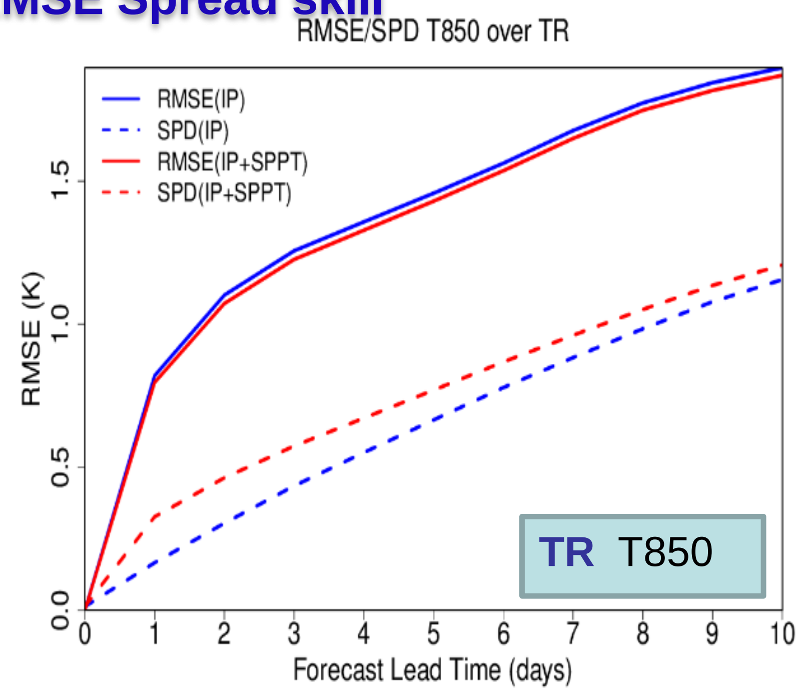
Talagrand Histogram

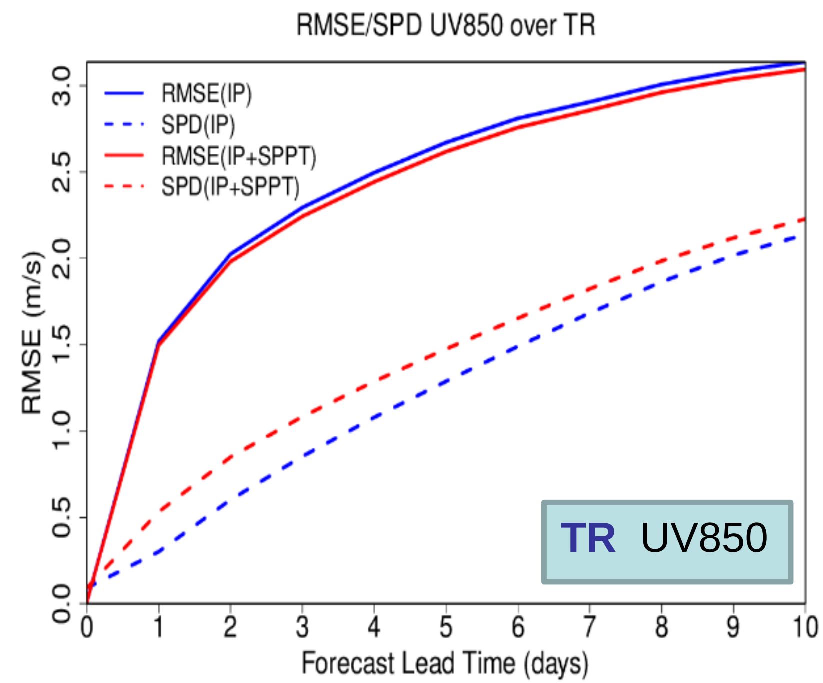
NH GZ500





RMSE Spread skill





Stochastic Physics （2）-SKEB

Stochastic kinetic energy backscatter (**SKEB**) scheme

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

(Charron et. al. 2010)

$$\left(\frac{\partial u}{\partial t}\right)_{\mathrm{SKEB}} = S_u \qquad S_u = -\frac{1}{a}\frac{\partial F_\psi}{\partial \phi}$$

$$\left(\frac{\partial v}{\partial t}\right)_{\mathrm{SKEB}} = S_v \qquad S_v = \frac{1}{a\cos\phi}\frac{\partial F_\psi}{\partial \lambda}$$

Stream-function forcing

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

3D random field

Dissipation rate

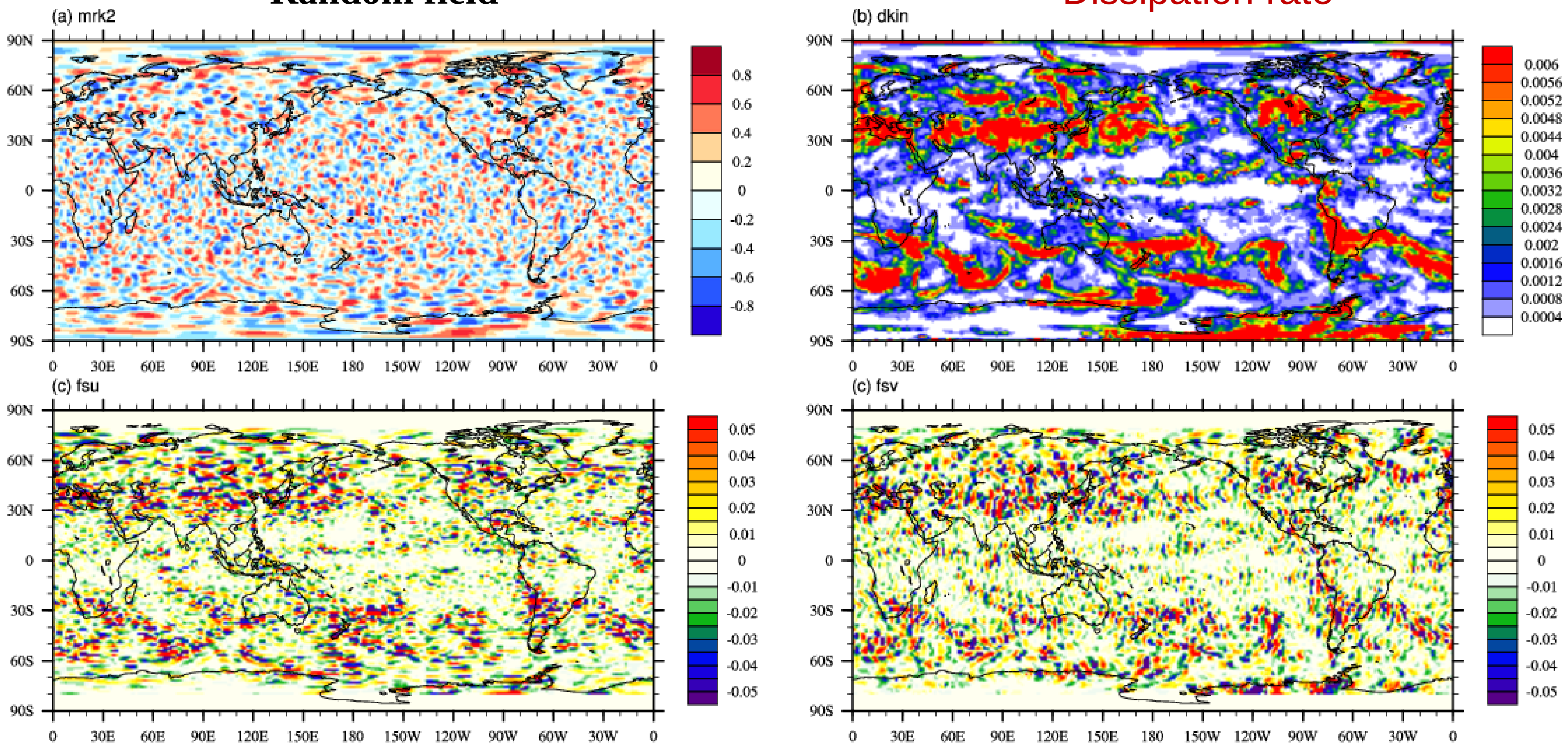
Random field (same random generator as SPPT with specified parameters)

from **explicit horizontal diffusion**

$$D_{\mathrm{num}} = \sqrt{(u \times du)^2 + (v \times dv)^2}$$

Structure of u、v wind forcing of SKEB

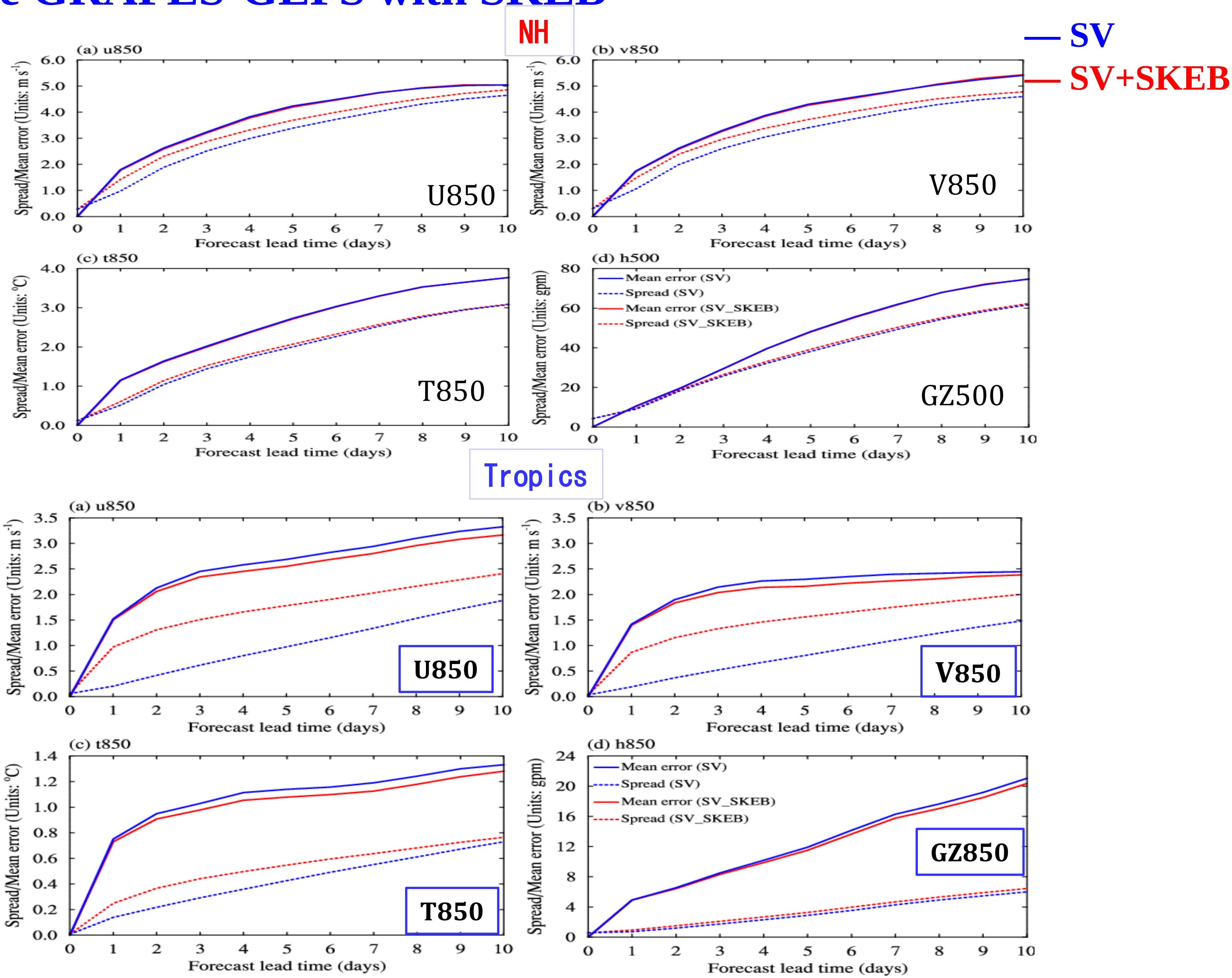
Random field | Dissipation rate



u wind forcing | **v wind forcing**

12 h forecast at model level 30 (initialized at 00 UTC 13 May, 2013)

The GRAPES-GEPS with SKEB



- SV-based initial perturbation
- The model uncertainties
- The performance of GRAPES-GEPS
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Operational GRAPES-GEPS (since Dec. 2018)

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

T639-GEPS

Forecast Model	T639L60
Resolution	0.28°; 60 layer top at 0.1hPa
Initial Perturbation	Breeding Vector-based
Model perturbation	SPPT
Ensemble Size	15 (14 perturbed members+control)
Forecast length	15 days

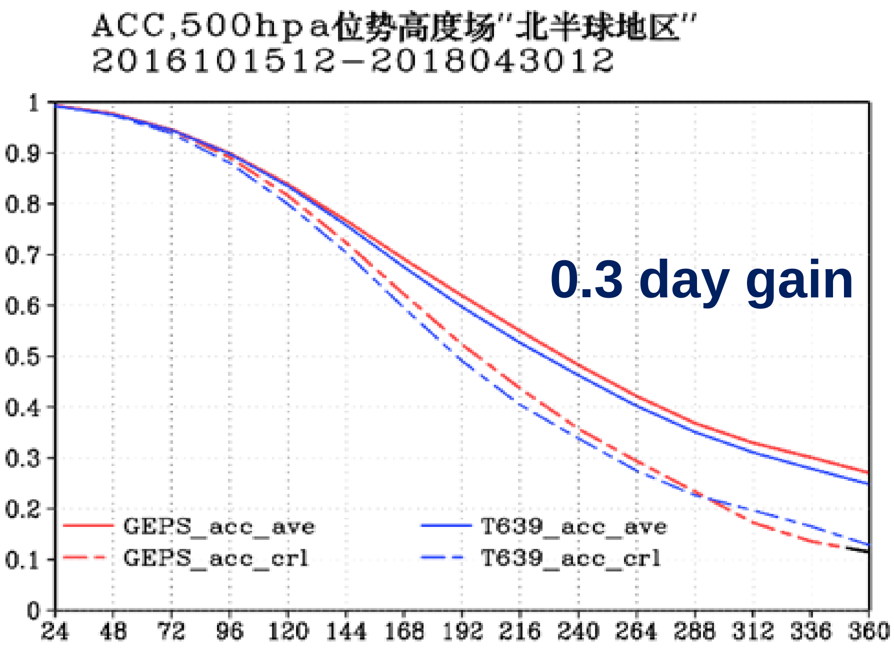
Operational GRAPES-GEPS

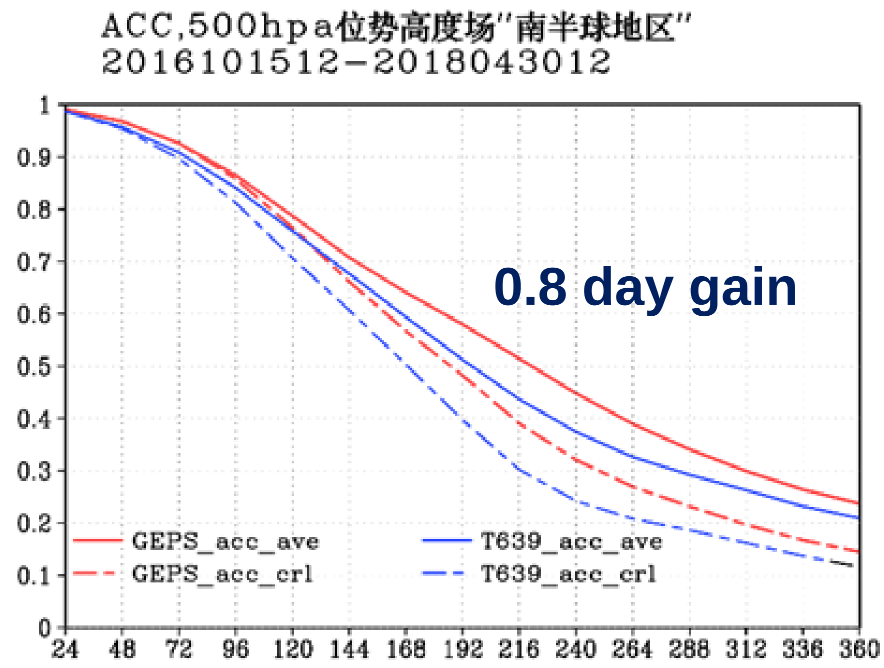
Forecast Model	GRAPES GFS
Resolution	0.5° ×0.5°; 60 layer top at 3hPa
Initial Perturbation	**SVs-based**
Model perturbation	**SPPT; SKEB**
Ensemble Size	31 (30 perturbed members +control)
Forecast length	15 days

Performance of GRAPES-GEPS compared with T639-GEPS (1)

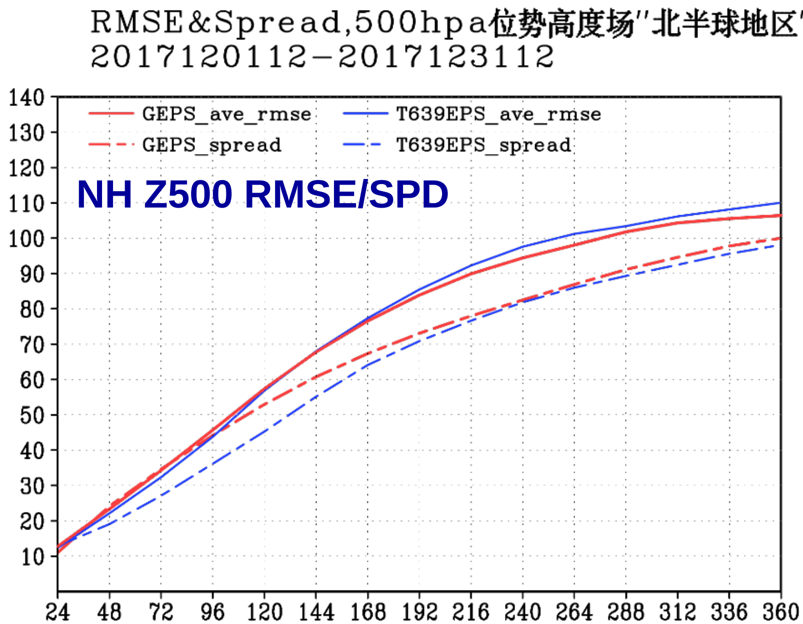
GRAPES-GEPS

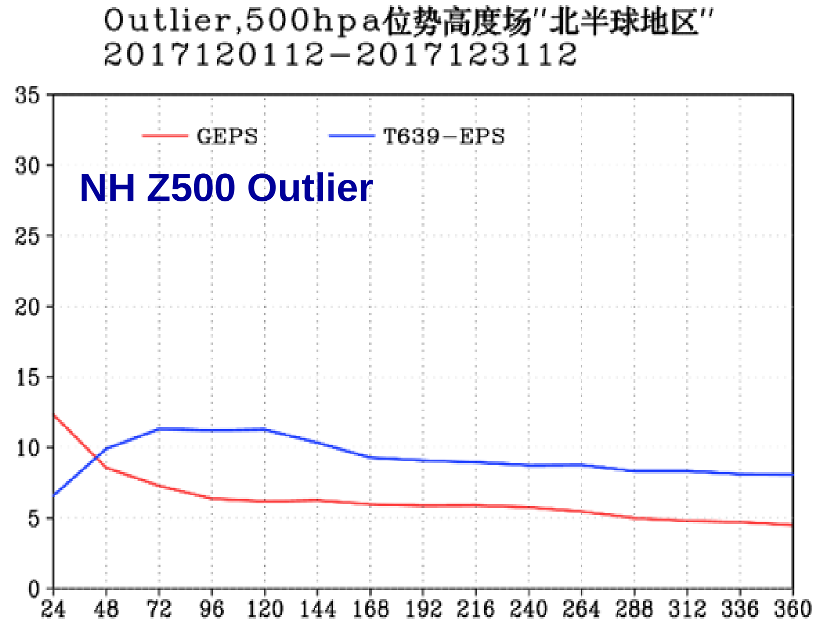
T639-GEPS

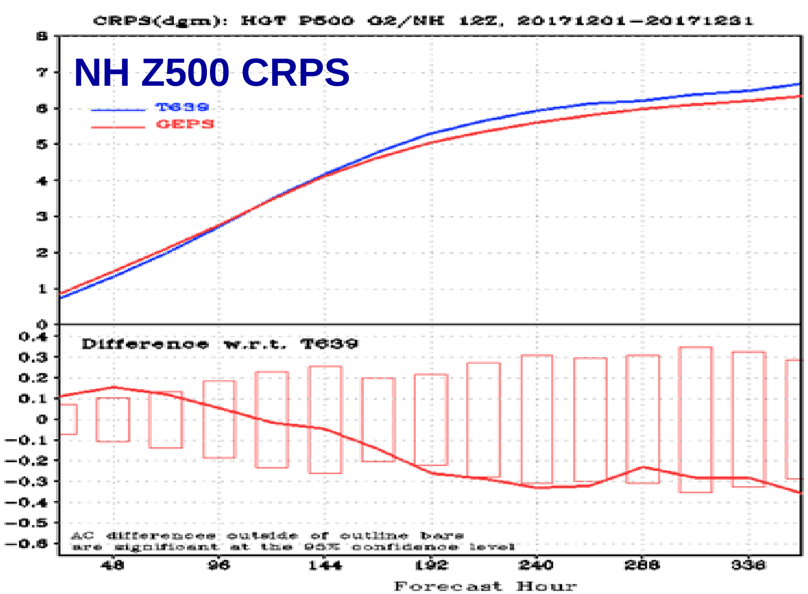


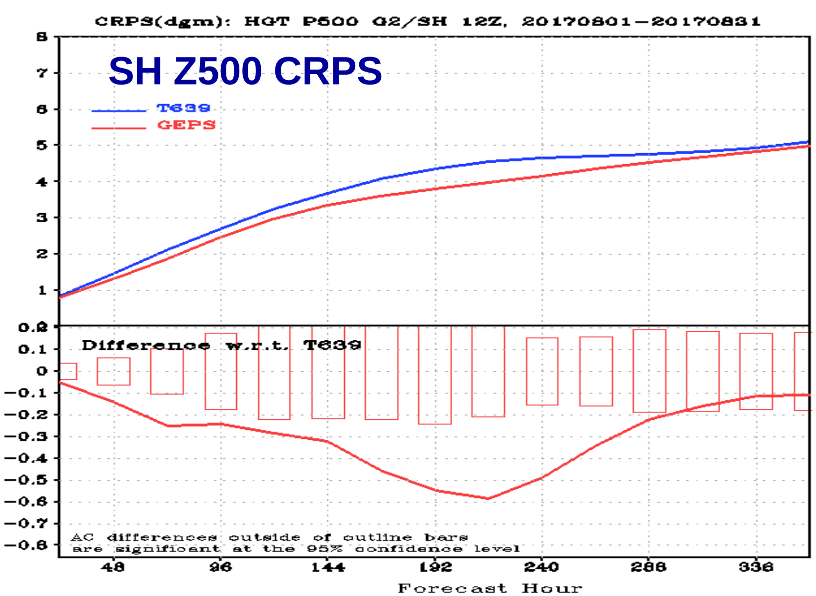


Performance of GRAPES-GEPS compared with T639-GEPS (2)



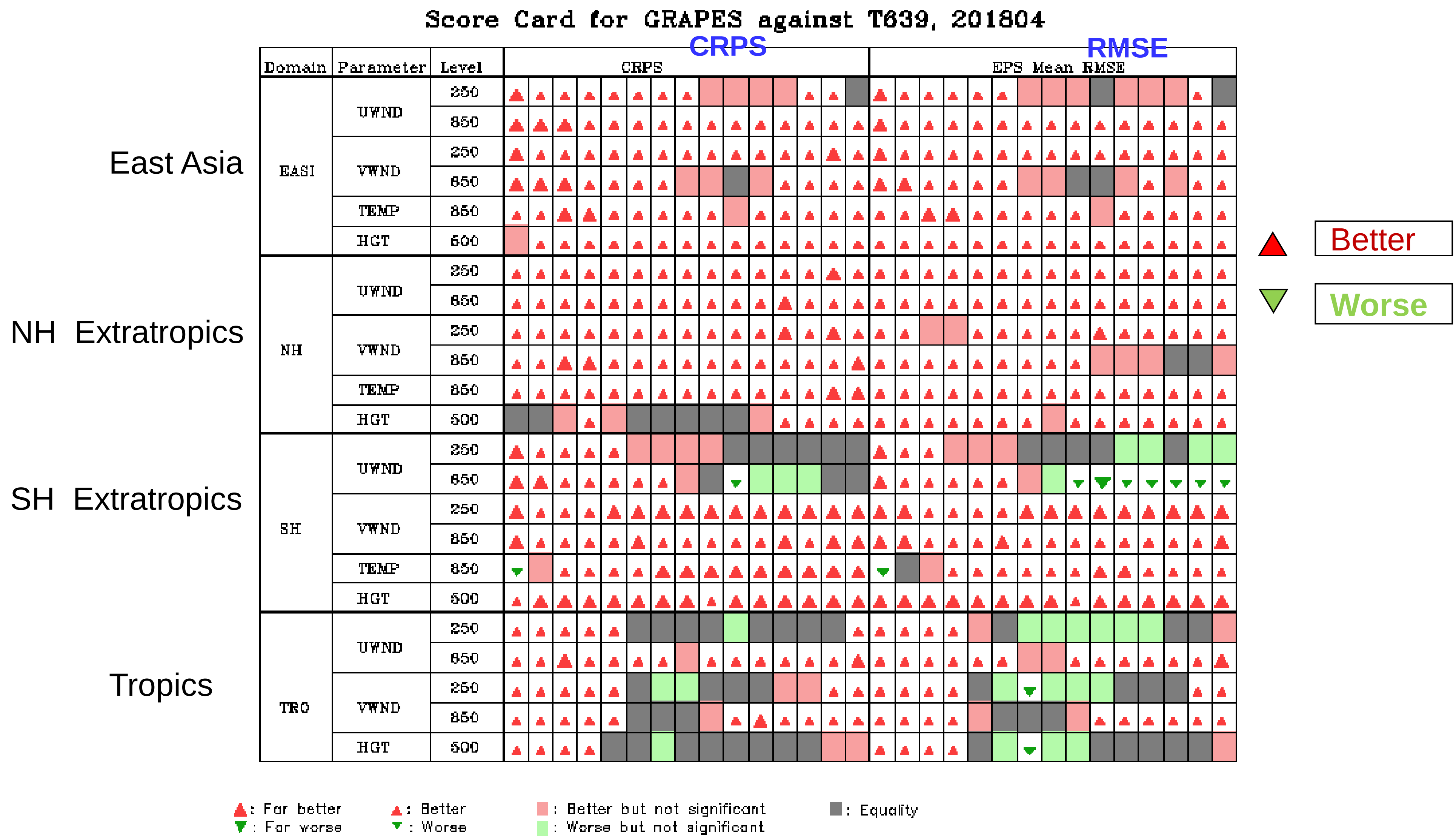






Performance of GRAPES-GEPS compared with T639-GEPS (3)

Score cards (CRPS; Ens Mean RMSE)

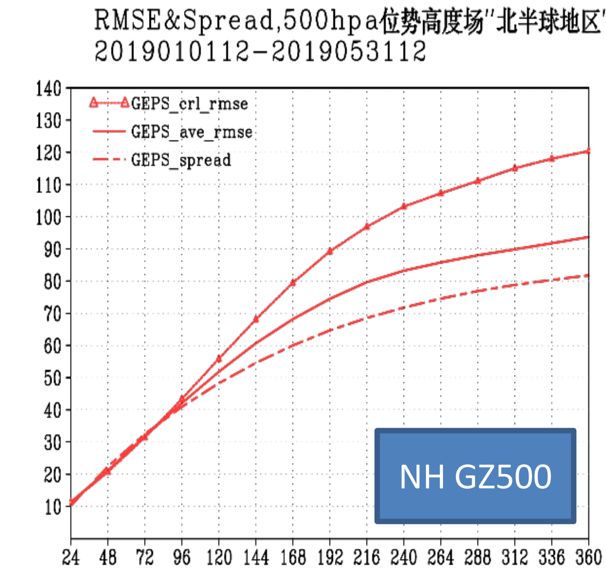


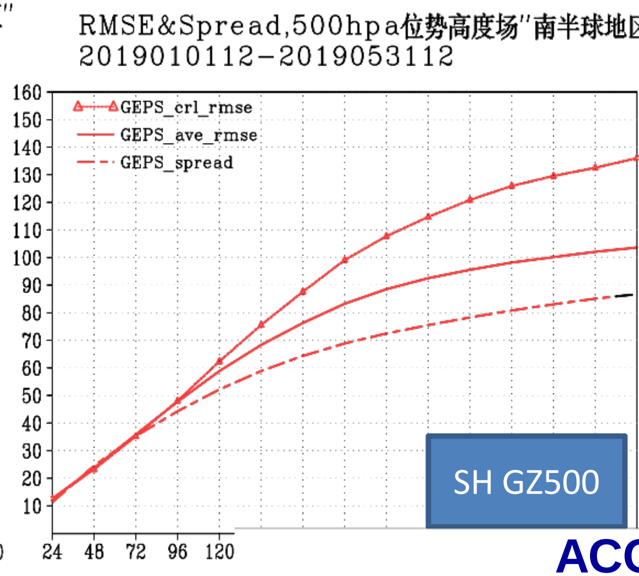
Overall, GRAPES-GEPS has better performance than T639-GEPS

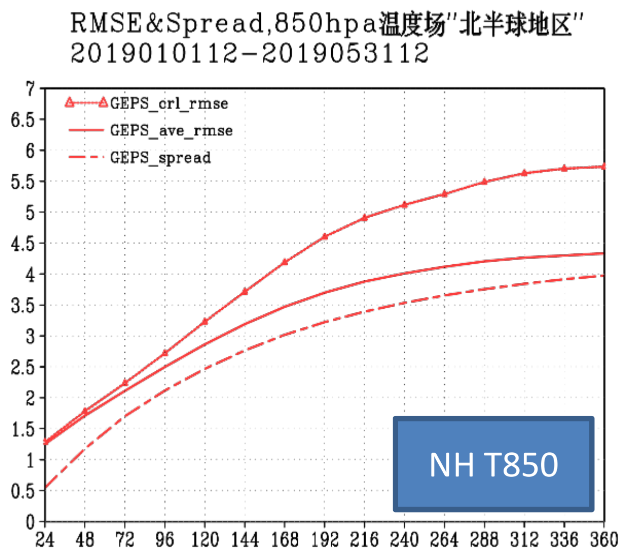
Performance of operational GRAPES-GEPS

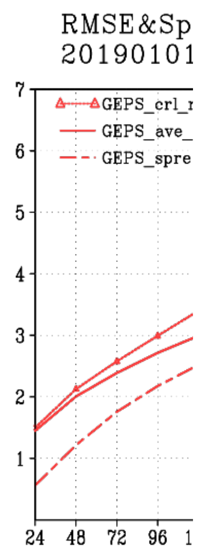
(201901-201905)

RMSE/SPD

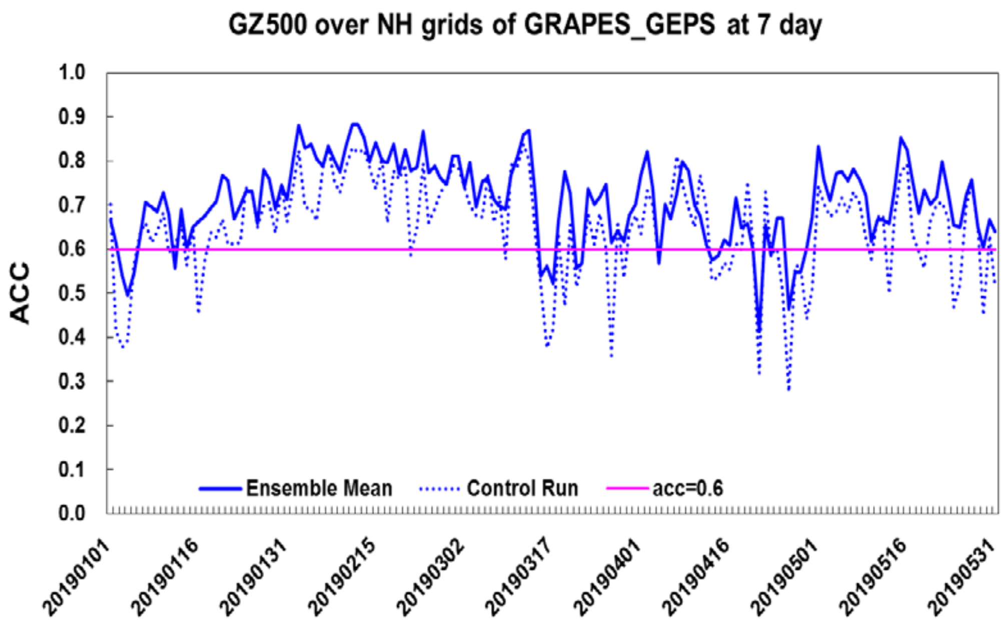








ACC of GZ500 at Day 7



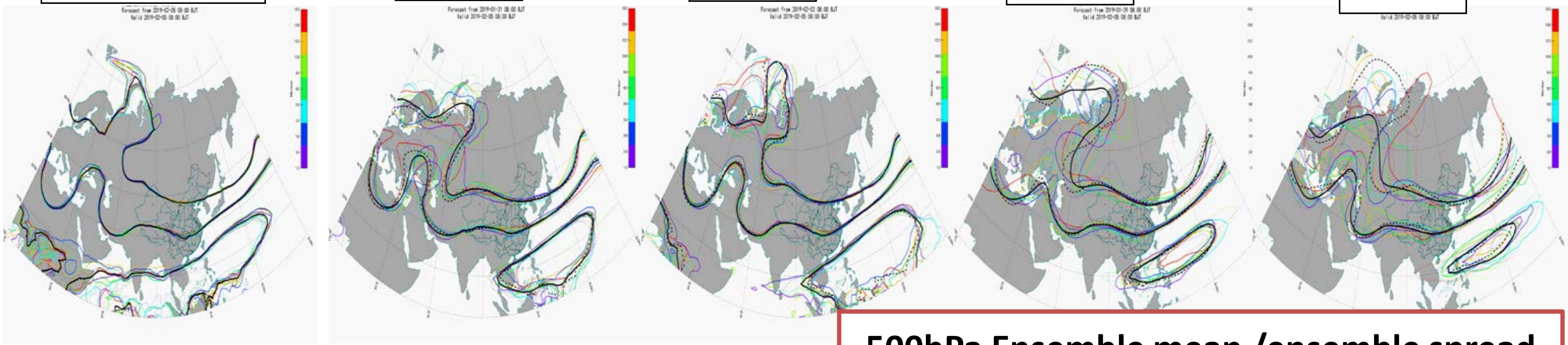
Forecast of blocking high at middle range

Example： 00 UTC 5 Feb.2019

The development Ural blocking high before breakout of cold wave

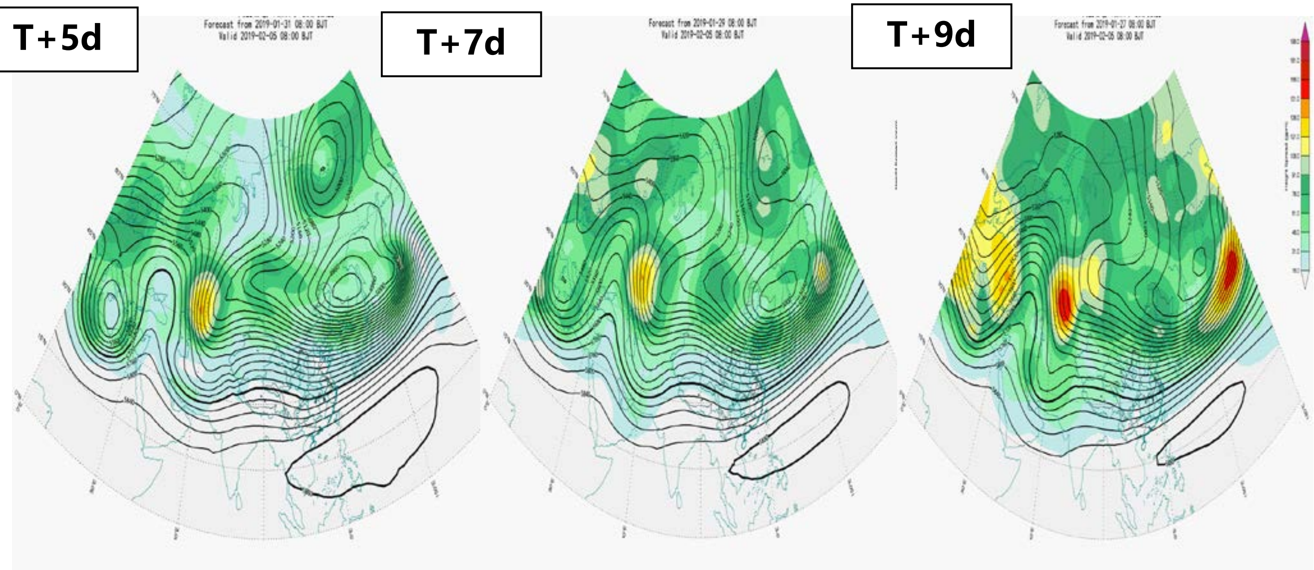
500hPa Spaghetti (5360、5680、5880)

Analyses | T+3d | T+5d | T+7d | T+9d



500hPa Ensemble mean /ensemble spread

T+5d | T+7d | T+9d

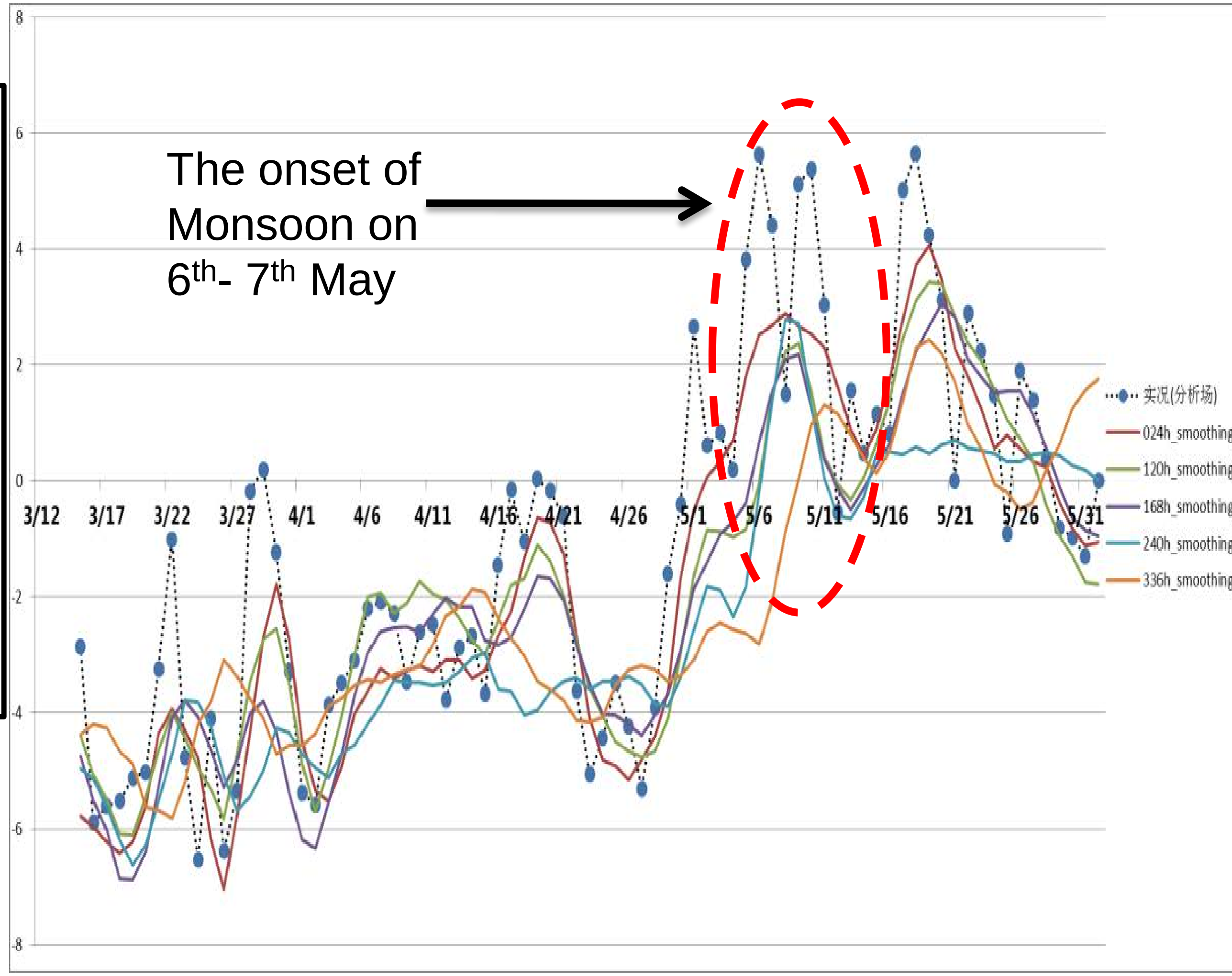


GRAPES_GEPS is able to give the useful information for the development of the Ural blocking high 7-10 days earlier

Forecast for onset of South China Sea Monsoon 2019

- The monsoon index

- Monitor Area of South China Sea monsoon 850hpa（10º-20ºN，110º-120ºE）
- 850hpa Zonal wind and pseudo-equivalent potential temperature are used as index of onset of monsoon (by National Climate Center of CMA)



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