中国气象局地球系统数值预报中心
CMA EARTH SYSTEM MODELING AND PREDICTION CENTRE

A Review of the 10 Years' Development of the CMA Global/Regional Ensemble Prediction System

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Outline

- **History**
- Methodology and performance
- Products and application
- Plans

1. Development History of CMA's Global/Regional Ensemble Forecasting(1)

CMA operational model

GRAPES (Global/Regional Assimilation PrEdiction System).

A Unified NWP system

a common dynamic core with different configurations of physics for Global and Regional applications

Four main components

Variational DAS

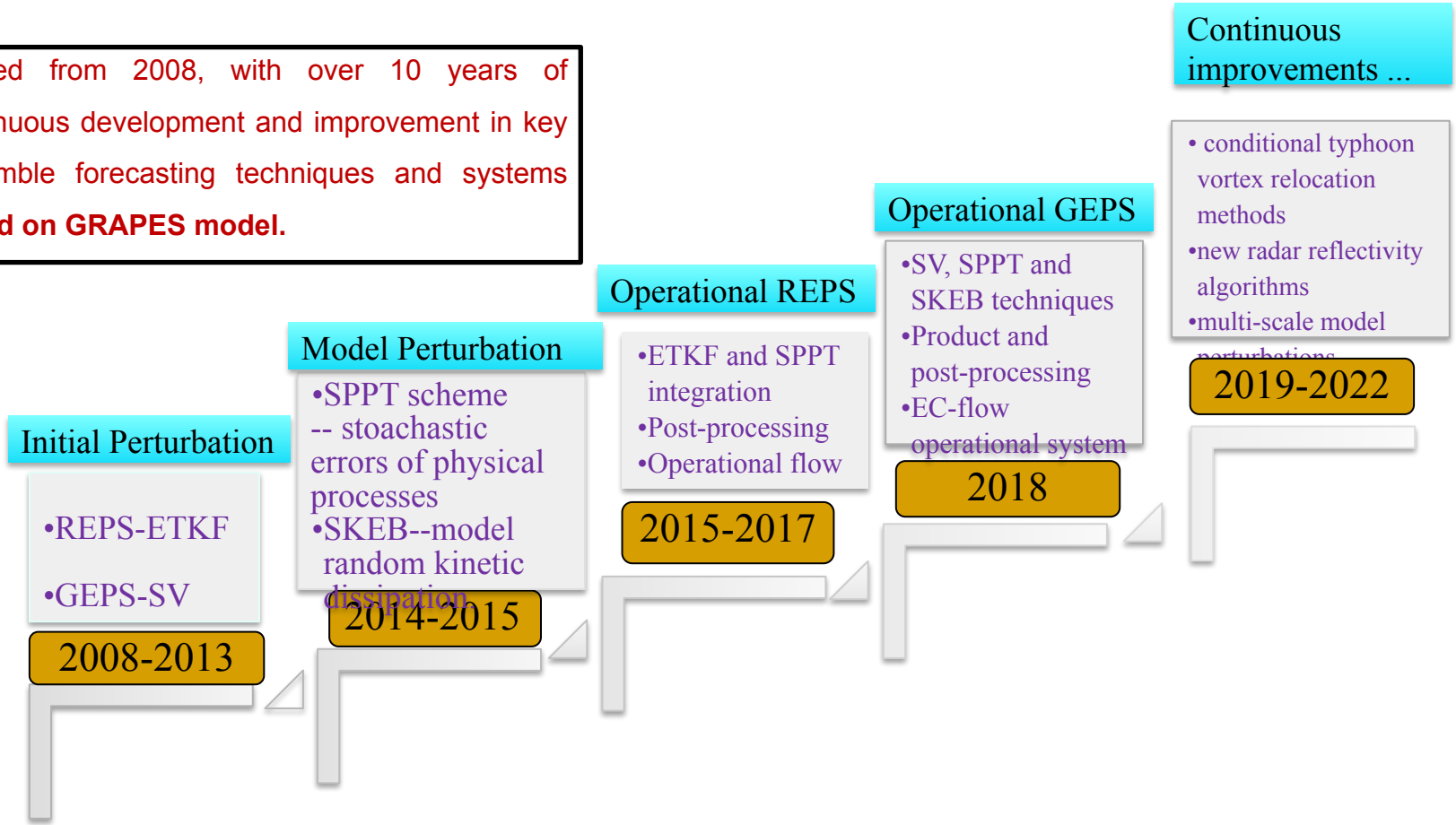
Unified dynamic core

Physical parameterization schemes

Parallel computing

1. Development History of CMA's Global/Regional Ensemble Forecasting(2)

Started from 2008, with over 10 years of continuous development and improvement in key ensemble forecasting techniques and systems **based on GRAPES model.**



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The Four Key Technologies in CMA's Ensemble Forecasting

01 Techniques for global large-scale system -singular vector initial perturbations

02 Techniques for regional mesoscale system – ETKF-based multiscale blended initial perturbations

03 Sub-grid physical process random error - SPPT and SKEB model perturbations

04 Systematic bias correction and extreme information extraction

(1) Designment of Singular Vector Initial Perturbation addressing fast-growing initial errors in Global Large-Scale Systems

• Designment of SV calculation scheme

The GRAPES Global Singular Vectors are calculated with total energy norm

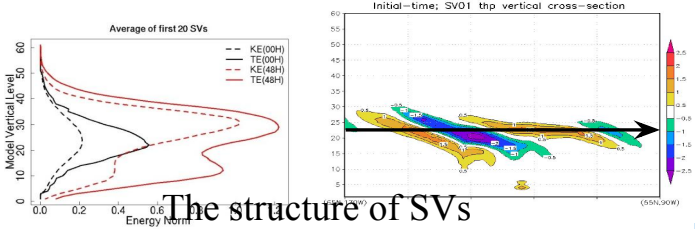
1. GRAPES SVs are calculated with the Euclidean vector $\hat{X}_i(t_0)$ through TLM($\boldsymbol{L}$) and ADM($\boldsymbol{L^T}$) :

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

2. Total energy norm E is defined as variables of TLM

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

3. The typical structures of SV at initial and final time



The structure of SVs

SV structures

1. the energy maximum of SVs is located in the middle troposphere,
2. the upward energy transfer to higher troposphere and downward energy transfer toward lower troposphere,
3. energy of SVs is westward tilt with height

•Generation of 3-D initial perturbatio

Generate 3-D initial perturbations with Gaussian sampling and rescaling technique

1. Define rescaling factor based on the analysis error

$$\boldsymbol{\beta_i} = \boldsymbol{\gamma} / \overline{\boldsymbol{f_i}}$$

2. Design pertrubastion with Gaussian sampling and linear combination

$$\boldsymbol{P_i} = \sum \boldsymbol{\alpha_{i,j}^N} . \boldsymbol{\beta_j} \ . \boldsymbol{X_j}$$

α denotes the random coefficients according to the Gaussian distribution

3.Genrating initial perturabtions with INI-SV and EVO-SV

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

Extratropic INI-SVs | Extratropic EVO-SVs | Tropical cyclones - SVs

Chen Jing *, Li Xiaoli. The review of 10 years development of GRAPES global/regional ensemble prediction system [J]. Advances in Meteorological Science and Technology, 2020,10 (02): 9-18-29(in Chinese)

(2) Developed a set of ETKF-based REPS initial perturbation methods

Account the error characteristics of observation errors and typhoon.

Ensemble Transform Kalman Filter Initial Perturbation Method (ETKF)

Principle: Rapidly estimates analysis error X_a from forecast variance X_f and observation error variance R.

$$X_i^a = X_i^f T_i C^T \Pi_i$$

$$T = C(\Gamma + I)^{-1/2} C^T$$

$$\Pi_n = \Pi_{n-1} \sqrt{\frac{\mathrm{tr}(\mathbf{d}_n \mathbf{d}_n^{\mathrm{T}}) - \mathrm{tr}(\mathbf{R})}{\mathrm{tr}(\mathbf{S}_n)}},$$

R: observation error variance

d_n: innovation vectors

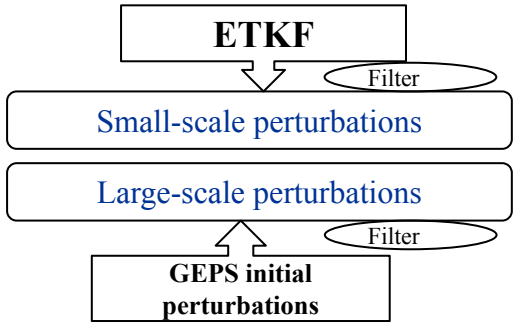
Z^f : ensemble perturbation in observation

S_n : forecast variance in observation

Multi-Scale Blended Initial Perturbation Method (MSB)

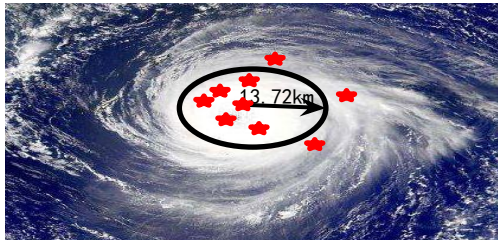
Advantage: Mixing initial errors from both global large-scale and regional meso to small-scale systems.

$$IP_{MSB} = IP_{GEPS-LS} + IP_{ETKF-SS}$$



Conditional Typhoon Vortex Relocation Technique in Ensemble Forecasting (CTVR)

Advantage: Effectively captures the location uncertainties of typhoon vortex center.



Key issues:

1. Determining the threshold for relocating the typhoon vortex center among ensemble members.
2. Mathematical process for separating the typhoon vortex.
3. Mathematical process for relocating the typhoon

Chen Jing *, Li Xiaoli. The review of 10 years development of GRAPES global/regional ensemble prediction system [J]. Advances in Meteorological Science and Technology, 2020,10 (02): 9-18-29(in Chinese)

(3) SPPT and SKEB Model Perturbation Techniques for Global and Regional EPS-Representing the growth of stochastic errors in sub-grid physical processes

Stochastic Physical Tendency Perturbation Technique (SPPT)

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

Stochastic Kinetic Energy Compensation Technique (SKEB)

$$F_\psi = \frac{\alpha \Delta x}{\Delta t} \Psi(\lambda, \varphi, t) \sqrt{\Delta t D(\lambda, \varphi, \eta, t)}$$

A space-time correlation random function $\Psi(\lambda, \phi, t)$

expansion of first-order auto-regressive process a(t) by spherical harmonic function.

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

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

$$\Psi(\lambda, \phi, t) = \mu + \left\{ 2 - \frac{1 - exp\left[\beta \left(\frac{\psi - \mu}{\Psi_{max-\mu}}\right)\right]^2}{1 - \exp(\beta)} \right\} (\psi - \mu)$$

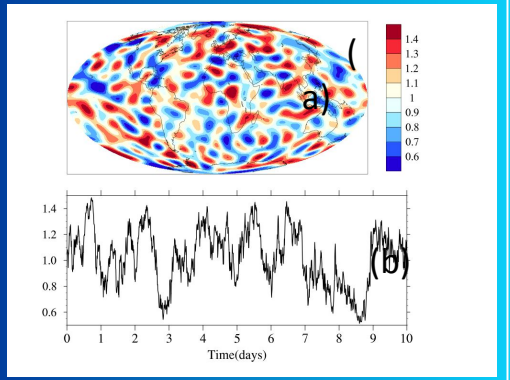
Represents the forecast uncertainty arising from model random errors.

$\Psi(\lambda, \phi, t)$

time scale correlations

spatial scale correlations

perturbation control functions



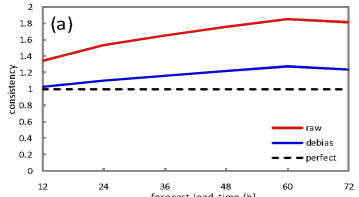
The horizontal distribution(up) and time series of the random number value at an arbitrary model grid(bottom)

9

(4) Ensemble Forecast Post-processing and Application Techniques

Focusing on the improvement of Extreme Weather Forecasting

Dynamic Correction Method by adding a bias tendency term during model integration to reduce model mean bias

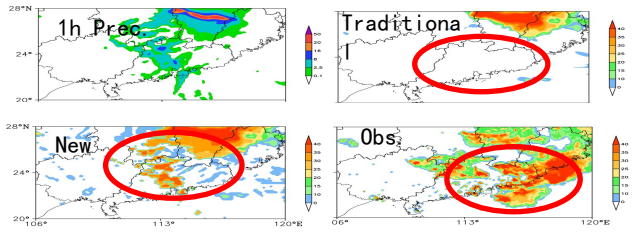


扣除系统性偏差的对比

Through linear regression, the linear bias rate is calculated. The linear bias part is then deducted during each step of the integration tendency calculation, enhancing the skill of probabilistic forecasting.

$$e(t) = \int_{t=0}^{t} \{A(e_j,t) + P(e_j,t) - \hat{B}_l(e_j)\}dt$$

New Algorithm for Radar Reflectivity of Sub-grid Convective Precipitation:



2019年4月18日00Z预报个例（16h-27h预报及实况比对）

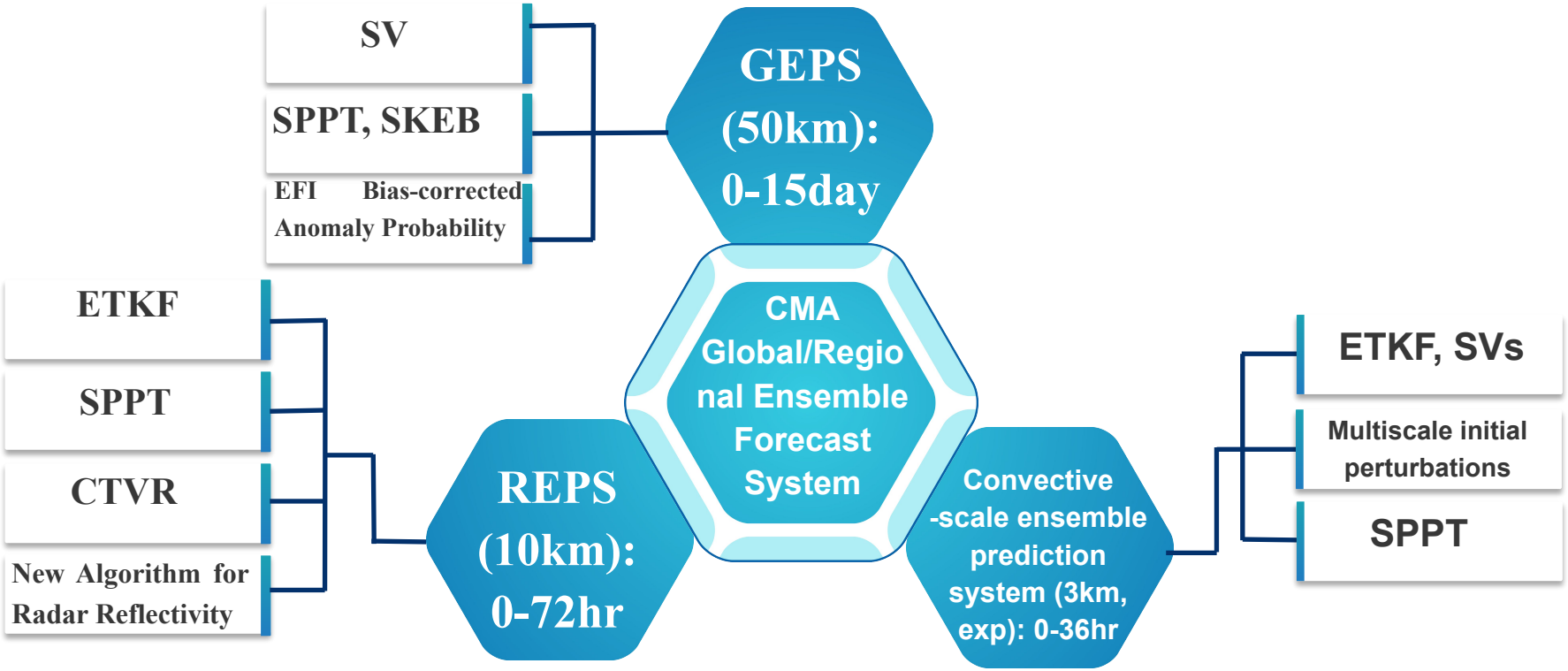
The estimation of cumulus convective precipitation is increased by subtracting the evaporation rate of the descending airflow from the cumulus convective precipitation rate. Based on the radar-estimated precipitation Z-R relationship, the radar echo is re-estimated for eac

$$Z_{new} = Z_{cu} + Z_{micro}$$

Three Types of Extreme Weather Products:

- Anomaly Probabilistic Forecasts(APF) for 500hPa geopotential height and 850hPa temperature and wind speed based on decaying average bias correction method.
- Extreme Forecast Index(EFI) for surface elements(2m temperature, 10m wind speed and precipitation with model climate produced by 2 year GRAPES-GFS model 10d forecast data).
- Probabilistic Forecasts for 2m Temperature (T2m PF) above or below a threshold with station topography calibration method

The application of key EPS approaches in CMA Global/Regional EPS



During the recent 10 years, GRAPES-based EPS experienced one to grow out of nothing and a unified multiscale ensemble prediction system spanning 0-15 days has been developed.

CMA Operational ensemble prediction system in 2023

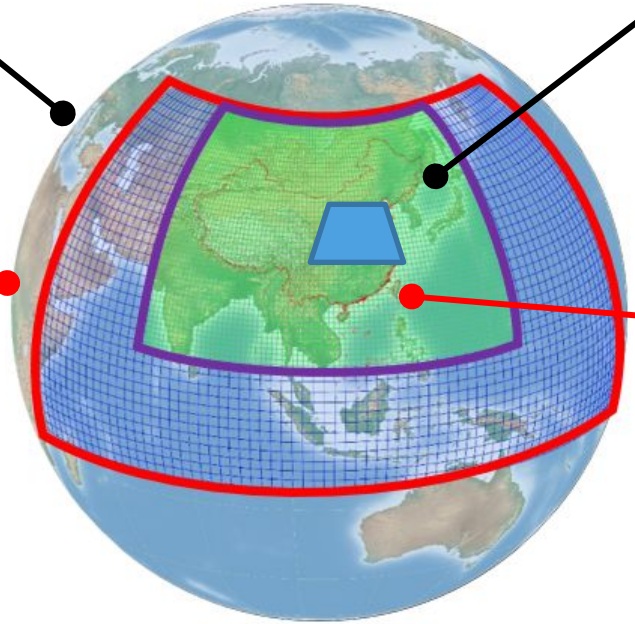
Global model:12.5km

CMA-GFS:(Global Assimilation Forecasting System)

- 87 vertical layers, the top reaches 0.1 hpa
- 12.5 km resolution
- Assimilation system 4DVAR
- 10-day forecast (00,12UTC)
- 5-day forecast (06,18UTC)
- Global Marine tropical cyclone forecast

Regional model:3 km

CMA-MESO (Regional Assimilation Prediction System)
The region of China is 3 km
It runs eight times a day, 00,12UTC forecast for the next 72 hours
Other times forecast 36 hours ahead



Global EPS:50km

CMA-GEPS:(Global Ensemble Prediction System)

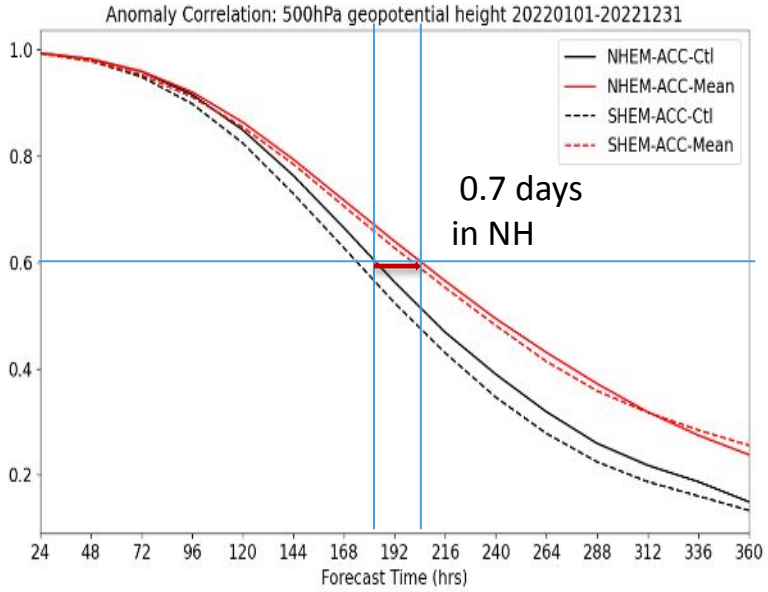
- 50 km resolution and 87 vertical layers, the top reaches 0.1 hpa
- Control forecast +30 members
- 15-day forecast (00,12UTC)

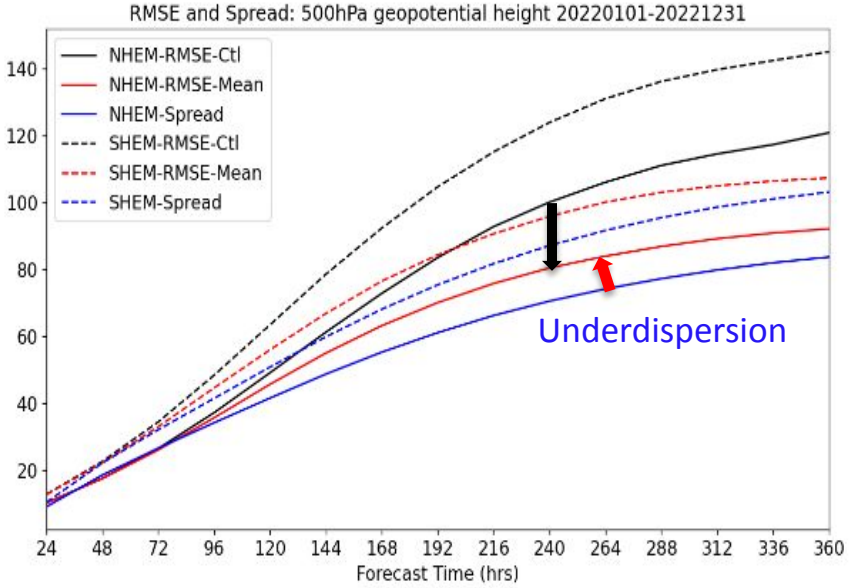
Region EPS:10km

CMA-REPS:(Regional Ensemble Prediction System)

- The region of China: 10 km resolution
- Control forecast +14 members
- 3.5 day forecast (00,12UTC)

CMA GEPS Performance in 2022





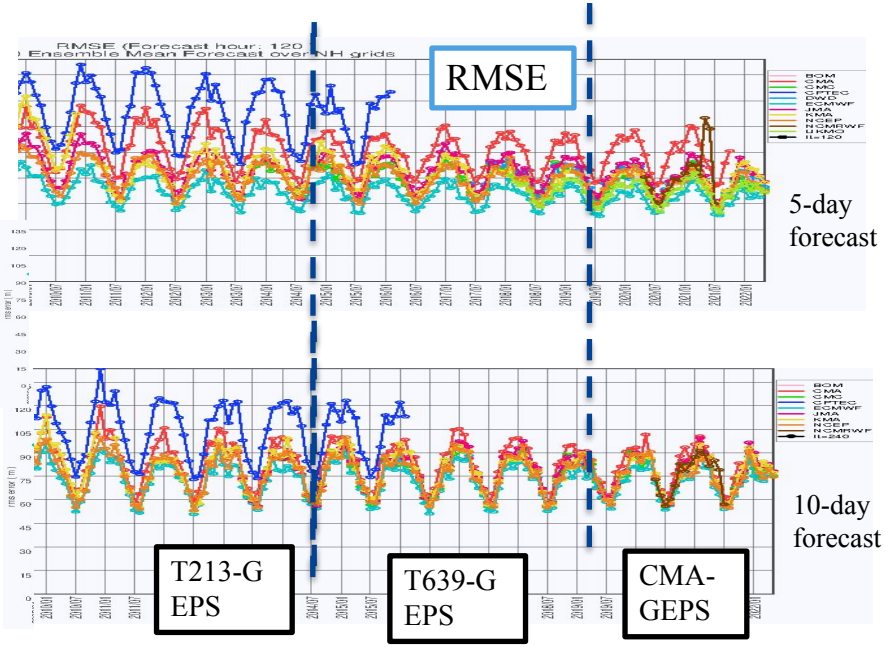
- ACC of **ensemble mean** is larger than that **of Cntl**.
- GEPS has 0.7 day gain in NH from 7.8 days to 8.5 days
- GEPS has 0.9 day gain in SH from 7.3 days to 8.4 days

- The RMSE of NH decrease from about **100 gpm of Cntl** to **80gpm of Ensembel mean**.
- Some underdispersions from the relationship between **RMSE(solid red line)** and **Spread(solid blue line)**

A comparison of CMA ensemble prediction systems with other NWP centers

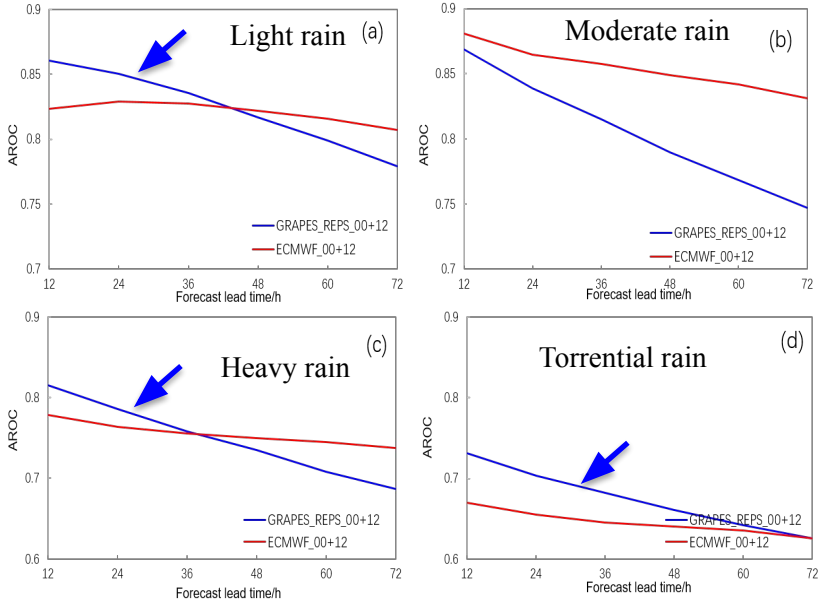
RMSE of 500hPa Geopotential Height over NH at 5-day(up) and 10-day(bottom) ensemble mean forecast

(Cited from the Japan Meteorological Agency, WMO Global EPS verification leading Center)



The 10-day forecast errors of the NWP centers are convergence

AROC scores of precipitation forecast for CMA-REPS and ECMWF in July-September, 2019-2020



AROC scores of the light rain, heavy rain, torrential rain in the first 36-48 hours is better than that of ECMWF EPS.

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CMA global/regional ensemble forecast products

Type	Global ensemble elements (0-15 days)
Ensemble spread and RMSE	500 Hpa geopotentic altitude, 850 hpa temperature, 700 hpa relative humidity, 850 Hpa relative humidity, mean sea level pressure, 2 m temperature, 10 m total wind speed, 24 hours accumulated precipitation (total 8 types)
Rank probability	24 hours accumulated precipitation, 10 m full wind speed (2 types)
Stamp map	24 hours accumulated precipitation(1 type)
The maximum of ensemble member	24 hours accumulated precipitation(1 type)
The mode of ensemble member	24 hours accumulated precipitation(1 type)
Single point box diagram	Ground elements with 6h interval（1 type）
Typhoon attack probability and track	Typhoon attack probability, ensemble member typhoon track（2 types）
Extreme weather prediction index	24 hours accumulated precipitation, 2 m temperature ,10 m full wind speed （3 types）
Probability of 2m temperature correction by terrain	2 m temperature(1 type)
Bias correction anomaly probability of circulation situation	Daily anomaly probability of 500hPa height and 850hP temperature, 3-day moving average anomaly probability, 5-day moving average anomaly probability, and 10-day moving average anomaly probability（8 types）
Noodle (spgt) plot	500 hpa geopotential(1 types)
Total product category	29 types

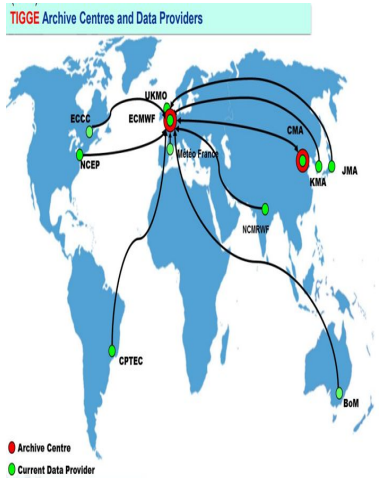
Type	The elements of Chinese Region elements (0-3 days)
Ensemble spread and RMSE	Mean sea level pressure, 2 m temperature, combined radar reflectivity, convective effective potential energy, convective suppression, optimal uplift index, 0-1/0-3/0-6 km vertical wind cut, sinking convective effective potential energy, hail index, K index, 3/6/12/24 hours accumulated precipitation and 10 m total wind speed (total 17 types)
Rank probability	Combined radar reflectivity, convective effective potential energy, convective rejection, optimal uplift index, 0-1/0-3/0-6 km vertical wind cut, sinking convective effective potential energy, hail index, K index, 3/6/12/24 hours accumulated precipitation and 10 m total wind speed (total 15)(15 types)
Stamp map	3/6/12/24 hours accumulated precipitation, combined radar reflectivity (total 5 types)
The maximum of ensemble member	3/6/12/24 hours accumulated precipitation (4 types)
The mode of ensemble member	3/6/12/24 hours accumulated precipitation (4 types)
Single point box diagram	Ground elements with 1h interval（1 type）
Typhoon track	Landing typhoon track and landfall (30 type)
Smoke plume map	Typhoon landing Time and minimum Pressure, Typhoon Landing time and maximum wind speed (2 types)
Total product category	78 types

29 types GEPS and 78types REPS products are distributing to national, regional and provincial weather offices.

Application (1)

Provided to WMO TIGGE archive center, WMC (Beijing) and SWFDP web

From 2019, GRAPES-based GEPS provide data to TIGGE archive Center



The Global Ensemble Prediction System provides the core support for WMC (Beijing)

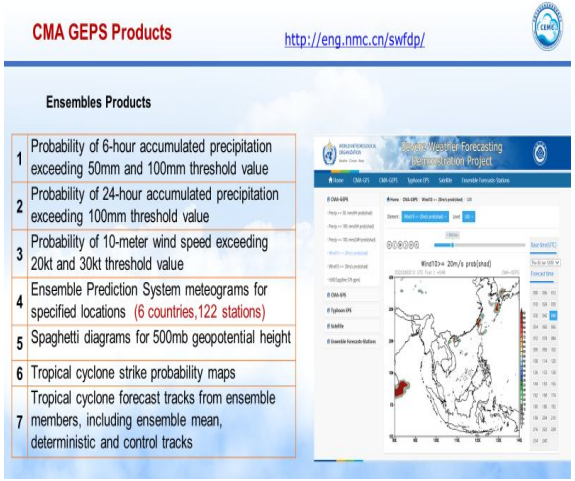
May 2017
The 69th Annual Meeting of the World Meteorological Organization

hina Meteorological Administration cognized the world meteorological center

To become a world meteorological center, you must have at least three functions:
Operation of autonomous global Deterministic numerical prediction system Operation of autonomous global aggregate numerical prediction systemOperation of the autonomous Global Long-range Forecasting System

The CMA Global Ensemble Forecast System becomes the core support of the World Meteorological Center (Beijing)

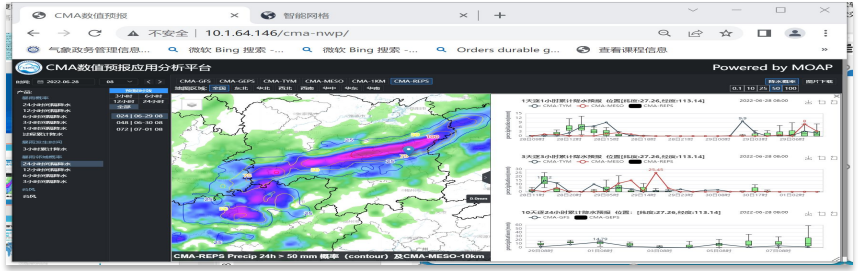
Support WMO SWFDPSeA web products



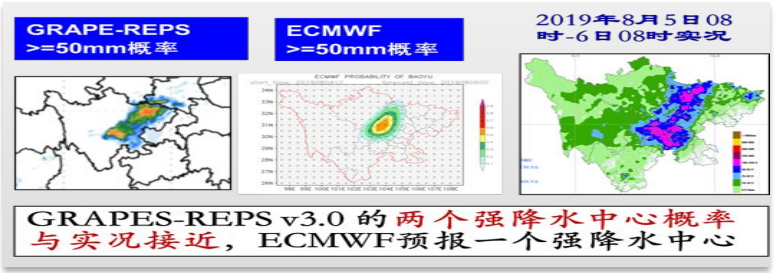
Application (2) :

Global/regional ensemble forecast products are used in daily weather forecast and services

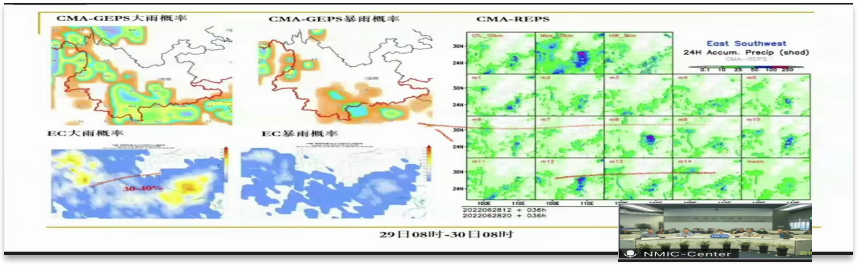
Weather business Intranet collection forecast product display

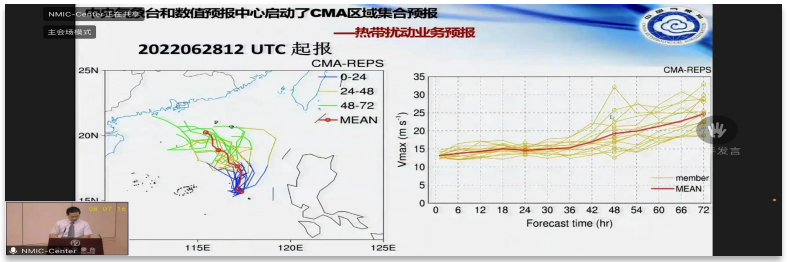


Sichuan 2019.8.5 rainstorm process application



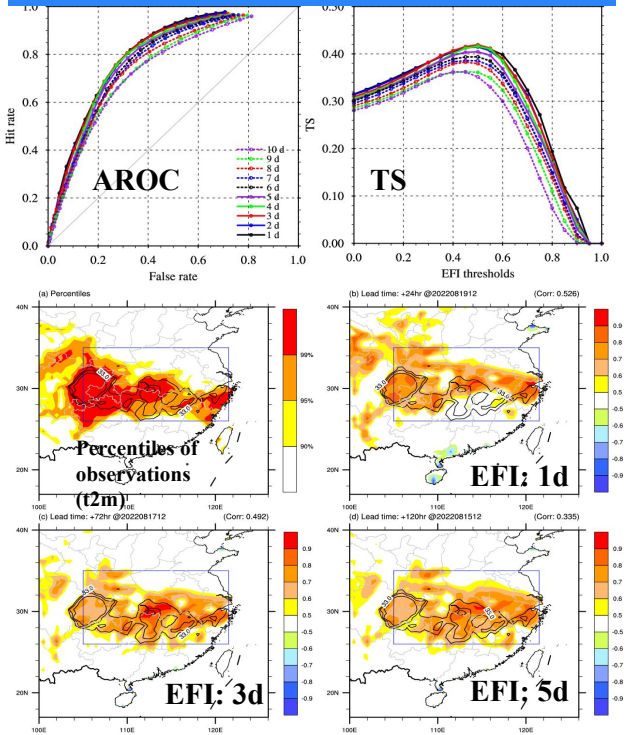
Forecasters used CMA ensemble forecast products in National Weather Forecast Discussion





The performance of EFI of T2m temperature forecast for extreme heat wave in China and Southern Europe in the summer of 2022

The middle and lower reaches of the Yangtze River

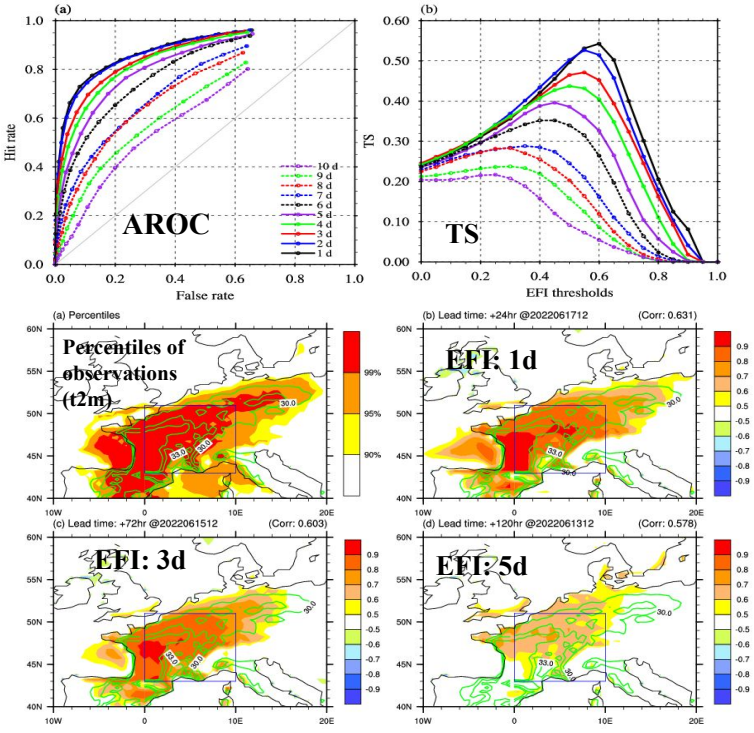


- 2m temperature (ERA5, contour line) on August 20, 2022 and EFI spatial distribution (shaded)

AROC and TS scores show the skillful forecast

EFI at 1 , 3 and 5 day leading time are similar to obs.

Southwest Europe



- 2m temperature (ERA5, contour line) on June 25, 2022 EFI spatial distribution (Shaded)

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Plans

For operational system before 2025

- To upgrade global medium-range EPS system from 50km to 25km resolution.
- To establish a Convective-Allowing EPS system over China with 3km resolution and 10-15 members.

For Initial perturbation scheme

- To develop a unified Global/Regional multi-scale SVs together with observation perturbations.

Thank You

Acknowledge to the Ensemble Forecasting Team from CEMC for prepairing the materials.