The typhoon model of Tropical Region Atmospheric Model System (CMA-TRAMS): development and evaluation

Shui-xin Zhong

zhongshuixin@126.com

Guangzhou Institute of Tropical and Marine Meteorology, CMA

Outline

1 Overview of TRAMS model

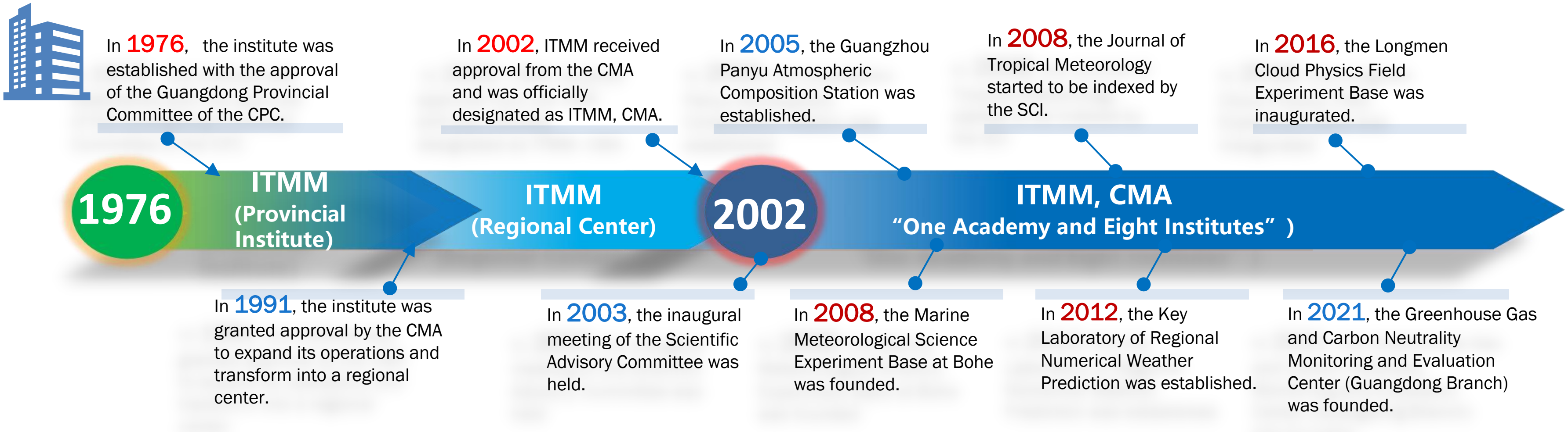
2 Technical development

3 Operational performance

4 Future plan

Overview Guangzhou Institute of Tropical and Marine Meteorology

- Since its establishment in 1976, the Guangzhou **Institute of Tropical and Marine Meteorology (ITMM)** has undergone 47 years of remarkable development.
- **Science directions: experimental observation** and the underlying **mechanisms** of tropical meteorology, regional **numerical modeling**, and tropical **environmental meteorology**.



Overview

Key Laboratory of Regional Numerical Weather Prediction

Academician Qingcun Zeng, recipient of the International Meteorological Prize (IMO) and the National Top Science and Technology Award of China, serves as the director of the academic committee.

Jointed LAB of Regional NWP

Group photo

Key technologies in dynamic core, physical scheme, data assimilation, and ensemble forecasting have been independently developed for the regional NWP models over tropics.

Dynamic core (1)
- 3D Reference Scheme
- Predictor-Corrector Scheme

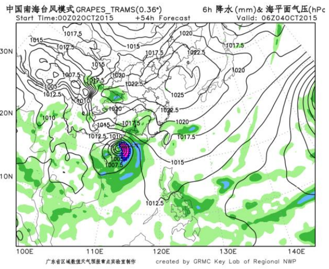
Physical scheme (2)
- Scale-Aware Cumulus Parameterization
- Tropical Convection Parameterization

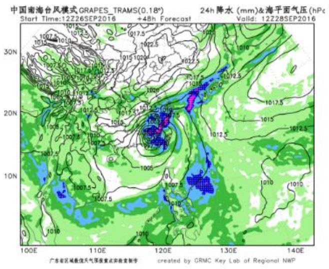
Data assimilation (3)
- X- Band Phased- Array Radar Data
- MOTOR-DA

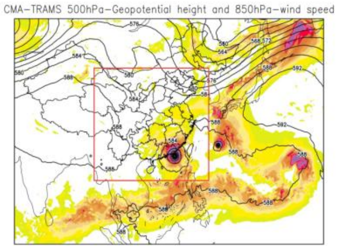
Ensemble forecasting (4)
- Mesoscale EPS for TC Forecasting
- Convection-Permitting ensemble

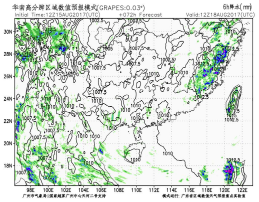
Overview of TRAMS model – Historical development

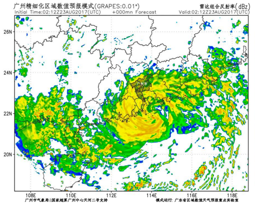
- ◆ CMA-TRAMS has been upgraded to version 3.0 with the horizontal resolution at 9 km since 2017;
- ◆ The 9-3-1 NWP system has been established since 2017 with the first 1km operation model in China.

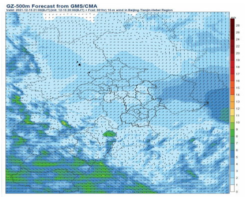










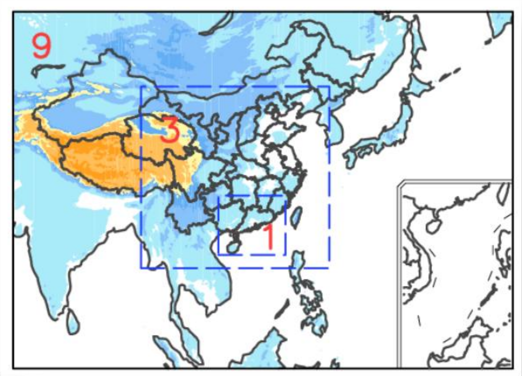


36km	18km	9km	3km	1km	500m
00,12UTC 5days	00,12UTC 7days	00,12UTC 7days 06,18UTC 3days	hourly 24hours	12 minutes 6 hours	2022 Beijing Winter Olympic Games

2009 — 2016 — 2017 — 2018 — 2020 — 2022

Overview of TRAMS model

- CMA-TRAMS (9km) mainly focuses on typhoon forecasting over the Western Pacific Region; TRAMS 3km and 1km are designed for the rainfall and short-range forecast.
- The model is running based on the High Performance computer system: The National Supercomputer Center in Guangzhou Tianhe-2;
- The model is developed by the key Laboratory of Regional Numerical Weather Prediction which is jointly established by CMA and Guangdong Province;



The domain of the CMA-TRAMS model

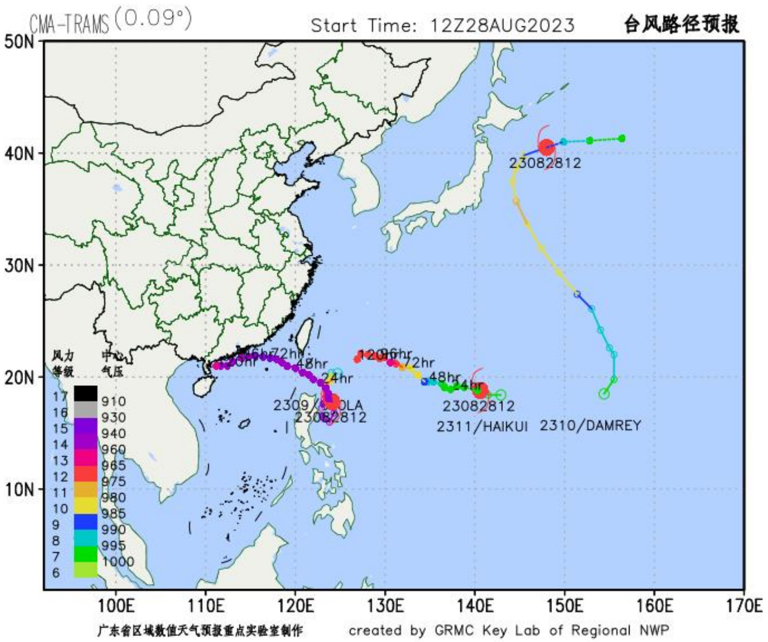
Guangzhou TIANHE-2

The platform of the Lab

Overview of TRAMS model – TRAMS-9km

◆ **TRAMS-9km** is a **typhoon model**, which provides 7 days forecasting of typhoon path, typhoon intensity, as well as large-scale environmental prediction(precipitation, wind and temperature).

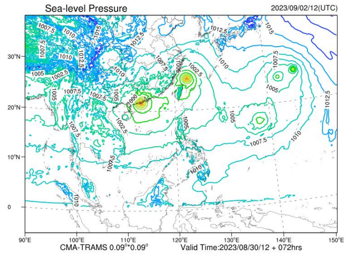
- **~ 9.0 km resolution**
- **cloud Nudging +Land-surface analysis**
- **65 levels, top at 31 km**
- **X*Y=1001*601, Δt = 90 s**
- **4 forecasts/1D**
  - **LST: 08, 20→ T+168h**
  - **LST: 14, 02→ T+72h**
- **Convection： scale-aware NSAS**
- **MicroPhys： WSM6**
- **PBL: NMRF**
- **GWDO: KA95**



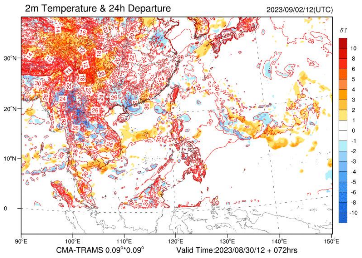
typhoon path forecasting by TRAMS-9km

Overview of TRAMS model – TRAMS-9km

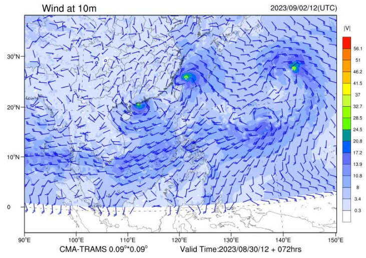
◆ **The menu of TRAMS-9km** products can be customized for the weather forecasters, e.g., the typhoon path, typhoon intensity, geo-potential height, precipitation, wind and temperature.



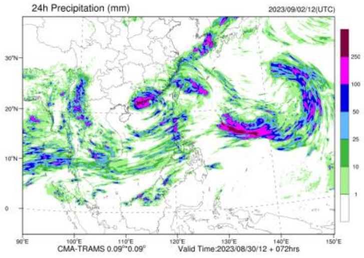
Sea-level pressure



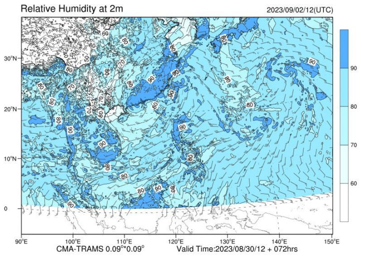
2m Temperature & 24h departure



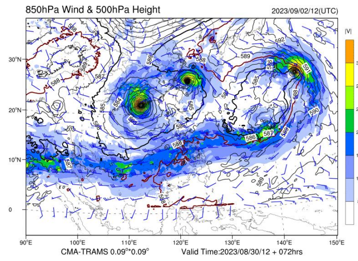
10m Wind



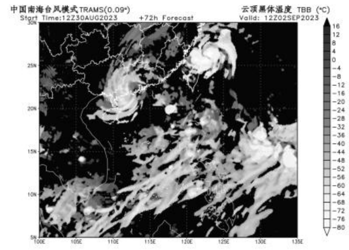
24h precipitation



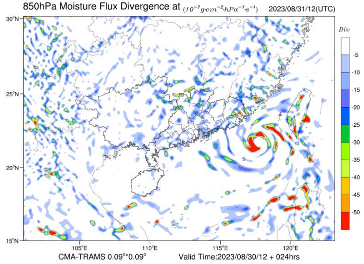
Relative humidity



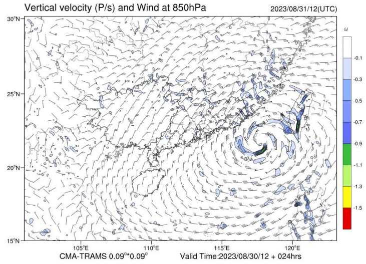
850hPa wind



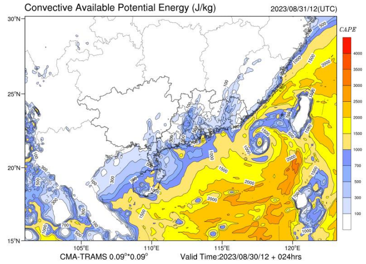
TBB (cloud-top blackbody temperature)



850 moisture flux divergence



Vertical velocity

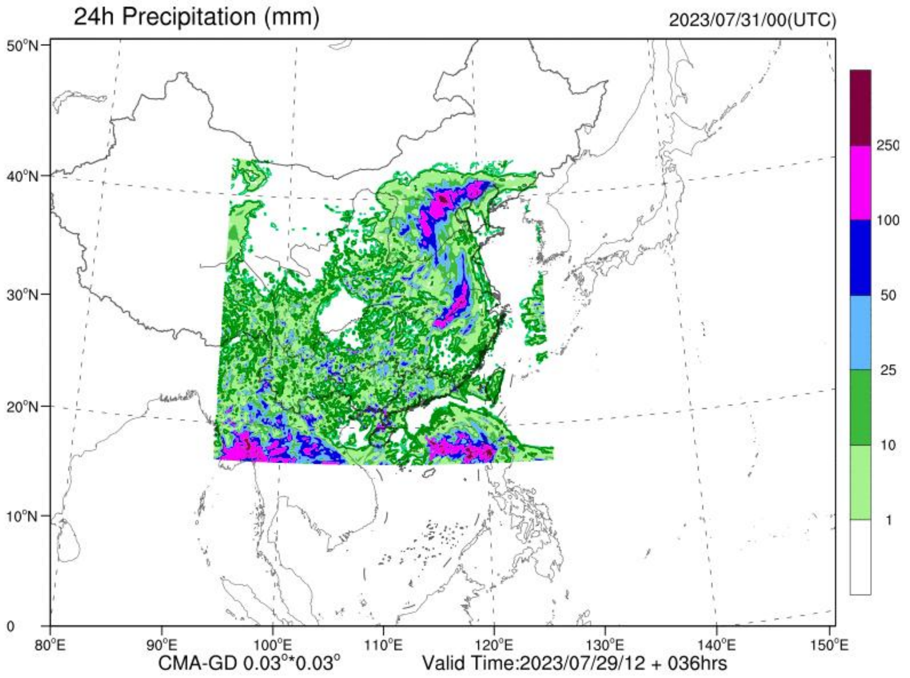


Convective available potential energy

Overview of TRAMS model – TRAMS-3km

◆ **TRAMS-3km** is a **regional model**, which provides 4 days forecasting of regular weather elements, especially for precipitation, wind and temperature forecasting.

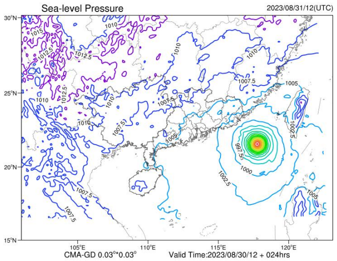
- **~ 3.0 km resolution**
- **cloud Nudging + Land-surface analysis**
- **65 levels, top at 31 km**
- **X*Y=1131*917**
- **2 forecasts/1D**
    - **00z, 12z→ T+96h**
- **Δt = 50 s**
- **Convection： scale-aware NSAS**
- **MicroPhys： WSM6**



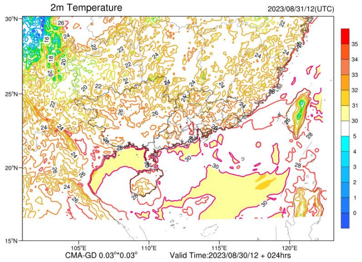
24h accumulative rainfall forecasting by TRAMS-3km

Overview of TRAMS model – TRAMS-3km

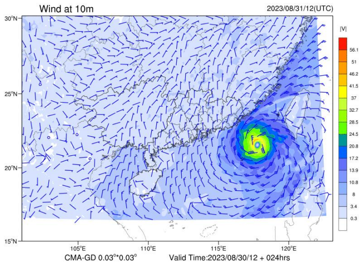
◆ **The menu of TRAMS-3km** products can be customized for the weather forecasters, e.g., Radar Reflectivity，geo-potential height, precipitation, wind and temperature.



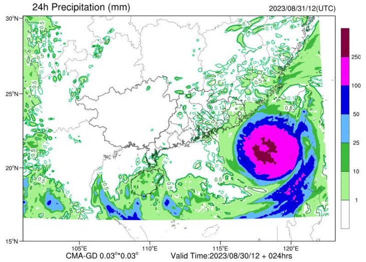
Sea-level pressure



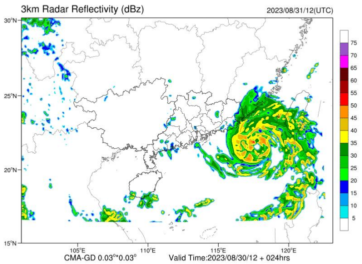
2m Temperature & 24h departure



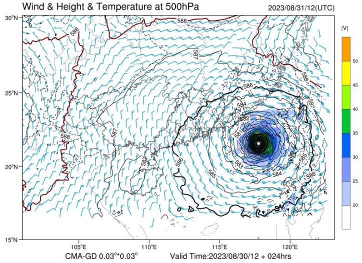
10m Wind



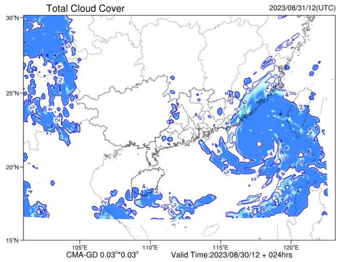
24h precipitation



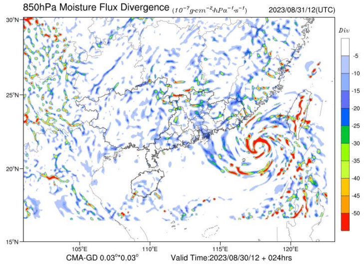
Radar Reflectivity



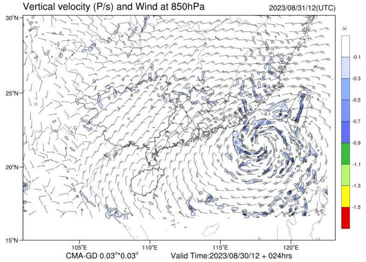
500hPa wind & height



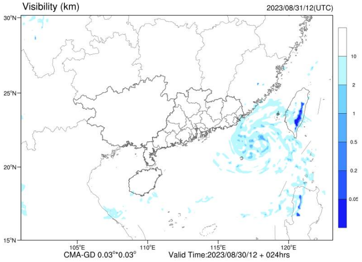
Total cloud cover



850 moisture flux divergence



Vertical velocity

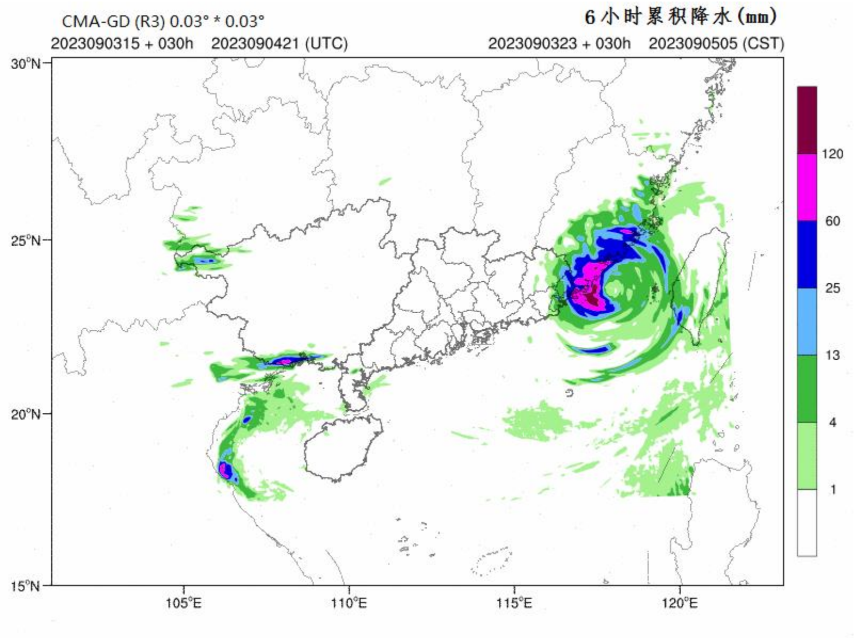


Visibility

Overview of TRAMS model – RUC-3km

◆ **RUC-3km** is a **hourly rapid update cycling model**, which initializes provides 30 hours for **short-range weather forecasting.**

- **~ 3.0 km resolution**
- **cloud Nudging +Land-surface analysis**
- **65 levels, top at 31 km**
- **Domain coverage: 96-123.39° E;16-31.39° N**
- **hourly forecasts/T+30h**
- **Δt = 50 s**
- **Convection： scale-aware NSAS**
- **MicroPhys： WSM6**

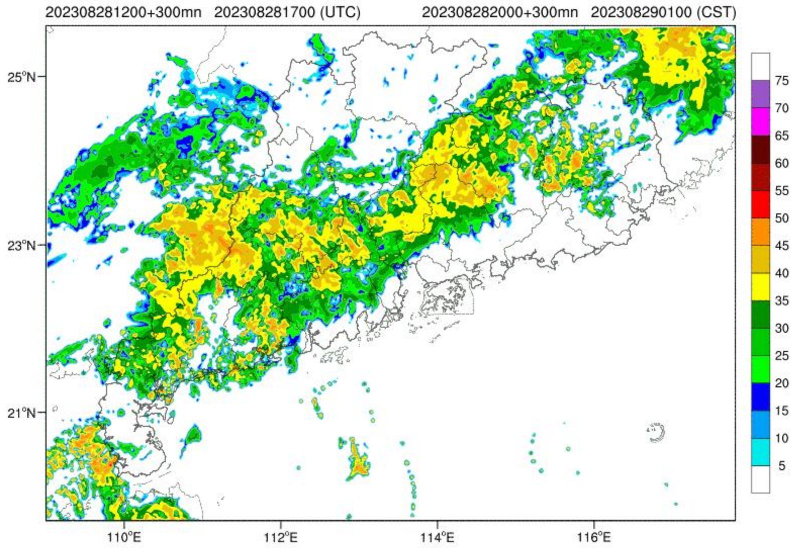


6h accumulative rainfall forecasting by TRAMS-3km

Overview of TRAMS model – TRAMS-1km

◆ **TRAMS-1km** is a **rapid update cycling model**, which initializes for every 12 minutes and provides 6 hours for **short-range weather forecasting.**

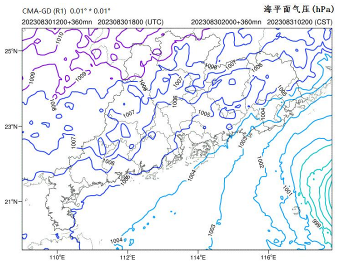
- **~ 1.0 km resolution**
- **Radar data nudging**
- **65 levels, top at 31 km**
- **X*Y=1201*901**
- **5 forecasts/1h**
  - ➢ **00min, 12min,… → T+6h**
- **Δt = 30 s**
- **Convection :not used**



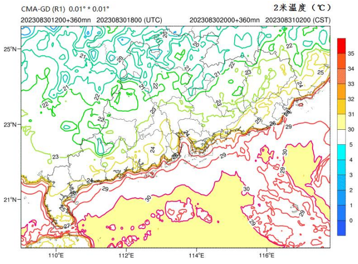
Radar reflectivity forecasting by TRAMS-1km

Overview of TRAMS model – TRAMS-1km

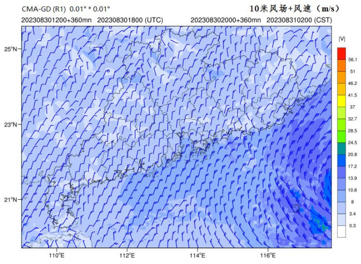
◆ **The menu of TRAMS-1km** products can be customized for the weather forecasters, e.g., hourly precipitation, radar reflectivity, wind and temperature.



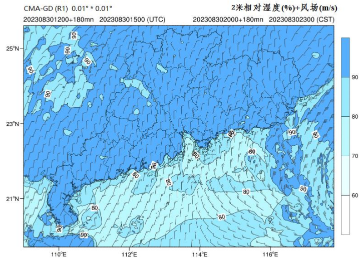
Sea-level pressure



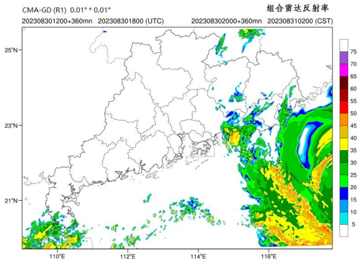
2m Temperature & 24h departure



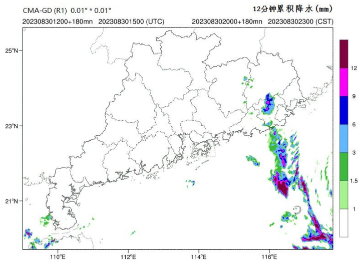
10m Wind



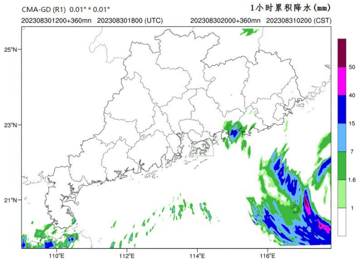
Relative humidity



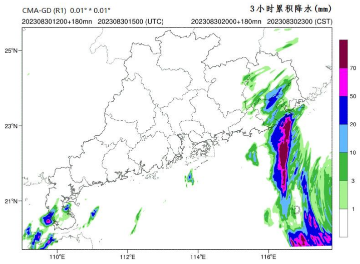
Radar Reflectivity



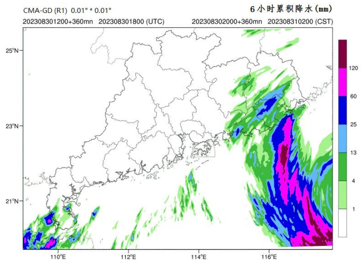
12min precipitation



1h precipitation



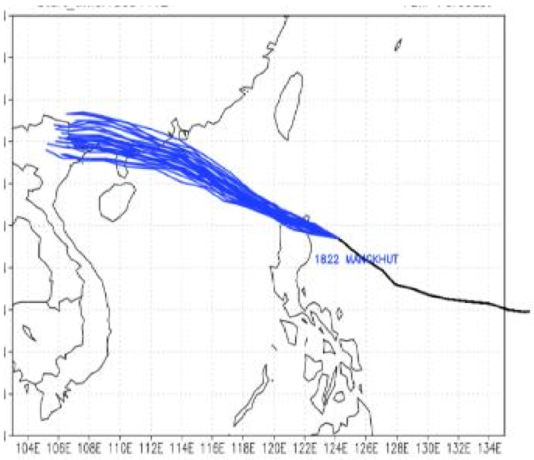
3h precipitation



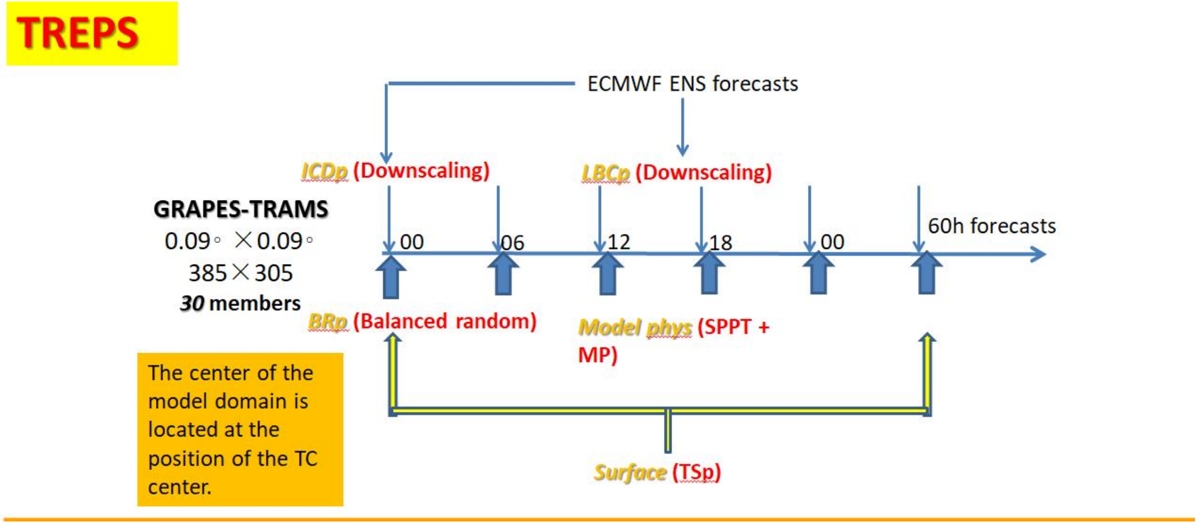
6h precipitation

Overview of TRAMS model – Ensemble forecasting

- A regional ensemble forecasting system based on TRAMS(CMA-TRAMS EPS) was running in operation with 30 members.
- Developed different perturbation techniques by considering scale characteristics and nonlinear interactions.
- Develop the "combination of multi-source and multi type disturbances" ensemble disturbance technology based on the understanding of disturbance multi-scale interactions.



TREPS forecast of Super Typhoon Mangkhut in 2018



Design of TREPS

Outline

1 Overview of TRAMS model

2 Technical development

3 Operational performance

4 Future plan

Technical development – model upgrade

◆ TRAMS has been upgraded to version 3 since 2019, which including the model dynamics, model physics, data assimilation.

TRAMS-V1.0: 1) Typhoon model(36km) 2) Regional model (9km)	TRAMS-V2.0: 1) Typhoon model (18km) 2) Regional model (3km)	TRAMS-V3.0 : 1) Typhoon model: **9km** 2) Regional model :**3km** 3) Regional model :**1km**
• Dynamics : Fully Compressible-Nonhydrostatic , Semi-Implicit Semi-Lagranian(SISL) difference scheme, • 1-D Isothermal Hydrostatic Reference Atmosphere, Charney-Philip grid, (Horizontal) Isometric Lat-Lon Coordinate & Arakawa-C grid, • implicit weighting factor=0.70.	• Dynamics upgrading: • SISL → Iterative SISL difference scheme; • 1-D Isothermal Hydrostatic Reference Atmosphere → 3-D Hydrostatic Reference Atmosphere • implicit weighting factor 0.70→0.55.	• Dynamics upgrading: • →new Iterative SISL difference scheme; • →new 3-D Hydrostatic Reference Atmosphere • Adding new assistive scheme like • 4th order horizontal diffusion and weak w_damping,
• Physics: Microphysics(WSM6), • Long-Wave&Short-Wave Radiation(RRTM), Surface Layer(M-O similarity theory), • Boundary layer(MRF), • Land Surface(SLAB), Cumulus • Convection(SAS).	• Physics upgrading: • Boundary layer(MRF→NMRF), • Land Surface(SLAB→SMS), • Cumulus Convection(TY:SAS→NSAS; MESO:SAS).	• Physics upgrading: Microphysics(WSM6→New WSM6), • Long-Wave&Short Wave Radiation(RRTM→RRTMG), • Surface Layer(imporved SFCLAY), • Land Surface(SMS,LAND SF ANALYSIS), • Cumulus Convection(scaleaware SAS).

Upgrade of TRAMS model

Technical development – Model Dynamics

- Three-dimensional (3D) 3D static atmospheric reference
- Step by step calculation of nonlinear terms
- Lagrangian advection correction
- Coupling Scheme of Physical and Dynamic Processes
- High order precision central difference scheme with non-uniform grids
- A New Algorithm for 3D Lagrangian Vector Projection
- A second-order precision vertical difference scheme under non-uniform layering
- Heating term of continuous equation and influence of water substance

Technical development –3D static atmospheric reference

- The 3D static atmospheric reference method greatly reduces non-static equilibrium disturbances, which is beneficial for reducing model prediction errors, especially in complex terrain areas.
- The scheme has been adopted into CMA-GFS V3.0 for the new model dynamics.

$$\Pi(\lambda,\varphi,z,t)=\tilde{\Pi}(\lambda,\varphi,z)+\Pi'(\lambda,\varphi,z,t) \quad (2\text{-}1\text{-}8)$$

$$\theta(\lambda,\varphi,z,t)=\tilde{\theta}(\lambda,\varphi,z)+\theta'(\lambda,\varphi,z,t) \quad (2\text{-}1\text{-}9)$$

$$T(\lambda,\varphi,z,t)=\tilde{T}(\lambda,\varphi,z)+T'(\lambda,\varphi,z,t) \quad (2\text{-}1\text{-}10)$$

Divide the model atmosphere into two parts that satisfy static equilibrium and its deviation

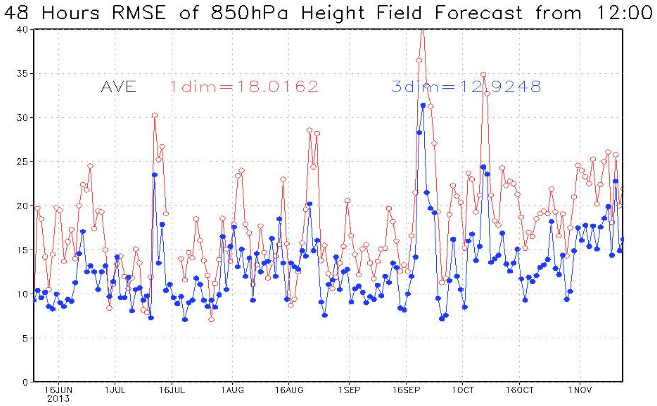
$$\frac{du}{dt}=-\frac{C_p\theta}{a\cos\varphi}\frac{\partial\Pi'}{\partial\lambda}-\frac{C_p\theta}{a\cos\varphi}\frac{\partial\tilde{\Pi}}{\partial\lambda}+fv+F_u+\delta_M G_u-\delta_\varphi f_\varphi w\cdots$$

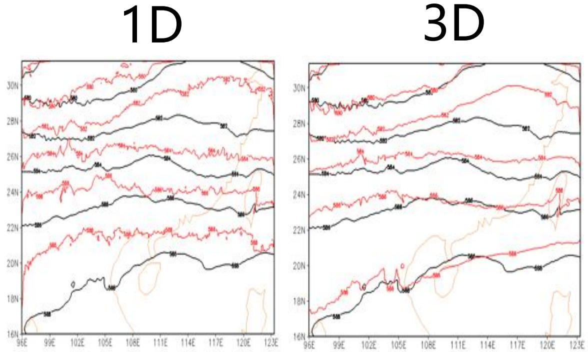
$$\frac{dv}{dt}=-\frac{C_p\theta}{a}\frac{\partial\Pi'}{\partial\varphi}-\frac{C_p\theta}{a}\frac{\partial\tilde{\Pi}}{\partial\varphi}-fu+F_v-\delta_M G_v\cdots$$

$$\delta_{NH}\frac{dw}{dt}=-C_p\theta\frac{\partial\Pi'}{\partial z}-C_p\theta'\frac{\partial\tilde{\Pi}}{\partial z}+F_w+\delta_M G_w+\delta_\varphi f_\varphi u\cdots$$

$$\frac{d\Pi'}{dt}=-\frac{d\tilde{\Pi}}{dt}-\frac{\Pi}{(\gamma-1)}D_3+\frac{F_e^*}{(\gamma-1)\theta} \quad (2\text{-}1\text{-}14)$$

$$\frac{d\theta'}{dt}=-\frac{d\tilde{\theta}}{dt}+\frac{F_\theta^*}{\Pi} \quad (2\text{-}1\text{-}15)$$

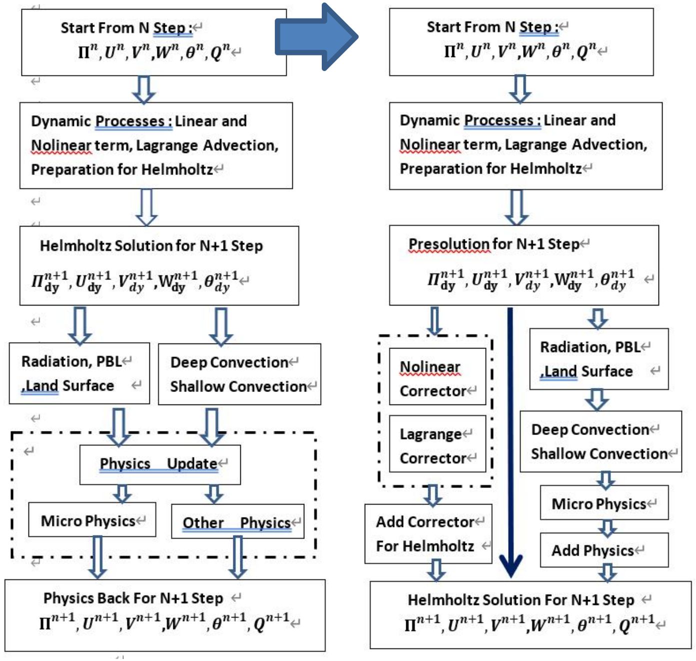


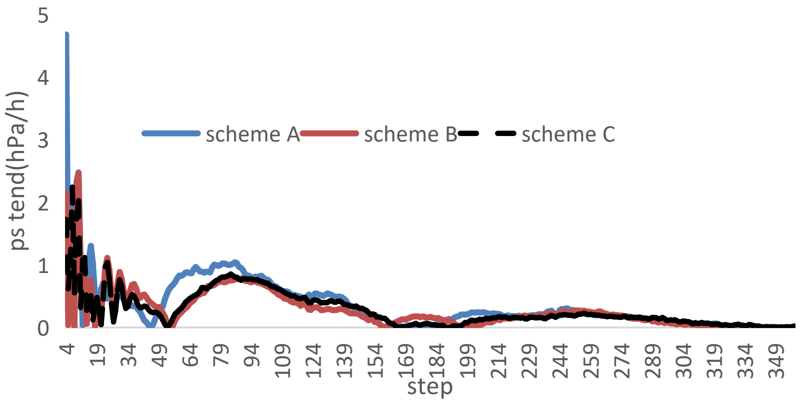


Comparison of 24-hour forecast for geopotential height(500hPa)
(red line: forecast; black line: analysis of the field)

Technical development –coupling between dynamic and Physics

- By Using the estimation correction method and considering the effect of hydrothermal physical feedback on the continuous equation, **the physical feedback of n+1 time step is used as a prediction increment to participate in solving the Helmholtz equation**, forming a coupling between physical and dynamic processes, and improving the overall prediction performance of the model





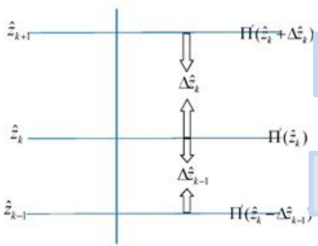
The initial integrated pressure increment of the model is smaller in the disturbance amplitude of the new scheme B compared to the original scheme A, which is beneficial for improving the accuracy of model.

Technical development –high-order precision differential schemes

- The ideal experiments were conducted for vertical direction with a 2nd order and a horizontal 4th order differential schemes to improve the accuracy of the model.

Table 1 Difference Schemes with 2nd、4th and 6th order accuracy

	First derivative	Second derivative
Second order	$\frac{f_{i+1}-f_{i-1}}{2\Delta x}$	$\frac{f_{i-1}-2f_i+f_{i+1}}{\Delta x^2}$
fourth order	$\frac{f_{i-2}-8f_{i-1}+8f_{i+1}-f_{i+2}}{12\Delta x}$	$\frac{-f_{i-2}+16f_{i-1}-30f_i+16f_{i+1}-f_{i+2}}{12\Delta x^2}$
sixth order	$\frac{-f_{i-3}+9f_{i-2}-45f_{i-1}+45f_{i+1}-9f_{i+2}+f_{i+3}}{60\Delta x}$	$\frac{-2f_{i-3}+27f_{i-2}-270f_{i-1}+490f_i-270f_{i+1}+27f_{i+2}-2f_{i+3}}{180\Delta x^2}$



1st order

$$\frac{\partial\Pi'(\hat{z}_k)}{\partial\hat{z}}=\frac{\Pi'(\hat{z}_k+\Delta\hat{z}_k)-\Pi'(\hat{z}_k-\Delta\hat{z}_{k-1})}{\Delta\hat{z}_k+\Delta\hat{z}_{k-1}}$$

2nd order

$$\frac{\partial\Pi'(\hat{z}_k)}{\partial\hat{z}}=\frac{1}{\Delta\hat{z}_k+\Delta\hat{z}_{k-1}}\left[\frac{\Delta\hat{z}_{k-1}}{\Delta\hat{z}_k}\Pi'(\hat{z}_k+\Delta\hat{z}_k)-\frac{\Delta\hat{z}_k}{\Delta\hat{z}_{k-1}}\Pi'(\hat{z}_k-\Delta\hat{z}_{k-1})\right]+\frac{\Delta\hat{z}_{k-1}-\Delta\hat{z}_k}{\Delta\hat{z}_{k-1}\Delta\hat{z}_k}\Pi'(\hat{z}_k)$$

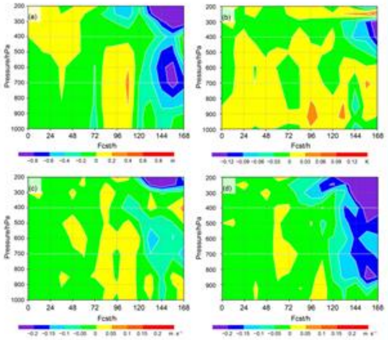
$$u^{n+1}=(\xi_{u1}\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}+\xi_{u2}\frac{1}{a}\frac{\partial}{\partial\varphi}+\xi_{u3}\frac{\partial}{\partial\hat{z}})\Pi'+\xi_{u0}, \quad (1)$$

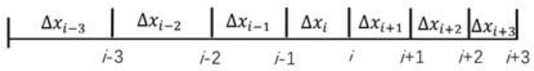
$$v^{n+1}=(\xi_{v1}\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}+\xi_{v2}\frac{1}{a}\frac{\partial}{\partial\varphi}+\xi_{v3}\frac{\partial}{\partial\hat{z}})\Pi'+\xi_{v0}, \quad (2)$$

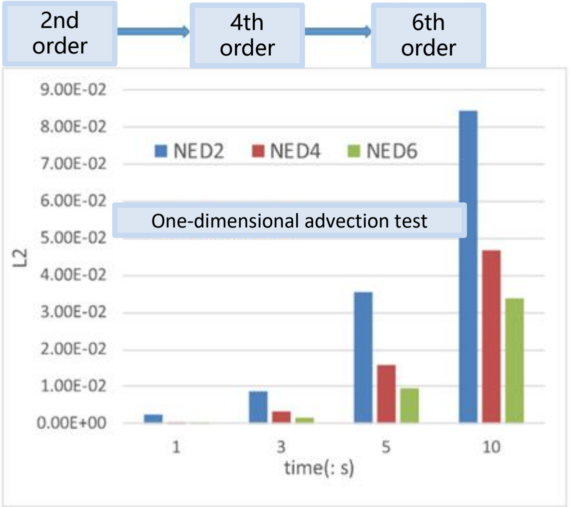
$$\hat{w}^{n+1}=(\xi_{w1}\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}+\xi_{w2}\frac{1}{a}\frac{\partial}{\partial\varphi}+\xi_{w3}\frac{\partial}{\partial\hat{z}})\Pi'+\xi_{w0}, \quad (3)$$

$$\theta'^{n+1}=(\xi_{th1}\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}+\xi_{th2}\frac{1}{a}\frac{\partial}{\partial\varphi}+\xi_{th3}\frac{\partial}{\partial\hat{z}})\Pi'+\xi_{th0}, \quad (4)$$

$$\Pi'^{n+1}=\xi_{\Pi 1}u^{n+1}+\xi_{\Pi 2}v^{n+1}+\xi_{\Pi 3}\hat{w}^{n+1}+\xi_{\Pi}\frac{\partial D_3}{\partial\hat{z}}+A_{\Pi}, \quad (5)$$







Technical development – Lagrangian 3D vector projection

- The Lagrangian 3D vector projection technology is developed to improve model calculation efficiency with significant reduction in computational complexity.

$$A_u = \Delta t \alpha_\varepsilon (\overline{N}_u)^n + (Y_u)^n_* \cos(\lambda - \lambda_*) + (Y_v)^n_* \sin\varphi_* \sin(\lambda - \lambda_*)$$
$$- (Y_w)^n_* \cos(\varphi_*) \sin(\lambda - \lambda_*)$$

$$A_v = \Delta t \alpha_\varepsilon (\overline{N}_v)^n + (Y_u)^n_* \sin\varphi \sin(\lambda - \lambda_*) + (Y_v)^n_* (\cos\varphi \cos\varphi_* + \sin\varphi \sin\varphi_* \cos(\lambda - \lambda_*))$$
$$+ (Y_w)^n_* (\cos\varphi \sin\varphi_* - \sin\varphi \cos\varphi_* \cos(\lambda - \lambda_*))$$

$$A_w = \Delta t \alpha_\varepsilon (\overline{N}_w)^n + (Y_u)^n_* \cos\varphi \sin(\lambda - \lambda_*) + (Y_v)^n_* (\sin\varphi \cos\varphi_* - \cos\varphi \sin\varphi_* \cos(\lambda - \lambda_*))$$
$$+ (Y_w)^n_* (\sin\varphi \sin\varphi_* + \cos\varphi \cos\varphi_* \cos(\lambda - \lambda_*))$$

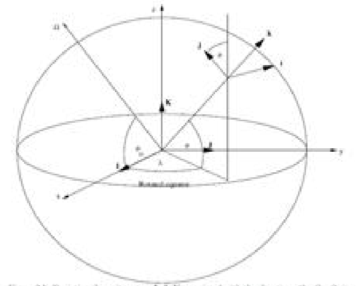


Figure 2.5: Depicting the unit vectors I, J, K associated with the directions Ox, Oy, Oz in the rotated system, and the unit vectors i, j, k associated with the zonal, meridional and

The improvement scheme refers to the approach of UK-MET, which uniformly projects the unit vectors of all arrival and departure points onto a fixed unit vector at the center of the sphere. The improved scheme has the same accuracy as the original scheme, but the computational complexity is significantly reduced.

Technical development – Model physics

- The TRAMS model has been upgraded and developed, forming a set of high-resolution model physics solutions suitable for the tropical region(subgrid orographic parameterization, ocean boundary layer, land surface model, etc.)

TRAMS-V1.0 → **TRAMS-V2.0** → **TRAMS-V3.0** → **TRAMS-V4.0**

TRAMS-V1.0

"36-12km"

- Cumulus Convection Scheme (SAS)
- Microphysical scheme (wsm6)
- radiation (RRTM&SWRAD)
- Near surface (MOST)
- Land surface (SLAB)
- PBL scheme (MRF)

TRAMS-V2.0

"18-9-3km"

- **New SAS scheme**
- Microphysical scheme (wsm6)
- Radiation (RRTM&SWRAD)
- **Improved drag coefficient**
- Land surface (SLAB)
- **New MRF scheme (NMRF)**
- **Subgrid orographic gravity wave drag scheme**

TRAMS-V3.0

"9-3-1km"

- **NSAS with mass flux limitation**
- WSM6 upgrade
- Radiation (RRTM&SWRAD)
- Near-surface flux parameterization
- Land surface (**SMS**)
- **SST parameterization**
- New MRF scheme (NMRF)
- Subgrid orographic gravity wave drag scheme

TRAMS-V4.0

"9-3-1-500m"

- AI+ Microphysical
- Near-surface flux
- **Land surface (SMS)**
- **SST parameterization**
- New MRF scheme (NMRF)
- **3D PBL scheme**
- **SST parameterization**
- Subgrid orographic gravity wave drag scheme

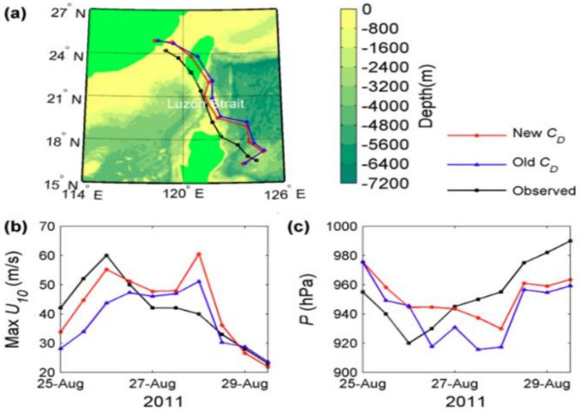
Technical development – PBL scheme

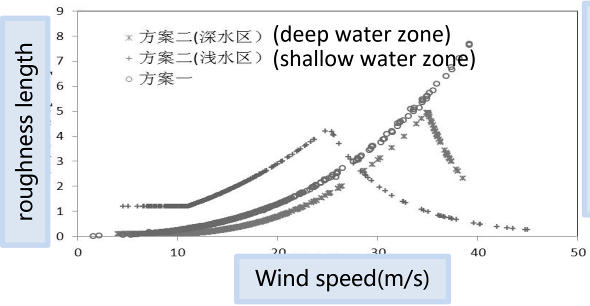
- Based on the observation data of the Bohe Ocean Meteorological Observation Platform, the following relationship between drag coefficient (CD) based on the water depth (d) and wind speed (U10) by using the method of function fitting statistics:

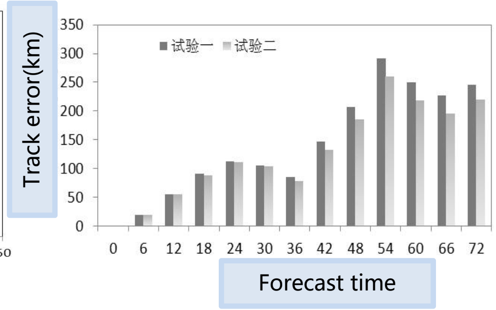
$$1000\times C_D=\max\left\{\frac{\hbar}{b+\tanh\left(\frac{gd}{u_{c\infty}^2}\right)^b},\ \frac{\exp\left[-\frac{(U_{10}-u_{ref})^2}{gd}\right]}{\tanh\left(\frac{gd}{u_{c\infty}^2}\right)^b}(p(1)\tilde{u}^2+p(2)\tilde{u}+p(3))\right\},$$

Convert the drag coefficient to roughness (z0):

$$1000\times z_0=\begin{cases}15.6\frac{u_*^2}{g}+10^{-2} & U_{10}<35ms^{-1}\\ 2.82 & U_{10}\geq 35ms^{-1}\end{cases}$$





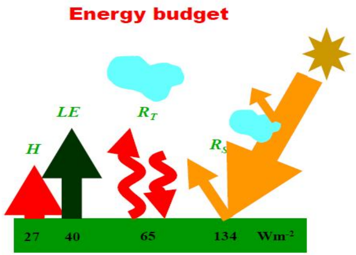


The improved Cd scheme has significantly improved the typhoon path and intensity forecast.

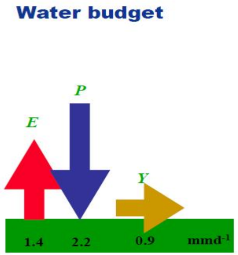
Zhao Z K, Liu C X, Li Q, et al. 2015. Typhoon air-sea drag coefficient in coastal regions. Journal of Geophysical Research: Oceans, 120,716-727.

Technical development – Land surface scheme

- **The prediction of soil moisture plays an important role in land surface processes. The coupling of land surface and boundary layer fluxes was implemented to improve the prediction of near-surface elements.**
- **A simplified land surface solution has been developed, which considers the daily changes in shallow soil moisture prediction and thin layer soil bottom temperature, which can improve the high sensible heat flux and virtual high latent heat.**



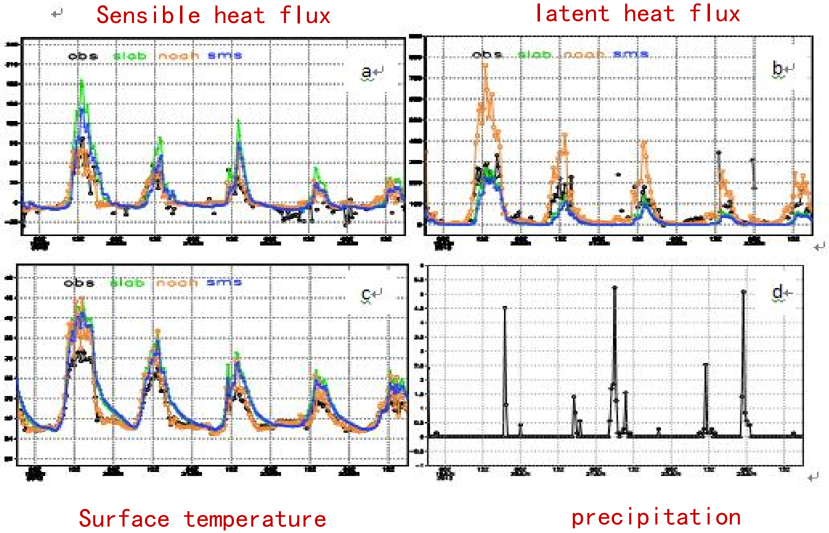
$$(\rho C)D\frac{\partial T_s}{\partial t} = R_n + LE + H + G$$



$$\frac{\partial S}{\partial t} = P + E + R$$

With S (water storage: accounting for soil moisture and snow

Using the forced recovery method to calculate the daily variation of bottom temperature of thin soil layers can simplify soil heat balance.



Technical development – Subgrid orographic parameterization

◆ A subgrid orographic parameterization scheme was proposed to consider the near-surface wind field feedback, and add momentum deposition term in the momentum balance equation.

$$\boldsymbol{A}\boldsymbol{M}_{\mathrm{v}} = \boldsymbol{F}_{\mathrm{sd}}. \quad (1)$$

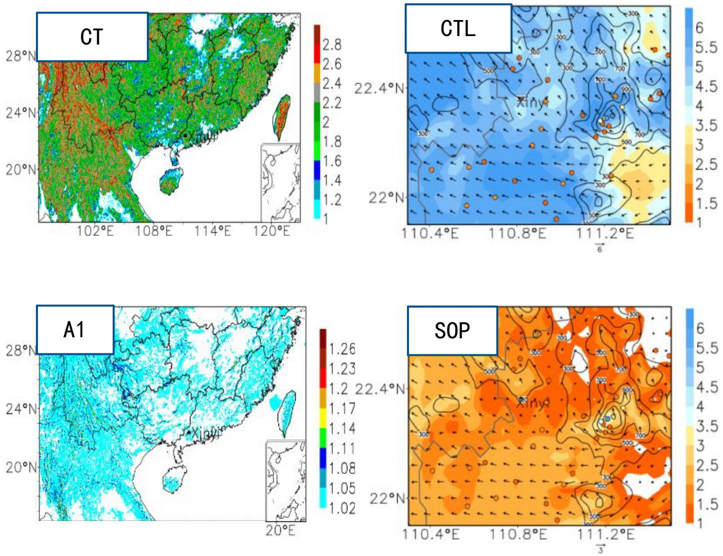
The vector of momentum tendency $\boldsymbol{M}_{\mathrm{v}}$ is solved using the matrix $\boldsymbol{A}$ and forcing $\boldsymbol{F}_{\mathrm{sd}}$, where the main diagonal of $\boldsymbol{A}$ on the first model level is defined as A_1:

$$A_1 = (1 + \delta_1); \quad (2)$$

$$\delta_1 = 2c_t \rho g \frac{u_*^2}{S\Delta z} dt. \quad (3)$$

Here, the subscript "1" stands for the first model level, ρ is the air density, g is the acceleration due to gravity, δ_1 represents the sink term, S is the wind speed at the first model level, u_* is the friction velocity, and Δz is the thickness of the first model layer. c_t is a function of $\Delta^2 h'_{i,j}$ and the standard deviation σ'_{sso}:

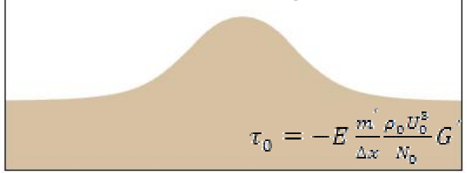
$$c_t = \begin{cases} 1, \Delta^2 h'_{i,j} > -20,\ \sigma'_{sso} < e \\ \ln \sigma'_{sso}, -10 < \Delta^2 h'_{i,j},\ \sigma'_{sso} > e \\ \alpha \ln \sigma'_{sso} + (1-\alpha'), -10 > \Delta^2 h'_{i,j} > -20, \alpha \\ \frac{\Delta^2 h' + 30}{10}, -20 > \Delta^2 h'_{i,j} > -30 \\ 0, \Delta^2 h'_{i,j} < -30 \end{cases}$$



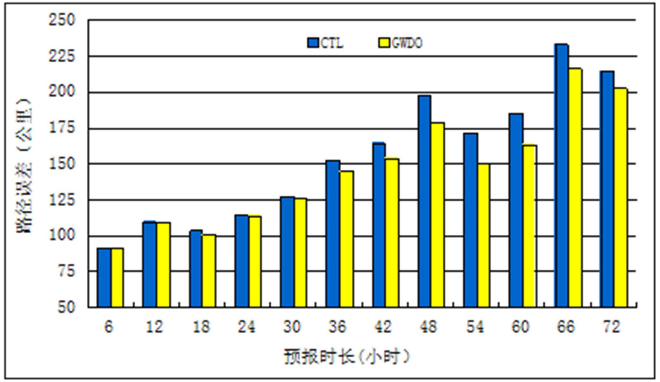
The new scheme significantly reduces the overestimation of low-level wind speed

Technical development – orographic gravtity wave drag parameterization

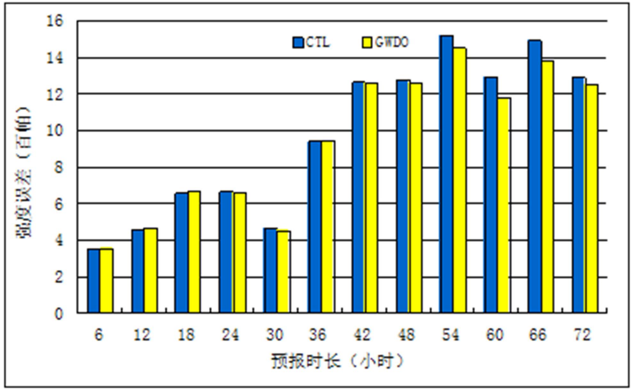
Kinetic energy>potential energy, airflow goes over the mountain and generate GWD



- The subgrid **orographic gravtity wave drag parameterization** scheme has been implemented in TRAMS model.
- **GWD** parameterization has **effectively improved the overall performance of TRAMS for typhoon forecasting.**



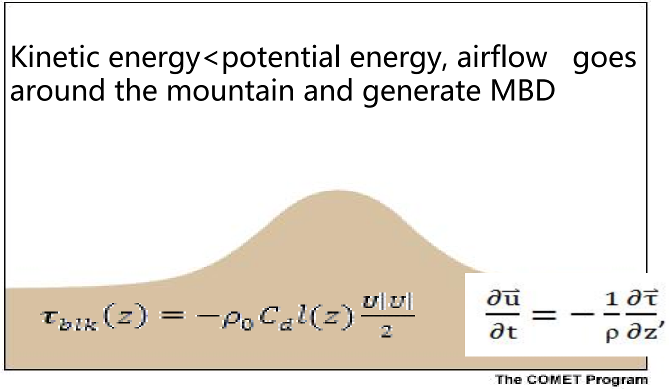
track error



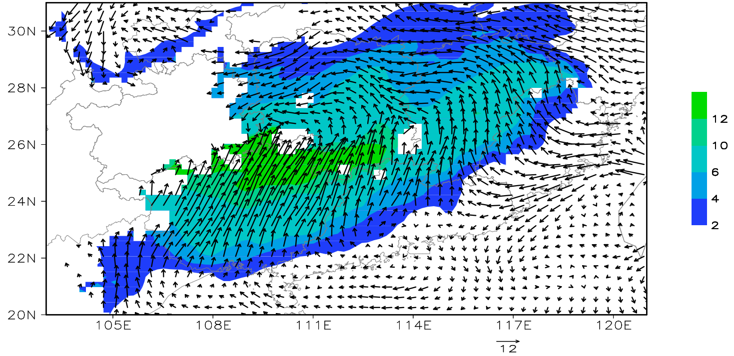
intensity error

The mean error comparison between CTL and GWDO experiment of 9 landing typhoons

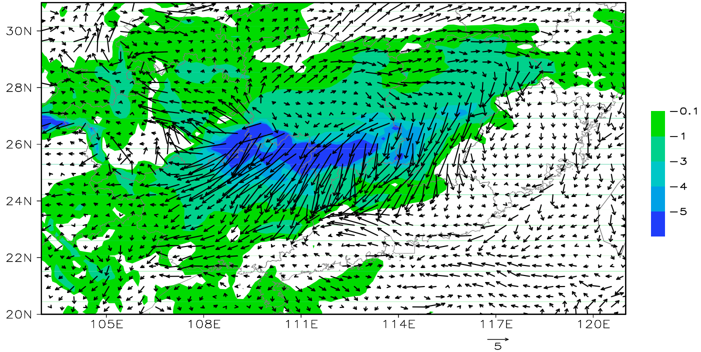
Technical development – Mountain blocking drag parameterization



- The subgrid Mountain blocking drag **parameterization** scheme has been implemented in TRAMS model.
- MBD has effectively improved the simulation of low-level southerly winds and high surface temperatures in winter and spring, which alleviated the southerly bias and weakened the excessive temperature deviation caused by strong southerly winds in the operational forecasting.



CTL(48hr)-ANA

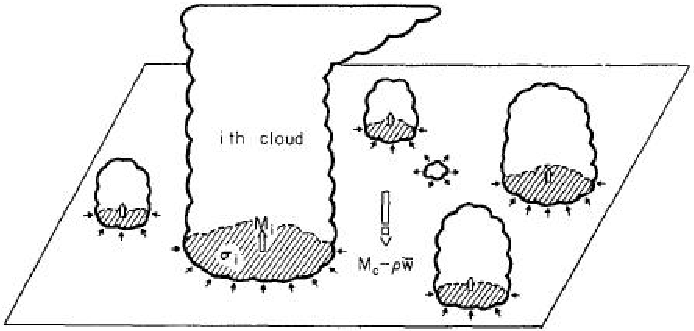


GWDO+MBD-CTL

Zhong, S. X., Chen, Z. T., Wang, G., Meng, W. G. and Huang, R. 2016. Improved forecasting of cold air outbreaks over shouthern China through orographic gravity wave drag para meterization, J. Trop. Meteor, 22:522-534. http://doi.org/10.16555/j.1006-8775-2016.04.007

Technical development – scale aware SAS scheme

- The impacts of the convection by considering the coverage rate of the cloud (scale-aware) was included.
- The scale aware SAS scheme was implemented into TRAMS model, which improves the typhoon forecasting of track and intensity, as well as the heavy rainfall forecasting.



$$\overline{h} = \sigma h_c + (1-\sigma)\tilde{h}$$

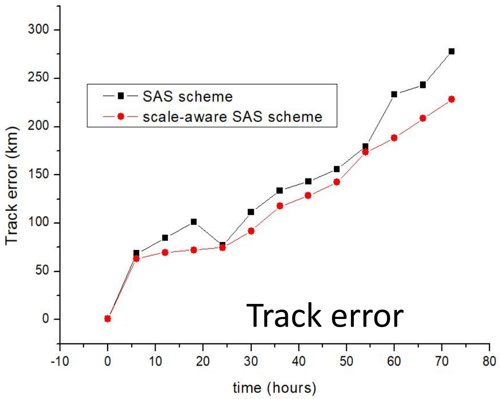
$$\overline{q} = \sigma q_c + (1-\sigma)\tilde{q}$$

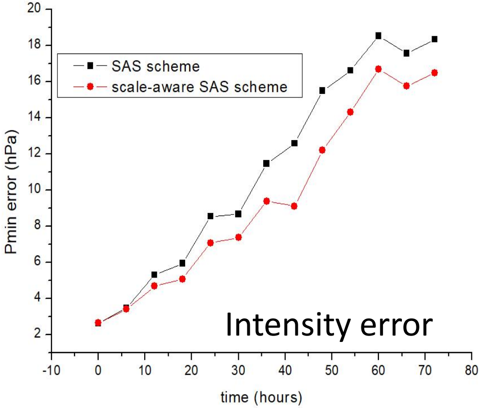
$$\sigma_u = \frac{3.14 R_c^2}{A_{grid}}, R_c = \frac{0.2}{\varepsilon_0}$$

$$\overline{w} = \sigma w_c + (1-\sigma)\tilde{w}$$

$$\frac{\partial\overline{h}}{\partial t}_{conv} = -\frac{1}{\rho}(E\tilde{h} - Dh_c) + \frac{1}{\rho}\frac{\partial}{\partial z}\left[M_c\tilde{h} + \rho\overline{w}(\overline{h}-\tilde{h})\right]$$

$$\frac{\partial\overline{q}}{\partial t}_{conv} = -\frac{1}{\rho}(E\tilde{q} - Dq_c) + \frac{1}{\rho}\frac{\partial}{\partial z}\left[M_c\tilde{q} + \rho\overline{w}(\overline{q}-\tilde{q})\right]$$





Technical development – Data assimilation

- New Generation Data Assimilation
- Technology of Multi-scale 3DVAR
- Application Technology of Satellite Data Assimilation
- Cloud Analysis (ADAS System) and warm Start Technology
- Radar water vapor (1D+3DVAR)
- Surface precipitation latent heat nudging

references

- Zhang Chengzhong et al. Application Experiment of Radar Retrieved Latent Heat in Short Range Near Precipitation Forecast of Flood Season in South China Regional Numerical Model. Journal of Tropical Meteorology, 2017, 33 (5): 577-587
- Zhang Chengzhong et al. Radar reflectance inversion of water vapor and its assimilation experiment based on Bayesian scheme. Journal of Tropical Meteorology, 2019,35 (02): 145-153
- Feng Yerong, Xue Jishan, Chen Dehui, et al. Design and testing of the dynamic framework for the GRAPES regional disturbance prediction model. Journal of Meteorological Reasearch, 2020,78 (5): 805-815
- Feng Yerong, Xue Jishan, et al 2021. Design improvement and numerical experiments of a framework for four-dimensional variational data assimilation system based on perturbation modes. Journal of Meteorological Reasearch, 79 (6): 1-19
- Li H. et al. A study on the application of FY2E cloud drift wind height reassignment in numerical forecast of Typhoon CHANTHU (1003) track, J. of Trop. Meteo,2015,21,34-42.
- Zhang X. et al. Impact of Assimilating Wind Profiling Radar Observations on Convection-Permitting Quantitative Precipitation Forecasts during SCMREX. Wea. Fore.，2016, 31：1271-1292.
- Zhang Xubin et al Quality Control and Assimilation Application of Wind Profile Radar Data. Journal of Meteorology, 2015, 73 (1): 159-176
- Wang Hong et al. Quality control of S-band dual polarization radar for data assimilation. Journal of Applied Meteorology, 2018, 29 (5): 546-558
- Wang Hong et al., 2016: Application of Bilinear Polarization Radar Data in Numerical Models: Construction of Simulators. Journal of Meteorological Reasearc.74, 229-243
- Lin, X. X., Y. R. Feng, et al., 2021: Improving the nowcasting of strong convection by assimilating both wind and reflectivity observations of phased array radar: A case study. J. Meteor. Res., 35(X), 1-18.
- Yali Wu，et al. Atmospheric Research，https://doi.org/10.1016/j.atmosres.2020.104912.
- Huang, Y. , et al., 2013. Improvement of the surface pressure operator in GRAPES and its application in precipitation forecasting in South China. *Advances in Atmospheric Sciences* , 30(2)：354-366.
- Zhang CZ et al. The impact of dropsonde data on a numerical simulation of landfalling Typhoon Mangkhut. Meteorol Appl. 2020;27

Technical development – Data assimilation

2012-2015

* muti-scale 3DVar
* Partial Cycle
* 1D+3D water vapor
* Latent heat nudging

2016-2023

* muti-scale EnKF
* 4DVar
* Incremental analysis update IAU
* Motor-DA(NEW DA)

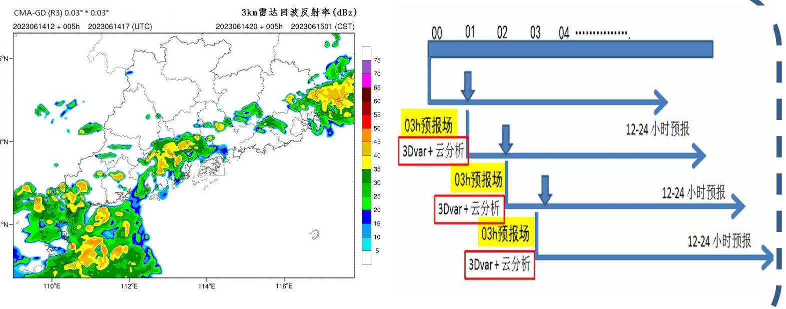
Low-frequency cycle assimilation for Single moment assimilation

High-frequency cycle assimilation for Multi scale and multi time assimilation

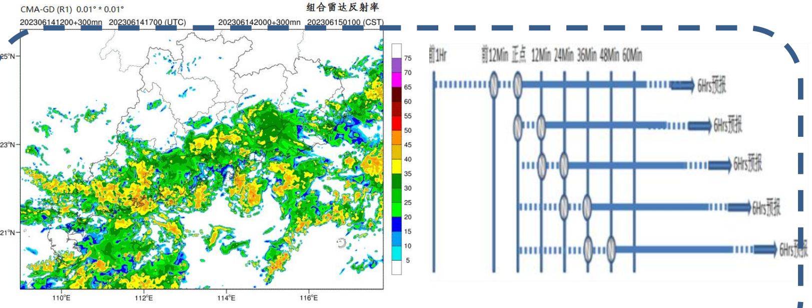
	data type	observed frequency
Satellite	EUMETSAT	Real time
	Himawari-8	10min
	FY2	15min
	FY3	15min
	FY4	15-18min
	GNSS/MET	hourly
radar	radar	6min
	Wind profile radar	5-10min
	X-band phased array radar	90sec
station	sounding	00UTC/12UTC
	Surface observation	hourly
	automatic station	6min
	buoy station	6min
	Island Station	6min
	Platform	6min
	Aircraft	hourly
else	Lightning positioning station	6min

Technical development – Operational DA system

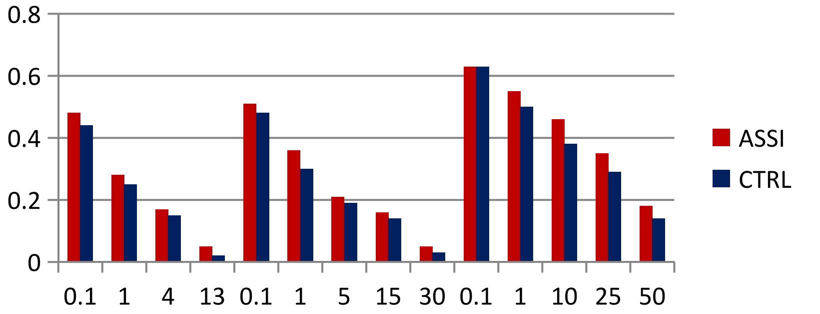
- The cloud analysis system has been in operation in the TRAMS-3KM and TRAMS 1KM model.
- The radar reflectivity data and FY-2G TBB data was used in the cloud analysis system.
- It can improve the operational forecasting ability of the rapidly update cycling system.



Operational DA system in TRAMS-3KM



Operational DA system in TRAMS-1KM



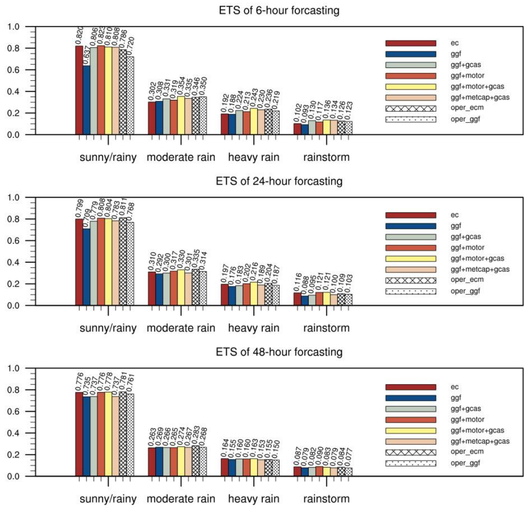
6h, 12h, 24h forecast average precipitation TS of different scales
Blue: Before assimilation; Red: After assimilation

Technical development – Operational DA system

- ◆New DA system (developed by Shenzhen institute of meteorological innovation) has been parallel running with TRAMS-3KM, which aims to establish a domestically developed and controllable forecasting system with CMA-GFS.
- ◆The experimental results showed that the NEW DA system had the comparable forecasting abilities with the operational cloud analysis system with the ECMWF data as the initial field and boundary.

the spatiotemporal multi-scale assimilation analysis system

New DA system by Shenzhen institute of meteorological innovation



Parallel running DA system in TRAMS-3KM in 2022

Technical development – 4Dvar assimilation

- Strictly derive perturbation equations from the original GRAPES equations and establish a perturbation prediction model.
- Developed a 4D-Var system framework based on disturbance patterns and built a new generation of assimilation system

$$\frac{\mathrm{D}u'}{\mathrm{Dt}} = -(u'u_x + v'u_y + \hat{w}'u_{\hat{z}}) + C_{\mathrm{P}}L_{\pi x}\theta' + L_{\theta}(\Pi'_x + Z_{sx}\Pi_{\hat{z}}{}') + fv'$$

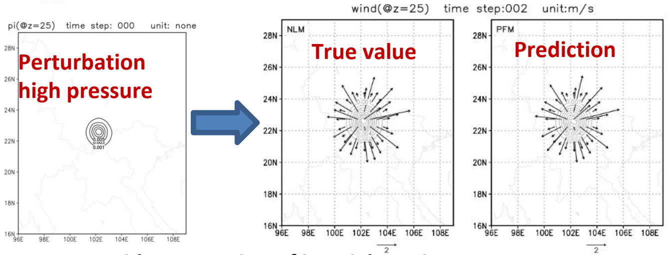
$$\frac{\mathrm{D}v'}{\mathrm{Dt}} = -(u'v_x + v'v_y + \hat{w}'v_{\hat{z}}) + C_{\mathrm{P}}L_{\pi y}\theta' + L_{\theta}(\Pi'_y + Z_{sy}\Pi'_{\hat{z}}) - fu'$$

$$\frac{\mathrm{D}w'}{\mathrm{Dt}} = -(u'w_x + v'w_y + \hat{w}'w_{\hat{z}}) + C_{\mathrm{P}}L_{\pi\hat{z}}\theta' + L_{\theta}Z_{s\hat{z}}\Pi'_{\hat{z}}$$

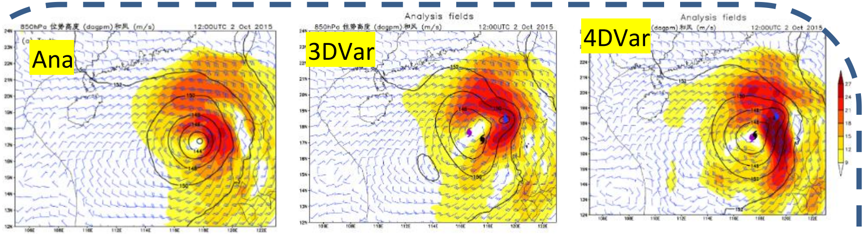
$$\frac{\mathrm{D}\Pi'}{\mathrm{Dt}} = -(u'\Pi_x + v'\Pi_y + \hat{w}'\Pi_{\hat{z}}) - \alpha_{\mathrm{D}}\Pi' - \alpha_{\Pi}D'_3 + \gamma_{\theta}P'_{\mathrm{w}}$$

$$\frac{\mathrm{D}\theta'}{\mathrm{Dt}} = -(u'\theta_x + v'\theta_y + \hat{w}'\theta_{\hat{z}}) + \gamma_{\Pi}P'_{\mathrm{w}}$$

$$\frac{\mathrm{D}q'}{\mathrm{Dt}} = -(u'q_x + v'q_y + \hat{w}'q_{\hat{z}}) - P'_{\mathrm{w}}$$



Rapid propagation of inertial gravity waves



850hPa Wind and Potential Height

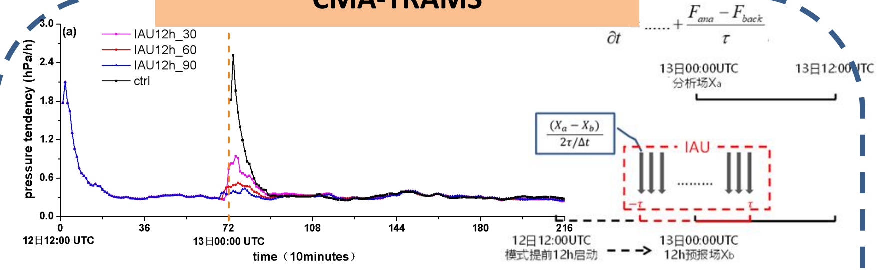
预报时效	位置偏差（km）				
	3DVar_1	3DVar_2	4DVar_1	4DVar_2	CTL
00h	115.1	73.9	30.8	54.0	230.8
06h	92.5	95.4	21.1	21.1	218.1
12h	74.5	39.4	24.7	11.2	196.1
18h	73.4	15.3	33.4	33.4	168.1
24h	84.3	53.2	35.0	30.5	142.4
30h	103.6	56.3	15.2	10.4	99.9
36h	83.4	45.4	15.2	20.7	75.7

track error of typhoon " Mujigae " by different assimilation schemes

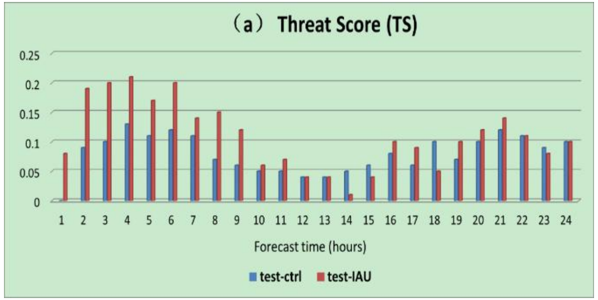
Technical development – IAU initialization method

- Develop **incremental analysis update (IAU) initialization** technology to gradually add assimilation analysis increments to the model, which could **alleviate the initial noise**, and achieve faster coordination of the model forecast.
- **IAU technology has been used in CMA-GFS.**

CMA-TRAMS

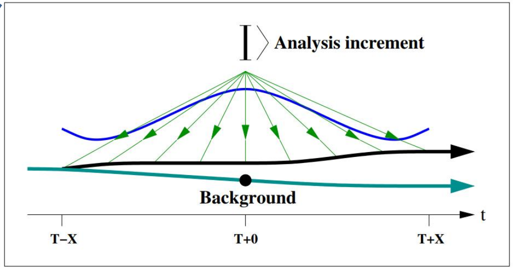


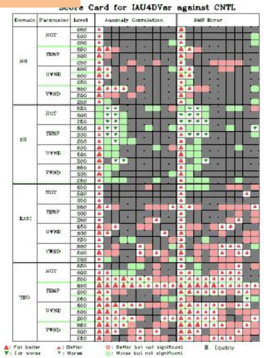
different relaxation durations on the tendency

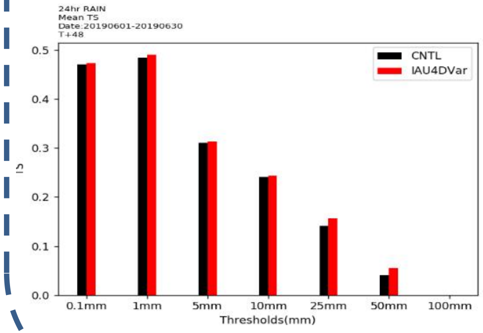


Hourly Precipitation Forecast TS Score - (April 1-30, 2019)

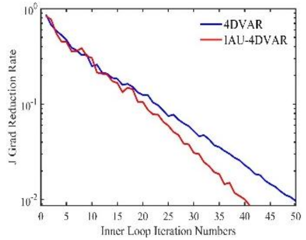
CMA-GFS







24-hour cumulative global precipitation TS score (June 1-30, 2019)



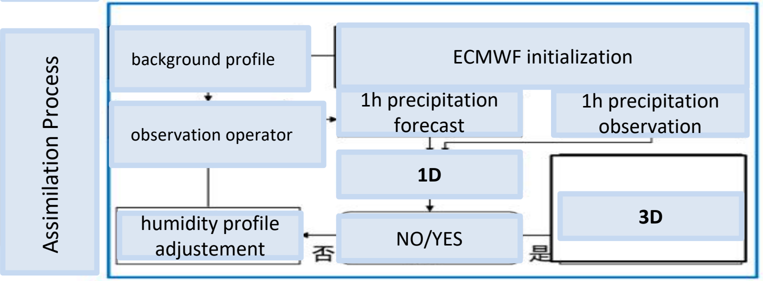
IAU-4DVAR Accelerated Inner Loop Iteration

Technical development – 1D+3D radar assimilation

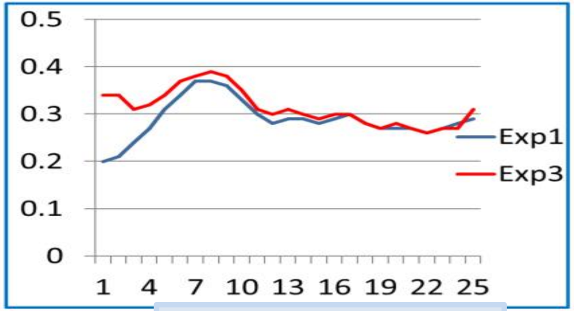
- ◆Linear combination of large-scale condensation and convection parameterization schemes using wet physical processes to form a 1D variational observation operator and to obtain reasonable humidity profiles.
- ◆Introducing the obtained humidity profile as an observation into the analysis using 3D variational assimilation to obtain the initial field of the model.

Technical Principles

variable	$X=(T_1,T_2,\ldots,T_n,q_1,q_2,\ldots q_n)^T$
objective function	$J(X)=\frac{1}{2}\left((X-X_b)^T B^{-1}(X-X_b)+(y-H(X))^T O^{-1}(y-H(X))\right)$
objective function gradient	$\nabla J(X)=(X-X_b)B^{-1}+H'O^{-1}(y-H(X))$



Precipitation rate observation operator = convective parameterization + large-scale condensation scheme



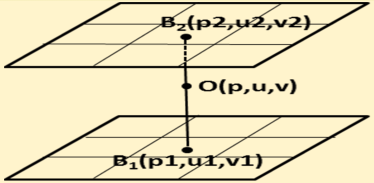
hourly light rain TS
EXP1- no radar assimilation
EXP3- with radar assimilation

After assimilating radar water vapor, the precipitation score in the first 24 hours was improved

Technical development – FY2E Satellite assimilation

- The FY2G TBB data was used in the cloud analysis system.
- The FY2E Cloud Guided Wind Data was used to correct the cloud height, which the cloud guidance wind could strengthen the southeast airflow on the east side of typhoon centers, which is conducive to guiding the typhoon center to move westward and obtaining the realistic typhoon path prediction.

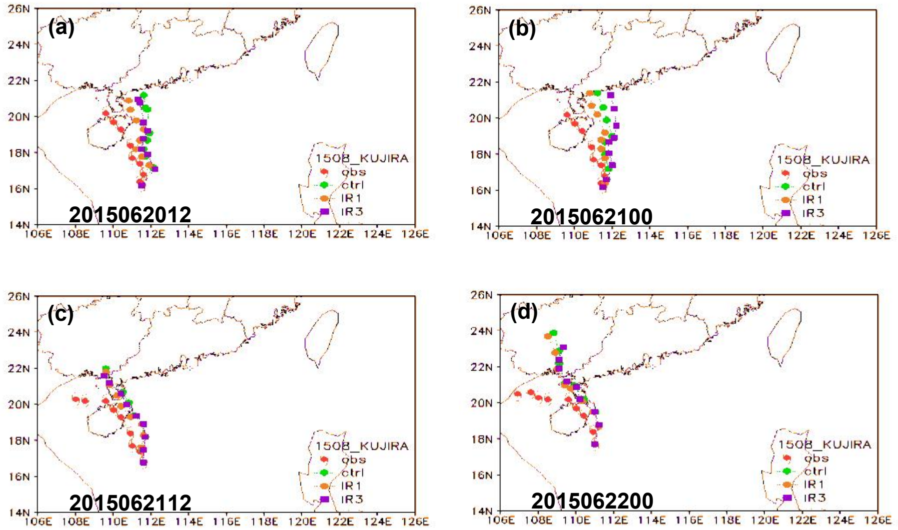
FY2E Cloud Guided Wind Data

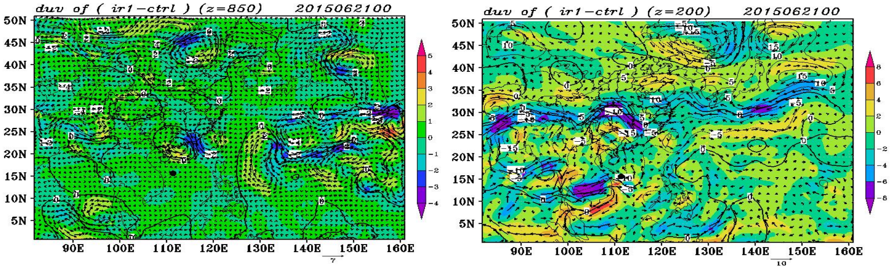


$$p' = \frac{w_2}{w_1+w_2} p_1 + \frac{w_1}{w_1+w_2} p_2$$

$$w_1 = \frac{(p-p_1)^2}{p} + \frac{(u-u_1)^2}{u} + \frac{(v-v_1)^2}{v}$$

$$w_2 = \frac{(p-p_2)^2}{p} + \frac{(u-u_2)^2}{u} + \frac{(v-v_2)^2}{v}$$

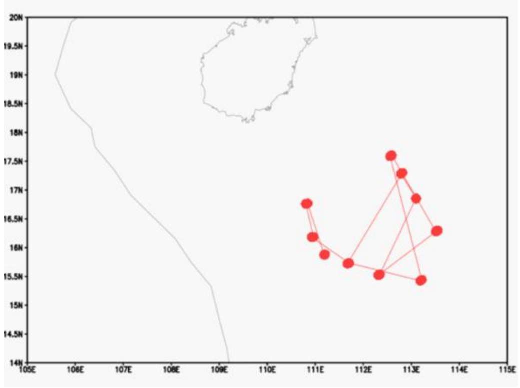




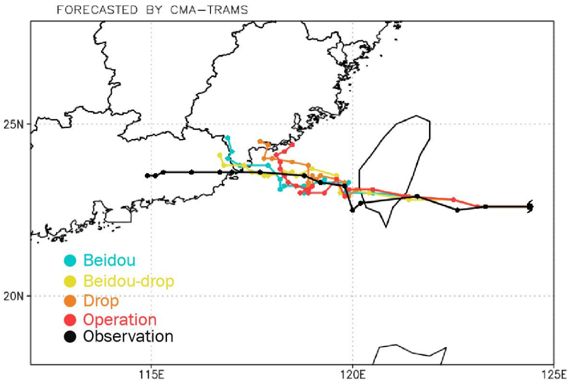
201508 typhoon “Kujira” experiment

Technical development – UAV and Beidou sounding experiment

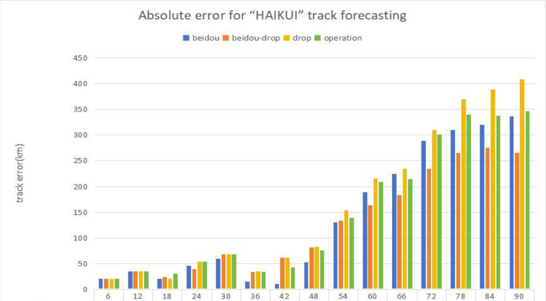
- The Unmanned Aerial Vehicle (UAV) drop sounding and Beidou sounding data was assimilated to examine the impacts on typhoon forecasting;
- The typhoon path forecast of HAIKUI turned westward after assimilating the UAV and Beidou sounding. The TS score was improved.



The UAV drop sounding Experiment (10 soundings)



Comparison of typhoon forecast

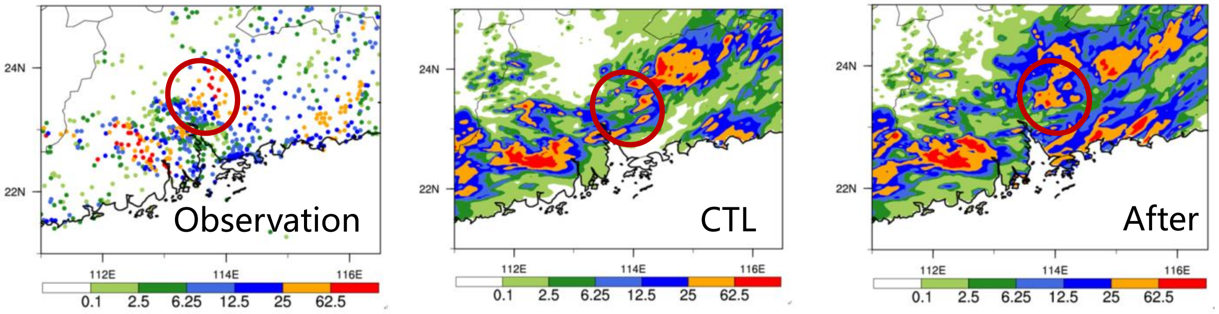


	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90
beidou	20.5	34.9	20.4	45.3	59.3	15.2	10.5	52.1	130.3	189	224.6	289.2	309.4	319.7	336.8
beidou-drop	20.5	34.9	23.3	39.1	67.5	33.4	61.1	81.6	132.9	163.5	183.4	234.4	265.3	275.3	265.3
drop	20.5	34.9	20.4	54	67.5	34.9	61.3	82.3	153.3	215.3	234.7	309.4	370.1	388.4	408.8
operation	20.5	34.9	30.7	54	67.5	33.4	42.3	75.5	139.5	208.9	214.9	301.2	339.7	337.5	346.7

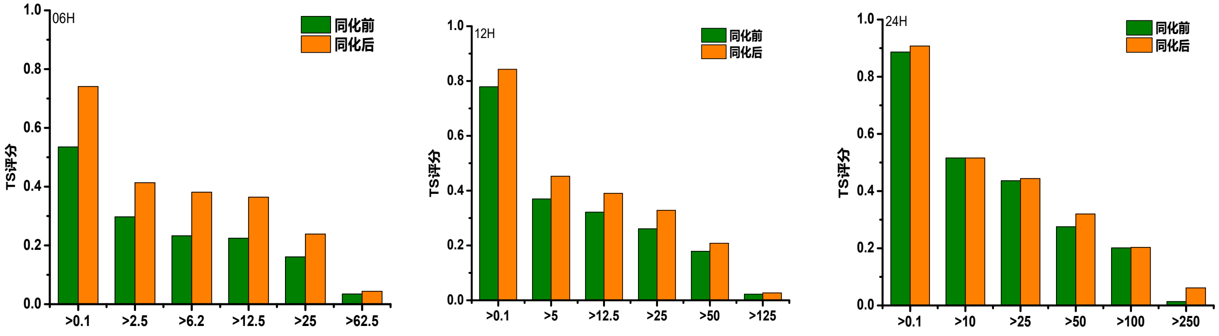
Typhoon track error

Technical development – X-band phased array radar experiment

- Before assimilation, there was a large amount of false precipitation in northern Guangdong;
- After assimilation, the coastal precipitation on both sides of the the Pearl River Estuary can be better reflected.
- The TS score for the 6hour cumulative precipitation can be improved by the highest of 63.9;
- The TS score for the 12 hour cumulative precipitation can be improved by the highest of 25.7%.



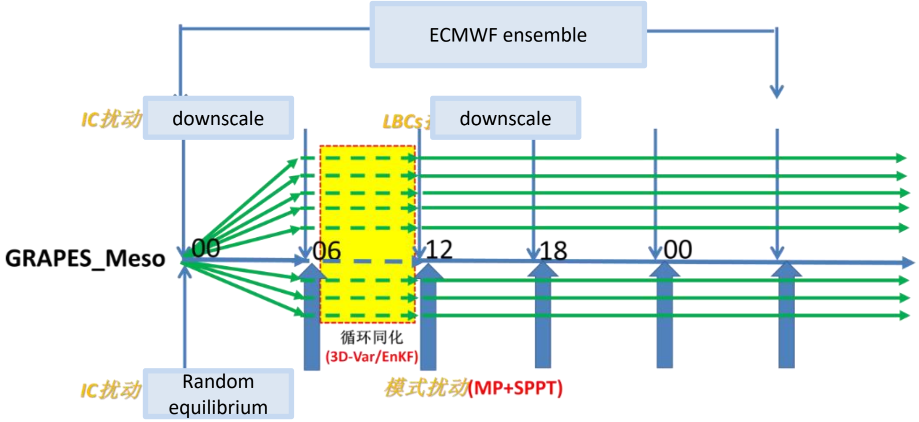
6h Accumulated precipitation



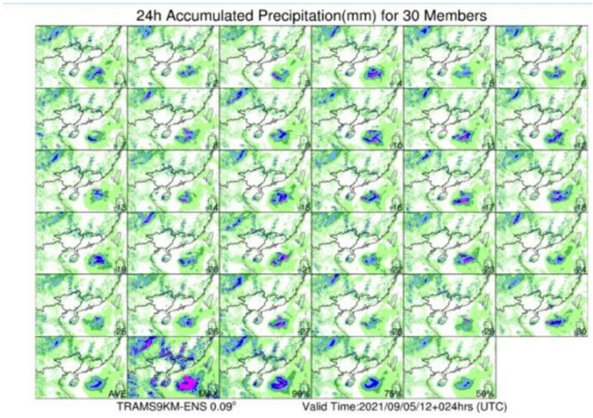
Average TS score of accumulated precipitation for 6h, 12h, and 24h

Technical development – ensemble forecasting

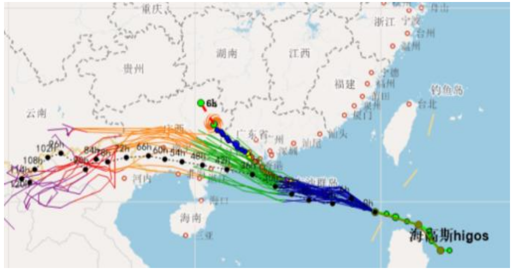
- Develop **different perturbation techniques** by considering scale characteristics and nonlinear interactions.
- Develop the "**combination of multi-source and multi type disturbances" technology.**
- A regional ensemble forecasting system based on TRAMS(CMA-TRAMS EPS) was running in operation with 30 members.



Regional ensemble forecasting system based on TRAMS(**CMA-TRAMS EPS**)



CMA-TRAMS (EPS) 30 members of Precipitation Stamp Map



CMA-TRAMS (EPS) typhoon track

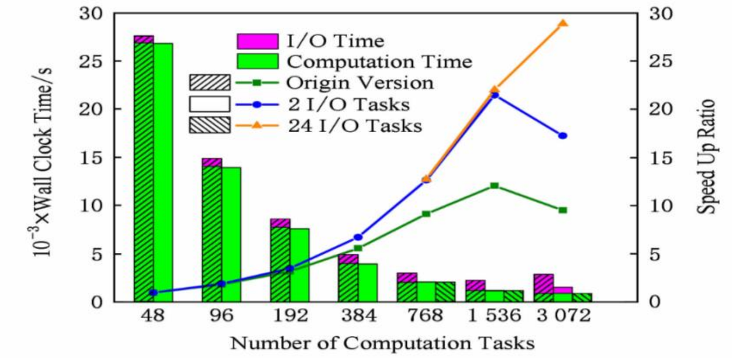
Technical development –High Performance computer

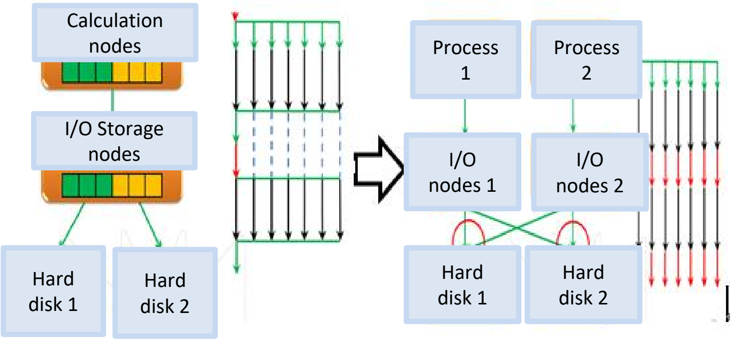
◆ Optimize **multi-process parallel I/O technology** and achieve higher computational efficiency to meet the requirements by 12 minute rapid update cycling based on "Tianhe 2"

◆ Developing multi process parallel I/O:

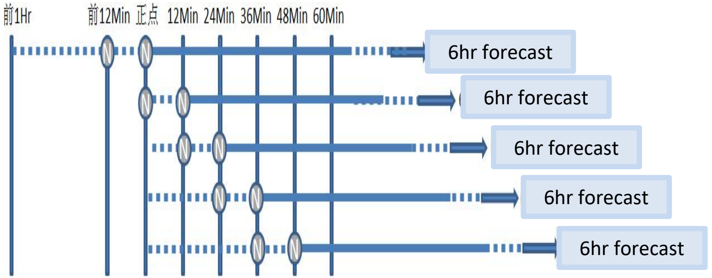
◆ The original output of a file takes 14 seconds, and after optimization, it takes 0.2 seconds.

◆ At present, the 1km model uses 100 computing nodes of Tianhe 2, completing a 6-hour forecast cycle within 8 minutes, which can meet the requirement of rapid updates in 12 minutes.





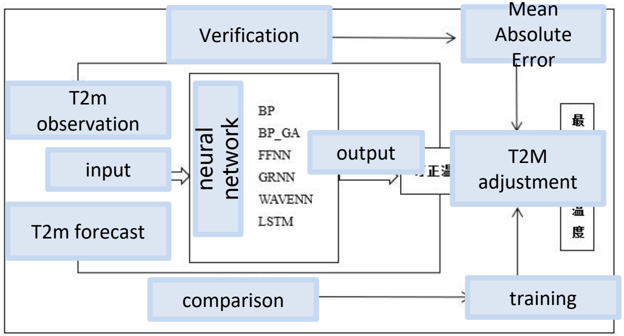
multi process parallel I/O

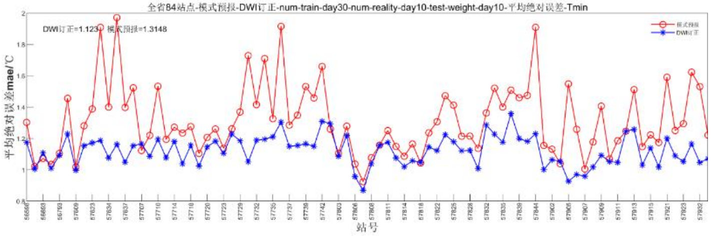


12 minutes updating and Nudging assimilation

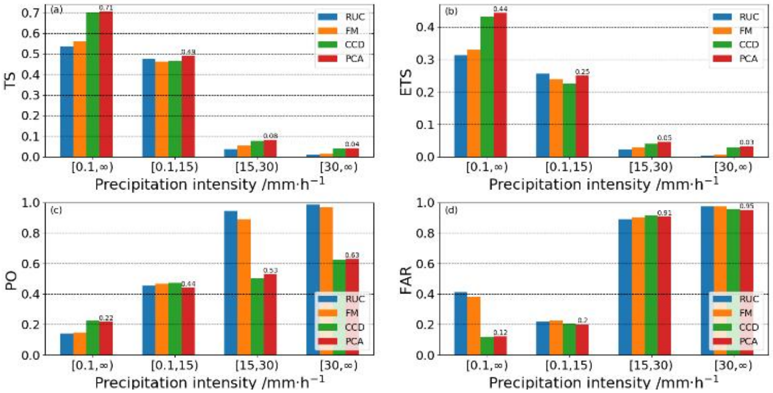
Technical development –Post-processing

- Systematic errors have been effectively alleviated by using **a random forest temperature correction** scheme and a **convolutional neural network** hourly precipitation prediction correction method, as well as an **AI dynamic weight integrated temperature** prediction scheme.





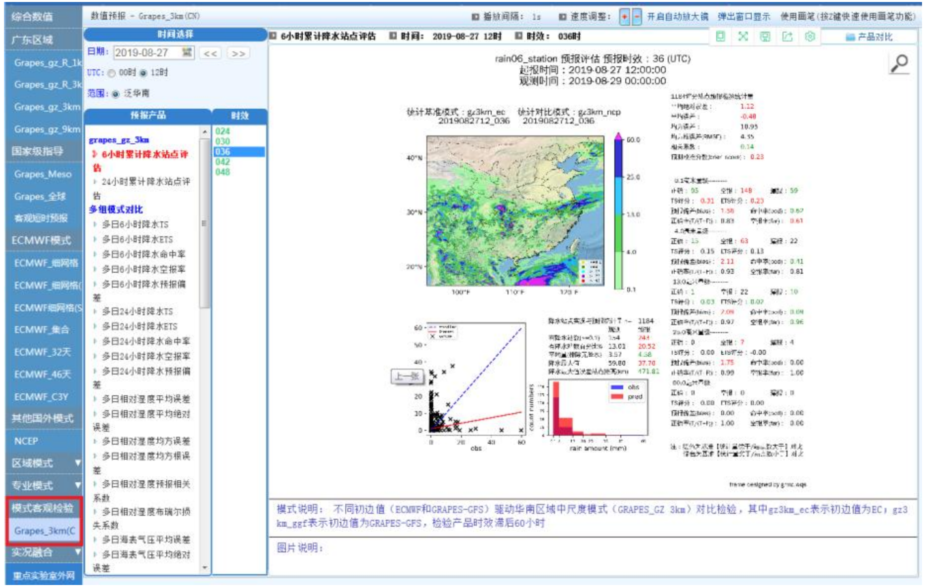
Correction effect of minimum temperature from 84 national stations in Guizhou Province to April October 2019 (0-72 hours)



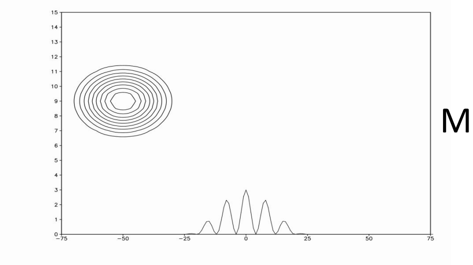
Precipitation correction method

Technical development –verification platform

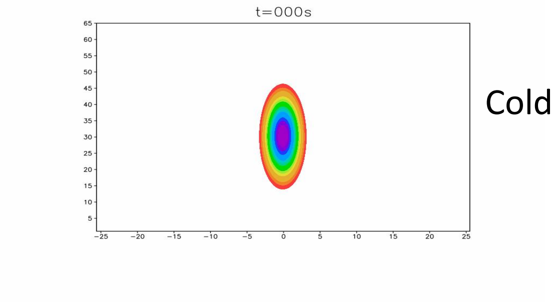
◆ Develop and establish a **verification, evaluation, and ideal experimental platform** to facilitate pattern development and version upgrade



Verification platform



Mass advection



Cold bubble

Ideal experiment-platform

End of part 1