Front. Earth Sci. 2022, 16(1): 144–157
https://doi.org/10.1007/s11707-021-0899-4

RESEARCH ARTICLE

Improvements in the GRAPES-TCM and the forecast performance analysis in 2019

Yan TAN[1,2], Xu ZHANG (✉)[1,2], Xiaolin XU[3], Wei HUANG[1,2]

1 Shanghai Typhoon Institute, China Meteorological Administration, Shanghai 200030, China
2 Key Laboratory of Numerical Modeling for Tropical Cyclone, China Meteorological Administration, Shanghai 200030, China
3 Center of Ecological Meteorology and Satellite Remote Sensing, Shanghai 200030, China

Abstract In 2019, the operational Global Regional Assimilation and Prediction System-Tropical Cyclone Model (GRAPES-TCM) was updated by adopting the characteristic parameters in the official real-time released TC data of CMA, introducing the horizontal sixth-order diffusion scheme and adjusting the operational flowchart. In the case of the Super Typhoon Lekima, the model exhibits a reliable prediction ability for the type of tropical cyclone (TC) with northwestern tracking. The track and intensity forecasts in 2019 are significantly better than those over the past five years on average. The updated model can provide a skillful forecast of landfall position and rapid weakening process. Moreover, the precipitation pattern is close to the observation. TC forecast in 2019 shows that the updated GRAPES-TCM has a smaller track error than that of the previous year, and the 24 h intensity forecasting ability is improved.

Keywords GRAPES-TCM, vortex initialization, numerical diffusion scheme, performance analysis

1 Introduction

Tropical cyclones (TCs) are one of the most catastrophic weather systems that affecting China and often cause great losses of life and national property (Chen et al., 2019; Yu and Chen, 2019). Over the past two decades, with the improvement in weather observation methods, numerical weather models, data assimilation techniques, and computation capabilities, numerical weather prediction (NWP) has greatly improved in model performance, such as in model accuracy and valid time. Although there is still a gap between the Chinese model and other international advanced TC models, it has narrowed; and compared with the global advanced level, the subjective forecast error of the TC track has decreased (Qian et al., 2012). However, the intensity forecast has not made significant progress. It is also impossible to accurately describe the structure and scale of TCs, which directly affects the prediction of heavy rainfall and strong winds. In recent years, many Chinese institutions have successively conducted research on regional high-resolution TC models, (Qu et al., 2009a; Qu et al., 2009b; Chen et al., 2016; Zhang et al., 2017; Ma and Chen, 2018; Huang et al., 2018), and researchers have focused on TC intensity predictions. Much research has been conducted on the initial TC vortex structure and intensity and on the optimization of the model physical parameterization scheme.

The Global Regional Assimilation and Prediction System (GRAPES) mesoscale model was introduced by the Shanghai Typhoon Institute (STI) in 2004, and a regional typhoon forecast model over the Northwest Pacific was developed, namely the GRAPES-Tropical Cyclone Model (TCM). After a series of studies, including the setup of the model domain, the selection of physical parameterization schemes, and the implementation of the vortex relocation technologies, the GRAPES-TCM was officially put into operation in 2006 (Huang et al., 2007). Since then the model has been continuously improved. Huang and Liang (2010) optimized the typhoon initialization scheme with model-constrained-3DVar technology, which is called the cycling data assimilation (CDA) scheme. Case study shows that the CDA scheme positively impacts the initial TC intensity and structure as well as the prediction of typhoon track and intensity. Tan and Liang (2012) and Tan and Chen (2014) also conducted researches on TC track ensemble prediction using GRAPES-TCM, providing probabilistic information of TC tracks.

Received June 3, 2020; accepted February 21, 2021

E-mail: zhangx@typhoon.org.cn

However, the current models still cannot provide accurate forecasting of TC landfall and its associated intensity, wind and heavy rainfall. To mitigate this situation, STI upgraded the GRAPES-TCM during 2013–2015, including the data assimilation, dynamic core, physical parameterization, and vortex initialization. A hybrid grid-point statistical interpolation-ensemble transform Kalman filter (GSI-ETKF) data assimilation system was established by Li et al. (2015), and according to a relevant case study, this hybrid system exhibited significantly improved results with respect to TC track forecasts compared to the standard GSI system. A height-based terrain-following coordinate (the Klemp coordinate) has been implemented into the GRAPES model and also compared with the original Gal-Chen coordinate by Zhang et al. (2015a). The results show that the pressure gradient force computational errors under the Klemp coordinate were mostly reduced. Moreover, the implementation of a generalized Mahrer Approach can further improve the computational accuracy of calculating the horizontal barometric pressure gradient force (Klemp, 2011). Meanwhile, Zhang et al. (2015b) introduced a stable extrapolation two-time-level scheme (SETTLS) into the model to determine the trajectory in nonlinear terms. The results show that the improved semi-implicit semi-Lagrangian scheme is numerically stable and leads to substantially less damping than the original time integration scheme does. In addition, the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) physics package was implemented into the GRAPES-TCM (Huang et al., 2018). The evaluation of the updated version shows that the forecast by the GFS experiment is consistent with the observations. The study of rainfall events reveals that a trigger method modification in the cumulus parameterization scheme can significantly improve the precipitation simulation, which subsequently improves the large-scale fields via more accurate feedback. Xu et al. (2019) implemented a new vortex initialization scheme in GRAPES-TCM. The scheme applies a relatively small correction in the storm vortex to maintain a certain model consistency. Hindcast demonstherates that the new vortex scheme can effectively improve the forecast of TC track and intensity.

Figure 1 shows the trend of the track and intensity prediction errors of the GRAPES-TCM over the past 10 years. Overall, both the track and intensity errors show a steadily decreasing trend. The most significant change in track forecast error occurred in 2014, where 48 h and 72 h errors decreased significantly. The intensity forecast error was greatly reduced in 2012. More attention should be paid to the model performance after the new version was adopted in 2015. Although there is a year-to-year fluctuation in the 24 h track forecast, the error kept below 90 km. The 48 h and 72 h forecast errors show monotonously decreasing trends. The intensity forecast error has slowly increased from 2012 to 2015; however, there has been a downward trend for leading time since 2015.

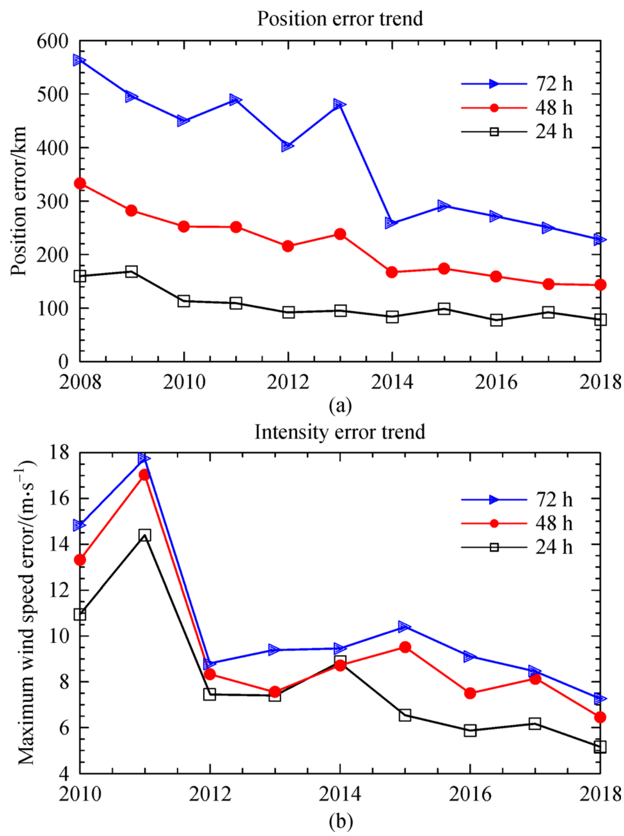

Fig. 1 Forecast error trends of GRAPES-TCM. (a) Track error trend for 2008–2018; (b) intensity error trend for 2010–2018.

In this study, recent model improvements are discussed and the operational forecast performance for all TCs in 2019 and the super typhoon Lekima are analyzed using the updated model. The remainder of the paper is organized as follows. Section 2 provides a general introduction of the GRAPES-TCM. The latest model improvements, which include the parameter selection in the vortex initialization scheme, the optimization of the dynamic core, and the evaluation of the effects before and after improvement are presented in Section 3. A performance analysis of the model for the entire typhoon season in 2019 is provided in Section 4. Section 5 briefly introduces Lekima and the forecast results of the model. Section 6 discusses and summarizes the major results.

2 GRAEPS-TCM

GRAPES-TCM, developed by STI, is a regional dynamic numerical weather prediction modeling system that is capable of producing high-resolution TC forecasts. All forecasts in this study were operational in 2019, and the model is storm-centric, with a domain that is expanded for

30° in the east–west or north–south directions. The model contains 51 vertical levels with the top level at 35 km, and the horizontal resolution is 0.1°. A two-time integrated scheme is adapted for model integration. The NCEP GFS physics package is implemented in the GRAPES-TCM (Huang et al., 2018), and the vortex relocation and intensity scale corrections are used in typhoon vortex initialization. The initial and lateral boundary conditions are provided by the GFS. In the case of a typhoon, the model makes predictions four times a day (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC) and provides a three-day forecast.

3 Model improvements

3.1 Parameter selection in the vortex initialization scheme

Xu et al. (2019) described the vortex initialization scheme currently used by GRAPES-TCM, which includes three parts: vortex relocation, vortex scale adjustment and vortex intensity adjustment. Vortex relocation refers to that when the typhoon vortex position of model initial field doesn't match the observation location, the initial field need to be decomposed into two parts, the typhoon vortex and the background field (without typhoon vortex), and then the typhoon vortex is translated to the observation location reasonably, to form an updated model initial field. Vortex scale adjustment means that when the spatial scale of typhoon vortex doesn't match the actual situation, too large or too small, it needs to be adjusted based on observation. The radius of the maximum wind and the estimated radius of the outermost closed isobar are used in the adjustment. The vortex scale is corrected by extending or compressing the model grid. When there is a certain difference between the typhoon intensity in the initial field and observed, the intensity needs to be corrected according to the observation. By calculating the wind speed of the environment field plus the vortex field, and comparing it with the observed maximum wind speed, the correction coefficient is obtained, and finally the revised wind speed is obtained. At the same time, it is also necessary to adjust the surface pressure, temperature and water vapor accordingly. In general, the TC vortex correction is as small as possible to reduce the influence of thermal factors on the vortex structure, and maintain the balance between dynamics and thermality in the vortex.

The required parameters include the longitude and latitude of the TC center, radius of the maximum wind, estimated radius of the outermost closed isobar, maximum wind speed, storm central pressure, and storm environmental pressure. The previous GRAPES-TCM vortex initialization scheme used Joint Typhoon Warning Center data (TCVitals) instead of the official real-time released TC data of the Chinese Meteorological Administration (CMA) (babj), because the babj does not provide all the elements required for vortex initialization, such as storm environmental pressure, estimated radius of the outermost closed isobar, and radius of maximum wind.

In the operational forecast, the typhoon message from TCVitals and babj are not exactly the same in typhoon number and reporting time, which may easily lead to confusion regarding the initial forecast time. In addition, the two sets of data also have differences regarding storm centers. The relationship between these parameters and the minimum TC pressure is analyzed by using the TCvitals data from 2016 to 2018, as shown in Figs. 2 to 4.

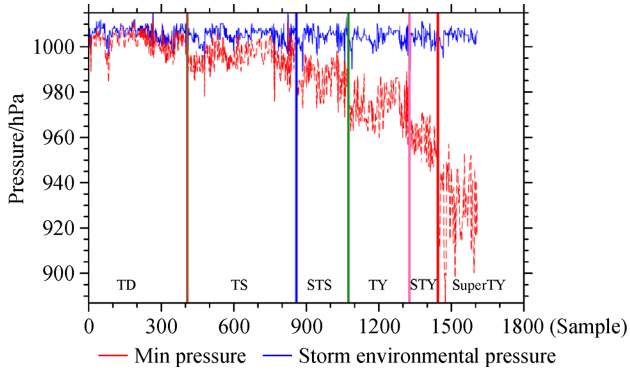

Fig. 2 Relationship between the minimum TC pressure and environment pressure.

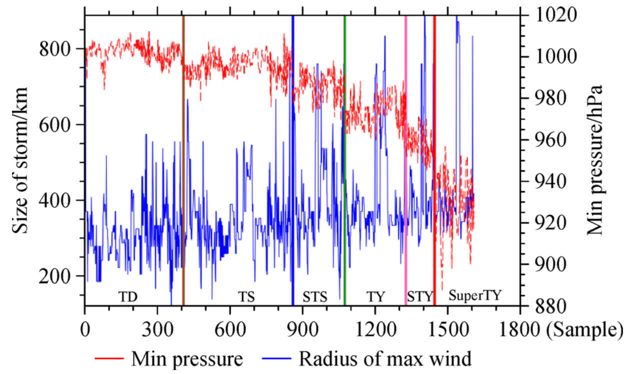

Fig. 3 Relationship between minimum TC pressure and storm size.

Based on the relationship between the minimum TC pressure and storm environment pressure, it can be seen that in the 1609 samples, the sum of the number of tropical storms (TS) and tropical depressions (TD) exceeds half of the total samples, followed by the number of typhoons (TY). The number of super typhoons is nearly 200, which is similar to the number of severe typhoons (STS). In terms of magnitude, the lowest TC central pressure is 887 hPa, while the highest is 1012 hPa. The magnitude varies significantly for each TC category. However, the environmental pressure does not change dramatically, and there is

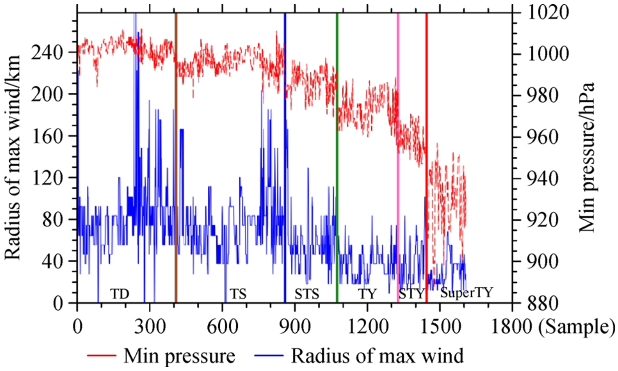

Fig. 4 Relationship between the minimum pressure of TC and maximum wind radius.

no linear relationship between the intensity of TC and the environmental pressure. The storm environmental pressure ranges from 989 hPa to 1015 hPa; therefore, the mean value (1005 hPa) is utilized as the characteristic value of this parameter to represent the environmental pressures of different TC categories.

The estimated radius of the outermost closed isobar can reflect the TC size. When the vortex scale is corrected, this parameter is required to adjust the TC scale. Based on the blue curve in Fig. 3, the vortex scale varies for different TC intensity categories, with a minimum scale of 121 km and a maximum scale of 888 km, and the value of the change is greater than 7 times. However, the size of weaker TDs is smaller than that of STS and above. The TD scale varies from 200 km to 550 km, and a large number of samples are concentrated around 300 km, with no vortices over 600 km. The minimum TS scale is close to the minimum TD scale, but a small number of vortices that are greater than 600 km have begun to appear as TSs, and the scale of the large sample concentration area has also slightly increased. The STS and super typhoon curves are nearly the same, where the change is concentrated between 350 km and 500 km, but the frequency of vortices larger than 600 km is significantly higher than that of TS. It is noticed that although the parameters change frequently, many TCs of each category are concentrated in the 300–400 km range; hence, the mode (370 km) of the data is selected as the characteristic parameter value to describe the changes of all TC intensity to a certain extent.

The maximum wind speed radius can also reflect the TC size. It is used to adjust the vortex scale in the vortex initialization scheme. Figure 4 displays the curve of this parameter against the typhoon intensity change. The magnitudes of the vortices of different category TCs vary significantly. The minimum radius of maximum wind is 9 km, and the maximum radius is 278 km, where its difference reaches 30 times. The radii of the maximum TD and TS wind speeds are similar. Most samples are concentrated in the 50–90 km range, and many samples are greater than 120 km. With the increase in TC intensity, the maximum wind radius clearly decreases. STS is in the transition zone; its large sample area is in the range of 40–80 km, and occasionally a value exceeds 100 km. The curve of typhoons and above exhibits consistency, and the large sample area is concentrated in the 20–60 km range, with almost no value exceeding 90 km. Based on the change in the radius of maximum wind speed, there is an intersection of all TC categories in the 40–60 km range. Similarly, the mode of the data (55 km) is selected as the characteristic value of this parameter to reflect all the TC intensity changes for the maximum wind speed.

Based on the above analysis, the environmental pressure in the newly constructed messages is set to 1005 hPa, the radius of the outermost closed isobar is set to 370 km, and the radius of maximum wind is set to 55 km, and the rest of information is taken from the babj file. In a study by Chen et al. (2019), two TCs with the largest and the smallest forecast errors for GRAPES-TCM were selected, namely TC1807 (Prapiroon) and TC1808 (Maria). To analyze the impact of the changes in the previously mentioned parameters on the forecast, a comparison test with 18 forecasts is performed with the new and old messages. The best tracks and intensities of the two TCs are shown in Fig. 5.

Figure 6 displays the track and intensity errors using newly constructed messages and TCvitals messages. From the track perspective, Prapiroon is one of the typical extratropical transition TCs. The largest forecast error of GRAPES-TCM occurs when the northerly component of the typhoon increases and it begins to move northeast beyond 25°N. Maria is a typical westward TC. After its formation, the storm moves steadily to the northwest and starts to turn into a super typhoon. The model has a sufficient forecast ability for this type of TC. The forecast performance of the model for these two types of TCs are similar to that in the report by Huang et al. (2007). As can be seen from Fig. 6, after using the new message information, the overall distribution of the error is similar except the specific values. It has nearly the same forecast effect as the original TCvitals, and there is no significant difference between these two comparison tests, which is the basis for message reconstruction. But the operational reporting rate has been significantly improved.

3.2 Dynamic core improvements

GRAPES-TCM model is a non-hydrostatic semi-implicit semi-Lagrangian model that is based on fully compressible atmospheric equations. The model adpots latitude-longitude grid points with Arakawa C staggering horizontally. In the vertical direction, a terrain following height coordinates and Charney-Philips staggering is used. Vector discretization is introduced to maintain the department point calculation accuracy in the semi-Lagrangian scheme.

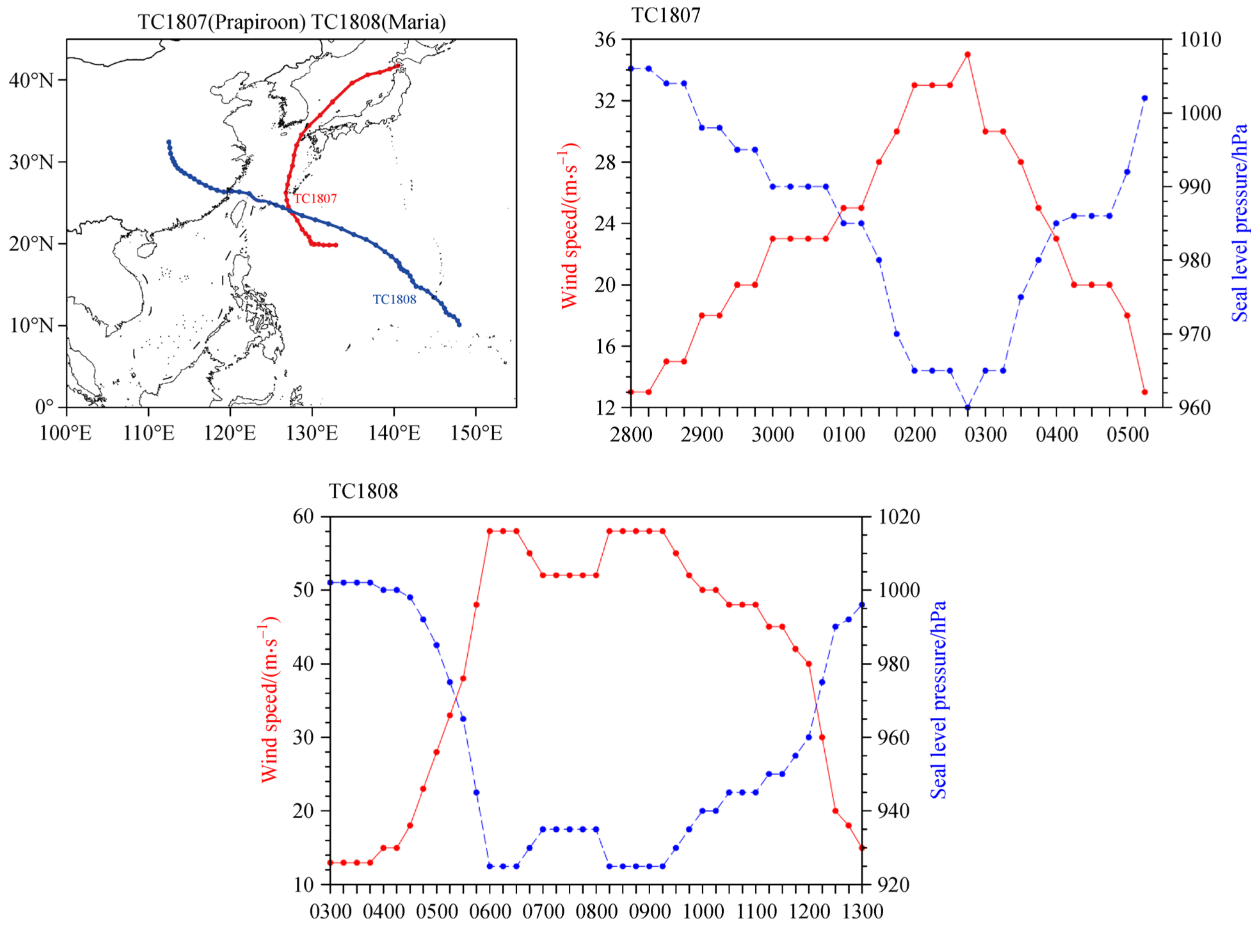

Fig. 5 Tracks and intensities of TC1807 (Prapiroon) and TC1808 (Maria).

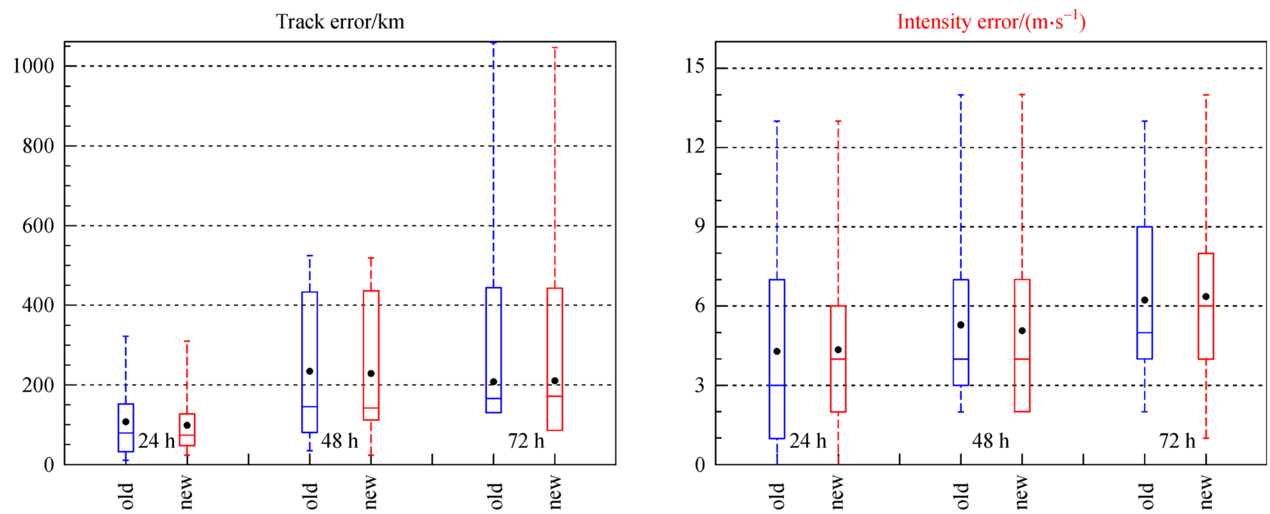

Fig. 6 Error distribution of predicted track and intensity with newly constructed messages (red) and old TCvitals messages (blue). The black dot is the mean error.

A reference atmosphere in the hydrostatic balance is induced to alleviate the difficulties caused by the numerical topography treatment.

Recently, the SETTLS was implemented into GRAPES-TCM to determine its trajectory and nonlinear terms. To stabilize the scheme, a warm reference temperature is required. The first-order decentered averaging of linear terms of the previous GRAPES-TCM version relaxes the restriction of a warm reference temperature, but its large weight results in a significant damping for low-wavenumber modes. Therefore, a second-order accuracy decentering of the linear terms and warmer reference temperature are applied in the GRAPES-TCM. Moreover, a height-based terrain-following coordinate (Klemp, 2011) was implemented into the regional GRAPES model.

Most numerical models employ numerical diffusion or computational mixing to control the small-scale (two grid intervals that are close in wavelength) noise that can arise from numerical dispersion, nonlinear instability, discontinuous physical processes, and external forcing. A non-physical, scale-selective, diffusion or damping process is incorporated into all the models through explicit terms in the predictive equations. Explicit numerical diffusion is often introduced by adding a term to the right-hand side of the time-dependent equations, and it takes on different forms, as shown in the following equation:

$$\frac{\partial \chi}{\partial t} = S + (-1)^{n/2+1} K_n \nabla^n \chi, \quad (1)$$

where χ is any dependent variable, K is the diffusion coefficient, and $n = 0, 2, 4, 6$ indicates the term order. The S represents other processes or sources. The sixth-order term is chosen because it is more scale-selective and only touches the shortest waves.

Higher-order diffusion terms, although they are more scale-selective, can introduce a new local extreme, or noise, near large gradients in the model solution. This effect is known as the Gibbs phenomenon. In these schemes, the diffusive flux is not necessarily the down gradient, which leads to the nonphysical artifacts. One remedy to this problem is described by Xue (2000), where diffusive fluxes are set to zero whenever they are in the same direction as the gradient:

$$-F_{i+1/2} = -F_{1+1/2}\max[0, sign(-F_{1+1/2}\delta_x \chi)]. \quad (2)$$

Figure 7 displays the error distributions of the predicted track and intensity with and without the sixth-order diffusion term for TC1807 and TC1808. It shows that the sixth-order diffusion term has little impact on the track forecast of TC. The overall distribution of the track error at 24 h is slightly reduced, with the 24 h mean error is reduced from 100 km to 98 km. It has little effect on 72 h track forecast. In other words, the diffusion term can improve the short-range TC forecast. However, the six-order diffusion term has a significant impact on the intensity of the TC. Both the error distribution and the mean error of intensity is different. With the addition of six-order diffusion term, the mean error of 24 h intensity forecast decreased from 4.8 m/s to 4.0 m/s, and the mean error of 48 h intensity forecast decreased from 4.5 m/s to 4.2 m/s, the mean error of 72 h intensity forecast is reduced from 6.8m/s to 6.15 m/s. A Student *t*-test for statistical significant is performed on Fig. 7, The results show that both the improvement of track and intensity forecasts at each leading time is statistically significant at the 10% significant level. Among them, the 48 h track forecast and the intensity forecast at 24 h, 48 h, and 72 h is statistically significant at the 5% significant level.

3.3 Result analysis

To evaluate the impact of improvements of the vortex initialization scheme in Section 3.1 and the dynamic core in Section 3.2 on forecast. In addition to TC1807 and TC1808, 8 TCs affected China in 2018 were selected for comparative experiment. Figure 8 shows the selected TCs in the experiment, with a total of 118 forecasts. Figure 9 shows the track and intensity error from the original and

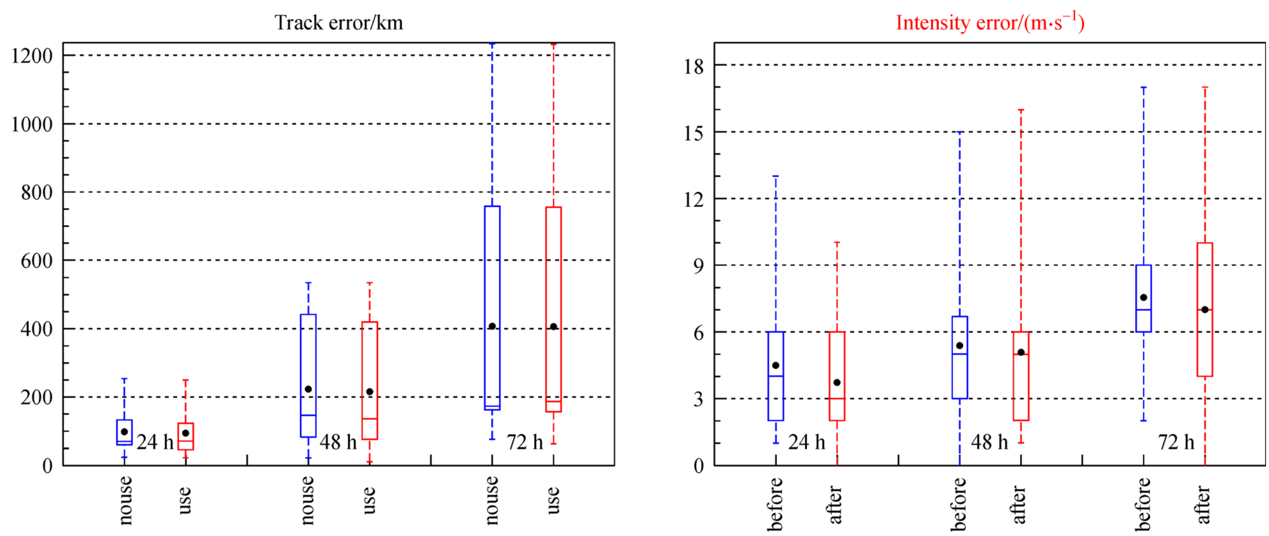

Fig. 7 Error distribution of predicted track and intensity with (red) and without (blue) the sixth-order diffusion term.

updated model. In the updated version, the extreme value of the 24 h and 48 h errors of track forecasting has no large difference from the original version, but the 72 h error distribution has a downward trend. The mean track error of 24 h, 48 h and 72 h decreased from 83.32 km, 173.24 km, and 263.18 km to 77.59 km, 166.60 km, and 241.27 km with the model improvements. The impacts of model improvement on intensity forecast are more significant than track forecast. Especially for 24 h intensity forecast, the maximum error decreased from 13 m/s to 10 m/s, and the mean error decreased from 4.48 m/s dropped to 3.7m/s. Similarly, the mean error of 48 h (72 h) forecast decreased from 5.38 m/s (7.84 m/s) to 5.08 m/s (7 m/s). It can be seen that improvements of the vortex initialization scheme and the dynamic core have positive effects on the track and intensity prediction. Similarly, the *t*-test for statistical significant is performed on 10 TCs in 2018, the improvement of track and intensity forecasts at each leading time is statistically significant at the 10% significant level. Among them, the track forecast at 48 h and 72 h and the intensity forecast at 24 h, 48 h, and 72 h is statistically significant at the 5% significant level.

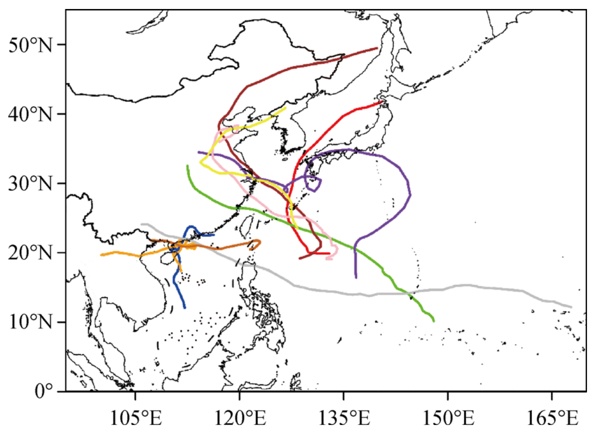

Fig. 8 TC track in 2018.

4 Forecast performance analysis in 2019

In the 2019 typhoon season, the operational forecast process of GRAPES-TCM was updated. In addition to the selection of the characteristic parameters of typhoon message and introduction of a sixth-order horizontal diffusion scheme, the forecast time is updated from twice a day to four times. Based on the existing vortex initialization scheme, the 12 h forecast vortex of the model is replaced by the 6 h vortex. The performance of this new forecast system in 2019 is as follows.

4.1 Track error distribution

There are 29 TCs in the Northwest Pacific Ocean in 2019, the 24 h track error distribution of GRAPES-TCM is shown in Fig. 10. Based on the multi-color error scatter plot, it can be seen that the blue dots are wildly distributed throughout the entire domain and have the greatest number, where most of the error lies in the 55–70 km range. From the geographic distribution perspective, there are more westward TCs in this low-latitude (< 16°N) area, and the model has a sufficient forecast ability for this type of TC, with most of the errors less than 70 km. The model also forecasted TCs generated in certain areas (> 136°E) well. This type of TC primarily moves north-westward with a more northerly component. Although there are some extreme individual TC and forecast initial time errors, the forecast errors are approximately 70–95 km. Additionally, the errors larger than 100 km are concentrated in two areas. One is the area around the eastern part of Taiwan Island, namely 120°E–132°E, 17°N–30°N, and there are two

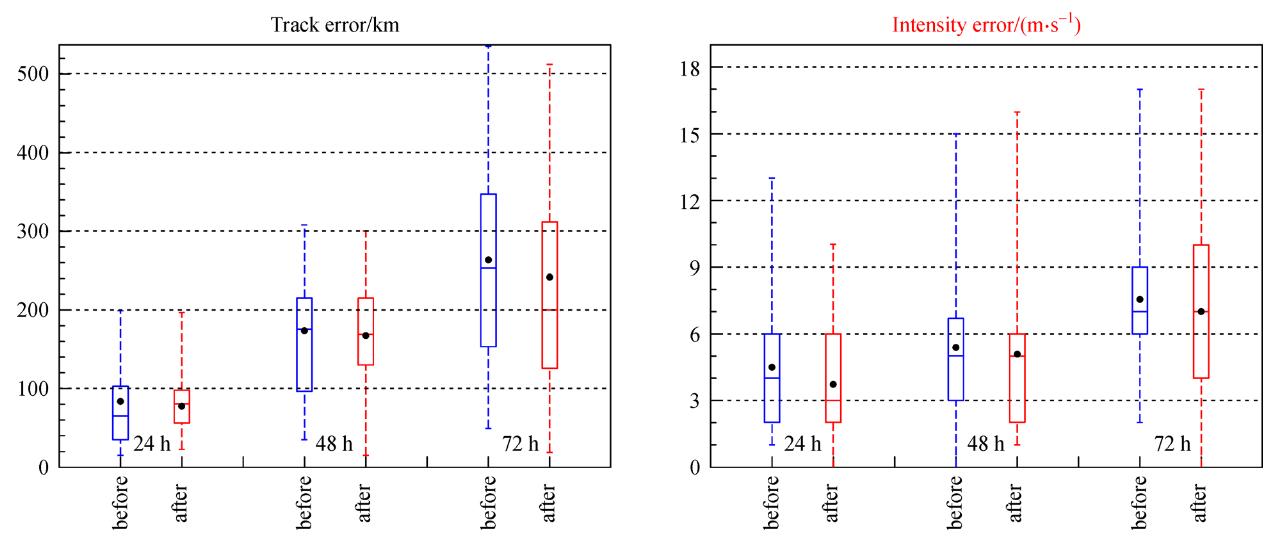

Fig. 9 Error distribution of predicted track and intensity before (blue) and after (red) improvement. The black dot is the mean error.

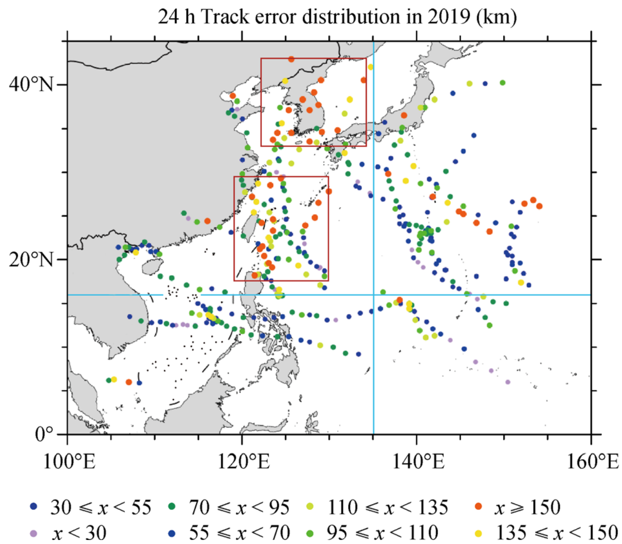

Fig. 10 Track error distribution for the 24 h forecast.

reasons for the forecast errors. First, the forecast error of movement occurs when the TC was born at the initial time. Second, the TC speed error occurs when the TC is rapidly increasing. The other is in the Korean Peninsula and the southern part of the Sea of Japan: 122°E–135°E, 37°N–43°N. In this area, TCs always have a long lifespan and are typically recurve at high latitudes. The model has a larger forecast error for this type of TC due to a lack of understanding of the interactions between TCs and synoptic systems at high latitudes.

4.2 Intensity error distribution

The intensity prediction of the GRAPES-TCM is shown in Fig. 11. The *x*-coordinate is the TC number, the *y*-coordinate is the absolute error of the maximum wind

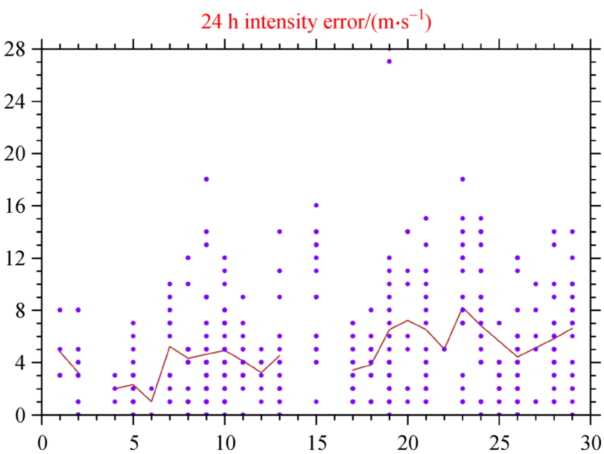

Fig. 11 Absolute error of maximum wind speed distribution in 2019 for the 24 h forecast. The *x*-coordinate is the TC number, *y*-coordinate is the absolute error of the maximum wind speed, and brown line is the mean error.

speed, and the brown line is the mean error. The intensity forecast of each TC is clearly different, even for the same TC with different lifetime stages, and the prediction is also different. Overall, when the TC intensity is weak and there is no development during its entire lifetime, the maximum intensity does not exceed the STS level (< 24.5 m/s), and the intensity forecast of this type of TC is stable at all times, with the maximum error not exceeding 8 m/s (e.g., TC1901, TC1905).

The top five maximum intensity errors are analyzed in Table 1. From the time of the forecast, the five forecasts all appeared in the evening, and four of them appeared at 1800 UTC. Additionally, the first four forecasts all involved the typhoon rapidly increasing within 24 h with the maximum wind speed increasing to 40 m/s, 35 m/s, 22 m/s, and 20 m/s. For these cases, although the model intensity error at the initial time does not exceed 3 m/s, it is difficult to accurately describe this TC progress. As a result, the increase in the maximum wind speed model forecast is much smaller than that of the observation, which makes the intensity error abnormally large. TC1915 is the opposite case, the maximum error occurs in the maintenance phase of the typhoon intensity. However, the model predicts the wind speed of TC will decrease rapidly from 50 m/s to 26 m/s. After further analysis, it can be seen that from 0200 September 9, 2019 to 0200 September 10, 2019, the TC intensity decreased rapidly, and the maximum wind speed decreased from 42 m/s to 23 m/s. It indicates that the model depicts the rapid TC weakening process, but the forecast is faster than that of the observations.

Table 2 shows the forecast of the 29 TCs in 2019. The statistical samples of the 24 h, 48 h, and 72 h forecasts are 350, 300, and 230, and the track errors are 84.9 km, 166.6 km, and 238.4 km, respectively. The absolute errors of the maximum wind speed are 4.9 m/s, 6.9 m/s, and 9.18 m/s for the 24 h, 48 h, and 72 h forecasts, respectively. Comparing the multi-year error trends in Fig. 1, the track error in 2019 increased slightly compared with that in 2018, of which the 48-h track error has the clearest increase, reaching 23 km. In terms of intensity forecast, the performance of the 24-h intensity is stable, the error continues to decrease. However, there is a slight rise in the 48-h forecast, and the 72-h intensity forecast performance is unsatisfactory. To find the reason for the poor performance of the 72-h intensity forecast, the large error area distribution where the error exceeds 20 m/s was analyzed, and it was found that large errors mostly occurred in the TC rapid enhancement phase. The model exhibits two different performances for this process. For example, TC1923 was a weak TC with a maximum wind speed of 18 m/s at 0000 UTC on November 3, 2019, and two days later, the TC increased rapidly and developed into a super typhoon (65 m/s). Although the model can reflect the development of the vortex to a certain extent, it cannot accurately describe the rapidity of the development of the processes. In another case, such as TC1925 at 0600UTC

Table 1 Top five maximum intensity errors (m/s)

TC ID	Time period	babj	SGTM	Error
1919	10061200UTC–10071200UTC	25–65	22–37	28
1919	10061800UTC–10071800UTC	30–65	28–38	27
1909	08161800UTC–08071800UTC	30–52	28–34	18
1923	11041800UTC–11051800UTC	45–65	42–47	18
1915	09071800UTC–09081800UTC	48–42	50–26	16

Table 2 Track and intensity error in 2019

Item	24 h	48 h	72 h
Sample	350	300	230
Track error/km	84.9	166.6	238.4
Intensity error/($m \cdot s^{-1}$)	4.9	6.9	9.18

on November 12, 2019. The maximum wind speed of the typhoon vortex increased from 18 m/s to 45 m/s within 72 h, but the model did not respond to this process, and the maximum wind speed forecast remained at approximately 14 m/s. The two types of situations mentioned above are closely related to the model resolution, selected physical process, and vortex initialization scheme, which is exactly how the model must be improved in future works.

5 Simulations of Typhoon Lekima

5.1 Overview of Typhoon Lekima

Lekima was the strongest tropical cyclone of the western North Pacific in 2019. It was formed in eastern Luzon Island on August 4, 2019. It further slowly moved to the northwest and gradually increased to a typhoon on August 7, 2019, and reached its peak intensity with a wind speed of 63 m/s (super typhoon) after 18 h. It made landfall on the coast of Wenling City, Zhejiang Province at 1745UTC on August 9, 2019 with a maximum wind speed near 52 m/s. The typhoon weakened rapidly after landfall and gradually curved northward, affecting Shanghai, Jiangsu, Shandong, etc., and then it entered the Yellow Sea and made landfall again on the coast of Qingdao City and Weifang City, Shandong Province on August 11, 2019 and dissipated on August 13, 2019 (Fig. 12).

5.2 Track, intensity, and precipitation forecast

The track and intensity forecasts by GRAPES-TCM are shown in Fig. 12. The red line is the subjective forecast, and the blue lines are model forecasts. The 24 h, 48 h, and 72 h track errors are 75.9 km, 113.37 km, and 192.9 km, respectively, which was significantly better than the average model forecast level in the past five years (2014–2018), namely 87 km, 158 km, and 259 km. Based on the track forecast, at the early stage of TC, the forecasted moving speed of TC was slow due to its weak intensity and the effect of TC1910. When the TC is

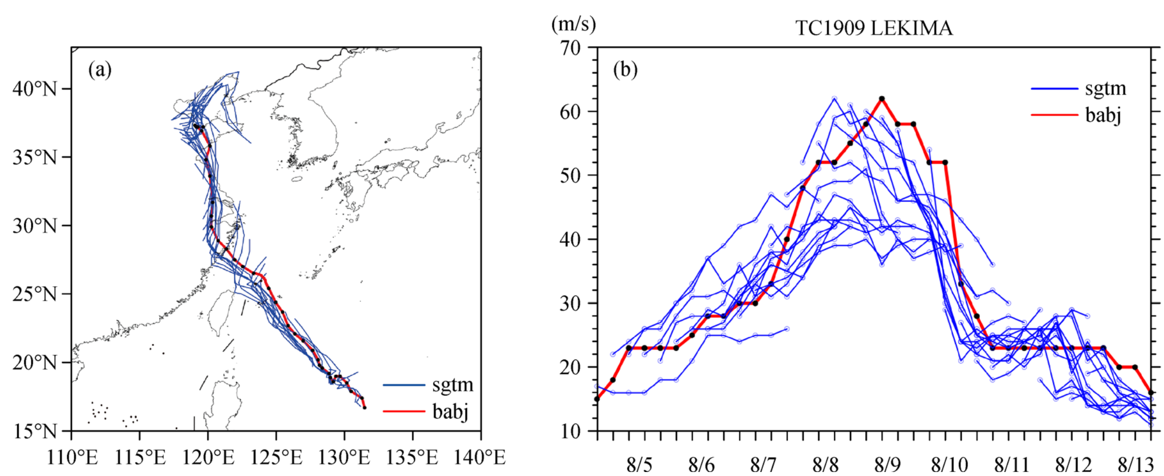

Fig. 12 (a) Track and (b) intensity forecast of Lekima. Red line is the subjective forecast, and blue lines are forecasts from GRAPES-TCM.

approaching the east coast of China, the forecast track appears to be southward. It is worth noting that the TC track forecast was significantly deviated due to the influence of the terrain near the Taiwan Island. Subsequently, the TC made landfall and kept moving to the north, and the model forecast agrees with the subjective forecast. Later in the TC lifetime, due to its combination of cold air at a high latitude, the TC intensity clearly weakened, which made it difficult to capture the center of the TC, thus resulting in a large track error.

The intensity errors of the model are 4.6 m/s, 7.6 m/s, and 9 m/s for the 24 h, 48 h, and 72 h forecasts, respectively. Compared with the average errors of the past five years which are 6.8 m/s, 8.1 m/s and 9.1 m/s for the 24 h, 48 h, and 72 h forecasts, respectively, it can be seen that the intensity forecast ability continues to improve within 2 d, especially within 24 h. The absolute error of the maximum wind speed is 4.6 m/s for 24 h, which is smaller than that of the previous year (5.14 m/s). Additionally, the error is reduced by 2.2 m/s, compared with the average error of the past five years, with a decrease of 32.3%. The intensity error of 48 h demonstrated an oscillating downward trend, and the error of 72 h was similar to the average error of the past five years. There are two stages during the entire life of Lekima: the rapidly increasing period from August 7, 2019 to August 8, 2019 and the rapidly decreasing period after its landfall on August 10, 2019. The model forecasts of these two periods are substantially different, in term of the TC enhancement phase, where the model forecast fails to capture the rapid increase in the typhoon intensity at 1200 UTC on August 7, 2019. The maximum forecast wind speed is 50 m/s, which is less than 10 m/s from the subjective forecast. Further analysis (not shown) demonstrates that although there is not much more difference in describing the large-scale circulation of the background field of the model, it is still difficult to reflect this rapid enhancement process. This process may be related to the model resolution and physical processes, which are more complicated; however, in terms of the rapid weakening process of TC on August 10, 2019, GRAPES-TCM provided a superior forecast, and the forecast was stable at multiple times, demonstrating a sufficient forecast consistency. In addition, when TC is in the development period, the initial intensity error of the model is essentially maintained at 1–2 m/s compared with the observation. However, when the TC is in the weakening period, the initial intensity error increases, and the frequency of errors above 3 m/s increase.

Figure 13 shows the automatic weather station 24 h accumulated precipitation observations at 12 h intervals from 1200 UTC on August 8, 2019 to 0000 UTC on August 12, 2019. This study focuses on the impact of heavy precipitation caused by Typhoon Lekima on the eastern coastal areas of China. Based on Fig. 12, it can be seen that as the typhoon gradually approached the eastern coast and subsequently made landfall, Zhejiang, Shanghai, Jiangsu, and Shandong were severely affected. The precipitation intensity was large, and the coverage of the heavy precipitation areas (greater than 100 mm) was wide. Additionally, a center of heavy precipitation exceeding 250 mm appeared in many time periods. There is a strong center of heavy precipitation exceeding 500 mm before and after the typhoon made landfall on August 9, 2019.

Figure 14 shows the 24 h accumulated precipitation forecast of the GRAPES-TCM. Comparing the precipitation observations of Fig. 13, the model highlights the strong precipitation area of Typhoon Lekima and reasonably predicts the precipitation distribution pattern of the landfall typhoon. It can be seen that before the TC made landfall, there is a large area of heavy precipitation (over 100 mm) surrounding the typhoon itself. Regarding the landfall in the evening of August 9, 2019, the precipitation was primarily concentrated in the Zhejiang Province, which was consistent with the observations. When the typhoon moved north, the forecast track was faster and its intensity was weaker than that in the observations, where the location of the precipitation area was northern even more, and the coverage of the heavy precipitation area was smaller, with much weaker intensity.

5.3 Landfall forecast

Lekima made landfall on the coast of Wenling City, Zhejiang Province in the evening on 9, 2019. Figure 15 shows the track of the GRAPES-TCM at 12 h intervals from August 7 to 9, 2019 and the corresponding sea level pressure field at 1800 UTC on August 9, 2019. The red line is the subjective forecast from the CMA. The forecast at 0000 UTC on August 7, 2019 indicated that Lekima would make a near 90° turn near 123°E north-east of Taiwan Island (Fig. 15(a)), suggesting that there was no possibility of landfall. However, from 1200 UTC on August 7, 2019, due to the influence of the Taiwan Island topography, the model predicted that the typhoon may land or skip the northern part of Taiwan Island (Fig. 15(b)). The adjustment of the model in the later period is clear, and the typhoon is predicted to continue to move northward and approach the coast of Zhejiang and Fujian in the later period. The forecast at 0000 UTC on August 8, 2019 indicated that both the model and subjective forecast suggested that the TC will move steadily northwest (Fig. 15(c)). The two types of forecasts also predict a landfall time of 1800 UTC on August 9, 2019. The difference is the specific landfall location of the two types of forecasts, and the model forecast is slightly southward by 1° in latitude. The forecast at 1200 UTC is similar to that 12 h before (Fig. 15 (d)). The model was consistent with the landfall time, but the landfall location of the new forecast was further south.

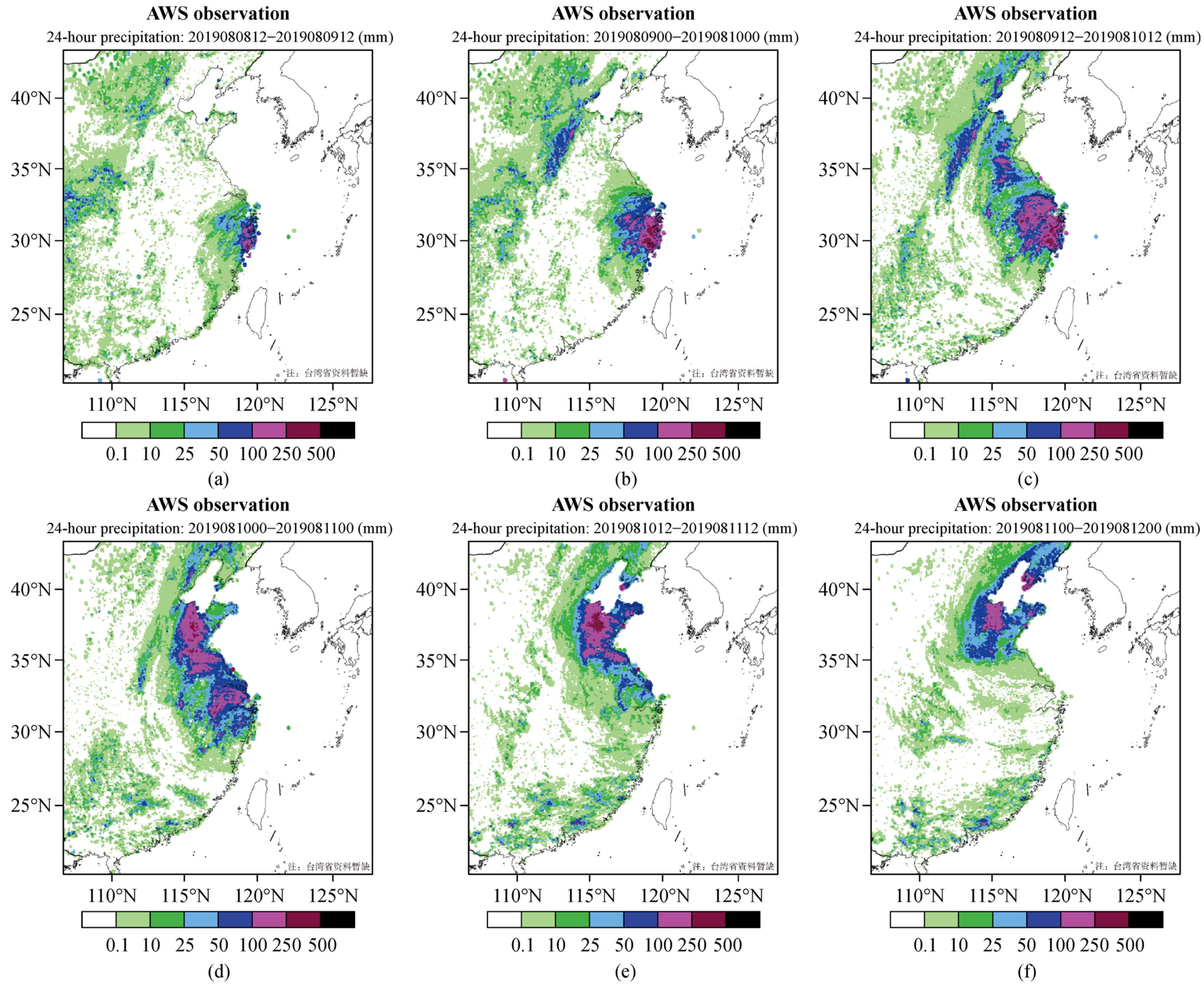

Fig. 13 Accumulated precipitation observation of 24 h forecast at 12 h intervals from 1200 UTC on August 8, 2019 to 0000 UTC on August 12, 2019.

Furthermore, this new forecast provides more accurate information that TC moves northward along the inland of the Zhejiang Province after landfall. At 0000 UTC on August 9, 2019, the TC was closer to the coast of Zhejiang, and the track forecast from the model was closer to that of the subjective forecast (Fig. 15(e)). For the landfall point predictions, the two forecast types are nearly the same, but the model prediction of the landfall time is slightly earlier than observation. Overall, it can be seen from the five forecasts of the landfall point that the model can provide a trend forecast of TC landfall 2 d in advance and provide a forecast about the timing and specific landfall location 42 h in advance. Moreover, there is little difference in the time and location predictions of the TC landfall in subsequent times, which reflects the consistency and stability of the forecast.

6 Discussion and conclusions

In 2019, the operational GRAPES-TCM was optimized by adopting the characteristic parameters in the babj message, introducing the horizontal sixth-order diffusion scheme, and adjusting the operational flowchart, increasing the operational reporting rate by 18% over the previous year. More than 350 forecasts were made for 29 TCs in 2019. Conclusions of the forecast analysis are as follows.

The model has a reliable forecasting ability for

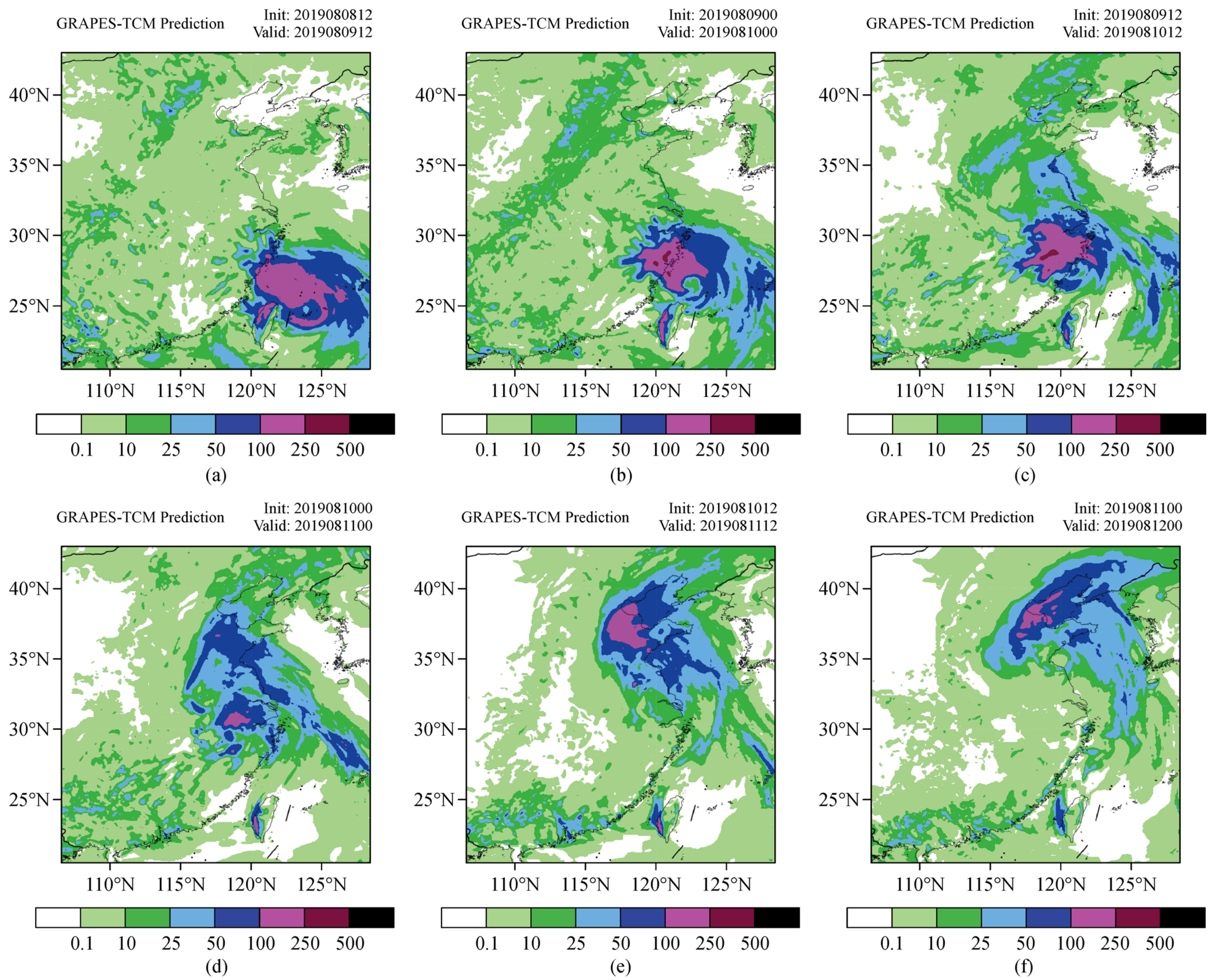

Fig. 14 24 h accumulated precipitation forecast at 12 h intervals from 1200 UTC on August 8, 2019 to 0000 UTC on August 12, 2019.

north-westward TCs such as Lekima. The track and intensity forecasts are significantly better than those of the averages of the past five years, especially the intensity forecast within 24 h; the error is reduced by 2.2 m/s compared with the average error, a decrease of 32.3%. GRAPES-TCM highlights the heavy precipitation area of the typhoon Lekima and reasonably predicts the precipitation distribution landfall pattern of the typhoon. The model can provide a trend forecast of the TC landfall 2 d in advance, and the timing and the specific location of landfall 42 h in advance. Moreover, there is little difference in the prediction of the time and location of the TC landfall in subsequent times, which reflects the consistency and stability of the forecast. In addition, the model provides a sufficient description of the rapid weakening process after the typhoon landfall.

The evaluation results of the TC forecast in 2019 demonstrates that the updated GRAPES-TCM exhibits a small oscillating track error compared with that of the previous year, and the forecast performance in each leading time is stable. The 24 h intensity forecasting ability continues to improve. Through the analysis of forecast, it can be seen that the model lacks the ability to forecast TCs that are rapidly increasing in a short time period, and there is a large forecast uncertainty for weak TCs and TCs affected by the influence of topography. In addition, in the initial stage of TC generation, when multiple TCs exist simultaneously, the existing vortex initialization scheme is not possible to handle multiple vortices simultaneously, resulting in an inaccurate description of the initial field and underestimation of the vortex intensity. Additionally, the existing vortex initialization scheme cannot reflect the interaction between multiple TCs. These deficiencies should be further improved in future research.

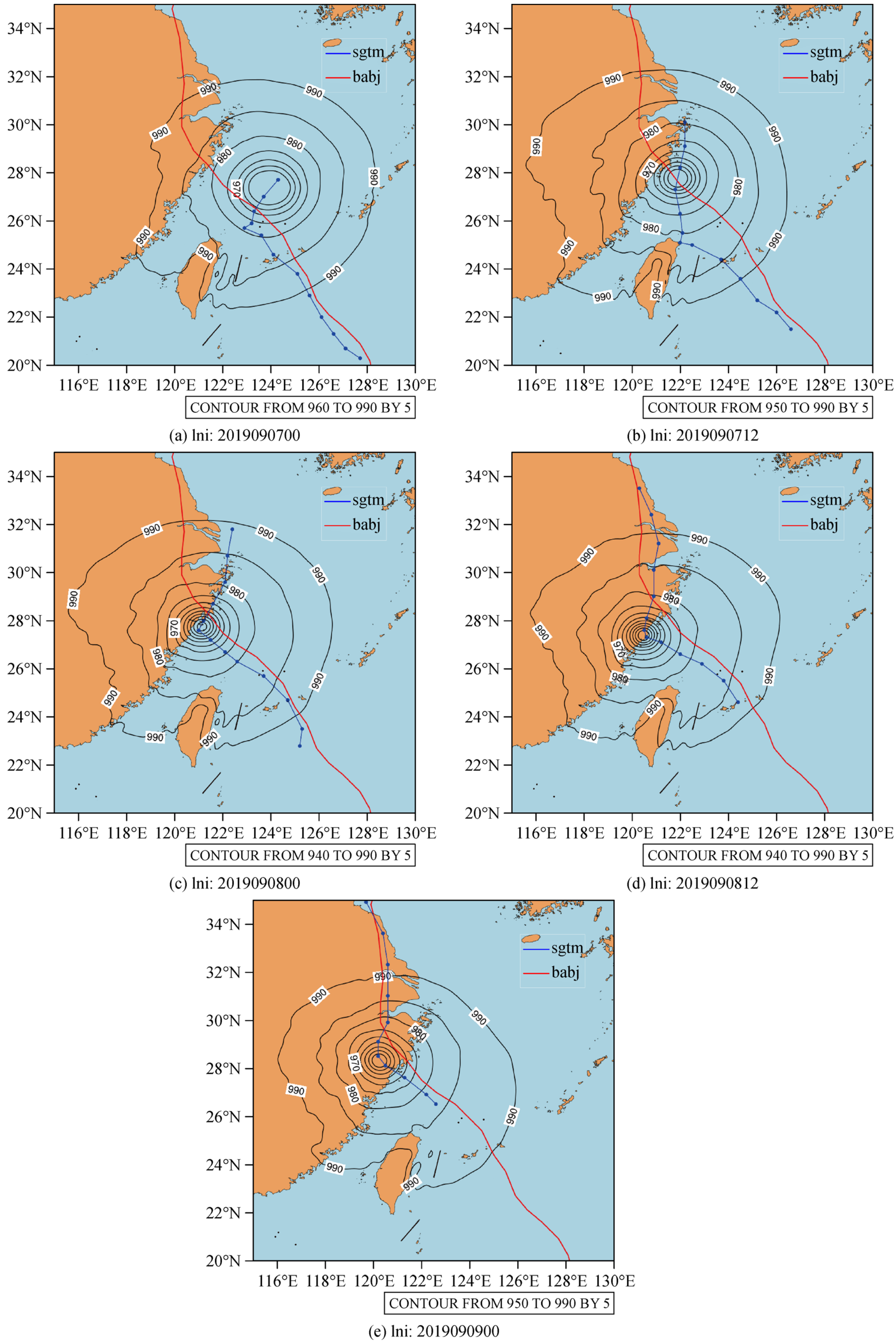

Fig. 15 Forecast track and sea level pressure at 1800 UTC on August 9, 2019. The red line is the subjective forecast, and the blue lines are forecasts from GRAEPS-TCM.

Acknowledgements This work is supported by the National Key Research and Development Program of China (Nos. 2016YFE0109700 and 2017YFC150190X), the National Natural Science Foundation of China (Grant Nos. 41975133 and 41975067), Science & Technology Committee of Shanghai (Nos. 19dz1200101 and 19dz1201500) and the National Defense Pre-Research Foundation (No. 305090417). We also thank the support from the Typhoon Scientific and Technological Innovation Group of Shanghai Meteorological Service.

References

Chen G, Zhang X, Bai L, Wan R (2019). Verification of tropical cyclone operational forecast in 2018. In: Annual report for ESCAP/WMO Typhoon Committee

Chen P, Yu H, Xu M, Lei X, Zeng F (2019). A simplified index to assess the combined impact of tropical cyclone precipitation and wind on China. Front Earth Sci, 13(4): 672–681

Chen Z, Dai G, Zhong S, Huang Y, Zhang Y, Xu D, Li M (2016). Technical features and prediction performance of typhoon model for the South China Sea. J Trop Meteorol, 32(6): 831–840 (in Chinese)

Huang W, Duan Y, Xue J, Chen D (2007). Operational experiments and its performance analysis of the tropical cyclone numerical model (GRAPES_TCM). Acta Meteorol Sin, 65(4): 578–587 (in Chinese)

Huang W, Liang X (2010). A cycling typhoon-like vortex initialization scheme and its application to GRAPES-TCM. Acta Meteorol Sin, 68 (3): 365–375 (in Chinese)

Huang W, Zhang X, Bao J, Chen B (2018). Implementation and improvement of the GFS physics package in the GRAPES regional model: single column experiments. Chin J Atmos Sci, 42(6): 1219–1234 (in Chinese)

Huang Y, Xue J, Feng Y, Chen Z, Zhang C, Li M, Li J (2018). An initialization scheme using forecast vortexes and its application in simulation of typhoons Linfa and Chan-Hom in 2015. J Trop Meteorol, 34(5): 598–609 (in Chinese)

Klemp J B (2011). A terrain-following coordinate with smoothed coordinate surface. Mon Weather Rev, 139(7): 2163–2169

Li H, Luo J,Chen B (2015). Assimilation of real observational data with the GSI-hybrid data assimilation system to improve typhoon forecast. J Trop Meteorol, 21(4): 400–407

Ma S, Chen D (2018). Analysis of performance of regional typhoon model in national meterorological center. J Trop Meteorol, 34(4): 451–459 (in Chinese)

Qian C, Duan Y, Ma S, Xu Y (2012). The current status and future development of China operational typhoon forecasting and its key technologies. Adv Meterol Sci Tech, 2(5): 36–43 (in Chinese)

Qu A, Ma S, Li J, Hu J, Liu Q (2009b). The initialization of tropical cyclones in the NMC global model. Part II: implementation. Acta Meteorol Sin, 67(5): 727–735 (in Chinese)

Qu A, Ma S, Liu Q, Li J, Hu J (2009a). The initialization of tropical cyclones in the NMC global model. Part I: scheme design. Acta Meteorol Sin, 67(5): 716–726 (in Chinese)

Tan Y, Chen B (2014). Study of multiple perturb tropical cyclone ensemble forecast. Plateau Meteor, 33(4): 1012–1021 (in Chinese)

Tan Y, Liang X (2012). An ensemble forecast experiment of a landfall typhoon. J Trop Meteor, 18(3): 314–321

Xu X, Liu Q, Chen B, Wang X (2019). Vortex initialization scheme in GRAPES-TCM Model: technical description and implementation. Chin J Atmos Sci, 43(5): 975–989 (in Chinese)

Xue M (2000). High-order monotonic numerical diffusion and smoothing. Mon Weather Rev, 128(8): 2853–2864

Yu H, Chen L S (2019). Impact assessment of landfalling tropical cyclones: introduction to the special issue. Front Earth Sci, 13(4): 669–671

Zhang J, Ma S, Chen D, Huang L (2017). The improvements of GRAPES_TYM and its performance in Northwest Pacific Ocean and South China Sea in 2013. J Trop Meteorol, 33(1): 64–73 (in Chinese)

Zhang X, Huang W, Chen B (2015a). Implementation of the Klemp height-based terrain-following coordinate in the GRAPES regional model: idealized tests and inter-comparison. Acta Meteorol Sin, 73(2): 331–340 (in Chinese)

Zhang X, Huang W, Chen B (2015b). Implementation of a 2nd order semi-implicit semi-Lagrangian trajectory algorithm and time integration scheme in the GRAPES regional model. Acta Meteorol Sin, 73(3): 557–565 (in Chinese)