Performance Evaluation of the GRAPES Model in Wind Simulations Over South China

ZHONG Shui-xin (钟水新), CHEN Zi-tong (陈子通), DING Wei-yu (丁伟钰), XU Dao-sheng (徐道生), ZHANG Yan-xia (张艳霞), WU Kai-xin (吴凯昕), LIANG Jia-hao (梁家豪), TIAN Qun (田群), WANG Li-wen (王立稳)

(Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction/ Guangzhou Institute of Tropical and Marine Meteorology, China Meteorological Administration, Guangzhou 510080 China)

Abstract: In the present study, the performance of the GRAPES model in wind simulation over south China was assessed. The simulations were evaluated by using surface observations and two sounding stations in south China. The results show that the GRAPES model could provide a reliable simulation of the distribution and diurnal variation of the wind. It showed a generally overestimated southerly wind speed especially over the Pearl River Delta region and the south of Jiangxi Province as well as the coastal region over south China. GRAPES also exhibited a large number of stations with the opposite surface wind directions over the east of Guangxi and the south of Jiangxi during the nocturnal-to-morning period, as well as an overall overestimation of surface wind over the coastal regions during the afternoon. Although GRAPES could simulate the general evolutional characteristics of vertical wind profile, it underestimated wind speed above 900 hPa and overestimated wind speed below 900 hPa. Though the parameterization scheme of gravity wave drag proved to be an effective method to alleviate the systematic deviation of wind simulation, GRAPES still exhibited large errors in wind simulation, especially in the lower and upper troposphere.

Key words: GRAPES; wind simulation; overestimated surface wind; systematic deviation

1 INTRODUCTION

The Global / Regional Assimilation and Prediction System for the Tropical Mesoscale Model (GRAPES_TMM [1]) has demonstrated strong wind biases, especially over the complex terrain in south China [2-3]. These biases could be partially improved by adopting the sub-grid orographic parameterization scheme [2, 4-5]. However, the biases persist in the GRAPES model especially during warm seasons, which may lead to strong biases in the simulation of warm-sector torrential rains over the complex region [6, 7]. The biases of wind simulations are ubiquitous in most of the numerical weather prediction (NWP) models. It has been found that the models show systematic overestimations of near-surface winds during stable conditions especially when modeling the nighttime boundary layer [7-13]. The overestimations of surface wind over complex terrain are more significant during the warm sector torrential rains over south China [3]. It is speculated that the overly strong southerly surface winds from the South China Sea would lead to strong wind biases [14].

It is argued that the biases could be generated due to a lack of parameterizations of the unresolved orographic features [5, 14-15] and the overly smooth topography used in the model [3]. For example, without the inclusion of the gravity wave drag induced by subgrid orography, the NWP models may exhibit excessively strong westerlies and southerly deviation as well as the warm pool effect [2]. These biases could also result from imperfect initial and lateral boundary conditions, as well as misrepresentations such as the synoptic-scale and topographic features [16]. Besides, the overly strong orographic drags in the low-order closure models and the enhanced friction velocity could also lead to strong wind biases [14, 16-18]. The systematic evaluations are crucial to recognizing the corresponding performances of the wind simulations of the model, which could provide suggestions on better use of the model products and further development of the modeling techniques.

High spatiotemporal observations provide further opportunities for in-depth evaluation of wind simulations. Currently, the hourly observations from more than 13, 000 weather stations could be obtained.
through the operational forecast system over south China. However, due to the lack of wind field evaluation of the model, there is a lack of in-depth study on the performance of GRAPES in wind field simulation, especially in the wind field simulation of complex areas over south China. For example, the characteristics of the biases including the overall trends, the distribution, and diurnal variations of the biases are not clear, and the seasonal performance of the wind simulation at the vertical layers is uncertain. The objectives of this study are to evaluate the performance of the GRAPES model in wind simulation and to assess possible gravity wave drag parameterization scheme to improve wind simulation. Questions that motivate the study include the following:

1. What are the overall performances of the GRAPES model in the simulation of the wind in south China?

2. What are the diurnal characteristics of the surface wind distribution and vertical profile of observation and simulation?

3. To what extent the gravity wave drag parameterization can improve the GRAPES simulations of wind?

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_i \left( F_c - O_a \right)^2 \right]^{1/2}, \quad \theta^{C} = \theta^O \] and \( \theta^{F} = \theta^O \).

\[
\text{Bias} = \frac{1}{N} \sum_i \left( F_c - O_a \right) \left\{ \begin{array}{ll}
\text{UN}_{\text{bias}}, & F_c < O_a \\
\text{OV}_{\text{bias}}, & F_c > O_a
\end{array} \right\}, \quad \theta^{C} = \theta^O \] and \( \theta^{F} = \theta^O \).

where \( F_c \) is the simulation and \( O_a \) is the observation. \( N \) is the number of stations. \( \text{UN}_{\text{bias}}, \) and \( \text{OV}_{\text{bias}} \) denotes the average biases by underestimation and overestimation, respectively. \( \theta \) denotes the wind direction. The subscripts represent the meridional \( (u) \) and latitudinal wind \( (\theta) \). The superscripts represent the simulation \( (F) \) and observation \( (O) \).

2.2 Experiment design

The model used in this study is an operational version over south China based on the GRAPES_TMM \[14\]. The diurnal variation of the bias by the 24hr simulation initialized at 1200 UTC is verified. The monthly performance of gravity wave drag parameterization in the 48hr simulation in May is further examined. The simulation domain comprises \( 913 \times 513 \) grid points \[5\], with a horizontal resolution of 3 km and 65 layers in the vertical direction. Initial conditions and lateral boundary fields are updated every 6 hours by the European Centre for Medium-Range Weather Forecasts (ECMWF).

The physical schemes use the same configuration as that in Zhong et al. \[14\], including the gravity wave drag induced by subgrid orography (GWDO) parameterization scheme. Subgrid orographic effects such as mountain blocking drag \[17\] and parameterization effects on atmospheric boundary layer \[13\] are not considered in the experiments. The interpolations of meteorological variables from the points of a regular grid to the stations are performed by the Cressman interpolation method \[21\]. The wind speed and direction hourly time series are extracted at the same locations and examined between simulation and observation at each station.

3 RESULTS

3.1 Overall performance

To reveal the overall performance of GRAPES in the simulation of surface wind, Fig. 1 gives the diurnal variation of the average RMSE and corresponding bias. It can be seen that GRAPES generally captured the diurnal variations of surface wind speed. Both the observation (OBS) and simulation (SIM) showed a single peak of the surface wind speed around 1800 Local Standard Time (LST) and reached its minimum value around 1000 LST. In particular, the model showed an overall underestimated wind speed, which was about 1 m s\(^{-1}\) stronger than the observations. The number of stations by underestimated (overestimated) surface wind reached more than 1400 (800). The magnitude of the biases with underestimation was 1.5–2.2 m s\(^{-1}\) and the biases with overestimation were 1.1–1.6 m s\(^{-1}\). In general, the surface wind speed and corresponding
RMSE of the GRAPES simulation reached the maximum in the afternoon and the minimum in the morning.

Figure 2 gives the distribution of the hourly average biases and corresponding accumulative hours over south China. It can be seen that the strong overestimated wind was mainly located over the flatter areas and the underestimated wind was mainly located over the mountainous regions. In particular, the model exhibited both strong underestimated and overestimated surface wind speed over the coastal regions and the Pearl River Delta (PRD) regions. The strong underestimated wind mainly located over the north of Yunkai Mountains (YK) and the PRD region, and the strong overestimated wind was mainly located over the south and southwest region of YK, as well as the PRD region.

It also can be seen that the coastal areas exhibited a high frequency of wind-simulation biases. The overestimations mainly existed over south of Jiangxi Province (JX), in the middle area of Guangxi Province (GX), and over the coastal areas and the PRD region in GD. The underestimations were mainly located over the mountainous regions of Guizhou Province (GZ) and Fujian Province (FJ), as well as the coastal areas and the PRD region in GD. Note that the surface wind over the mountains partly represents the tropospheric low-level wind. The performance of the GRAPES simulation on the vertical profile of the wind speed needs to be further verified. We address this issue in the following sections.

For the bias of the opposite direction between the simulated and observed wind (Fig. 3), the model showed similar characteristics of the diurnal variation and magnitude of the bias in Fig. 1. However, it showed a larger number of stations with overestimated and underestimated surface wind. In particular, GRAPES showed a strong underestimation of surface wind speed with the opposite simulated-wind directions to observation in the west of GZ and FJ (Fig. 4). This may be related to the strong simulation-bias of the wind speed over mountains by GRAPES[3].

Similarly, in terms of overestimation of wind speed,
GRAPES also showed strong simulation-bias over the coastal region. Previous studies showed that the coastal regions over south China were prevailing southerly wind during warm seasons [20, 22-24]. In addition, significant northerly wind occurred at night and early in the morning in the mountainous regions, especially in the environment related to warm sector torrential rains (WSTR) [6, 24]. Corresponding wind bias of GRAPES may lead to the rain belt deviation of the simulation over this region, especially for the WSTR during warm seasons [5, 24].

3.2 Diurnal distribution
To reveal the diurnal characteristics of surface wind, the performance of GRAPES in the simulation of strong southerly wind in the afternoon and the land breeze during late night and early morning are examined. Fig. 5 shows the distribution of the biases at 0400 LST and 1600 LST. It can be seen that in the afternoon, GRAPES exhibited an overall overestimated southeasterly wind especially over the coastal regions and the mountainous region in the west of GX. In the nocturnal-to-morning period, GRAPES exhibited overly strong northeasterly land breeze over the PRD region and northeast of GD. GRAPES also exhibited a generally overestimated southerly wind over the south of JX.

Figure 6 gives the comparisons between the simulation and observation of the surface wind. GRAPES generally captured the northerly land breezes in the early morning and the southerly sea breezes in the afternoon over south China. Nevertheless, the model showed an overall overestimation of surface wind speed. In particular, during early morning, observed surface wind over east of GX and south of JX was weak southwesterly winds and northerly land breezes, respectively. However, GRAPES exhibited an opposite northeasterly wind over the east of GX and southerly wind over the south of JX, as well as southerly wind over the west of GX. These biases can be further validated with the large number of opposite wind directions during the nocturnal-to-morning period as
shown in Fig. 3 and Fig. 4.

For the afternoon, GRAPES also exhibited an overall overestimation of the southerly sea breezes, especially over the coastal region of GD and GX. It is speculated that the overestimation of wind speed may be related to the unrealistic representation of the sub-grid orographic effects. Zhong et al. developed a sub-grid orographic drag scheme by adding a sink term in the momentum equations and improved the model performances of GRAPES in the simulation of surface wind. However, GRAPES nevertheless exhibited strong biases in the simulation of the surface wind over south China, especially over the complex region during warm seasons.

3.3 Verifications based on sounding data

For the vertical wind profile, GRAPES generally captured the evolutionary characteristics of the vertical profile (Fig. 7), including the upper-level westerly jet in March and the weakening stage in April, as well as the transition phase from the westerly wind to the easterly wind in May (Fig. 8). However, the model showed an underestimated southerly wind in 900-300 hPa and an underestimated easterly wind above 300 hPa from June to August. In addition, it showed overestimated wind speed below 900 hPa, which was consistent with the results of the surface wind verification in sections 3.1 and 3.2.

Note that the NWP models may inherit the bias from the initial and lateral boundary conditions. The initial conditions (ICs) from the ECMWF were also investigated. It can be seen that ICs exhibited similar biases as GRAPES simulations. However, the ICs of the ECMWF showed a weaker overestimation below 900 hPa and a weaker underestimation of wind speed above 900 hPa than the GRAPES simulation. The strong bias of wind simulation by the NWP models might also associate with the inaccuracies from the planetary boundary layer (PBL) parameterization schemes.
which could lead to systematic errors in the simulation of boundary layers wind. In addition, the inaccuracies from the subgrid orographic parameterization schemes (e.g., GWDO and subgrid-scale orographic effects) might further lead to unrealistic simulations such as overly strong westerly wind and southerly winds.

3.4 Gravity wave drag effects

To examine GWDO effects on wind simulation, a month of control experiments (CTL) was conducted without the inclusion of the GWDO effects. It can be seen that GRAPES overestimated the wind speed below 900 hPa and underestimated the wind speed above 900 hPa at HK and Qingyuan station (Fig. 9). Both the 24 hr and 48 hr simulations of the wind profile by GWDO experiment showed generally more realistic wind profiles. In particular, the GWDO simulation exhibited a weaker wind speed than the CTL simulation did, especially above 900 hPa. The bias of the GWDO simulation was generally smaller than the bias in the CTL especially in the middle and upper troposphere (Fig. 10).

Previous studies found that the GWDO parameterization could improve the forecast of the wind distribution at the lower troposphere, help alleviate the excessively strong westerlies in winter simulations and alleviate the overly strong easterly in summer simulations. In this study, the results further demonstrated that the GWDO parameterization can improve GRAPES performances on wind simulation. However, it still exhibited large errors, especially in the lower troposphere. It is speculated that the current scheme might underestimate gravity wave drag. Moreover, the stratification properties have significant impacts on the GWDO scheme. For example, the lower stability of the atmospheric layers may cause too much wave breaking and contribute to excessive drag to the upper levels. On the other hand, the stronger stability of the lower layers due to underestimation of the low-level temperature may lead to a more stable stratification and cause too much drag in the low troposphere. In this respect, it should further validate the parameterization scheme when modeling the integrated effects of the multi-scale weather systems, especially over complex terrains.

4 CONCLUSION AND DISCUSSION

In this study, the performance of the GRAPES model in the simulation of the wind over south China
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Figure 9. Comparison of monthly mean wind profile by (a, c) 24 hr and (b, d) 48 hr simulation and observation in May 2018 at (a, b) Hong Kong Kings Park station and (c, d) Qingyuan station.

Figure 10. Comparison of monthly mean wind speed difference between the simulation and observation in May 2018 at (a) Hong Kong Kings Park station and (c) Qingyuan station by (a, c) 24 hr simulation and (b, d) 48 hr simulation.
was evaluated. A total of 7 months of simulations were conducted and the results were verified by using the surface wind observations in south China and sounding data at Hong Kong King Park station and Qingyuan station. The results show that the GRAPES can provide reliable estimates in wind simulation, but it also exhibited some typical bias. Main findings are summarized as follows:

1) GRAPES generally captured the diurnal characteristics of surface wind over south China. It exhibited a generally overestimated southerly wind speed especially over the PRD region, south of JX, and the coastal regions over south China. The underestimated wind was mainly located over the mountainous regions of GZ and FJ, as well as the coastal regions in south China.

2) GRAPES exhibited a large number of stations with opposite surface wind directions especially over the east of GX and over the south of JX during the nocturnal-to-morning period. For the afternoon, GRAPES showed an overall overestimated surface wind over the coastal regions.

3) GRAPES could simulate the general evolution characteristics of the high-level wind, including the upper-level westerly jet in March and the weakening trend of the jet in April, as well as the transition phase from the westerly wind to the easterly wind in May. However, it showed an underestimated southerly wind above 900 hPa and an overall overestimated wind speed below 900 hPa.

4) The simulations with GWDO parameterization provided a more realistic simulation. However, GRAPES still exhibited large errors in wind simulation, especially in the lower troposphere.

More detailed evaluations should be conducted to examine GRAPES performances in the simulation of diurnal characteristics of the wind over places such as the lee side and the windward slope of mountains as well as the valleys over complex terrain. In addition, more target sensitive experiments should be conducted to evaluate and improve performances in wind simulation, including the planetary boundary layer parameterization and subgrid orographic parameterization. The schemes of model physics with vertical flux exchanges between the lower and upper-level troposphere need to be further validated and parameterized.

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