ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 24, NO. 6, 2007, 1099–1108

Numerical Weather Prediction in China in the New Century —Progress, Problems and Prospects

XUE Jishan* (薛纪善) and LIU Yan (刘 艳)

State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081

(Received 30 January 2007; revised 3 July 2007)

ABSTRACT

This paper summarizes the recent progress of numerical weather prediction (NWP) research since the last review was published. The new generation NWP system named GRAPES (the Global and Regional Assimilation and Prediction System), which consists of variational or sequential data assimilation and nonhydrostatic prediction model with options of configuration for either global or regional domains, is briefly introduced, with stress on their scientific design and preliminary results during pre-operational implementation. In addition to the development of GRAPES, the achievements in new methodologies of data assimilation, new improvements of model physics such as parameterization of clouds and planetary boundary layer, mesoscale ensemble prediction system and numerical prediction of air quality are presented. The scientific issues which should be emphasized for the future are discussed finally.

Key words: numerical weather prediction, new progress, China

DOI: 10.1007/s00376-007-1099-1

1. Introduction

Great progress in the research and operations of numerical weather prediction (NWP) in China have been made since the beginning of the new century. They are driven by the requirements for high quality weather forecasting and the availability of more powerful computer resources and abundant observational data. Recognizing the key role of the development of NWP in upgrading meteorological operations and services, the Chinese Ministry of Science and Technology and the Chinese Meteorological Administration conducted a series of research and development projects to enhance the research on NWP. Among them, the most important are the state key research project, the development of the Chinese New Generation Numerical Weather Prediction System, and the state basic science research project, the China Heavy Rain Experiment and Study. The former is aimed directly at the development of new generation NWP systems mainly for operational implementation; the latter emphasized the research on new theory and methodology with potential to improve NWP of heavy rain events. Both projects, completed around 2005 and renewed recently to reach their long term goals, along with others sponsored by the Chinese National Natural Science Foundation and other funding agencies, have attracted more scientists involving in NWP research than ever before. In comparison with the past, the scientific interests are expanded and a number of works are devoted to issues that have been dealt with less than several years ago, such as the assimilation of remote sensing data and the development of non-hydrostatic model, both being crucial for upgrading Chinese NWP operations. Most studies in this period are related to the development of the new generation Chinese NWP system so that the operational applications of the results are emphasized. In the years prior to 2003, the research focuses were to set up the bases of the new NWP system, such as development of the fundamental framework of the non-hydrostatic model and variational data assimilation, so that few integrated results came out. After the completion of these basic studies, more work turned to the integration of system components developed in the earlier years and optimization of a new system based on batch experiments. The new concepts and methods with potential to further improve NWP are also studied widely in recent years.

In a review published in 2004, after a brief introduction to the objectives, research topics, and ex-

*Corresponding author: XUE Jishan, xuejsh@cma.gov.cn

pected outcome of the project of Development of Chinese New Generation Numerical Weather Prediction System, the authors summarized the main scientific achievements reached up to 2002, including the dynamic core of a new non-hydrostatic model and variational data assimilation system for satellite radiance. Since this earlier review, a fully new Global and Regional Assimilation and Prediction System (GRAPES) has been established and the research focuses have turned to the refinement rather than the setting up of the systems and further development of NWP technologies. It is not surprising that the performance of the Chinese new generation NWP system, not being a mature system yet, is not as satisfactory as some advanced systems that have been developed over a long period of time by scientific teams abroad, and more efforts must be made for further development in the future.

This paper summarizes the recent progresses of NWP researches since the last review (Xue, 2004) was published, with the stresses in the achievements of GRAPES project, for they constitute the main advances in NWP in China. Important results beyond GRAPES project are also introduced in order to depict the panorama of development of NWP in China. The achievements in data assimilation is presented in section 2, followed by advances in high resolution model and quantitative precipitation forecast, global medium range prediction systems, model physics, ensemble prediction, and application in environmental issues in section 3 through section 7. Finally, section 8 concludes the review with a discussion on issues which should be emphasized in the future.

2. Data assimilation

2.1 *Development of GRAPES-Var and GRAPES-EnKF*

GRAPES-Var is the variational data assimilation component of GRAPES, including GRAPES-3DVar (3 Dimensional Variational) and GRAPES-4DVar (4 Dimensional Variational). The global version of GRAPES-3DVar inherits most subroutines from the regional version, which was developed in 2001–2002 and briefly described by Xue (2005), except that a spectral filter takes the place of a recursive filter in the latter for preconditioning of control variables. Assimilation cycles combining both regional and global versions of GRAPES-3DVar and GRAPES prediction model are built up and an extensive series of pre-operational trials are conducted. The GRAPES-3DVar is capable of directly assimilating both conventional and nonconventional observation data, such as radiances from polar orbital satellite NOAA15 (National Oceanic and Atmospheric Administration), NOAA16 and NOAA17, atmospheric motion vectors from geostationary satellites and Velocity Azimuth Display (VAD) data from Doppler radar, etc. The use of remote sensing data in GRAPES-3DVar is of great significance in the alleviation of the sparseness of conventional observational data in NWP.

Following GRAPES-3DVar, GRAPES-4DVar is developed (Xue, 2006). It is the extension of GRAPES-3DVar in that the time integration of the prediction models is introduced into the system to assimilate all observations distributed within a time window, thereby obtaining the flow-dependent background error statistics. Preliminary results of experiments of GRAPES-4DVar with real conventional and non-conventional observational data are encouraging, showing substantial improvements of forecasts in comparison with those of GRAPES-3DVar. GRAPES-4DVar is the first four-dimensional variational assimilation system capable of implementation in the real operational environment developed in China, and one of few variational assimilation systems based on non-hydrostatic prediction models currently available. Its accomplishment means a breakthrough in the area of data assimilation in China, and sets up the foundation for further updating of the Chinese data assimilation system. The tangent linear and adjoints of the GRAPES prediction model in GRAPES-4DVar were completed by using an automatic differential tool, YH-TAD, developed by mathematicians participating in the GRAPES project. The tangent linear and adjoints of GRAPES may be used in studies of the sensitivity of forecast errors to the initial conditions and other model parameters, as well as in ensemble forecast systems.

GRAPES-EnKF (GRAPES-Ensemble Kalman Filter), developed recently, is an alternative in data assimilation of GRAPES. It is based on the GRAPES-3DVar so that it can share most codes, including optimization algorithms and observational operators of 3DVar, with the covariance matrix of background errors derived from ensemble statistics so as to take the flow-dependent features of model errors into account. GRAPES-EnKF may be superior to 4DVar for only the forward model, rather than before the linear tangential and adjoint is integrated, the latter two being controvertible in cases where strong nonlinear physical processes dominate. It may be an alternative of 4DVar for storm-scale NWP for nonlinear physical processes are essential in these circumstances, and used in ensemble prediction system for constructing initial perturbations. A diagnostic system based on an ensemble transform Kalman filter (ETKF) in the framework of GRAPES-EnKF has also been built to study the targeted observations. Case studies show positive effects of extra observations in the upstream over the northwestern Pacific Ocean on the prediction of tropical cyclones making landfall in China.

2.2 *New methodologies of data assimilation*

The research on data assimilation beyond the project of GRAPES in recent years focuses mainly on how the new approaches of variational data assimilation or methodologies differ from variational methods. A new approach called "3-dimensional variational data assimilation of mapped observation (3DVM)" is proposed, based on the new concepts of mapped observation and backward 4DVar (Wang and Zhao, 2005). 3DVM produces an optimal initial condition (IC) that is consistent with the prediction model by taking the model as dynamical and physical constraints and best fits it to the observations within the assimilation window through the model solution trajectory. The main difference between the concepts of 3DVM and the 4DVar lies in that the IC derived from 3DVM is referred to the end rather than the beginning of the assimilation window. The new approach greatly reduces the computing cost and also improves the assimilation accuracy, because the tangent linear and adjoint approximations in calculating the gradient of the cost function are avoided. It is shown in a case study of assimilation of AMSU-A (Advanced Microwave Sounding Unit-A) data that the new approach produces satisfactory IC for 72-hour simulation with 1/7 computing costs of 4DVar. Mu and Wang (2003) studied the problem in variational data assimilation related to the "on-off" switches in physical parameterizations of the NWP models. They analyze the impacts of different treatments of switches in tangent linear models on minimizing the cost function in 4DVar and indicate that keeping the switches in the tangent linear model the same as in the forward model might yield a local minimum rather than the global minimum if the cost function has multiple minima. They proposed a new way to obtain the global descent direction which is helpful to find the global minimum (Mu and Zheng, 2005).

Qiu and Chou (2005) proposed an approach of four-dimensional data assimilation called 4DSVD based on Singular Value Decomposition (SVD) derived from a coupled data set which is created by integrating the NWP model and simulated observational operators. The analysis is simply completed by projecting the observational data onto the space spanned by the singular vectors. Four-dimensional data assimilation is simplified to a linear inverse problem with this approach so that the adjoint of both the prediction model and observational operators and the covariance matrix of background error are no longer needed.

2.3 *Remote sensing data assimilation*

The development of GRAPES-Var builds a base for the assimilation of most remote sensing data, among which the data from ATOVS (Advanced TIROS Operational Vertical Sounder) on board the polar orbiting satellites of the NOAA series greatly dominate the volume currently ingested into GRAPES system. Results from a number of trials have demonstrated the positive impacts of direct assimilation of ATOVS data with GRAPES-3DVar on predictions of the track and intensity of tropical cyclones (Xue et al., 2003; Dong and Xue, 2005). In order to improve the practical effects of the assimilation of satellite data, a few scientific issues have been studied. Dong et al. (2005) tested an algorithm to improve the estimation of emissivity of land surface in the microwave band. The land surface emissivity is first retrieved from specific channels sensitive to land surface characteristics, and then these retrieved values are fed into the radiation transfer model for other channels. Real data experiments show that the new scheme results in better performance of GRAPES-Var.

Direct assimilation of the data of radial velocity and reflectivity derived by Doppler weather radars also have been studied in the framework of GRAPES-3DVar. In order to assimilate these data, the control variables are expanded to include the vertical velocity and the parameters of cloud microphysics, and new observation operators are introduced into GRAPES-Var. It has been shown that Radar data assimilations not only improve the analysis of the wind field, but also provide cloud information, resulting in positive impacts on the prediction of mesoscale storms (Gu, 2006). The assimilation of radar data gives a way to initialize the clouds for time integration of NWP model with an explicit cloud scheme rather than using convective parameterization. This so called "hot start" of model integration results in a better forecast in a trial of rainstorm events than so called "cold start" and has the potential to improve very short term forecasts (Liu et al., 2007). Positive contributions of remote sensing data on the mesoscale NWP are also shown by research with GRAPES and other systems (e.g. Xu et al., 2004; Wan et al., 2005, 2006; Li et al., 2006b; Zhang and Ni, 2005).

With the increase of the number of available ground- and space-based GPS data, more and more scientists devote themselves to assimilating this kind of data into NWP models, most showing obvious positive impacts. An experiment with the data of atmospheric precipitable water (PW) obtained from a set of 11 ground GPS receivers in the Yangtze River Delta shows that GPS PW results in better forecasts of 6h accumulated precipitation prediction in earlier hours of model integration (Yuan et al., 2004). The observational operators for space based GPS in terms of the bending angle or ray-tracing method were developed with improved parallel computing algorithms, setting up a base for assimilation of GPS/MET (Wang and Wang, 2003; Zhang et al., 2004).

3. High resolution model and quantitative precipitation forecasts

GRAPES is designed to meet the needs of numerical prediction for different scales with the focus on very-high-resolution modeling. A number of idealized tests, such as density flow and mountain wave, and spectral analyses of kinetic energy derived from GRAPES model output with different resolution are conducted in order to evaluate the ability of the model to simulate the atmospheric motions in different scales. The results fit well with the theoretical solutions and those of the non-hydrostatic models developed abroad in recent years. These results show that upgrading model resolution and introducing non-hydrostatic dynamics improve the modeling of small scale motion without harmful impact on large scale motions, and the use of the semi-Lagrangian scheme of time integration for non-hydrostatic model with very high resolution is acceptable, supporting the feasibility of a unified dynamic core when applied to models for diverse uses in GRAPES (Xue, 2006).

The prediction model of GRAPES may be implemented with limited area or global configurations and a number of options of model physical schemes are provided. Table 1 lists physical parameterization schemes currently available in the GRAPES model for a regional setting. The regional GRAPES model and GRAPES-Var constitute the assimilation and prediction system GRAPES-Meso which is in fully operational implementation in the national and a few of regional meteorological centers after a long time in pre-operational experiments. The performance of the new operational NWP system is comparable to those of operational NWP models of other countries. In cases of typhoon or tropical storms over the northwestern Pacific Ocean, the new typhoon model based on GRAPES-Meso gave the minimal forecast error of the tracks in the real time run of 2003–2005.

AREM is an advanced version of a regional Etacoodinate model (REM) developed in the late 1980s which intends to handle the effects of the Tibetan Plateau and many other steep mountains in the NWP model by introducing steep mountain approximation. Recent developments include increasing spatial resolu-

Table 1. Physical parameterization schemes in GRAPES-Meso.

Explict precipitation	Convection precipitation	Longwave radiation	Shortwave radiation	Surface layer	Land surface	Boundary layer
(1) Kessler	(1) New Kain-Fritsch	(1) RRTM	(1) Dudhia simple shortwave	(1) Similarity theory	(1) Thermal diffusion	(1) MRF
(2) Lin (Purdue)	(2) Betts-Mille-Janjicr	(2) GFDL	(2) GFDL scheme	(2) MYJ surface	(2) OSU/MM5 LSM	(2) Mellor-Yamada-Janjic
(3) NCEP simple ice	(3) Kain-Fritsch	(3) ECMWF	(3) GSFC		(3) improved NCAR LSM	(3) Second order turbulent closure scheme
(4) NCEP mixed phase			(4) ECMWF			
(5) Eta old microphysics						
(6) Eta new microphysics						
(7) CAMS simply ice scheme						
(8) Large scale precipitation iterative coagulation scheme						
(9) ECMWF larger scale precipitation coagulation scheme						

tions and updating physical parameterizations. It is run operationally in Hunan, Hubei, and Anhui Provincial Bureaus of Meteorology along the Yangtze River, and shows great capability of the AREM in forecasting heavy rainfall events over most of China region. Case studies show that the AREM captures reasonable structures and evolutions of the rainfall systems along the Yangtze River (Yu and Xu, 2004).

A high resolution non-hydrostatic tropical atmospheric model was developed by using a ready-made regional atmospheric modeling system (Shen and Sumi, 2005). The motivation is to investigate the convective activity associated with tropical intra-seasonal oscillation (ISO) through cloud resolving calculations. The model domain with the size of 2000 km$\times$2000 km and a spatial resolution of 5 km covers the forefront of an ISO-related westerly. The results indicate the importance of stratus-cumulus interactions in the organization of the cloud clusters embedded in the ISO. In addition, a comparison of grid sizes of 2-km and 5-km is conducted, which suggest no distinctive differences although some finer structures of convection are discernible in the 2-km case. The significance of this study resides in supplying a powerful tool for investigating tropical cloud activity without the controversy of cloud parameterizations.

4. Development of global medium range prediction

GRAPES-Global is the first global assimilation and prediction system developed by Chinese scientists, and is one of the few non-hydrostatic global models available now. It inherits many features of GRAPES-Meso with the refinements of the model to reduce the errors due to the spherical geometry and optimization of physical parameterization schemes for diverse geographic and climatic conditions. Besides, an efficient scheme of parallel computing for global configuration also was developed. The prototype of GRAPES-Global was completed around 2004. The results of ideal experiments of pole-ward flow, balanced flow, and the Haurwitz wave are consistent with other mature global models or the theoretical solutions. A series of hindcast trials have been undertaken using GRAPES-Global assimilation and prediction system since 2005. Figure 1 depicts the 500 hPa height anomaly correlation coefficient (ACC) averaged over five months in the summer and winter of 2005. For comparison, the results of the current operational system (T213) are also displayed. The significant improvement in forecast skill of GRAPES-Global can be seen in this figure. Tests for selected cases of high impact weather events in recent years, e.g., typhoon Matsa (Fig. 2), give similar results.

GRAPES-Global is currently discretized in latitudinal-longitudinal grid mesh, with which the polar singularity is always a tough issue to deal with. To avoid the problems completely, a new mesh called the Yin-Yang grid is studied as an alternative candidate of grid mesh for future GRAPES-Global model. The Yin-Yang grid is a newly developed grid system in spherical geometry with two perpendicularly-oriented latitude-longitude grid components (called Yin and Yang respectively) overlapping each other, and effectively avoiding the coordinate singularity and the grid convergence near the poles. In this overset grid, the way of matching data between the Yin and Yang components is the key to maintaining the accuracy and robustness in numerical solutions. Li et al. (2006a) designed an interpolation scheme for boundary data exchange, which maintains the accuracy of the original advection scheme and is computationally efficient. Numerical results show that the quasi-uniform Yin-Yang grid can get around the problems near the poles, and the numerical accuracy in the original semi-Lagrangian scheme is effectively maintained. A new version of GRAPES-Global adopting the Yin-Yang grid is being developed. The development of the global 3DVar with Yin-Yang grid also succeeded, showing comparable results with the original global 3DVar and is easy to code. Besides the progress of GRAPES-Global, the operational global medium range assimilation and prediction system of the National Meteorological Center has been upgraded from T106 to T213 in 2003.

5. Model physics

Unlike the earlier work on model physics, recent research in this field pay more attention to understanding the inherent mechanism of physical processes related to the formation and evolution of the weather system in China, and attempt to improve the parameterization scheme based on more physical considerations.

Chen et al. (2003) investigated the impacts of schemes of diabatic processes, including cumulus convection, planetary boundary layer (PBL), and radiation on the predictions of model variables in cases of heavy rain events. Their results show that the PBL and convection parameterization dominate the contribution of diabatic physical processes to the short term forecasts of precipitation, giving a clue of the primary issue in refining the NWP models.

Studies on the dynamic and thermodynamic conditions for middle cloud formation over east China indicate that the middle stratiform clouds downstream of

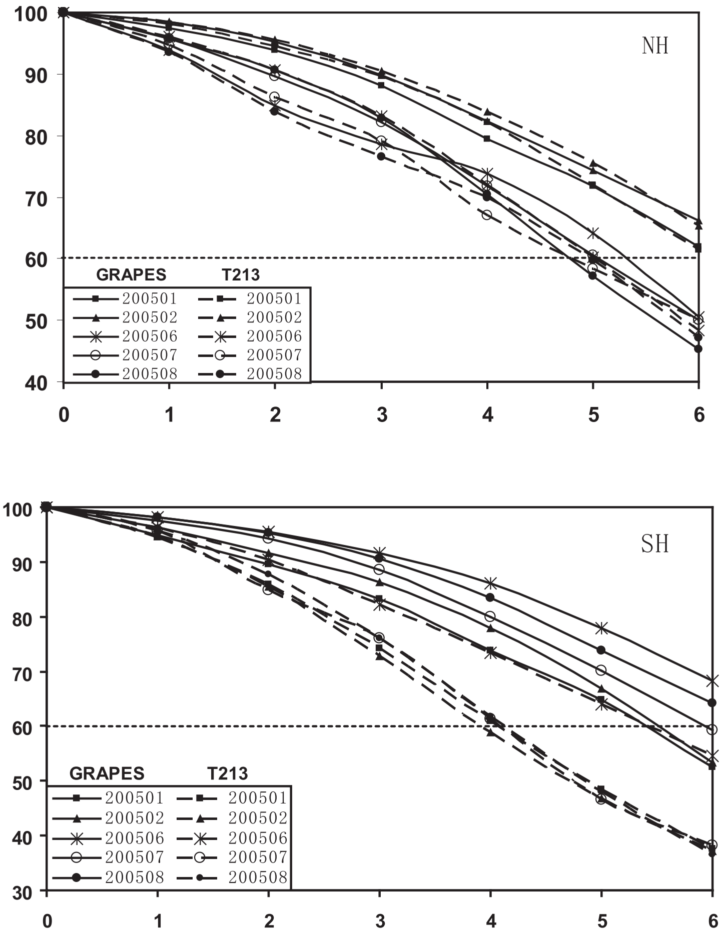

Fig. 1. 500 hPa height anomaly correlation coefficient averaged over five months in summer and winter of 2005 for both GRAPES-Global and T213.

the Tibetan Plateau are maintained by the frictional and blocking effects of the plateau. It is also found that the temperature inversion at the elevation of the plateau over east China generated by the warm air advection from the plateau provides a favorable thermodynamic condition for middle clouds and causes a diurnal cycle in the mid-troposphere over east China. The middle cloud amount decreases and the cloud top falls in the daytime, but the reverse happens at night (Li et al., 2005). Zhou et al. (2005) introduced a radiation transfer scheme based on delta-4 stream, correlated-k distribution into mesoscale model MM5, resulting in detailed information about cloud radiation properties. Their results present the importance of the radiation process in mesoscale precipitation.

Sun et al. (2005) developed a new PBL model (namely MY-4) with reference to Mellor-Yamada's Level 4 turbulent closure concept. Having been coupled with the mesoscale model MM5, it is utilized to simulate a heavy-rain event taking place over south China during 8–9 June 1998. The model output indicates that the rainfall process is better captured in terms of its intensity and geographical distribution by more accurate simulation of the major weather systems and the reduction of the false rainfall centers.

Up to now no convective parameterization scheme is developed based upon observations in China. It is widely accepted that the optimization of convective parameterization schemes in climatic conditions of the East Asia monsoon is one of the key issues to improve the prediction of precipitation. A number of works evaluated the performances of various convective parameterization schemes in modeling heavy rain events in China (e.g. Xu et al., 2006). It is found that different convective schemes often result in obvious discrepancy in the predicted precipitation field. This discre-

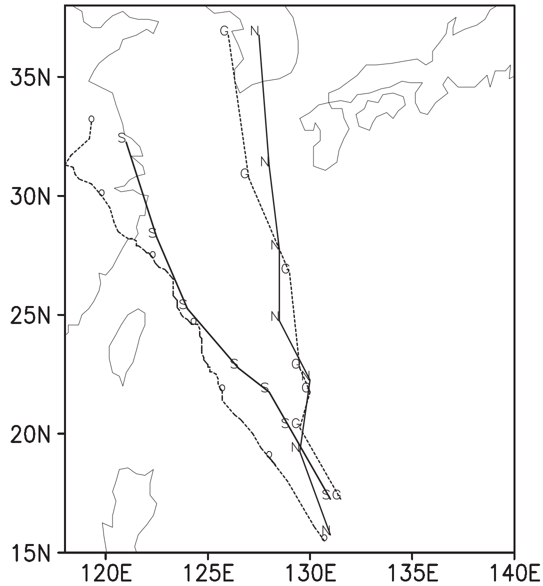

Fig. 2. Track prediction of typhoon Matsa in 2005 using GRAPES global assimilation and prediction system. N: NCEP; G: Xb(T213)+GTS; S: Xb(T213)+GTS+ATOVS; O: Beijing Observation.

pancy further creates different feedback to the large scale environment and precipitation in grid scale. However, most work of this kind is carried out with only a few selected cases and their conclusions are diverse. More studies with batch cases are necessary in order to reach the goal of refining the parameterization schemes in the climatic conditions of China.

6. Ensemble Prediction

Ensemble prediction has attracted more and more Chinese scientists in recent years, with a focus on mesoscale ensemble techniques. The strategy of the multi-model ensemble is adopted by a number of researchers. Some studies simply use different suites of schemes of model physics in the same dynamic frame, taking into account the fact that the model physics dominates the uncertainty of model forecasts in the mesoscale regime. This simple approach gives satisfactory results in case studies. Chen et al. (2006) designed a new initial perturbation method called DPMM (Different Physical Mode Method) for ensemble prediction of heavy rain. DPMM attempts to generate initial perturbations reflecting the uncertainty of convection instability by introducing the difference in prediction due to the use of various cumulus convective parameterization schemes. Huang et al. (2006) proposed an approach perturbing the initial location and intensity of tropical cyclones combining with the Bogus Data Assimilation scheme to generate a series of bogus vortex and initial conditions for model integration. The results are encouraging.

The development of global ensemble prediction system (GEPS) has been developed in the National Meteorological Center since the late 1990s (Li and Chen, 2002). Since the performance of the original GEPS based on singular vectors is not satisfactory, a new GEPS is being developed based on breeding growing modes (Gong Jiandong, personal communication). Meanwhile the study on GRAPES-GEPS is underway, combined with ETKF.

7. Application in environmental problems

GRAPES-Meso provides a base for numerical prediction of air quality in urban areas or large domains. The NWP model of sand and dust storms in GRAPES-DAM is developed by coupling GRAPES-Meso with an aerosol module which includes emission, dispersion, dry deposition, rain out, and scavenging of sand and dust particles in the air. The pre-operational tests were undertaken in the Chinese Academy of Meteorological Sciences. Similarly, based on the GRAPES-Meso, a forecast system towards city environments, GRAPES-Mega City, is developed. GRAPES-Mega City includes the parameterization scheme of urban canopy and introduces atmospheric chemistry and aerosol processes in order to improve the modeling of the urban heat island and to predict the air quality. It further drives a simple dynamical model to simulate the air flow features in street block scale and obtains the details of wind and temperature distribution in the city scale. These models have set up the foundation for the development of a new generation air quality model, and are expected to be applied in the city meteorological service.

Similar research was conducted based on other atmospheric models. Fang et al. (2004) established a user-oriented multi-scale numerical modeling system to simulate the urban meteorological environment. The system mainly involves three spatial scales: the urban scale, urban sub-domain scale, and the single to few buildings scale. The effects of building distribution, azimuth and screening of shortwave radiation and the influence of anthropogenic heating are taken into account. The simulated results are reasonably in agreement with the observational data. Li et al. (2003) developed an urban canopy parameterization (UCP) based on some advanced canopy parameterization, in which the effect of urban infrastructure and anthropogeny on the urban boundary layer and the rational representation of urbanization in mesoscale models are considered, and coupled with MM5. Sun et al. (2003) developed an integrated dust storm numerical modeling system in which a physical-based wind erosion scheme, a dust transportation model and the mesoscale NWP model MM5 with a geographic information database were coupled. Results show that the model can successfully simulate the dust emission and dust concentration in the air.

8. Concluding remarks

The development of the Chinese new generation numerical prediction model system GRAPES is one of the prominent scientific achievements in the recent years. Significant progress also has been made beyond the GRAPES project. The advanced variational assimilation and non-hydrostatic prediction model developed recently will constitute a new foundation of operational numerical predictions and modeling studies of high impact weather events. The efforts of introducing sophisticated schemes to deal with complex terrain in the model and upgrading the model physics will help to further improve the model performance. The results mentioned in previous sections also provide a new base for numerical modeling of environmental issues and climate changes.

From the point of view of long-term development of NWP in China, current achievements either in or out of the GRAPES project are very preliminary. More effort must be made to promote the operational application of GRAPES and to continuously improve its performance. Some scientific issues relevant to NWP should be emphasized in the near future. The most crucial problem is that little attention has been paid to the optimization of numerical schemes and physics on the climatic background in the East Asian monsoon area. There are four issues essential for the development in the near future.

(1) Data assimilation. The new data assimilation system has not resulted in as good an analysis and prediction as expected even though the observational data sources have been expanded due to the ingestion of remote sensing data. The major problem may come from the lack of careful tuning of the system details. For example, the complicated terrain and surface characteristics in the East Asia cause great variability of surface emissivity which are not accurately modeled in the current forward radiation transfer model used in satellite data assimilation. The assimilation of radar and other high-resolution remote sensing data is also a big challenge.

(2) The treatment of complex topography in the mesoscale model. A great number of tests with new model show that the semi-Lagrangian semi-implicit scheme used by the GRAPES model, even though accurate in the case of flat terrain, brings errors in predictions of both dynamic fields and precipitation. In addition, with the increase of model resolution, the dynamic and thermodynamic impacts of local terrain on the mesoscale weather systems must be taken into account. However little research has been conducted up to now which has been devoted to the numerical algorithms for high-resolution models to handle the complex topography in China.

(3) Model physics on the climatic background in the East Asia. Most of the model physical parameterization schemes adapted by Chinese NWP models were developed based on the studies with data in regions other than the East Asian monsoon area. Some of the schemes may not simulate the real physical processes in this area due to the dependence of the dominating mechanism on the climate and geographic conditions. It has been apparent for a long time that the development of physical parameterization schemes appropriate to the Chinese climate background is one of the most crucial issues in order to improve the NWP in China, but no satisfactory progress has been made. The combination of schemes for different physical processes should also be studied carefully. In some cases, the performance of an individual scheme may become worse when the parameterization of another physical process is changed. In other words, the interaction of different physical processes must be taken into account when the model physics is optimized.

(4) Ensemble forecast system. Even though the importance of the ensemble forecast has been recognized widely by Chinese scientists, the number of studies on this topic is still small. A number of scientists devoted to developing mesoscale ensemble prediction systems by use of the so-called model perturbation approach as stated above, but the resulting predictions are satisfactory only in limited cases, and its theoretical base is arguable. It is likely that before the operational implementation of mesoscale ensemble prediction systems based on this approach, more research must be carried out in order to reduce the arbitrariness of the algorithms and improve its performance. The techniques to perturb initial fields in a global ensemble system also need more studies in order to improve the current operational system to support the mesoscale ensemble prediction system.

Acknowledgements. This work is jointly funded by the national key-research project "Innovative Researches on Chinese Numerical Weather Prediction System" (Grant No. 2004BA607B) and the project of National Natural Science Foundation of China "Study on Weather Prediction Associated with Heavy Precipitation in China" (Grant No. 40233036). The authors thank the scientist team of the project "Innovative Researches on Chinese Numerical Weather Prediction System" for generously providing a number of up-to-date achievements and allowing us to cite their part of tables and figures.

REFERENCES

Chen, J., J. Xue, and H. Yan, 2003: The impact of physics parameterization schemes on mesoscale heavy rainfall simulation. *Acta Meteorologica Sinica*, **61**, 203–218. (in Chinese)

Chen, J., J. Xue, and H. Yan, 2006: A new initial perturbation method of ensemble mesoscale heavy rain prediction. *Chinese J. Atmos. Sci.*, **29**, 717–726. (in Chinese).

Dong, P., and J. Xue, 2005: An adjusted parameter scheme of land surface emissivity for assimilation of microwave satellite data. *Proc. SPIE: Atmospheric and Environmental Remote Sensing Data Processing and Utilization: Numerical Atmospheric Prediction and Environmental Monitoring*, Huang et al., Eds, San Diego U.S., The International Society for Optical Engineering, 274–280.

Dong, P., Z. Liu, and J. Xue, 2005: The Use of ATOVS Microwave Data in the Grapes-3Dvar System. *Proc. Fourteenth International TOVS Study Conference*, Beijing, China, The World Meteorological Organization, 274–280.

Fang, X., and Coauthors, 2004: The multi-scale numerical modeling system for research on the relationship between urban planning and meteorological environment. *Adv. Atmos. Sci.*, **21**, 103–112.

Gu, J., 2006: Three dimensional variational method study on directly assimilation of Doppler radar data. Ph.D. dissertation, Chinese Academy of Meteorological Science, 228pp. (in Chinese)

Huang, Y., Q. Wan, J. Yuan, and W. Ding, 2006: Experiments of ensemble forecasts of typhoon track using DBA perturbing method. *Journal of Tropical Meteorology*, **22**, 49–54. (in Chinese)

Li, X., J. He, and B. Bi, 2003: The design of urban canopy parameterization of MM5 and its numerical simulation. *Acta Meteorologica sinica*, **61**, 526–539. (in Chinese)

Li, X., D. Chen, X. Peng, F. Xiao, and X. Chen, 2006a: Implementation of the semi-Lagrangian advection scheme on a quasi-uniform overset grid on a sphere. *Adv. Atmos. Sci.*, **23**, 792–801.

Li, Y., R. Yu, Y. Xu, and T. Zhou, 2005: AREM simulations of cloud features over Eastern China in February. *Adv. Atmos. Sci.*, **22**, 260–270.

Li, Y., G. Zhu, and J. Xue, 2006b: Microphysical retrieval from Doppler radar reflectivity using variational data assimilation. *Acta Meteorologica Sinica*, **20**, 20–27.

Li, Z., and D. Chen, 2002: The development and application of the operational ensemble prediction system at the national meteorological center. *Quarterly Journal of Applied Meteorology*, **13**, 1–15. (in Chinese)

Liu, H., H. Xu, Z. Hu, J. Xue, and T. Shen, 2007: Radar reflectivity factor applied to initialize cloud-resolving meso-scale model. Part I: Retrieval microphysics elements and vertical velocity. *Acta Meteorologica Sinica*, in Press. (in Chinese)

Mu, M., and J. Wang, 2003: A method for adjoint variational data assimilation with physical "on-off" processes. *J. Atmos. Sci.*, **60**, 2010–2018.

Mu, M., and Q. Zheng, 2005: Zigzag oscillations in variational data assimilation with physical "on-off" processes. *Mon. Wea. Rev.*, **133**, 2711–2720.

Qiu, C., and J. Chou, 2005: Four-dimensional data assimilation method based on SVD: Theoretical aspect. *Theor. Appl. Climatol.*, **83**, 51–57.

Shen, X., and A. Sumi, 2005: A higher solution nonhydrostatic tropical atmospheric model and its performance. *Adv. Atmos. Sci.*, **22**, 30–38.

Sun, J., L. Zhao and S. Zhao, 2003: An integrated numerical modeling system of dust storm suitable to north China and its applications. *Climatic and Environmental Research*, **8**, 125–142. (in Chinese)

Sun, J., X. Zhou and P. Zhao, 2005: A planetary boundary layer model and its application to heavy rain modeling. *Chinese Science Bulletin*, **50**, 275–285. (in Chinese)

Wan, Q., J. Xue, and S. Zhuang, 2005: Study on the variational assimilation technique for the retrieval of wind fields from Doppler radar data. *Acta Meteorologica Sinica*, **63**, 129–145. (in Chinese)

Wan, Q., J. Xue, Z. Chen, and C. Liu, 2006: The test of applying radar TREC wind in three-dimensional variational assimilation. *Journal of Tropical Meteorology*, **12**, 59–66.

Wang, B., and Y. Zhao, 2005: A new data assimilation approach. *Acta Meteorologica Sinica*, **63**, 694–701. (in Chinese)

Wang, Y., and B. Wang, 2003: The variational assimilation experiment of GPS bending angle. *Adv. Atmos. Sci.*, **20**, 479–485.

Xu, G., Q. Wan, L. Huang, J. Xue, and D. Chen, 2006: Application and study of precipitation schemes in weather simulation in summer and winter over China. *Acta Meteorologica Sinica*, **20**, 28–38.

Xu, X., G. Zheng, and L. Liu, 2004: Dynamical and microphysical retrieval from simulated Doppler radar observations using the 4dvar assimilation technique. *Acta Meteorologica Sinica*, **62**, 411–422. (in Chinese)

Xue, J., 2004: Progresses of researches on numerical weather prediction in China: 1999–2002. *Adv. Atmos. Sci.*, **21**, 467–474.

Xue, J., 2005: Development of 3DVar for operational application in CMA. *Proc. Proceedings of 4th WMO International Symposium on Assimilation of Observations in Meteorology and Oceanography*, Prague Czech, The World Meteorological Organization, 142.

Xue, J., 2006: Progress of Chinese numerical prediction in the early new century. *Journal of Applied Meteorological Science*, **17**, 602–610. (in Chinese)

Xue, J., H. Zhang, G. Zhu, and S. Zhuang, 2003: Development of a 3D Variational Assimilation System for ATOVS Data in China. *Proc. Thirteenth Inter-*

national TOVS Study Conference, The World Meteorological Orgnization, Quebec, Canada, 30–36.

Yu, R., and Y. Xu, 2004: Arem and its simulations on the daily rainfall in summer in 2003. *Acta Meteorologica Sinica*, **62**, 715–724. (in Chinese)

Yuan, Z., J. Ding, and M. Chen, 2004: Preliminary study on applying GPS observations to mesoscale numerical weather prediction model. *Acta Meteorologica Sinica*, **62**, 201–212. (in Chinese)

Zhang, L., and Y. Ni, 2005: Four-Dimensional variational data assimilation of radar radial velocity observations. *Chinese J. Atmos. Sci.*, **30**, 433–440. (in Chinese)

Zhang, X., Y. Liu, B. Wang, and Z. Ji, 2004: Parallel computing of a variational data assimilation model for GPS/MET observation using the ray-tracing method. *Adv. Atmos. Sci.*, **21**, 220–226.

Zhou, G., C. Zhao, S. Ding, and Y. Qin, 2005: A study on impacts of different radiative transfer schemes on mesoscale precipitations. *Quarterly Journal of Applied Meteorology*, **16**, 148–158. (in Chinese)