Progresses of Researches on Numerical Weather Prediction in China: 1999–2002

XUE Jishan* (薛纪善)

Chinese Academy of Meteorological Sciences, Beijing 100081

(Received 20 March 2003; revised 24 July 2003)

ABSTRACT

The recent progresses in the research and development of (NWP) in China are reviewed in this paper. The most impressive achievements are the development of direct assimilation of satellite irradiances with a 3DVAR (three-dimentional variational) data assimilation system and a non-hydrostatic model with a semi-Lagrangian semi-implicit scheme. Progresses have also been made in model physics and model application to precipitation and environmental forecasts. Some scientific issues of great importance for further development are discussed.

Key words: progress, numerical weather prediction, three-dimentional variational, semi-Lagrangian, semi-implicit

1. Introduction

Research on numerical weather prediction in China goes back to the 1950s. Since the mid 1980s, three big research projects focusing on global medium-range weather, tropical cyclones and heavy rain, and short-term climate prediction respectively were carried out consecutively. As the result of these research projects, the operational numerical prediction systems for global medium-range weather, tropical cyclones over the western Pacific, and rainfall over China were set up. The progresses in modeling techniques have resulted in obvious improvement of forecast skill in comparison with a decade ago. For example, the time range of reliable global weather forecasts (6 days) is almost double the number (3–4 days) in the earlier 1990s. The products of numerical models are the main basis for forecasters in operational forecast centers when they prepare routine forecasts for the public. However the current skill of numerical weather prediction is still not as satisfactory as people expect. The backward data assimilation technique not being capable of handling huge amounts of satellite data, and the parameterization schemes of the model physics being improper to the Eastern Asian monsoon area, are the two main problems causing the degradation of numerical prediction in China. These two problems are closely related to the lack of an advanced high-resolution model dynamical frame.

In the late 1990s, in order to enhance its observing capability, China started to set up its network of next generation weather radars and initiated its new meteorological satellite project. These two projects imply that more and more remote sensing data will be available for the use of numerical prediction models. So the effective application of radar and satellite data in numerical weather prediction becomes urgent. At the same time, China has built up its capability of manufacturing high performance computers, so it is much easier for Chinese scientists to get computer resources to support research on numerical modeling. The improvements in observational networks and computer resources bring forth a good opportunity to upgrade the Chinese operational numerical weather prediction system, and hence the call for more research works on the development of advanced models. In comparison to a decade ago, when introducing a model from abroad was thought of as the most efficient way to upgrade the Chinese operational model system, most Chinese scientists and policy makers now agree that it is time to develop new model system based on the efforts of Chinese scientists. In 2001, a key state research project, the Research and Development of the Chinese New Generation Numerical Weather Prediction System, was launched. The goal of this 5-year research project is to develop an advanced Global and Regional

*E-mail: jsxue@cams.cma.gov.cn

Assimilation and Prediction System (GRAPeS) which will have the capability of improving routine forecasts to meet the needs for high quality weather services. Earlier than GRAPeS, a state basic science research project, the China Heavy Rain Experiment and Study (CHeRES), was initiated. This research project emphasizes the theoretical researches relevant to numerical prediction of heavy rain, so it provides some theoretical basis applicable to GRAPeS. Implementation of these two projects and other projects supported by the National Natural Sciences Foundation or other agencies have caused advances in the researches of numerical weather prediction. The progresses in data assimilation, high-resolution model development, model physics, and precipitation forecasts will be given in the following sections of this paper, ended by a discussion about near future development. The progress in climate system models will be a special topic in this volume, so it is not included in this paper. Some works which have been completed recently have not been published or are only presented in the selections of research achievements of some state projects not published formally, but they are of great importance in reflecting Chinese new progresses in researches on numerical weather prediction. They are cited in this paper without references, listed with the approval of the authors.

2. Data assimilation

For a long period, the sparseness of observational data in some key areas was a major difficulty encountered in the effort to improve the numerical weather prediction in China, since most disastrous weather systems originate in the Tibetan Plateau or the western Pacific where few conventional data are available. The development of advanced data assimilation schemes capable of assimilating remote sensing data is thought to be the first objective of the GRAPeS project. In 2001, the scientist team of GRAPeS completed the scientific design and coding of a three dimensional variational assimilation system GRAPeS-3DVAR (three–dimentional variational) (Xue, 2002). It is set on a grid system suitable to both global and regional data assimilation. A spatial filter based on spectral decomposition or a recursive filter is used as a preconditioning to accelerate the convergence of iteration used in minimizing the cost function. The fast radiation transfer model and its tangential and ajoint (RTTOV) developed by ECMWF (Ewopean Cencre for Medium-range Weather Forecasting were then introduced into this 3DVAR frame for direct assimilation of satellite irradiances. The results of preliminary experiments assimilating irradiances from satellite NOAA (National Oceanic and Atmospheric Administration)–16 in microwave channels (AMSU-A and AMSU-B) show prominent improvements in the forecast of typhoon track and intensity by introducing satellite information (Zhang, 2003). But more impressive is the inner structure of the typhoon revealed by the assimilation of AMSU data (see Fig. 1 and Fig. 2). Not only the warm core and spiral belts of moisture, but also the asymmetric horizontal wind field and secondary vertical circulation is inferred. In addition to direct assimilation of satellite irradiances, some products derived from polar or geo-stationary satellites (e.g., cloud drift wind derived from satellites FY-2 and GMS-5), Quikscat sea surface wind data are also assimilated with GRAPeS-3DVAR (Xue, 2002). The combined use of irradiances in microwave channels from polar orbiting satellites and cloud drift winds also improves the analysis of the large-scale environment of tropical storms and shows positive impact on the forecasts of typhoons. The application of satellite-derived moisture is also studied and found to be useful in improving the forecasts of rainfall (Meng, 2002; Zhou et al., 2002).

The assimilation of radar data is another issue attracting the attention of a number of scientists. By use of radar observation data collected in two field experiments, the South China Heavy Rain Experiment in 1998 and the CHeRES in 2001–2002, the retrieval and assimilation of Doppler weather radar data were studied. The research works include wind retrieval from single and dual Doppler radar observations, and assimilation of moisture profiles using precipitation estimated from radar observations. Some simple but practical algorithms were developed. One example is the horizontal wind field estimation based on tracking the movement of clouds. The assimilation of these data shows a positive impact on improving typhoon forecasts.

The techniques to assimilate the vertical profile or column integration of moisture from the Global Positioning System (GPS) data or other satellite-borne sensors are also studied. The key point is the vertical distribution of water content. Different approaches, from the simplest statistical model to the sophisticated variational approach consistent with model parameterization of cloud and precipitation, are studied. There are evidences showing that the impact of using these kinds of moisture information on heavy rain forecasts is obvious. However the results are case dependent, so more experiments should be done before a conclusion of the effectiveness of these approaches is reached.

Progress is also being achieved in the research on four-dimensional variational assimilation (4DVAR).

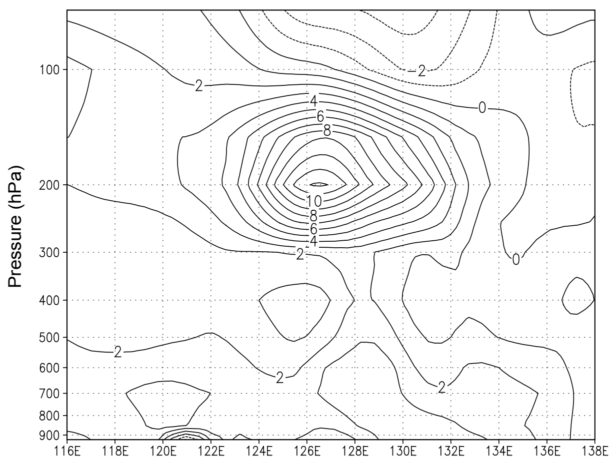

Fig. 1. The cross section of the temperature anomaly (K) with assimilation of NOAA-16 AMSU data for typhoon Rammasun at 1800 UTC 2 June 2002. (Zhang, 2003)

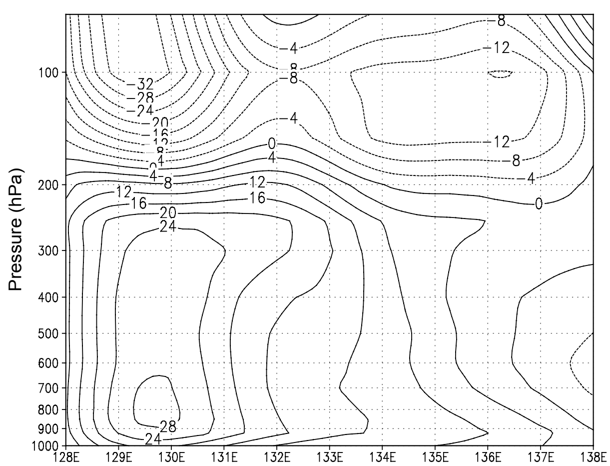

Fig. 2. The cross section of the tangential wind speed (m s^{-1}) with assimilation of NOAA-16 AMSU data for typhoon Rammasun at 1800 UTC 2 June 2002. (Zhang, 2003)

Based on a regional numerical weather prediction model developed in the Institute of Atmospheric Physics (AREM), Mu et al. (personal communication) developed an experimental system of 4DVAR. Much attention has been paid to the so-called 'on-off' problem encountered in developing the adjoint of some physical parameterization schemes, such as convection (Zhu et al., 2002a, b). 4DVAR with constraints and the technique to develop the adjoint of Lagragian models were studied (Zhu, 2001; Wang et al., 1999).

3. Dynamic core of high resolution models

One goal of GRAPeS is to meet the needs in numerical predictions of different scales with one generic dynamic core. The highest spatial resolution should not be lower than 1 km. For this purpose, the model dynamic core should be optionally either non-hydrostatic or hydrostatic, and either global or of a limited area. Along this line, a new high-resolution dynamic model has been set up. It is a non-hydrostatic semi-implicit semi-Lagrangian model based on the fully compressible atmospheric equations. The model employs latitude-longitude grid points with Arakawa-C staggering horizontally. In the vertical, a terrain-following height coordinate and Charney-Philips staggering are used. A vector discretization is introduced in order to keep the accuracy of the calculation of the departure point in the semi-Lagrangian scheme. The vital issue in the deployment of a semi-implicit scheme for a non-hydrostatic model is the algorithm solving the three-dimensional Helmholtz equation of the pressure variable, which is sensitive to vertical boundary conditions related to the formulation of vertical acceleration. A reference atmosphere in hydrostatic balance is induced to alleviate difficulties caused by the numerical treatment of topography. A series of ideal trials were carried out. The model correctly simulates the evolution of geostrophic balanced flows and other hypothetical flow patterns. Simulation experiments with an isolated bell-shaped mountain were employed to verify the model's ability to reproduce the well-studied mountain waves.

Progress is also being made in the improvement of existing numerical schemes and the development of new schemes for modeling atmospheric motions of different scales. A new algorithm for the application of the symplectic geometry method in numerical solutions of the general evolution equation was developed (Zhao et al., 2002). An adaptive grid technique based on the variational principle was also suggested (Kang, 2000a, b; Kang et al., 2002). The conservative property of numerical schemes was stressed by a number of studies. Some researchers devoted effort to improving the long-term integration with the semi-Lagrangian scheme. Chen and Gao (2000) and Chen and Ji (2001) proposed the application of a non-interpolating semi-Lagrange scheme, and developed an energy-conserving semi-Lagrangian scheme by introducing energy interpolation. The semi-Lagrange or semi-implicit scheme was also used in modeling convective clouds (Lou et al., 2002). In addition to the importance of energy conservation for long term integration, the fully energy-conservative scheme was also found to be capable of eliminating systematic errors and improving the weather forecasts (Zhong et al., 2002).

4. Model physics

Clouds and precipitation may be what Chinese scientists are concerned with mostly. More attention is now paid to explicit schemes due to the increase of model resolution. Lou et al. (2002) developed a new dual-parameter mixed-phase microphysical scheme with five species of water substances using a quasi-implicit calculation method. The scheme includes water content and number content concentrations of cloud, ice crystals, rain, and graupel, a total of 11 cloud variables and 31 microphysical processes. The processes of deposition, freezing, ice nucleation, auto-conversion of cloud to rain or ice to snow, and snow to graupel were improved compared to other explicit schemes currently used in mesoscale models. This scheme was introduced to mesoscale model MMS (The PSO/NCAR mesoscale model version 5) with prognostic variables added. The results of a simulation of a tropical storm with this new scheme were compared with three explicit schemes in MM5. Some micro-physical variables seemed well simulated with the new scheme, but the intensity of the storm was not as good as with the original explicit schemes. The scheme was also used to simulate the heavy rain events in South China and in Eastern China. The results indicate that graupel, snow, and ice are important in cold areas of clouds and most raindrops result from the melting of graupel and snow particles.

Efforts were also made to the parameterization of boundary layer processes. Zhou et al. (2002) designed a new boundary layer model based on Mellor-Yamada's second-order turbulent closure method Level 4. The model was coupled with MM5 to simulate a rainstorm that occurred in South China in June 1998. Compared with the MM5 boundary layer scheme, the new model better reproduces the major weather system and rainfall pattern. Specifically, the new model captures the major features of turbulence in the boundary layer, which removed the unreasonable rainfall in the western area of South China that exist in simulations with other schemes.

Using surface observation data in the Tibetan Plateau, Xu et al. (personal communication) verified the flux of sensible heat derived by a newly-developed boundary layer model based on the theory of multiscale turbulence. The boundary layer model was then coupled with the mesoscale atmospheric model MM5. The comparison with observations indicates that multiscale turbulence theory well describes the vertical heat transport process in the real atmosphere and is more feasible than classic similarity theory. Not only is it as accurate as classic similarity theory in the computation of gradient transport, but it also gives a reasonable result for anti-gradient transport. The simulations of heavy rain events in both South China and Central China indicate that in the case of complex terrain and surface categories, the forecasts of the detail of both the location and intensity of heavy rain with parameterization based on multiscale turbulence theory are better than with the MRF (Medium Range Forecast) scheme or the Blackadar scheme. The simulation also indicates that heating by the land surface contributes to the formation of the low-level jet and mesoscale systems. Accordingly, in cases of complex terrain and land surface, the parameterization of the boundary layer based on the theory of multiscale turbulence has the potential to improve the prediction of heavy rain. The treatment of a heterogeneous surface in the parameterization of the atmosphere boundary and land surface processes was also studied, and some proposed approaches were shown to be encouraging (Zeng et al., 1999; 2000; Liu et al., 2002).

The impacts of the parameterization of atmospheric radiation on short and medium range numerical weather forecasts have also been noticed recently. Shen and his collaborators (Shen et al., 2002) made a series simulation with different parameterization schemes to assess their impact on medium range and extended prediction and concluded that a sophisticated parameterization scheme for the transfer of radiative energy is of importance not only for climate simulation, but also for medium range forecasting. The radiative energy transfer model was also used for predicting the intensity of ultraviolet radiation, which is an element stressed in environmental issues (Shen and Kuang, 2002).

5. Precipitation forecast

Improvement of the numerical prediction of precipitation has always been a main objective of research in numerical weather prediction. The project CHeRES developed an experimental NWP system focusing on the heavy rain along the Yangtze River in the Meiyu season (Yu et al.,2002). The core of the system is a regional model AREM (Advanced Regional Eta-coordinate Model) developed by Yu et al. (2002). The prototype of AREM is the dynamic frame of a regional eta-coordinate model (REM) which has been developed by Yu (1989) since 1989 aiming at dealing with the significant effects of topography on the precipitation in China. REM has been popularly used for summer precipitation predictions and heavy rain studies since 1992. In upgrading AREM, much attention has been paid to the standardization and modularization of model codes and the introduction of advanced model physics. The model physical processes consist of large-scale condensation, modified Betts-Miller convective adjustment, bulk aerodynamic surface flux, and non-local diffusion planetary boundary layer parameterization. To evaluatine the capability of AREM in modeling rainfall in China, hindcast experiments were first conducted using historic data of June and July in 1998 and 2001. The threat scores (TS) for light rain (1 mm d^{-1}), moderate rain (10 mm d^{-1}), and heavy rain (25 mm d^{-1}) were 0.57, 0.32, and 0.18 respectively in 1998, and even higher in 2001. So the performance of AREM is encouraging for these two years. In 2002, the model was tested for real-time forecasts. The TS skills along the Yangtze River for 1 mm d^{-1}, 10 mm d^{-1} and 25 mm d^{-1} were 0.47, 0.29, and 0.17 respectively, showing the stable performance of the model. The model was also used for studying the mechanism of heavy rain forming along the Meiyu front. Some case studies with AREM show that the model can capture the structures and evolutions of the rain systems. For example, the model revealed the mechanism of the formation and evolution of a mesoscale vortex in the east periphery of the Tibetan Plateau that caused torrential rainfall over the Sichuan Basin and downstream areas. Careful analysis of the model integration shows that when the mesoscale eddy moved from the top of the Tibetan Plateau to the upper level of the Sichuan Basin and overlapped the southwest vortex, the coupled vortex was able to reach the upper troposphere. When the system became mature, the ascending motion was strong in the center of the vortex, and the large latent heating in the middle troposphere enhanced the deep convection. The heavy rain was mainly caused by deep convective clouds. This experiment helps our understanding of the mechanism of torrential rain.

In addition to the development and improvement of a model system, the ensemble approach is found to be a way having the potential to improve the heavy rain forecasts. The research on this topic is discussed in the next section.

6. Ensemble prediction

The development and application of ensemble prediction techniques are among the major advances in the area of NWP in recent decades. In early 1992, both the National Centers for Environmental Prediction U.S. and ECMWF set up their operational ensemble prediction systems, reflecting the fact that the ensemble prediction technique had come to maturity. The researches on ensemble prediction in China did not start as early as in the U.S. or Europe. One reason for the delay of the researches on ensemble prediction was the shortage of computer resources necessary for ensemble prediction. The situation changed in the later 1990s when more computer resources became available. In 1999, two ensemble prediction systems based on lagged average forecasts (LAF) and singular vectors (SV), respectively, were developed and used in extended forecasting. In the first version of the SV ensemble prediction system, a low resolution model T21L19 was used for constructing the initial perturbation. This low resolution model was upgraded to T42L19 and the forecast model was upgraded from T63L19 to T106 in its new version (Liu, 2000; Li and Chen, 2002). Much attention was paid to the performance of the system in predicting the evolution of the subtropical high over the Western Pacific. For this purpose, some special evaluating indices were developed; the result favors the use of the ensemble prediction system in medium range forecasts (Mao and Wang, 2000). Different from the initial perturbation methods in popular use, Gong et al. (1999) suggested a new approach which combines the lagged average forecast and 4DVAR in the construction of the initial perturbation. Preliminary tests give encouraging results.

A new area in ensemble prediction is the application of the concepts of ensemble prediction in short range forecasts, especially in forecasts of severe weather events like heavy rain. Chen's recent study (Chen, 2003) shows that ensemble prediction based on model perturbation is more effective in depicting the uncertainty of the numerical prediction of heavy rain events in comparison with that based on the perturbation of initial conditions. However, further study (Chen et al., 2003) shows that the perturbation of initial conditions is also effective if the proper model elements are perturbed. Most heavy rain events in China occur on the large-scale backgrounds of weak baroclinity. The perturbation algorithms for initial conditions used by most operational centers are based on the theory of dynamic instability, so they are not able to capture the diversity of predictions of heavy rain due to the uncertainty in the initial conditions. An approach to disturb the initial fields relevant to the mesoscale gravity waves based on the model perturbation is proposed in their work. A hybrid method of perturbations in initial conditions, in model physics, and in boundary conditions is also tested in Chen's work and gives better results than a single perturbation.

7. Application of numerical weather prediction in environmental problems

As the resolution of numerical weather prediction models increases, the model outputs are more useful in driving models of environmental elements. On the basis of Shao's dust storm model (Shao, 2000), an integrated experimental numerical prediction system for dust storms has been developed at the National Meteorological Center/China Meterological Administration (NMC/CMA). The system comprises an atmospheric model, a land surface model, a wind erosion scheme, a transport and deposition scheme, and a geographic information database. The system is nested with operational global model T213. The system captured the main features of severe dust storm events in the spring of 2002 in its pre-operational trials.

Efforts were also made in the development of prediction models for urban pollution. A high-resolution model of the concentration of pollutants in Beijing City was developed at the Chinese Academy of Meteorological Sciences (CAMS). The atmospheric model is based on the mesoscale non-hydrostatic model MM5 with atmospheric chemistry processes and transportation of pollutants included. The resolution of the model is as high as 500 meters, so small-scale terrain and the main features of the city land surface and building blocks are resolved to some extent in the model. The model is expected to be applicable to the environmental management of Beijing City (Xu Xiangde, personal communication).

Wang et al. (2002a, b) used a regional climate model to drive a high-resolution distributed hydrology-soil-vegetation model (DHSVM). They improved the parameterization schemes for land surface and vegetation and the evapotranspiration process in the model. The model is used to study the hydrological process in North China and the local response to the climate change. The model succeeded in simulating the water cycle in the period 1979–1991, proving its usefulness in solving water resource issues.

8. Summary and discussion

Stimulated by the requirements for high quality products of numerical weather prediction and the rapid progress in the observing system and computer power in China, a key state research and development project was launched in China. This 5-year project, known as GRAPeS, aims at developing a Chinese new generation data assimilation and prediction system for global medium range and regional mesoscale weather prediction. In the past two years, the scientist teams of the GRAPeS project have completed the development of a non-hydrostatic model dynamic core and some main physical processes. A 3DVAR system capable of assimilating both conventional and satellite irradiance data was also set up. In addition to the studies conducted by this state key project, pronounced progresses also came forth out of the scientist team of GRAPeS on ensemble forecasting, numeric algorithms of dynamic models, model physics, and coupling of atmospheric models with land surface, hydrological, or pollutant transport models. The achievements have set up a solid foundation for the new generation numerical system in China. However, the achievements are still preliminary from the point of view of the long-term goals of the development of the numerical prediction system. In the near future, some scientific issues relevant to numerical weather prediction must be emphasized, and are enumerated in the following paragraphs.

(1) Assimilation of radar and other high-resolution remote sensing data. Few studies have dealt with the assimilation of radar observations up to now, even though more and more data have become available. The assimilation of radar data may be more difficult than satellite irradiances due to more uncertainties in dealing with the reflection of radar beams by rain and cloud drops. The incompleteness of the radar observations and inconsistency in the spatial resolution with other observational platforms and background fields are also big challenges. More studies on the physical basis of assimilation of radar data may be necessary before an effective operational scheme is set up.

(2) Numerical algorithms for high-resolution models. The fully compressible high-resolution model retains the three-dimensional acoustic waves which cause new difficulties in numerical computations. For instance, the semi-Lagrangian scheme commonly used in current models may be unstable in these cases. For the same reason, the treatment of model terrain seems more difficult in the high-resolution models. Some schemes of treating terrain used in hydrostatic models are no longer effective in non-hydrostatic models. The inaccurate computation of dynamic and thermodynamic variables around the small-scale mountains may cause more serious problems and destroy the model integration ultimately due to the three-dimensional propagation of the acoustic waves. The development of a new terrain scheme is necessary for the accurate prediction of mountain-induced rain.

(3) Model physics. The heavy rain events in China often occur against the background of weak baroclinicity. However the parameterization schemes used in the models are based on the studies on either baroclinic mid-latitudes or typical tropical atmosphere. This discrepancy is thought to be one of the main reasons causing big errors in forecasts of rainfall. More studies with the data of field experiments are essential for improving the forecasting of rainfall.

(4) Coupling with and development of models be-

yond atmosphere. Many evidences show the impact of physical processes out of the atmosphere on the short and medium range variability of weather. Coupling with land surface models is among the most important issues for future model development. The complexity of the characteristics of the land surface in China makes the problem very complicated and difficult. The first step may be the development of coupled atmospheric and land surface models focusing on the timescale of several days. Since most studies on land surface or hydrological process models are motivated for studying climate change, new research is required.

Acknowledgments. The work was supported under the auspices of the Chinese Ministry of Science and Technology for item 2001BA607B. The author is indebted to colleagues in the scientist teams of the projects GRAPeS and CHeRES for providing their recent results.

REFERENCES

Chen Jiabin, and Gao Xuejie, 2000: An application of the mass conservation law to the spectral climate model of the National Climate Center. *Chinese J. Atmos. Sci.*, **24**, 608–614.

Chen Jiabin, and Ji Zhongzhen, 2001: A study on energy-conserving semi-Lagrangian scheme. *Chinese J. Atmos. Sci.*, **25**, 837–846.

Chen Jing, 2003: The ensemble prediction for heavy rain in China. Ph. D dissertation, the Chinese Academy of Meteorological Sciences, 183pp.

Chen Jing, Xue Jishan, and Yan Hong, 2003: The impact of non-adiabatic physics parameterization schemes on mesoscale heavy rainfall short-range simulation. *Acta Meteorologica Sinica*, **61**, 203–218. (in Chinese)

Chen Zeyu, Hu Yingqiao, Yan Muhong, and Gao Youxi, 2000: An atmospheric model with semi-Lagrangian and semi-implicit Eulerian equations: Preliminary numerical tests on deep convection. *Chinese J. Atmos. Sci.*, **24**, 804–820. (in Chinese)

Gong Jiandong, Li Weijing, and Chou Jifan, 1999: Forming proper ensemble forecast initial members with four dimensional variational data assimilation method. *Chinese Science Bulletin*, **44**(10), 1113–1115.

Kang Hongwen, 2000a: A study on the application of adaptive grids technique in numerical model. Part 1: One-dimensional case test. *Chinese J. Atmos. Sci.*, **24**, 615–624. (in Chinese)

Kang Hongwen, 2000b: A study on the application of adaptive grids technique in numerical model. Part 2: Two-dimensional case test. *Chinese J. Atmos. Sci.*, **24**, 749–760. (in Chinese)

Kang Hongwen, Gu Xiangqian, Liu Chongjian, and Wang Pengyun, 2002: Adaptive grid technique based on the variational principle and its weight function. *Adv. Atmos. Sci.*, **19**(4), 705–718.

Li Zechun, and Chen Dehui, 2002: The development and application of the operational ensemble prediction system at the National Meteorological Center. *Journal of Applied Meteorological Science*, **13**(1), 1–15.

Liu Jinda, 2000: Ensemble prediction ushered in new era in numerical weather prediction. *Meteorological Monthly*, **26**(6), 21–25.

Liu Jingmiao, Ding Yuguo, Zhou Xiuji, and Wang Jijun, 2002: Land surface hydrology parameterization over heterogeneous surface for the study of regional mean runoff ratio with its simulations. *Adv. Atmos. Sci.*, **19**(1), 89–102.

Lou Xiaofeng, Hu Zhijin, Shi Yueqing, Wang Penyun, and Zhou Xiuji, 2002: The development of a new explicit microphysical scheme and simulations of hurricane and heavy rainfall. *International Conf. on Mesoscale Convective Systems and Heavy Rainfall/Snowfall in East Asia,* Tokyo, Japan, Japan Science and Technology Corporation Chinese Academy of Meteorological Society, 293–296.

Mao Henqing, and Wang Jianjie, 2000: The status and trends of operational application of ensemble prediction. *Meteorological Monthly*, **26**(6), 26–30.

Meng Zhiyong, Xu Xiangde, and Chen Lianshou, 2002: T_{BB}-nudging four-dimensional data assimilation method and simulations on heavy rain process in Wuhan on 20 July 1998. *Chinese J. Atmos. Sci.*, **26**, 663–676.

Shao, Y., 2000: *Physics and Modeling of Wind Erosion.* Kluwer Academic Publication, 393pp.

Shen Yuanfang, and Kuang Shi, 2002: Research and experiment of ultraviolet forecasting by atmospheric radiative transfer model. *Journal of Applied Meteorological Science*, **13**(3)(Suppl.), 223–231.

Shen Yuanfang, Yi Lan, Chen Yi, and Hu Guoquan, 2002: Impacts of changes in radiation parameterization on model medium-range and monthly forecasting. *Journal of Applied Meteorological Science*, **13**(3), 299–311.

Wang Jun, and Chen Jiabin, 2000: An application of non-interpolating semi-Lagrangian scheme to one-dimensional Burgers equation and two-dimensional shallow water equations. *Chinese J. Atmos. Sci.*, **24**, 493–508.

Wang Shourong, Huang Ronghui, and Ding Yihui, 2002a: Improvements of a distributed hydrology model and its climatological-hydrological off-line assimilation experiments. *Acta Meteorologica Sinica*, **60**(3), 290–300.

Wang Shourong, Huang Ronghui, and Ding Yihui, 2002b: Numerical simulation experiments by nesting hydrology model DHSVM with regional climate model RegCM2/China. *Acta Meteorologica Sinica*, **60**(4), 421–427.

Wang Yunfeng, Wu Rongsheng, Wang Yuan, and Pan Yinong, 1999: Application of variational algorithms in semi-Lagrangian framework. *Adv. Atmos. Sci.*, **16**(3), 419–430.

Xue Jishan, 2002: Satellite data assimilation plan in CMA. *Topic Chairman and Rapporteur Reports of the Fifth WMO International Workshop on Tropical Cyclones (IWTC-5)*, WMO/TD. No.1136.

Yu Rucong, 1989: Design of the limited area numerical weather prediction model with steep mountains. *Chinese J. Atmos. Sci.*, **13**(2), 139–149.

Yu Rucong, Xu Youping, Cheng Rui, and Li Kun, 2002: A regional numerical prediction model and its simulations on the heavy rainfalls along the Yangtze River. *International Conf. on Mesoscale Convective and Heavy Rainfall/Snowfall in East Asia*, Tokyo, Japan, 339–344.

Zeng Xinmin, Zhao Ming, and Su Bingkai, 1999: Study on boundary layer numerical model with inclusion of heterogeneous multi-layer vegetation. *Adv. Atmos. Sci.*, **16**(3), 431–442.

Zeng Xinmin, Zhao Ming, and Su Bingkai, 2000: A numerical study on effects of land-surface heterogeneity from combined approach on atmospheric process Part 1: Principle and Method. *Adv. Atmos. Sci.*, **17**(1), 103–120.

Zhang Hua, 2003: Implementation study for the Direct Assimilation of ATOVS Radiances, Ph. D. dissertation, Lanzhou University, 105pp.

Zhao Ying, Wang Bing, and Ji Zhongzhen, 2002: Symplectic-like difference scheme for generalized Hamiltonian systems. *Adv. Atmos. Sci.*, **19**(4), 719–726.

Zhong Qing, Chen Jiatian, and Sun Zuoling, 2002: Elimination of computational systematic errors and improvements of weather and climate system models in relation to baroclinic primitive equations. *Adv. Atmos. Sci.*, **19**(6), 1103–1112.

Zhou Bing, Xu Haiming, Wu Guoxiong, and He Jinhai, 2002: Numerical simulation of CMWDA with impacting on torrential rain forecast. *Acta Meteorologica Sinica*, **60**(3), 308–317.

Zhou Xiuji, Zhao Ping, and Sunjian, 2002: A new PBL model with second-order turbulent closure and its implement into MM5. *International Conference on Mesoscale Convective and Heavy Rainfall/Snowfall in East Asia*, Japan Science and Technology Corporation Chinese Academy of Meteorological Society. Tokyo, Japan, 297–301.

Zhu Jiang, Masafumi Kamachi, and Zhou Guangqing, 2002a: Nonsmooth optimization approaches to VDA of models with on/off parameterizations: Theoretical issues. *Adv. Atmos. Sci.*, **19**(3), 405–424.

Zhu Jiang, Wang Hui, and Masafumi Kamachi, 2002b: The improvement made by a modified TLM in 4DVAR with a geophysical boundary layer model. *Adv. Atmos. Sci.*, **19**(4), 563–582.

Zhu Keyun, 2001: On the 4D variational data assimilation with constraint conditions. *Adv. Atmos. Sci.*, **18**(6), 1131–1145.