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Progress in Climate Prediction and Weather Forecast Operations in China

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ABSTRACT

The current status of weather forecasting and climate prediction, and the main progress China has made in recent years, are summarized in this paper. The characteristics and requirements of modern weather forecast operations are described briefly, and the significance of Numerical Weather Prediction (NWP) for future development is emphasized. The objectives and critical tasks for seamless short-term climate prediction that covers the extended-range (15–30 days), monthly, seasonal, annual, interannual and interdecadal timescales, are proposed.

Key words: weather forecast, climate prediction, operation in China

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1. Progress of weather forecasting in modern times

Weather forecasting is the earliest type of meteorological operation, and to date remains the most major operation in the field. Weather forecasts originated in the 19$^{\text{th}}$ century, but since the 1970s and 1980s, due to the application of Numerical Weather Prediction (NWP), enormous progress has been made in weather forecasting operations (Table 1). Characterized by operational levels and service capacity, weather forecasting in China can be divided into three stages: synoptic experience forecasts; modern development of meteorological prediction techniques; and the development of refined weather forecasts (Jiao, 2010).

The period of synoptic experience forecasts refers to those forecasts made by the basic technical method of synoptic analysis and the forecasters' experiences in synoptic meteorology. Weather operations between the 1950s and 1970s in China belonged to this stage. From the late 1970s to the 1990s, modern meteorological prediction technology became greatly developed, and the important symbols for the progress of weather forecasting skills can be stated as follows (Li et al., 2004):

(1) The meteorological satellite and weather radar began to be used in weather forecasting; quantitative weather monitoring and analyzing technology developed quickly; monitoring and prediction abilities for disaster weather systems, such as torrential rainfall and typhoons, improved drastically; and short-term nowcasting warnings began to be developed.

(2) Computer technology was applied in weather predictions, with analysis and application platforms for weather forecasting built upon these advancements. Traditional forecasting methods involving mapping analysis of limited meteorological data were subsequently completely reformed.

(3) The application of NWP transformed the business of weather foresting from one based upon experience-based qualitative forecasts into a new stage of development involving increasing levels of quantitative analysis.

Therefore, weather forecasting has improved greatly over the years. A clear technical route for weather forecasts has gradually formed, featuring NWP, the integration and application of various data from satellites and radars, the numerous prediction methods now available, and of course the emergence of human–computer interactions in weather forecast sys-

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Table 1. Time list of important improvements in weather operational forecasts at the NMC.

Date	Important improvements in weather operational forecasts
June 1994	Provide the 48∼72 hour weather forecast of whole country for public by CCTV.
August 1996	Issue the 24 hour weather forecast of foreign city.
2001	Issue regularly the 72 hour short term precipitation forecast and the 120 hour medium term precipitation forecast which are updated daily. The 6∼10 day precipitation trend forecasts are also issued. The 48 hour weather forecast of foreign city is added.
2003	Issue regularly 24 hour, 48 hour short term forecast of dust storm, fog and high temperature, 24 hour severe convective weather forecast and 144 hour, 168 hour medium term precipitation forecasts which are updated daily.
June 2004	Develop regularly short term disaster weather forecast and its secondary and derivative hazards forecasts.
March 2007	Issue the whole country 24 hour ranges at 12 hour interval precipitation forecast, disaster weather forecast, important weather watch, 48 hour weather forecast of foreign city and surface map analysis of Asia and Europe.
June 2008	The whole country 24 hour ranges at 12 hour interval QPF and the synoptic verification of NWP products are added.
April 2009	Issue severe convective weather potential forecast.
January 2010	Issue meteorological disaster watch.

tems. This technical route marks the fact that weather forecasting operations have stepped into a new era supported by modern technology and approaches.

Currently, weather forecasting operations in China have entered the stage of developing refined forecast products. Since the new century, especially in 2007 when the China Meteorological Administration's (CMA) *Suggestions on Developing Modern Meteorological Operations* was implemented, modern weather operations have developed rapidly. In 2010, the CMA's *Guidelines on Developing Modern Meteorological Operations* was put forward, which points out that the new characteristics of modern weather predictions include some key points, as follows:

(1) The elements of weather forecasts have become many more in number, having developed from conventional temperature and rainfall forecasts to the various disaster weather forecasts that exist today. These include quantitative precipitation, fog (haze), maximal high (minimal low) temperatures, gales, hail, strong convective weathers etc., and even further types such as dust storms, forest (grassland) fire risk level, agrometeorological disasters, and geological hazards. In addition, there are also more specialized meteorological forecasts like those related to hydrology, transportation, the environment, health indexes, and so on.

(2) The time range for forecasts has extended and the resolutions of forecasts have improved significantly. Today, the ordinary weather forecast has been extended to three days, and the temporal resolution of public weather forecasts has been improved from 24-h to 12-h intervals, sometimes even reaching the hourly level. Meanwhile, spatial resolutions have also improved, from hundreds of kilometers in the past, to the situation today where we see town- or even village-level resolutions of around 10–20 km. In the National Meteorological Center (NMC), CMA, the quantitative precipitation forecast is released at a resolution of 6-h intervals, while the positioning of typhoon tracks has been improved from every 3 hours to hourly, and the longest range of typhoon forecasts has extended from 72 to 120 hours. Improvements in forecasting operations in recent years have focused on weather disasters at the mesoscale and microscale and extended-range forecasts. Nowcasting warning systems have been built at the national, provincial and city levels, and 10–30-day extended-range forecasts have begun at the national level.

(3) Much exciting progress has been made in the service abilities of forecasts. For instance, the specific forecasts for the 2008 Beijing Olympic Games, the 2009 National Day, and the 2010 Shanghai Expo, all of which depended on a variety of monitoring methods and forecasting skills, demonstrated the improvements that have been made in the ability of forecasts to deliver accurate and timely information at appropriate quantities depending on the situation. Increasingly, in the major cities like Beijing and Shanghai, forecast services are determined by customers' precise needs. For example, expressions like "showers after noon", "rain during rush hour", "torrential rain in the east", "geological disaster likely to occur in Miyun County" are now used in public forecasts by the Beijing Meteorological Bureau. Traditional approaches and wording in forecasts have changed to better meet the demands of the consumer, indicating the progress that has been made in refining and adapting forecasts in response to the end user.

Weather forecasting operations in China can be divided into five levels: national, regional, provincial, city and county level. Among these, NMC plays a leading role nationwide in weather forecasting techniques and products, with continual improvement in the content and forms of weather forecast products (Duan, 2010).

1.1 *The development of weather forecasting operations*

The continual development of weather forecasting operations at the national level has greatly improved the accuracy of forecasts, enhancing their ability to guide the end user, and has contributed significantly to the prevention and mitigation of meteorological disasters. Monitoring and warning systems for the main types of disaster (torrential rain, gales, hail, strong convective weather, cold spells, heat waves, thick fog, dust storms etc.) have been firmly established in China, and forecasting skill in particular has experienced major improvements over the last decade. For example, the threat score (TS) for 24-h torrential rain has improved by 5% in the last 10 years, and 6-h interval quantitative precipitation forecasts are being performed with steadily increasing accuracy. For the mid-term range, weather process, 10-day precipitation and average temperature forecasts have been implemented. However, 4–7-day daily-element rolling forecasts and the 11–20 days extension forecast are still at an early stage. Refined weather-element forecasts have been continuously developed, and are now at the stage where detailed objective forecasts on the meteorological elements of temperature, precipitation, wind etc. have been achieved at more than 2500 observation stations home and abroad, relying on the core technology of model output statistics (MOS) and multi-model ensemble forecast approaches. Finally, the National Weather Forecast Database (NWFD) has been set up and the verification of numerical forecasting products has been conducted.

1.2 *Improvements in typhoon forecasting*

With the improvements in weather monitoring systems and the development of numerical forecasting skills for typhoon tracks, the monitoring, forecasting and warning operations for typhoons have achieved great progress in the last decade. Typhoon warning systems now cover not only the western Pacific Ocean, but also the Indian Ocean at the national level. The time range of the tropical cyclone track forecast has extended to 96 h from 72 h (Table 2) and errors in modeled typhoon tracks are decreasing year by year. For instance, in 2009, the 24-h, 48-h and 72-h typhoon track forecast errors were 119 km, 205 km and 299 km respectively, out of which the 24-h and 48-h errors decreased by 50%. Errors for typhoon track 72-h forecasts at present are similar to 48-h forecasts in the early 1990s, which is close to the advanced levels of forecasting achievable in other parts of the world.

The considerable improvements in operational tropical cyclone track forecasting in China have emerged from the continuous progress and advancements in NWP and integrated observation systems. Based on satellite data from FY-2D and FY-2E, updated every 15 minutes, and Doppler radar data updated every six minutes, the position and strength of tropical cyclones can be obtained in more detail. These data are assimilated into NWP and ultimately improve both integrated and objective track forecasting. Being able to reliably locate the center position of a tropical cyclone has emerged as a very important point. When NWP is revised by a more exact position of the tropical cyclone, track forecasting also improves markedly (Xu et al., 2010). A comparison of official 24-, 48-, and 72-h tropical cyclone track prediction error trends among China, Japan and USA is given in Fig. 1.

1.3 *NWP operational improvements*

The current state-of-the-art and use of NWP tech-

Table 2. Time list of important experiments in typhoon monitoring and forecasting at the NMC.

The northwest Pacific and the South China Sea	Global area
The 72 hour operational forecast test was performed in Jun 2001.	
The 72 hour forecast was issued regularly in May 2003.	The monitoring of tropical storm in the Bengal Bay was performed on 15 May 2003.
	The monitoring of the Atlantic hurricane was performed in Jun 2005.
	The monitoring of the global tropical cyclone was performed in Apr 2006.
The 96 hour operational forecast test was performed in May 2007.	
The 96 hour forecast was issued regularly in 2008.	
The 120 hour operational forecast test was performed in 2009.	

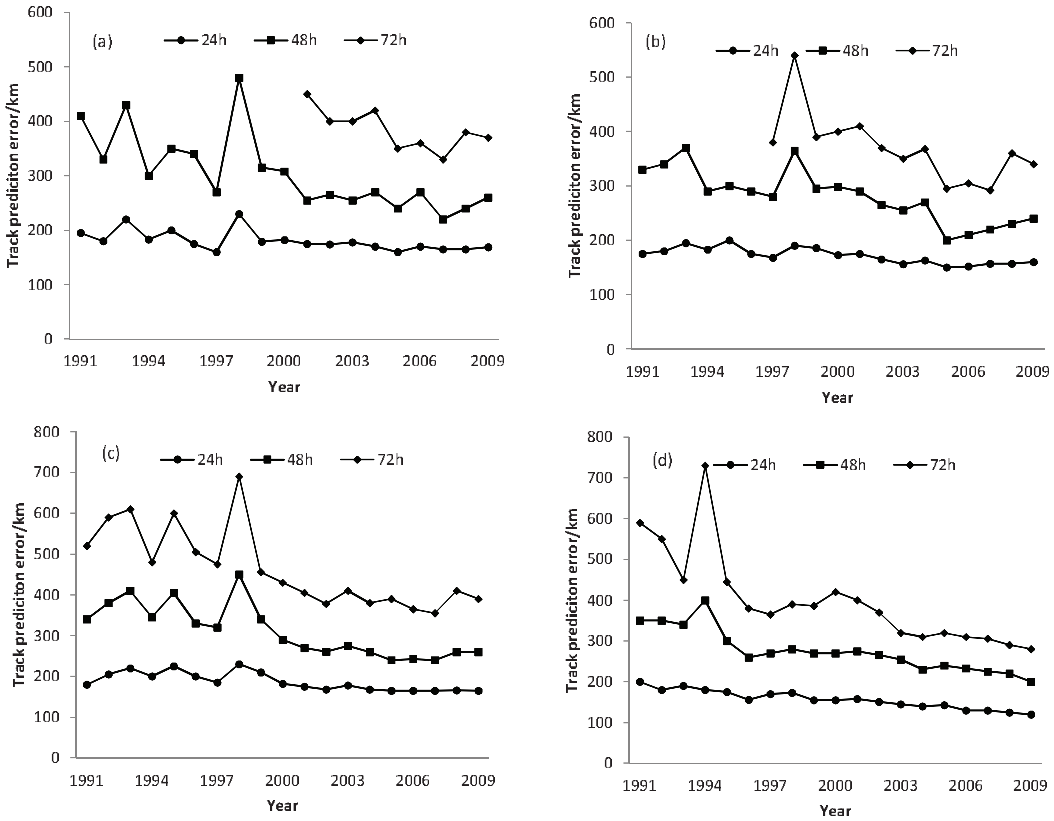

Fig. 1. Comparison of 24 h, 48 h and 72 h official tropical cyclone track prediction error trend among China, Japan and USA. (1991–2009, units: km) (a) National Meteorological Center of China Meteorological Administration, (b) Japan Meteorological Agency, (c) Joint Typhoon Warning Center of USA, (d) National Hurricane Center of USA (North Atlantic Basin) (From Xu et al., 2010).

nology can be taken as a reflection of the level of modernization and the advancements made in meteorological operations in any given country. The gap between developed countries and China in the field of NWP technology is very big, and in order to establish and improve the operational mechanisms favorable to NWP research and development, a lot of work has been carried out to integrate technological resources and reform their management. In order to build up an efficient operating mechanism to promote the development of new-generation NWP models in China, the CMA founded the NWP Center in May 2010, so as to centralize the professionals in NWP research and operations and form a group engaged in developing operational NWP models.

Currently, China has established a national-level NWP operational system that contains the following parts: the global 3-D variation data assimilation (3DVar) system, a global NWP model, a regional/mesoscale NWP model, a typhoon track NWP model, and a global ensemble forecast system. Meanwhile, some other specialized NWP model systems have been developed for sandstorm, ocean wave, ultraviolet index, and air pollutant transport/diffusion forecasting, amongst others. Therefore, NWP operational ability has improved significantly, within which it should be noted that the available forecast time has now reached 6.5 days for the global mid-term NWP system (T639L60) (Table 3).

At present, the mid-term prediction model T639L60 and the regional prediction model GRAPES-MESO are two of the most important symbols of the modernization of meteorology in China. Compared to previous forecast models, the current global and regional mesoscale numerical model systems at the national level possess features as follows:

(1) The resolutions of the models have improved significantly. The resolution of the global model has risen from 60 km to 30 km, and the model vertical layers up to 60 layers from 31 layers. The resolution of the regional model has improved to 9 km from 27 km, and that of the mesoscale in the region of North China has reached 3 km.

(2) The semi-implicit/semi-Lagrange integration

Table 3. The development course of the NWP operational system at the NMC.

Date	The development of the NWP operational system
1978	Begun to develop the NWP operational system
1979	The A model was immigrated to form the fax product.
September 1981	Northern hemispheric model performed quasi-operational run.
February 1982	B model performed operational run.
October 1983	To construct the global medium term NWP operational system.
January 1990	The spectral model T42L9 performed quasi-operational run (T42 for short).
June 1991	T42L9 performed operational run
Novermber 1992	The spectral model T63L16 performed test run (T63 for short).
June 1994	T63L16 performed quasi-operational run.
June 1995	T63L16 performed operational run. The range of forecast of T63 longer 1.5 days than T42.
June 1997	The spectral model T106L19 performed operational run.
September 2002	The spectral model T213L31 performed operational run. The longest usable days of forecast are 6 days.
December 2007	The spectral model T639L60 performed operational run. The longest usable days of forecast are 6.5 days.
March 2009	The global medium term NWP operational system GRAPES-GFS performed quasi-operational run.

scheme and a scheme that splits fast and slow waves (split–explicit) are the two major integration schemes used in the current operational models.

(3) With the increase of model resolution, the physical processes of the models have been improved as well, especially the improvement of the grid scale condensation scheme (cloud/precipitation). Thus, more refined and explicit descriptions on cloud/precipitation processes in the regional and mesoscale models can be made, and also, the cloud prediction scheme has been used in global models (T213L31, TL639L60).

(4) The data assimilation system has been upgraded technically from optimal interpolation to 3-DVar, achieving direct assimilation of radiance data from the ATOVS satellite, which has greatly affected the accuracy of prediction results.

(5) Development of the GRAPES model to integrate an operational forecast system has been conducted by Chinese scientists. The GRAPES-MESO model is already in use and the GRAPES global mid-term model is in real-time quasi operation.

1.4 *Prediction system development and application*

Since 2005, the National Meteorological Service System for Decision-making, the National Information System for Meteorological Operation Service, the Meteorological Disaster Information Collecting and Reporting System, and the Assessment System for Meteorological Disaster Risk , have all been established successively, collectively contributing to meteorological information sharing services at the national, provincial, regional and county levels. In 2008, the MICAPS3.0 system was applied in the NMC and provincial weather observatories, with special versions of the system (e.g. for typhoons) having since been developed. Furthermore, Severe Weather Automatic Nowcasting (SWAN) systems have gained some initial results, and the National Weather Forecasting Database (NWFD) has been formed. All of these achievements have served to bring individual meteorological operations together into a unified, resource-sharing and efficient system.

2. Objectives and missions of modern weather operations

To develop modern weather operations is a key aspect of preventing and mitigating meteorological disasters, and is also crucial for adapting to the needs of the public in terms of the meteorological services they require. The demand for these developments has been stated a concept as "public-oriented, economy-oriented and decision-making-oriented" requirement.

In early 2010, the CMA issued the *Guidelines on Developing Modern Meteorological Operations*, which proposed a new project to develop modern weather forecasting operations. Such a modern approach is symbolized by the development of refined forecasts that offer greater degrees of accuracy, higher temporal and spatial resolutions, covering a greater range of weather phenomena, and adapting to the various needs of the end user. It does not be achieved if without the supporting of the development of NWP, the integrated application of various kinds of data and new forecast techniques. One of the most critical needs is to strengthen the knowledge of forecasters in order that they can use this modern scientific technology in a successful manner.

Modern weather operations include NWP, weather forecasts, product inspection and assessment and integrated analysis of forecast systems, as well as reasonable operational structure. Its features are represented by refined forecast products supported by core forecasting techniques and rational operational flow.

By 2015, the objectives for modern weather operations in China are as following: to establish an operational system with a reasonable layout, complete functions and advanced technology; to realize the stable operations of a global/regional NWP system with GRAPES as the main component, including a 4-D variation data assimilation system, GRAPES and T639L60; to perfect the monitoring, analysis, forecasting and warning operations for disastrous weathers, improving the forecast lead time and accuracy; to enhance the quality and accuracy of meteorological element forecasts, quantitative precipitation forecasts and disastrous-weather-hit area forecasts; to develop technology for extended-range weather forecasts; to apply ensemble prediction technology to mid-term and extended predictions, as well as probabilistic disaster forecasts; and to improve forecasters' capacities for using and analyzing mesoscale model outputs and integrated analysis of various kinds of data.

Generally, to develop modern weather operations and enhance the quality and accuracy of weather products, the following aspects should be stressed (Duan, 2010): numerical weather prediction, weather analysis, severe weather forecasting skill, forecasting technical summary and product validation, technical system supporting for forecasting operation.

2.1 *Numerical Weather Prediction* (*NWP*)

For NWP, the first point is to develop and improve a variational assimilation analysis system and put it into operation. The main tasks to do this include: (1) Advance the application level of global model satellite remote data assimilation, as satellite remote data account for more than 80% of total assimilated data; (2) Build a regional variation assimilation system, effectively assimilating and using the dense, high temporal and spatial resolution data from Doppler weather radar, satellites and auto-stations, and realizing fast data assimilation analysis on an hourly basis.

The second point is to establish a global and regional NWP model system, and analysis and forecasting system, at resolutions of 25 and 3–5 km at the global and regional scale, respectively. The main tasks for this include: (1) To improve the parameter scheme of precipitation and land surface processes that affect prediction skill in the East Asia region; (2) To optimize the cloud processing and forecasting schemes in the process of radiation; (3) To develop the physical parameter scheme to enable it to reflect China's weather and climate features.

The third point is to develop a global and regional ensemble prediction system and put it into operation. The main tasks for this include: (1) To extend the global ensemble forecast to two weeks; (2) To perfect the construction of China's TIGGE Center and develop multi-model ensemble prediction techniques based on the multi-operation center product; (3) To develop the downscaling technique of probabilistic prediction, thus further enhancing the refined probability forecast level.

2.2 *Weather analysis*

Based on the integrated application of multiple observation data and NWP products, and taking the MICAPS system as a platform, synoptic-scale analysis operations gradually convert to an integrated analysis on the synoptic scale and mesoscale weather systems. Weather analysis operations are especially focused on the analyses of various characteristic lines, specific areas, characteristic systems and physical quantities that impact drastically upon the generation and development of disastrous weathers. Meanwhile, the capability of diagnosis for the spatial structure, element allocation and physical process evolution of mesoscale systems and the impact on types, intensities and areas experiencing disastrous weather will be strengthened. Moreover, validation, assessment and correction of NWP products will play a more and more important role in operations. At the national level, more attention will be paid to dynamic verifications of numerical forecast pattern fields, element fields, and main weather systems, as well as the analysis of regular errors. By comparing the errors of different model products, it is possible to analyze the evolving patterns of the characteristic lines and weather systems related to NWP products and correct the information regarding tracks and intensities of main weather systems, thus improving the usability of NWP products.

2.3 *Weather forecasting*

Based on multiple data fusion technology, high-resolution NWP products and ensemble NWP products, as well as relying on the interpretation and application technology of NWP products, forecasters' experiences, and using the technology of combining dynamics and statistics, it is possible to develop seamless weather forecasting operations. The main tasks to achieve this include the following important points:

(1) Strengthen strong convective weather forecasting operations. Using the SWAN system technique, enhance forecasters' capacities to analyze and apply forecast products with high resolutions, de-

velop the objective diagnostic and analysis technology for physical parameters of disastrous weather with dynamic thermal features on the basis of multiple data. Strengthen the integrated analysis capability of mesoscale weather systems and the characteristic physical quantities thereof. Develop probabilistic forecast operations of short-term disastrous weather based on ensemble forecasts.

(2) Strengthen the operation of Quantitative Precipitation Estimation (QPE) and Quantitative Precipitation Forecasts (QPFs). By using the QPE skill applied in the SWAN system, comprehensively utilize satellite, radar and intensive auto-observation data, creating QFE products which are current nationwide. Develop the QPF technique to combine subjective grade rainfall forecasts with high-resolution numerical model products, and make 6-h temporal resolution precipitation forecast products within the range of 72 hours at regular times.

(3) Strengthen mid-term and extended probabilistic forecasts of disastrous weathers. Utilizing interpretation and application technology of mid-term ensemble numerical forecast products, develop mid-term probabilistic forecast approaches for high temperature, severe precipitation, cryogenic weather and other disastrous weathers and produce the corresponding forecast products. Progress the Ocean-atmosphere-land Coupled Model and ensemble forecast operation system thereof; research and develop probabilistic forecast products of extended-range precipitation and temperature anomalies. Enhance the refined severe typhoon forecast and marine meteorological prediction.

(4) Improve the refined forecast levels of typhoon tracks, intensities and the winds and rains they bring. Achieve 12-h temporal resolution in the 72-h range forecast, bringing the error level of 24-h typhoon track forecasts near to 100 km, and the error of typhoon intensity down to around 4.5 m s^{-1}. Advance the mid-term prediction approach for typhoon track and intensity, especially devoting major efforts to integrated forecasts, ensemble forecasts and probabilistic forecast techniques on the basis of the global and regional models; prolong the typhoon forecast to a range of 120 h, and deliver probabilistic forecast products for typhoon track and intensity.

(5) Strengthen refined forecast operations of meteorological elements. Make efforts to spread the Meteorological Elements Objective Forecast Integrated System (MEOFIS) and promote the interpretation and application work that is based on the T639 model and the operational regional NWP model, supplying technology and references for scientific research and operation of the interpretation and application of NWP products all over the country.

2.4 *Forecasting technical summary and product validation*

Establishing a normal mechanism for a forecast technical summary is very important to promote the forecasting skill of the forecasters. The NMC will continue to establish a normal mechanism for a forecast technical summary, as well as sum up in a timely fashion those serious weather processes seen in different regions, accumulate forecasting experiences and explore related scientific problems. Another step is to set up a verification system for different kinds of forecast products. The main tasks to achieve this include: (1) Improve validating operations of conventional weather element forecasts; (2) Establish and perfect the validations of short-term nowcasting forecasts of disastrous weather, hit-area forecasts of disastrous weather, mid-term weather forecasts, and extended weather trend forecasts; (3) Advance the real-time verification and assessment of the performance of operational numerical model forecasting. Place importance on improving the forecast skill of all kinds of the NMC's forecast products relative to NWP products.

2.5 *Technical system of forecasting operation*

A technical platform is a base to improve the efficiency of forecasting operations and also the reliability of forecasting as well. It is urgent in the future to advance the current MICAPS used all over the country and the SWAN system that connects the national unifications to the localized factors, and build up refined NWFD. The missions include three points as follows:

(1) Take MICAPS as the core and basis for a national comprehensive weather forecast operation, and establish an intensive and special MICAPS platform for forecasting operations around the country. In the next three years, MICAPS 3.2 will be released, with all special versions to be upgraded, a WEB version to be issued, and a uniform frame version crossing platforms to be developed. Realize the blending of the software frames of computer and workstation versions, to form standard basic software frames, supporting the development of MICAPS and its various special versions.

(2) Promote the construction of SWAN, continuing with research, development, spread and application of SWAN all over the country. Improve the application level of mesoscale fast assimilation of radar, satellite and automatic weather station data; realize the automatic recognition of mid- and small-scale weather systems, such as short-term severe rainfall, hail, thunderstorms, tornados etc.; develop the approaches of quantitative precipitation estimation and nowcasting forecasts, strong convective short-term and nowcasting forecasts, and lightening nowcasting forecasts; and realize the integrated indication and analysis of forecast

products based on the technical frame of MICAPS. Weather stations at different levels should build local short-term nowcasting forecast systems according to the features of local disastrous weathers under the setup of the standard function of MICAPS.

(3) Set up and improve the NWFD, which contains the 7-day, nationwide city–county and 5-km grid meteorological objective interpretation and application forecast products and implement the functions of real-time supply, direct access on the internet, and real-time evaluation of element forecasting results.

3. China's climate predicting operation

China is located in the monsoon region in East Asia, with large interannual climate variation. The frequent droughts and floods impact very seriously on the economy and society, and so climate prediction has been a key component of meteorological operations. The NMC began to deliver long-term predictions in 1958, and organizes a prediction conference on drought and flood every year. After the National Climate Centre (NCC) was founded in 1995, this operation was transferred to the NCC. Meanwhile, a lot of research has also been carried out at the Institute of Atmospheric Physics, Chinese Academy of Sciences, and some is involved in climate prediction operations. In the past several years, much significant climate prediction research has been conducted, which has contributed to, or has the potential to help improve, climate prediction.

3.1 *Climate monitoring*

Climate monitoring is the critical basis for climate prediction. Due to climatic large-scale evolution and complex interactions, climate monitoring in China must not only focus on weather elements and their variation, but also needs building to even larger-scope monitoring operations of other elements in meteorological and climatic systems. Since its foundation, the NCC has established global and regional climate monitoring operations. Through more than a decade's development, the NCC has made great progress and achievements in the content, scope and methods of its monitoring operations (Xiao, 2010).

An integrated monthly timescale monitoring system has been built for the atmospheric system, which focuses on the basic climate situation of the global surface, the basic conditions of atmospheric circulation, the Northwest Pacific Subtropical High, and other important systems. With increasing demands in terms of concern about extreme weather events and refined monitoring, the monitoring of climatic elements has expanded from the traditional focus on monthly mean temperature and precipitation, to other elements like daily high temperature, low temperature, average temperature and rainfall amounts. In 2005, the NCC/CMA established a daily climate dataset of global stations that is adoptable for climatic operations. By 2009, the network of monitoring sites available for climatic element monitoring in China has increased to more than 2000 stations from 600, drastically improving the precision of monitoring outputs. China is located in a typical monsoon region, so the summer monsoon in East Asia is always the focus of climate monitoring. In recent years, the NCC/CMA has developed a suite of monitoring standards and operations for the East Asian summer monsoon, thus enabling daily monitoring of the summer monsoon. In addition, in 2009, monitoring operations for the East Asian winter monsoon were also established.

In marine monitoring, monthly real-time monitoring operations for ocean surface and sub-surface temperature have been established. Supported by the national the Ninth Five-year Science and Technology Program, an ENSO operation system has also been established, along with a monthly monitoring and prediction system for the tropical Pacific ENSO. Thus, there exists a rolling monitoring and prediction capability to analyze the evolution of monthly-scale ENSO with the comprehensive characteristics of ocean and atmosphere. The ENSO monitoring and prediction products are delivered on internet.

With respect to snow cover and sea-ice monitoring, the monitoring operations for Northern Hemisphere snow cover and Southern Hemisphere sea ice were established respectively in 2004 and 2006, basically on a monthly timescale. Snow cover monitoring is based on NOAA satellite remote data, covering the snow-accumulated days and anomalies as well as the square meters of snow cover in different regions of the Northern Hemisphere, Eurasia, China, as well as the three big snow-accumulated regions [Qinghai–Xizang (Tibetan) Plateau, Xinjiang, and Inner Mongolia]. Sea ice monitoring is mainly carried out on a monthly basis and in terms of anomalies of sea ice at the north and south poles. Related NCC/CMA products are delivered online every month, providing snow and ice monitoring information for short-term climate prediction.

3.2 *Climate prediction*

At present, short-term climate prediction is conducted mainly through methods combining physical statistics with dynamic model outputs, in which the improvement of prediction accuracy is not so significant, similar to the international situation. Operation centers abroad usually analyze the prediction skill over

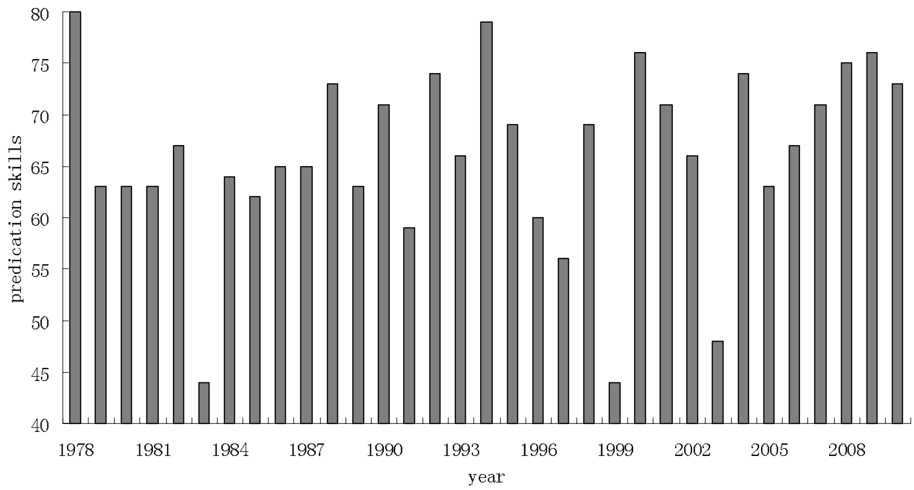

Fig. 2. Predication skills for the summer precipitation over China during 1978–2008. (Provided by National Climate Center).

target areas to begin with, and prediction is not issued to areas with low prediction skill. However, prediction operations in China cover the whole territory of the country from the viewpoint of satisfying service needs. Figure 2 shows prediction skill scores of annual summer precipitation between 1978 and 2010. The skill scores derive from comparing the results between prediction and observation at 160 stations over China at six levels (Tian et al., 2010). It can be seen clearly that the annual scores (prediction skill) differ greatly, with the highest score (80%) in 1978 and the lowest (44%) in 1983 and 1999. The average score during the 33 years is 65%, with a normal difference of 8.7%. Figure 2 also shows that the scores increased after 2000. In addition, the distribution of the scores indicates that, among the 11 years from 2000 to 2010, seven years achieved more than 70%. However, in the 22 years before 2000, almost 11 years had above average scores, only five years of which achieved a score over 70%.

Therefore, it can be concluded that short-term climate prediction in recent years has improved to some extent. It has benefited from a lot of research and the relationship between scientific research and operation becoming closer. Actually, new approaches and more effective climate prediction models for statistical, dynamical, and a combination of dynamical and statistical models and downscaling models (Sun et al., 2011a, 2011b) in climate prediction have been proposed and applied successfully.

Since 2003 and 2006, the Institute of Atmospheric Physics, Chinese Academy of Sciences began to make seasonal predictions for dust weather frequency and typhoons using dynamical models, which represents pioneering work in this field (Wang et al., 2003; Wang et al., 2006). The prediction results are sent to NCC every year as one of the resources for integrated prediction. Recently, several new schemes or methods have been presented to improve the climate in China, such as the "analog year" prediction theory (Wang and Fan, 2009), the year increment prediction scheme (Wang et al., 2000; Fan et al., 2008; Fan et al., 2009; Fan and Wang, 2009), and a prediction method that merges information from GCMs and observations (Lang and Wang, 2010). The analog year prediction approach was proposed by Wang and Fan (2009) and considers both modeled and observed spatial patterns of historical "analog years" in the tropics, and has proved its effectiveness in improving the summer precipitation in China, since the prediction skill of climate models in seasonal climate prediction on precipitation in China is rather low. The interannual increment prediction approach proposed by Fan et al. (2008) has been successfully applied to seasonal climate prediction for summer precipitation and temperature in China, as well as tropical cyclone genesis predictions (Fan et al., 2008; Fan et al., 2009; Fan and Wang, 2009; Fan and Wang, 2010). The rationality of this approach may arise from the existence of a tropospheric biennial oscillation (TBO), facilitating the capture or identification of marginal changes in the underlying variables. This approach shows good prediction skill in interannual and decadal variability. A new prediction approach that merges information from GCMs and observations was designed for the seasonal prediction of dust storm and summer precipitation in China by Lang (2008) and Lang and Wang (2010). To improve the dynamical model's prediction, the effect of some bias correction methods have been analyzed and discussed. These schemes or methods can significantly improve the summer rainfall over China.

Initially, the main service of short-term climate prediction was to crop production, but with the growing needs of the social economy and the development of technology, short-term climate prediction has also gotten involved in more different kinds of products, such as temperature, precipitation, typhoon quantity, frequency of cold surges, frequency of sandstorms, conditions for crop production, forest and grassland fire risk, and so on. A real-time climate dynamical prediction experiment was carried out for the first time by Wang et al. (2006) for typhoon frequencies over the Western North Pacific in 2006. Fan (2007) established an effective statistical model for typhoon genesis frequency containing new predictors of winter North Pacific sea ice and NPO. Lang (2008) suggests that the IAP9L-AGCM model possesses a large potential skill for predicting the large-scale climate background closely related to Western North Pacific typhoon activity. As a national climate operational unit, the NCC/CMA has preliminarily integrated and established a seasonal comprehensive predicting system for the Northwest Pacific typhoon activities in the field of oceanic climate.

Today, the operational products cover the monthly, seasonal and annual time ranges. The predicting objector is not only temperature and precipitation, but also cold airs, frost, typhoon and the climatic trend prediction of some special events such as spring seeding climate, mei-yu, etc. The predicting scope is not limited to China. On the basis of dynamic modeling, the certainty and probabilistic prediction products with 10-day, monthly and seasonal prediction time ranges have been released, as have global circulation and element operational prediction.

3.3 *Climate model prediction in China*

Model prediction has become a more and more important technical basis for short-term predicting operations. The great achievements in the short-term prediction have raised expectations in terms of using numerical climate models in climate prediction. It is generally considered that current climate prediction techniques are still at a low level and that progress lies in the improvement and application of numerical prediction models. China was one of the first countries to carry out climate predicting operations using numerical models. Since the foundation of the NCC/CMA in 1995, China has preliminarily established a suite of complete dynamic climate predicting model systems, supported by the national 95th Science and Technology Program (Luo, 1998). From 2001 to 2004, the NCC/CMA continuously improved and tested the performance of this model system (Ding, 2004), having carried out an historic reforecast and three-year quasi-operational testing verification. In 2005, as the first-generation dynamic climate model system for short-term climate prediction, the NCC Climate Prediction Model System was put into operation, which contains a monthly dynamic extended forecast model, ocean–atmosphere coupled global climate model, high-resolution regional climate model, and ENSO prediction model, as well as a monthly, seasonal and annual operational dynamic model system which is composed of a pre- and post-processing system (Fig 3). This suite performed well in the testing of climate prediction at the monthly, seasonal and annual scales. The validation on the reforecast of the last decade suggests that this model system has improved with respect to the movement and development of the monsoon and monsoon rain belt.

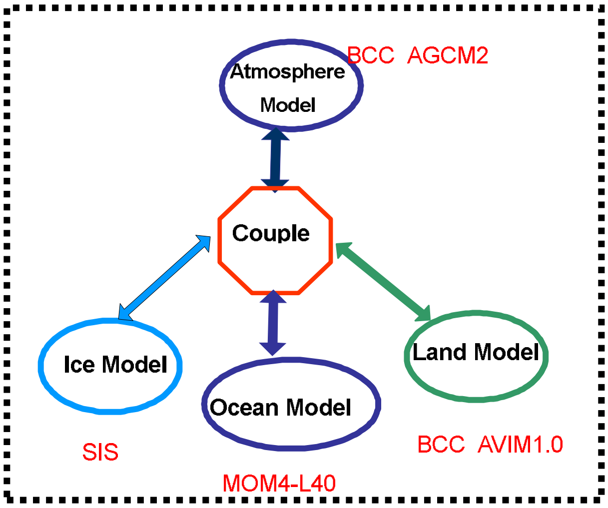

Fig. 3. The frame of NCC operational predication model system V.2.

Based on model outputs, research into the interpretation and application methods of climate dynamic products has been carried out. Monthly prediction is mostly based on dynamical extended range forecasts (DERFs). There are 40 members in the DERF operational system, among which 20 members come from singular vector methods (Liu, 2000), while the other 20 members resulted from lagged average forecasts (LAFs) with four different times' initial condition each day in five days. The blending methods of dynamical and statistical approaches were introduced by Li and Chen (1999), and are based on the relationship between monthly observed precipitation anomalies and monthly circulation from ensemble dynamical extended range forecasts (DERFs). The results show that the method is useful for forecasting monthly rainfall anomalies using potential height of ensemble DERF through independent sample tests. Based on the optimization information extracted from monthly DERFs, the downscaling precipitation prediction was demonstrated as a good reference for monthly climate prediction (Jia et al., 2010). The downscaling methods can be applied in operational climate prediction because of their clear physical meanings (Gu et al., 2011). This model system has become one of the major approaches for short-term climate prediction, and the products have been widely applied to climate predicting operations in the provincial meteorological departments of China.

From the late 1990s, the IAP GCM has been used for short-range climate prediction at the IAP (Wang et al., 2000). Since then, the IAP AGCM has been improved both in dynamic processes and physical parameterization. A hindcast and operational experiment indicated that it can capture quite well the large-scale patterns of the summer flood/drought situations over China. The study showed that besides sea surface temperature anomalies, atmospheric initial conditions and land surface characteristics have important influences on Eastern Asian seasonal climate prediction (Lin et al., 2004; Chen and Lin, 2006). The prediction results were provided to the NCC as important references.

In order to improve the simulating capacity of the climate model system and the prediction level against meteorological disasters, the NCC has initiated research and development of China's climate system model in recent years. After several years of development, a climate system model dealing with the multisphere interaction of ocean, land (biology), ice and atmosphere was established, of which the global atmospheric circulation spectral model BCC_AGCM2.0.1 has achieved a series of important progresses (Wu et al., 2008), including developing and advancing the parameterization schemes of model physical processes, such as developing the new cumulus convective parameterization scheme, improving the processing of the problem of clouds vertically overlapping in BCC_AGCM2.0.1, and drawing the NASA solar radiation transfer model CLIRAD-SW into BCC_AGCM2.0.1 etc. The test results revealed the BCC_AGCM2.0.1 model has a better simulating capability for precipitation, temperature, atmospheric thermal structure and circulation, and other climate conditions and seasonal variations, especially for the northward movement of East Asian monsoon rainfall, and it also shows some simulating potential for MJO activity. It is expected that the climate model system BCC_CSM1.0 will support future operations as the second-generation short-term climate model prediction system. In the meantime, as a short-range climate prediction approach, the IAP GCM has been developed from the IAP2L to the IAP9L with more multisphere interaction processes involved.

Compared to the physical statistic prediction method, the superiority of the climate model is to have sufficiently considered the physical processes of the climate system. By constantly improving and adopting the ensemble prediction method, the climate model has become more and more capable in predicting operations. Now, the NCC monthly-scale prediction skill of numerical models is as good as the subjective comprehensive prediction. However, the prediction level of the dynamic method still cannot meet the needs of predicting operations and the historic data cannot be used so well. Starting from 2007, some key technical research has been carried out to improve the dynamic seasonal prediction through a series of experiments on new dynamic statistical prediction methods by sufficiently using historical information (Ren et al., 2009; Zheng et al., 2009). Based on the method of combining the data diagnosis and analysis with numerical simulating, the physical factors are selected respectively in the different climate regimes of China for the flood season prediction. The information pick-up technique for scale separation and leading mode of climate model prediction is developed. Another new prediction method is developed based on synoptic eddy and low-frequency flow (SELF) dynamics. On the simple barotropic model, develop the anomaly forecast skill and model that can directly forecast the first and second order moment anomaly of the seasonal varying probability density function.

It is estimated that the prediction ability of the climate model still has a long way to go to meet operational needs, but it can provide more and more useful information. The method of combining dynamics with statistics will become the dominant one in climate predicting operations. Based on dynamic climate model outputs and through statistical analysis, the downscaling statistical interpretation and application of the dynamic products can be done to predict the climatic situation of a region or some specific places.

3.4 *The application service of short-term climate prediction in China*

The climate operational service in China began with the application of climate information to crop production. Because of a great many uncertainties in climate predicting, the prediction information is taken as references for decision-making by society and government departments. In recent years, with the development of climatic operations, the climatic application products have been provided to more and more users. The current products include core element predictions, such as the percentages of temperature and precipitation anomalies at monthly, seasonal and annual scales.

For specific user needs, the temperature and precipitation anomalies in the flood season and in other critical periods, the spring sandstorm prediction trend, the first frost in the north, the spring-seeding weather conditions in South China, the summer low temperature in the northeast, the forest and grassland fire prediction trend in autumn and winter, the climatic trend prediction of typhoon and cold airmass etc. is also provided by the NCC. As the regional climate center of the World Meteorological Organization (WMO), the NCC presents some operational products to WMO members, such as the monitoring and outlooks of the global, Asian and China's droughts, ENSO monitoring and outlook, East Asian monsoon monitoring and predicting etc.

4. The target for short-term climate prediction in China

A climate prediction service is increasingly needed in order to improve economic and social development in China. However, the present service is not good enough to keep pace with such development. In addition to the uncertainty, the low level of refinement and the lack of extended predictions etc. are the main problems that climate prediction faces now. Therefore, it is an urgent objective for short-term climate prediction operations in China to establish seamless operations covering the extended-range (15–30 days), monthly, seasonal, annual, interannual and interdecadal timescales, and to perfect focused service products to meet the demands of socioeconomic development. The main task for modern climate prediction is to accelerate the research and application of prediction models, to strengthen monitoring and diagnosing, to establish seamless prediction operations, and to enhance the service of operational products.

4.1 *Establishing an ocean–atmosphere coupled climate numerical prediction model*

Based on the CMA's climate system model BCC_CSM, a second-generation climate operational prediction model system has been established (Fig. 2), in which the horizontal resolution of the atmosphere/land surface model reaches about 1°. This model obtains the coupling of atmosphere, ocean and land surface through the coupler, and is able to simulate low-frequency activities very well, including the advance and retreat of the East Asian monsoon rain belt, MJO etc., which indicates the precipitation prediction skill for China has been raised to international standards. This model prediction system will be used in climate monthly forecasts, seasonal predictions and interannual predictions. It can also be applied to 10–30 day extended forecasts, providing technical support for the seamless operational prediction system.

4.2 *Strengthening the multisphere and multiscale monitoring and diagnosing of the climate system*

Monitoring and diagnosing of the climate system is a basic stepping stone to effective climate prediction. The basic integrated operational system in future will include monitoring of monsoon, atmospheric circulation, land surface, ice-snow, and marine elements.

For monsoon and atmospheric circulation monitoring, it is very important to make better use of the available observation data, apply the assimilation technology widely to climate system monitoring operations, and comprehensively use remote sensing data and conventional observation data. Refining the temporal resolution of climate monitoring is an obvious trend both for climate operations and application. Climate monitoring has not only been needed on monthly and seasonal scales, but also on weekly, 5-day and even daily scales. The mission for operations is to integrate the monitoring and analysis for the multiple atmospheric circulation indices and physical diagnostic data, and to carry out monitoring diagnosis on high impact indices, such as (1) South China Sea monsoon, East Asian subtropical summer monsoon and Asian-Australian monsoon; (2) Madden-Julian Oscillation (MJO), Antarctic Oscillation (AAO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and (3) stratosphere (ozone) etc. In addition, because of global warming, extreme weather and climatic events occurring more often and causing increasing amounts of economic loss with each year, a monitoring and testing system for such events is a great necessity, not only in China, but worldwide as well.

For land surface and ice-snow monitoring, an urgent task is to develop global land surface and ice-snow monitoring including land surface temperature, land surface albedo, vegetation coverage, soil humidity, frozen soils in alpine areas, plateau thermal situation, days and thickness of accumulated snow and marine ice. The focus of operations should include satellite remote sensing of drought, vegetation coverage and snow cover on the Tibetan Plateau and frozen soils in alpine areas in some key geographical ranges, such as weekly snow cover monitoring index, integrating the analysis of satellite remote sensing data and conventional data over plateau regions, multiple snow cover monitoring index, Antarctic sea ice oscillation index and sea ice density monitoring index for the Barents Sea, Bering Sea and Okhotsk Sea regions.

For marine monitoring, more effort should be made to realize the seamless and refined monitoring of oceanic multiple temporal resolutions all over the globe. It is important to establish an operational system of 5-d to monthly scale rolling monitoring, attribution and diagnosis for the global marine climate anomaly, especially enhancing the monitoring and prediction capability for drastic marine anomalous signals of different types, such as ENSO, Indian Ocean Dipole (IOD), Pacific Ocean meridional anomaly mode, and so on.

4.3 *Establishing seamless prediction*

Climate prediction operation aims to provide different timescale products to the end user. A challenge is to establish seamless prediction. The emphasis is to enhance the 15–30 day extended prediction ability, build processes capable of predicting within 30 days, improve the seasonal and annual prediction ability, and develop interdecadal prediction.

Extended-range prediction is dominated by objective dynamic model prediction, adopting the method of combining dynamic models with statistics. This can be considered to involve developing multi-model ensemble forecasts, whose core and critical technique is to develop climatic prediction models that can simulate low-frequency activities, such as MJO. Some recent research has been carried out on the impact of the MJO on precipitation in China (Tao and Wei, 2007; Jia et al., 2011), and the prediction testing according to the analysis and diagnosis of low-frequency activity of the MJO has begun. The findings indicate that it has some reference values to the process prediction within 30 days. In addition, using the method of combining dynamics and statistics together, and based on the available operational model products, analysis of the predictable steady components indicated that it is feasible to set up prediction formula and numerical frameworks for stabilizing components by the method of model variables and base vectors of predictable attractors at the scale of 10–30 days (Ren and Chou, 2005; Zheng et al., 2009). It is hopeful that an effective 10–30 day extended prediction operation system can be established.

Supported by dynamic model prediction, the target for operational monthly prediction is mainly to improve forecast accuracy at the monthly scale and refine monthly prediction processes. At the same time, based on the dynamic and statistical downscaling method, the main task is to improve the resolution of forecast products, develop interpretation and application products of dynamic climate models, carry out research on probabilistic prediction techniques, and quantitatively evaluate the uncertainty of forecasting products. The forecast products delivered to end users should be probabilistic products containing analysis of uncertain information.

For seasonal prediction, the prediction technical systems combining ensemble prediction technology with dynamic model technology should be studied and developed to establish rolling seasonal-scale prediction operations. On the basis of promoting summer flood forecasts and winter cold-wave predictions, there is a dire need for a dynamic mechanism research on spring and autumn prediction, gradually building up to seasonal prediction operations that can be refined monthly. Meanwhile, it is important to strengthen the ensemble and probabilistic prediction capacity of seasonal dynamic climate models.

More research is needed on interannual- and interdecadal-scale prediction. It is possible to set up interannual ensemble prediction technical systems combining ensemble prediction technology and dynamic application technology, to gradually form interannual- and interdecadal-scale prediction products.

5. Discussion

In order to meet the increasing needs of end users and different social communities, establishing seamless prediction is very important to operational organizations such as the CMA. To establish seamless prediction, the emphasis must be to enhance the current nowcasting ability, to build intra monthly scale process prediction operations, to improve seasonal and annual prediction abilities, and to develop interdecadal prediction.

More studies and research are needed to improve forecasting and prediction based on science and technology, especially in nowcasting, extened-range forecasting and climate prediction. More attention has to be paid to the linkage between weather and climate. For example, four stages of heavy snowfall and freezing precipitation were observed almost continuously over southern China from January to February 2008, which resulted in the most severe damage to local transportation, electric power lines, communication systems, agriculture, and forestry since 1950. The weather forecast for each stage seems successful, but there is no early warning for such a long-lasting heavy snowfall and freezing precipitation event. Many studies have been carried out to investigate the event and try to understand its multiscale meteorological mechanisms (Gao et al., 2008; Sun and Zhao, 2010; Peng et al., 2010). It is suggested that climatic prediction and weather forecasting should be considered as an integral concept. Extened-range forecasting is just the gap between weather forecasting and short-range climate prediction, and a key linkage between them as well.

How to use a mass of weather forecasts and climatic prediction information, especially the production with some uncertain information, is another even more important question. Enhancing the relevance of climate services to user needs and making the users involved in the prediction process may be a possible way to improve the products themselves.

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