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ORIGINAL PAPER

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Weather and seasonal climate prediction for flood planning in the Yangtze River Basin

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Abstract This paper describes the use of numerical weather and climate models for predicting severe rainfall anomalies over the Yangtze River Basin (YRB) from several days to several months in advance. Such predictions are extremely valuable, allowing time for proactive flood protection measures to be taken. Specifically, the dynamical climate prediction system (IAP DCP-II), developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP), is applied to YRB rainfall prediction and flood planning. IAP DCP-II employs ensemble prediction with dynamically conditioned perturbations to reduce the uncertainty associated with seasonal climate prediction. IAP DCP-II was shown to successfully predict seasonal YRB summer flooding events based on a 15-year (1980–1994) hindcast experiment and the real-time prediction of two summer flooding events (1999 and 2001). Finally, challenges and opportunities for applying seasonal dynamical forecasting to flood management problems in the YRB are discussed.

Keywords Dynamical climate prediction · Rainfall anomalies · Flood risk

Introduction

With a length of approximately 6,300 km, the Yangtze river (Changjiang) is the largest river in China (and the third longest in the world) with a drainage area of 1.8 million km^2, approximately 20% of the nation's territory (Yan and Zhang 2003; Luo and Le 1996). This drainage area, hereafter referred to as the Yangtze River Basin (YRB), encompasses about one-third of the total population (with a population density of approximately 200 people per km^2), industrial output, and agricultural production of China (Howarth et al. 1996; Yan and Zhang 2003). From ancient times, the YRB has been a central economic, agricultural and social region of China due to its moderate temperature, abundance of natural resources, and convenient access to land and water communications (Zhang et al. 1999). The average annual precipitation of the YRB (located in the East Asian monsoon region) is approximately 1,000 mm, with higher rates (1,300–1,600 mm) in the Dongtinhu and Poyinghu lowland lake region (Weibin and Kempe 1987).

Summer monsoon related rainfall anomalies may lead to flood disasters in the YRB: 214 summer floods have been recorded from roughly 206 B.C. to 1911 A.D., averaging approximately once every 10 years. Since the nineteenth century, catastrophic flooding has occurred more often, and with greater intensity (Zhang and Sun 2004; Luo and Le 1996; National Climate Center 1998). Human activities have a profound effect on the geology and hydrology of the YRB, significantly increasing flood risk. Before the fifteenth century, the middle reaches of the Yangtze river contained branches with semi-parallel channels (Yin and Li 2001), forming the Changjiang-Hanshin plain. In 1548, during the late Ming Dynasty, completion of the Great Jinjiang Levee (on the northern bank of the middle Yangtze river) significantly constrained the river. Over the next four centuries, river bed siltation raised the Yangtze river bed level in the southern sections of the Changjiang-Hanshin plain. The 1998 flood affected the entire YRB with rainfall anomalies exceeding the climatological mean by more than 100% (Fig. 1): high water levels lingered for more than 70 days (an unusually long period) leading to over 30 billion US dollar in economic losses and more than

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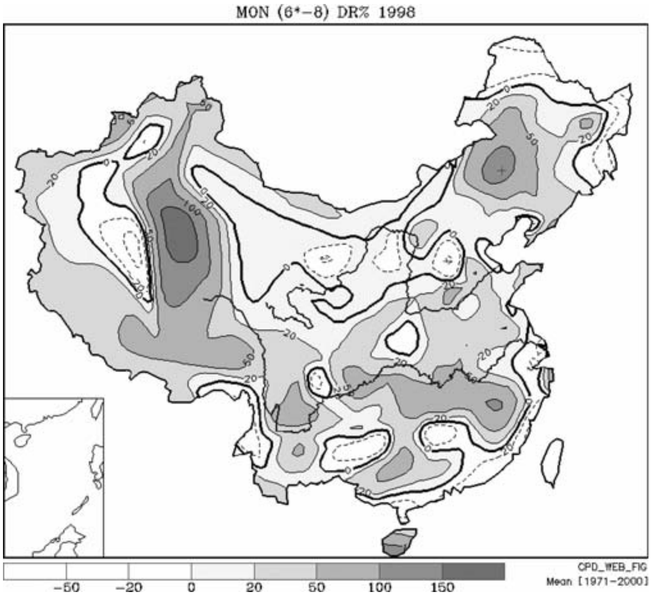

Fig. 1 The observed percentage summer rainfall anomalies (averaged over June, July and August) for 1998 in China

3,600 deaths (National Climate Center 1998; Yin and Li 2001).

Numerical weather/climate prediction models have matured to the point where advances increasingly focus on severe or hazardous events. For example, the meteorological community has developed effective early detection systems to manage the risk associated with heavy rainfall and damaging floods (Pielke and Downton 2000; Yu et al. 1999a, b, 2000). Improved forecasting of heavy rainfall events facilitates flood planning and management: communities can undertake more extensive and proactive flood emergency measures (including the evacuation of citizens in the flood plain area, the reinforcement of levees, the dredging of river beds, and the channeling of flood water). In the YRB, recent weather prediction advances include the identification of mechanisms responsible for severe rainstorms (Zhao et al. 2004), the simulation severe flood events (e.g., Xiong et al. 2003), and the real time prediction of heavy rainfall occurrences (e.g., Chen et al. 1998; Lin et al. 2003). This is expected to significantly protect lives and property in the YRB and represents a paradigm shift for flood planning and management in China (where structural measures such as dykes and levees have been used for millennia as the primary means of flood protection).

Weather and seasonal climate predictions of summer rainfall in the YRB and Huaihe River Basin (HRB) are considered, with a lead-time from several days to several months. The meso-scale model version 5 (MM5), a dynamic meso-scale meteorological model (developed by Pennsylvania State University and the National Center for Atmospheric Research) is applied to the real-time prediction of rainfall over the YRB and HRB in 2003 (with a lead time of 1–2 days). A physical basis for seasonal climate prediction is discussed, as well as various approaches for seasonal flood prediction. Next, the skill of seasonal climate predictions for the flood events over YRB and HRB is analyzed, with specific reference to the second generation dynamical climate prediction system (IAP DCP-II), developed by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences. Here, hindcast and real-time prediction experiments are carried out for both the YRB and HRB, with particular emphasis on simulating/predicting the distribution patterns of seasonal rainfall anomalies. Finally, the authors address uncertainties pertaining to seasonal climate prediction and ensemble techniques for seasonal flood prediction and discuss opportunities for applying weather and seasonal climate prediction to flood planning.

Dynamic weather prediction for flood planning: MM5

In this section, the MM5, a dynamic meteorological model developed by Pennsylvania State University and the National Center for Atmospheric Research (NCAR) (Dudhia 1993; Grell et al. 1995) is used for the real-time prediction of YRB and HRB rainfall with 1-day lead time. The predictive skill of MM5 in the YRB and HRB is also assessed. The MM5 is a grid point, three-dimensional, limited area meteorological model with parameterization schemes for different physical processes such as cumulus convective parameterization schemes, explicit precipitation schemes, and planetary boundary layer schemes. MM5 has been used for many applications, including the simulation and prediction of heavy rainfall (e.g., Chen et al. 1998; Davis et al. 1993; Ferretti et al. 2000; Yu et al. 1999a, 2000).

The real-time prediction of the 2003 YRB and HRB heavy rainfall event involves two nested MM5 integrations, with a horizontal resolution of 45 and 15 km, respectively. The prediction domain is centered at 30°N, 120°E, with 100×120 grid cells for the 45 km resolution case, and 142×163 grid cells for the 15 km resolution case. The threat score (Ts), commonly referred to as a critical success index, is used as a measure of forecast accuracy (it is sensitive to hits, and penalizes both misses and false alarms) in order to assess MM5's performance on the prediction of rainfall over the YRB and HRB. Ts is defined as:

$$\mathrm{Ts} = \frac{N_{\mathrm{A}}}{N_{\mathrm{A}} + N_{\mathrm{B}} + N_{\mathrm{C}}} \qquad (1)$$

where N_{A} is the number of correctly predicted grid cells (number of hits), N_{B} is the number of misses (missed grid cells), and N_{C} is the number of false alarm grid cells, respectively. Ts is calculated for determining the accuracy of a prediction, which is the critical success index to measure the fraction of observed events that were correctly predicted. When the value of Ts exceeds 0.5 more than half of the observed ''rain'' events have been correctly forecast. The Ts range is from 0 (no skill) to 1 (perfect score).

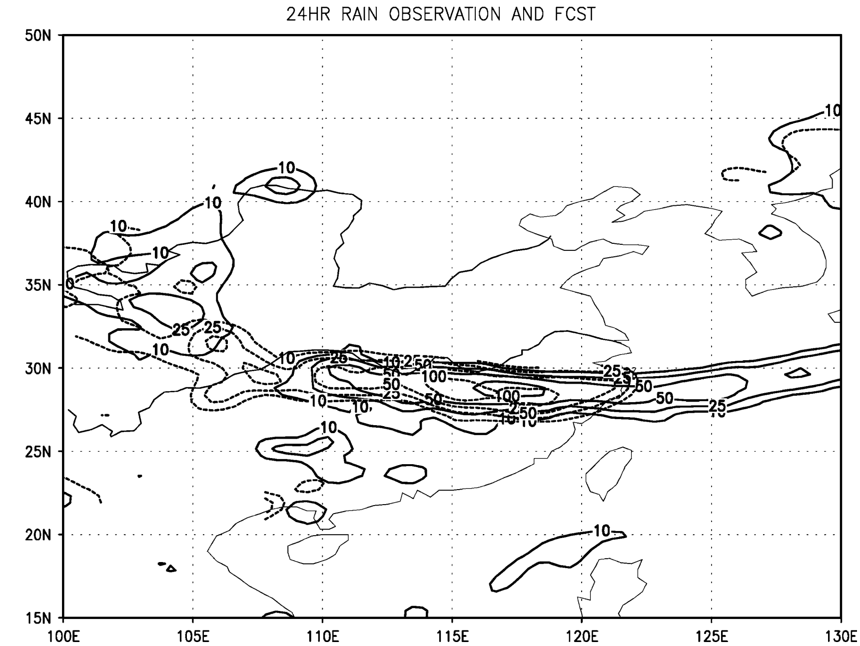

Fig. 2 Twenty-four hour accumulated precipitation for the June 24, 2003 heavy rainfall in the YRB. The observed data (*dashed line*) and MM5 predicted data (*solid line*) are shown

During the summer of 2003, with the onset of Meiyu season on June 21, several heavy rainfalls successively occurred over the YRB and the HRB from June 21 to July 11, 2003. MM5 was applied to the real time prediction of these heavy rainfall events in the YRB and HRB from June 21 to July 11, 2003, with a 1-day lead time. The daily precipitation Ts scores over the YRB and HRB by MM5 with a horizontal resolution of 45 and 15 km are listed in Tables 1 and 2, respectively. Here, Ts(10 mm), Ts(25 mm), and Ts(50 mm) represents the Ts for rainfall events exceeding 10, 25, and 50 mm, respectively. As shown in Table 1, at a horizontal resolution of 45 km, the averaged Ts are 58.5, 44.8, and 23.2 for Ts(10 mm), Ts(25 mm), and Ts(50 mm), respectively. Table 2 shows that, at a horizontal resolution of 15 km, the Ts values are 56.4, 43.1, and 23.0 for Ts(10 mm), Ts(25 mm), and Ts(50 mm), respectively. These results suggest that the MM5 model has the potential to predict severe rainfall events over the YRB and HRB. As expected, the value of Ts(10 mm) is higher than Ts(25 mm) and Ts(50 mm) scores as higher rainfall amounts are more difficult to predict accurately, with current numerical models.

Figure 2 illustrates the MM5 forecast performance of the June 24, 2003 YRB heavy rainfall event (24-h accumulated precipitation). Note that predicted rainfall regions (solid contour lines) are highly consistent with the actual rainfall for station observations (dashed line regions). This is supported by the high Ts(50 mm) value (around 48.8) for the June 24 storm, when averaged over a larger areas (all of China). As well, Fig. 3 shows that the July 9, 2003 HRB severe rainstorm was well-predicted by MM5. This is supported by the high Ts(50 mm) value (around 42.1) for the July 9 storm, when averaged over all of China.

Dynamic seasonal prediction in the YRB and HRB: applying the IAP DCP II

In Sect. 2, MM5 was used to carry out a real time prediction of rainfall quantity and patterns over the YRB

Table 1 MM5 precipitation Ts values with a 45 km horizontal resolution (expressed as a percentage)

Date	Ts(10 mm)	Ts(25 mm)	Ts(50 mm)	Date	Ts(10 mm)	Ts(25 mm)	Ts(50 mm)
21 June	30.34	18.75	0.00	02 July	56.25	27.08	0.00
22 June	63.75	53.22	34.31	03 July	77.88	58.82	45.71
23 June	64.56	59.26	38.78	04 July	36.69	35.00	36.84
24 June	67.31	69.93	59.09	05 July	56.84	44.63	5.45
25 June	54.05	34.15	8.51	06 July	52.80	42.31	4.55
26 June	65.28	51.11	24.24	07 July	26.06	10.29	4.17
27 June	60.70	50.46	38.46	08 July	71.23	68.75	44.09
28 June	43.28	24.61	14.29	09 July	64.32	60.16	42.10
29 June	71.61	56.79	11.67	10 July	72.25	42.52	18.06
30 June	75.47	61.61	34.29	11 July	48.31	27.87	20.00
01 July	69.39	43.64	2.33				

Table 2 MM5 precipitation Ts values with a 15 km horizontal resolution (expressed as a percentage)

Date	Ts(10 mm)	Ts(25 mm)	Ts(50 mm)	Date	Ts(10 mm)	Ts(25 mm)	Ts(50 mm)
21 June	29.04	16.03	0.00	02 July	51.01	26.83	0.00
22 June	62.41	55.49	31.89	03 July	71.90	56.25	43.20
23 June	64.16	50.56	31.92	04 July	36.78	35.12	44.04
24 June	66.01	67.21	55.05	05 July	51.27	37.66	4.66
25 June	51.82	33.95	14.35	06 July	54.03	51.38	6.74
26 June	64.12	48.17	19.52	07 July	23.80	11.26	5.79
27 June	59.56	44.91	33.51	08 July	67.28	68.46	45.65
28 June	42.55	21.54	17.61	09 July	64.18	56.90	39.92
29 June	70.52	54.67	17.60	10 July	70.10	43.87	19.45
30 June	72.39	58.71	34.74	11 July	45.73	25.81	11.62
01 July	65.04	40.96	5.94				

with a lead time of one to several days. However, additional lead time of summer rainfall anomalies (ideally several months) can provide more time to plan for flood disasters (leading to fewer economic losses and less social disruption). Accordingly, the seasonal dynamic climate prediction (DCP) system from the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP DCP) is applied to the prediction of rainfall anomalies over the YRB and HRB, with particular emphasis on the prediction of distribution patterns of seasonally averaged rainfall anomalies.

DCP Development began in 1989, when the IAP AGCM was first applied to seasonal and extra-seasonal predictions of summer monsoon rainfall anomalies over the YRB (Zeng et al. 1990). Since 1990, the DCP system has been used primarily for real time climate prediction (Li 1992; Yuan et al. 1996; Zeng et al. 1997). For example, the DCP system has been applied to the prediction of YRB summer rainfall anomalies, including the 1991 flood and the 1994 drought (Yuan et al. 1996). Since 1995, advances in the DCP model, including improvements in the GCM, land surface model, and correction system, have led to an increase in the model's predictive skill. The second generation of the IAP Dynamic Climate Prediction system (IAP DCP-II) is described by Lin et al. (1998).

As shown in Fig. 4, IAP DCP-II consists of five components: (a) IAP ENSO prediction system, (b) prediction integrations and anomaly coupling technique, (c) ensemble prediction technique, (d) correction system, and (e) prediction products and analyses. These components have been applied to YRB flooding. For example, the IAP ENSO prediction system (Zhou et al. 1998) is extremely valuable for forecasting heavy rainfall in the YRB. Originating in the Pacific Ocean, ENSO (a coupled ocean–atmosphere phenomenon centered over the tropical Pacific) is an important source of year-to-year climate variability. Specifically, the interannual variability of the East Asian Summer Monsoon is affected by ENSO phenomena (Wu et al. 2003; Weng et al. 2004). Many studies have shown that a positive rainfall anomaly in the YRB is often preceded by a warm winter equatorial eastern Pacific Ocean. For example, the extraordinary 1998 YRB flood was preceded by the 1997 El Nino phenomena (e.g., Chang et al. 2000; Shen and Lau 1995). In short, ENSO has

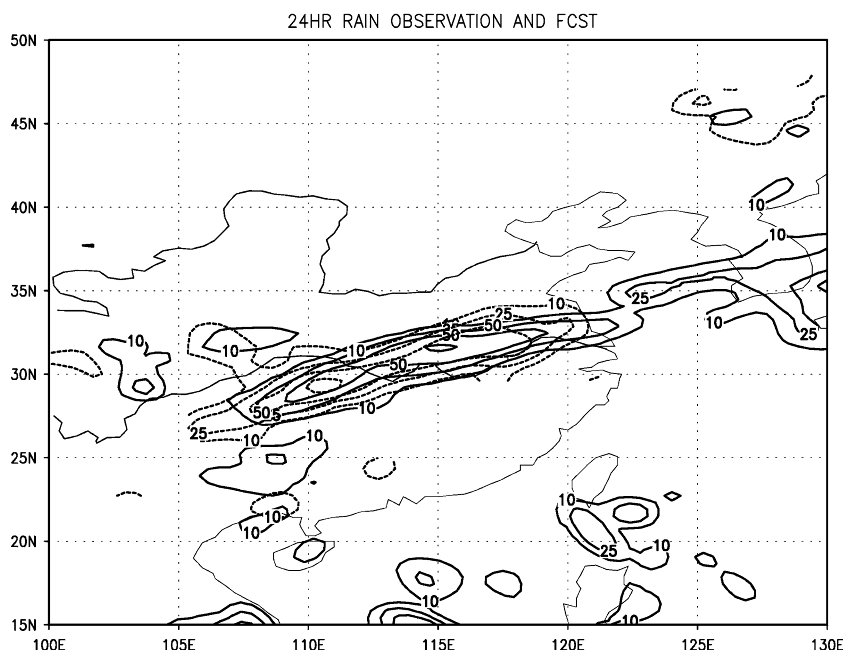

Fig. 3 Twenty-four hour accumulated precipitation for the July 9, 2003 heavy rainfall in the HRB. The observed data (*dashed line*) and MM5 predicted data (*solid line*) are shown

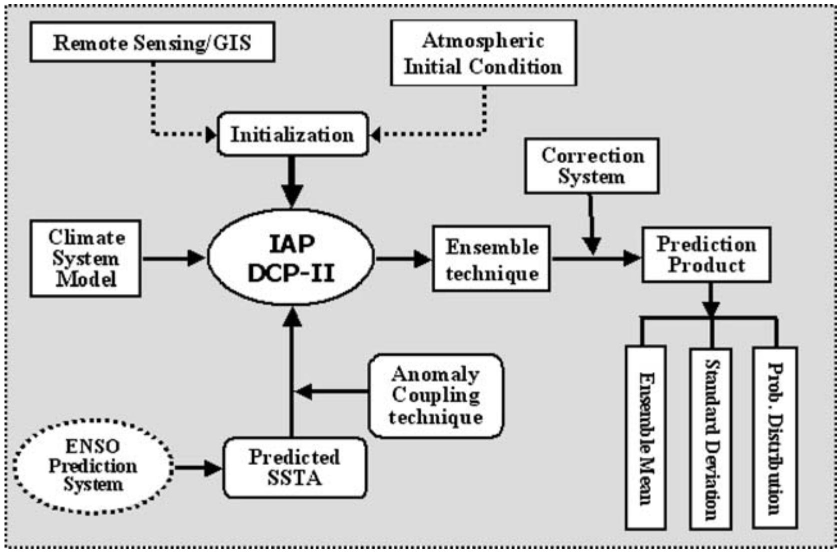

Fig. 4 Configuration of IAP DCP-II

wide-ranging consequences for climate anomalies in China, particularly droughts and floods (e.g., Huang and Wu 1989).

Assessment of rainfall predictive skill over the YRB and HRB using IAP DCP-II

A set of hindcast experiments were performed (1980–1994) in order to assess the ability of IAP DCP-II to accurately predict summer rainfall anomalies (over the YRB and the HRB). The anomaly correlation coefficient (ACC) is used to calculate the correlation between observed and predicted (hindcast) summer rainfall anomalies over the YRB and HRB (105°E–120°E, 26°N–34°N), using IAP DCP-II. These results are shown in Fig. 5, in terms of summer rainfall anomaly percentages. The predictive skill of IAP DCP-II is relatively high: specifically, the ACC exceeds 0.50 for several years. Moreover, the average ACC for the hindcast period is 0.30. Mote (2000) notes that an ACC value of 0.30 or higher is generally acceptable. This suggests that IAP DCP-II constitutes a valuable tool for the prediction of drought/flood conditions over the YRB and HRB.

When IAP DCP-II is applied to the real-time prediction of summer rainfall anomalies over the YRB, a two-tiered approach is adopted (e.g., Bengtsson et al. 1993). First, surface boundary conditions, including the tropical Pacific sea surface temperature anomaly (SSTA), are predicted by the IAP ENSO prediction system. Second, the predicted surface boundary conditions are used to drive the AGCM ensemble integrations (in order to reduce the model's dependence on atmospheric initial conditions). For example, Lin et al. (1998) generated an ensemble of 28 runs (from February 1st to 28th, consecutively) with different initial atmospheric conditions obtained from NCEP real-time analysis (Kalnay et al. 1996). Final prediction results are then obtained by averaging the total ensemble results.

Figure 6 shows the observed and predicted percentage summer rainfall anomalies over China for 1999 using IAP DCP-II. Figure 6a illustrates that in the

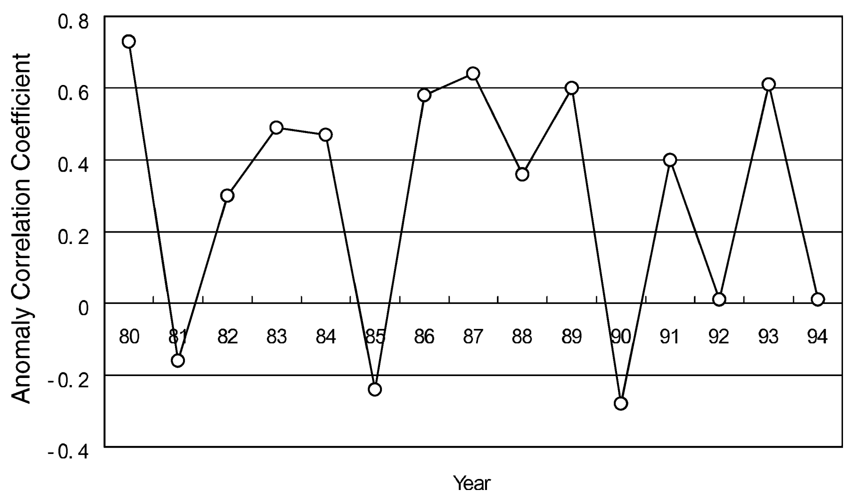

Fig. 5 ACC between observed and hindcast results over the YRB and HRB, in terms of percentage summer rainfall anomalies, using the IAP DCP-II

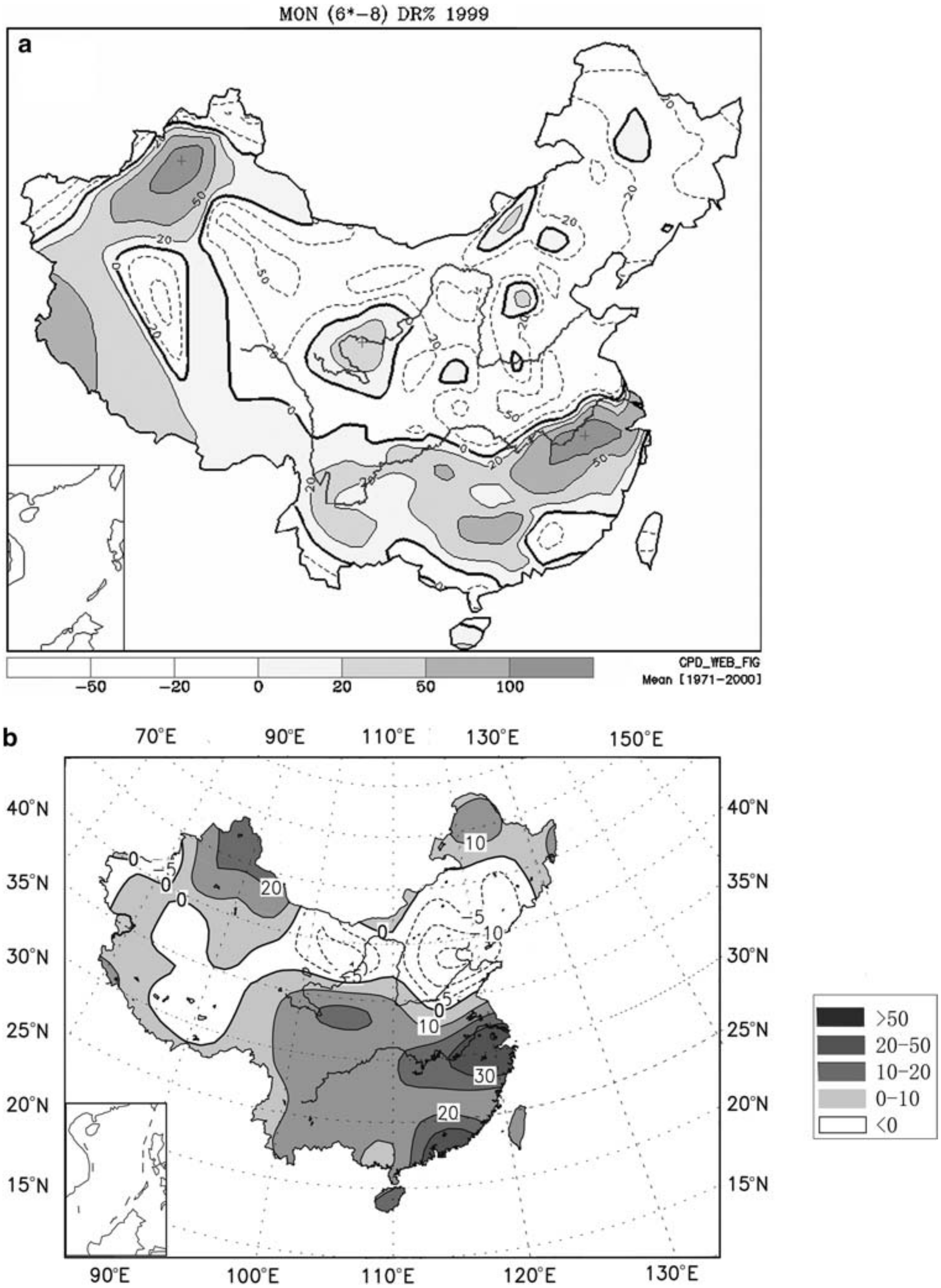

Fig. 6 Percentage summer rainfall anomalies for 1999 over China using **a** observed data and **b** IAP DCP-II predictions

summer of 1999, the rainfall anomalies are generally positive in southern regions and negative in northern regions. Specifically, the summer rainfall is above normal in most of the YRB, with the largest positive rainfall anomalies occurring over the lower reaches of the YRB. Figure 6b shows the predicted percentage rainfall anomalies for the summer of 1999. When observed and predicted results are compared, it is clear that, on balance, IAP DCP-II adequately predicts the large-scale features of rainfall anomalies for the summer of 1999. Specifically, the ACC between observed and predicted data is 0.73 for the YRB. This is true even for regions with large positive rainfall anomalies (such as the lower reaches of the YRB).

Figure 7a, b shows the 2001 observed and predicted summer rainfall anomalies, respectively. Although the IAP DCP-II predictions over large parts of western China are inconsistent with actual observations, the prediction results for eastern China are satisfactory. In particular, IAP DCP-II predictions are acceptable over the YRB, particularly with respect to negative rainfall anomalies over middle and upper reaches of the YRB, and large positive rainfall anomalies over lower reaches of the YRB. Specifically, for the summer of 2001, the

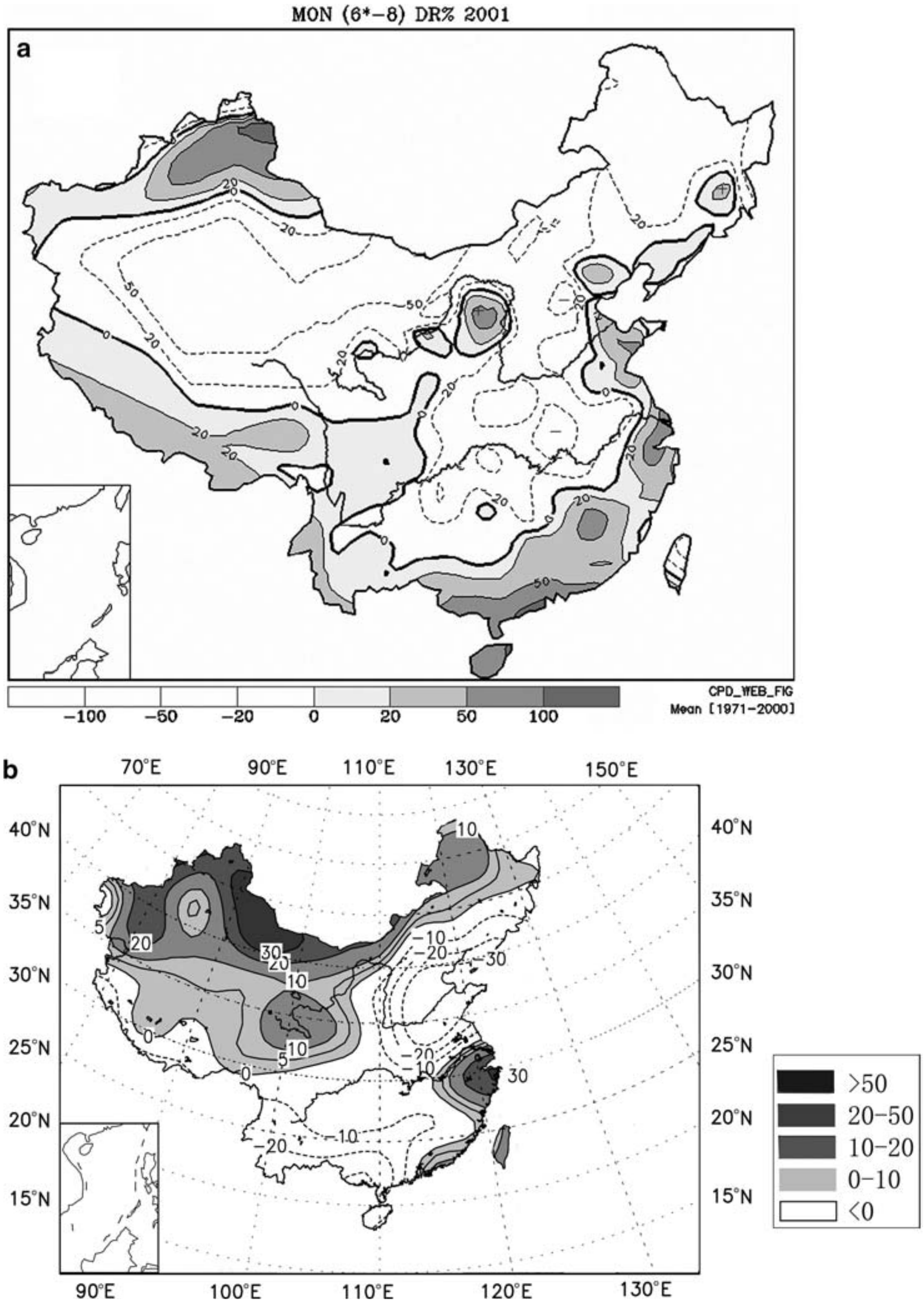

Fig. 7 Percentage summer rainfall anomalies for 2001 over China using **a** observed data and **b** IAP DCP-II predictions

ACC between observed and predicted data is 0.52 (for the entire Yangtze and Huaihe River Valley).

Uncertainties pertaining to dynamic seasonal prediction and the ensemble technique for seasonal flood prediction

Due to the chaotic nature of the atmosphere (Lorenz 1969), predicting the evolution of future weather states is sensitive to the specified initial state; small errors in the analysis (or timing) of such features may lead to large differences in the forecast evolution. In terms of seasonal climate prediction, the atmospheric initial conditions are also quite important, even are secondary to land and sea initial conditions (Wang et al. 2000a, b).

Figure 8 shows the ACC of the observed and IAP DCP-II predicted percentage summer rainfall anomalies over China for 2002, with 28 different atmospheric initial conditions from consecutive days in February (February 1–28, 2002) obtained from NCEP real-time analysis (Kalnay et al. 1996). Note that large variations occur when only a single integration of a real-time dynamic climate prediction model is realized (the ACC values in Fig. 8 vary from 0.02 to 0.43). This variation also exists in real-time seasonal predictions for other years (Lin et al. 2004). One reason for this variation is that the

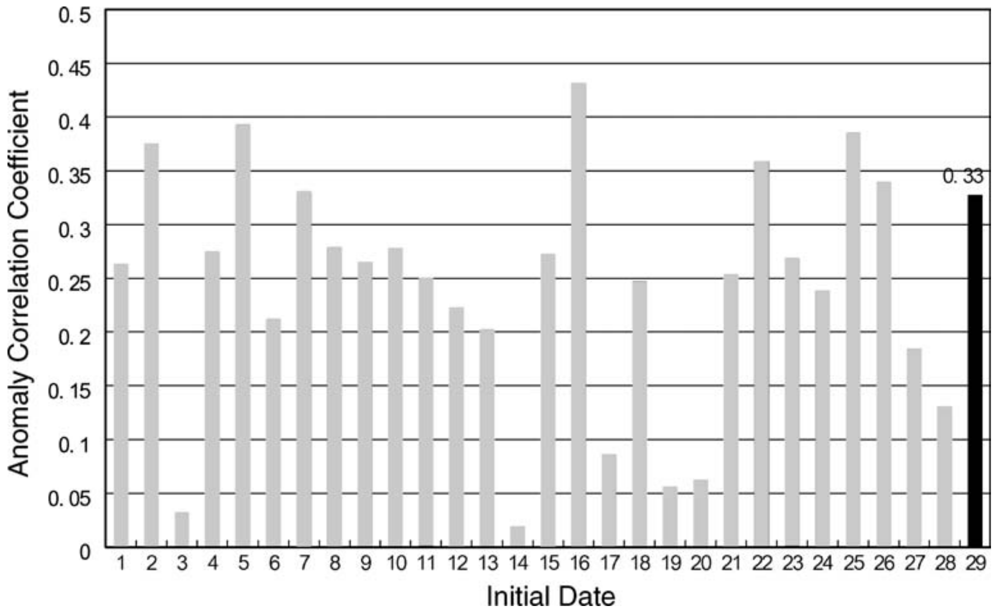

Fig. 8 ACC for predicted and observed percentage summer rainfall anomalies over China for 2002. *Each bar* indicates one individual forecast initiated from a different date in February, 2002. The ensemble mean ACC (0.33) is also shown (*shaded bar*)

development of severe flood events usually involves strong nonlinear interactions between different scales of atmospheric processes.

The ensemble technique for seasonal prediction (EPS) is used to improve the real-time predictive skill of the IAP DCP-II prediction system. Developed in the early 1990s, EPS constitutes an effective technique for improving climate forecast skill: probability forecasts are generated by using a number of runs of a climate model (differing by perturbations to the initial conditions and the model physics). By sampling the probability distribution of the forecast, the ensemble technique can quantify the uncertainty in the seasonal forecasts arising from synoptic-scale baroclinic instabilities (Mureau et al. 1993; Toth and Kalnay 1997). Figure 8 illustrates that when the ensemble technique is applied to the seasonal climate prediction of summer rainfall anomalies in China, the ensemble-mean prediction skill is about 0.33, leading to more accurate results than non-ensemble prediction.

Moreover, the ensemble technique provides additional statistical information such as the standard deviation of the ensemble prediction and its probability distribution. This captures valuable information related to the spread of individual predictions and the reliability of ensemble prediction. For example, in the 1999 prediction of summer rainfall anomalies in China, the standard deviation of predicted summer rainfall anomalies is small (less than 10%) in some eastern and southern parts of China (Fig. 9a), including middle reaches of the YRB. In addition, the probability of a positive rainfall anomaly in southern regions of China is high (Fig. 9b). Specifically, in the YRB, the probability for positive rainfall anomalies is extremely high (exceeding 90%). These results suggest that the seasonal prediction of summer rainfall anomalies over the YRB is highly reliable. Accordingly, IAP DCP-II seasonal prediction products likely constitute a valuable tool for flood planning and management.

Conclusions

This paper introduces a weather and climate prediction system for the real-time prediction of severe flooding events (with lead time from several days to several months) over the YRB. First, a meso-scale meteorological model (MM5) was applied to the prediction of flooding events over YRB and HRB with a lead time of 1–2 days. Prediction results for the summer of 2003 suggest that the MM5 model is capable of predicting heavy rainfall events over YRB and HRB. Next, the dynamical seasonal climate prediction system (IAP DCP-II), developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences, was introduced and applied to the prediction of rainfall anomalies over the YRB with a lead time of up to several seasons. Hindcast experiments for summer rainfall anomalies over a 15-year period (from 1980 to 1994) were used to assess the predictive skill of IAP DCP-II for the YRB and HRB. The average value of the ACC during the hindcast period is approximately 0.30, which suggests that IAP DCP-II may be capable of handling the seasonal prediction of summer flooding events over YRB and HRB. Successful prediction of summer flooding events in 1999 and 2001 further confirmed the predictive skill of the IAP DCP-II system.

There are a number of uncertainties related to the seasonal climate prediction, including uncertainties in initial conditions (atmospheric initial conditions, land surface initial conditions, ocean initial conditions, etc.) and uncertainties in the parameterization schemes for physical processes within climate models (e.g., cloud

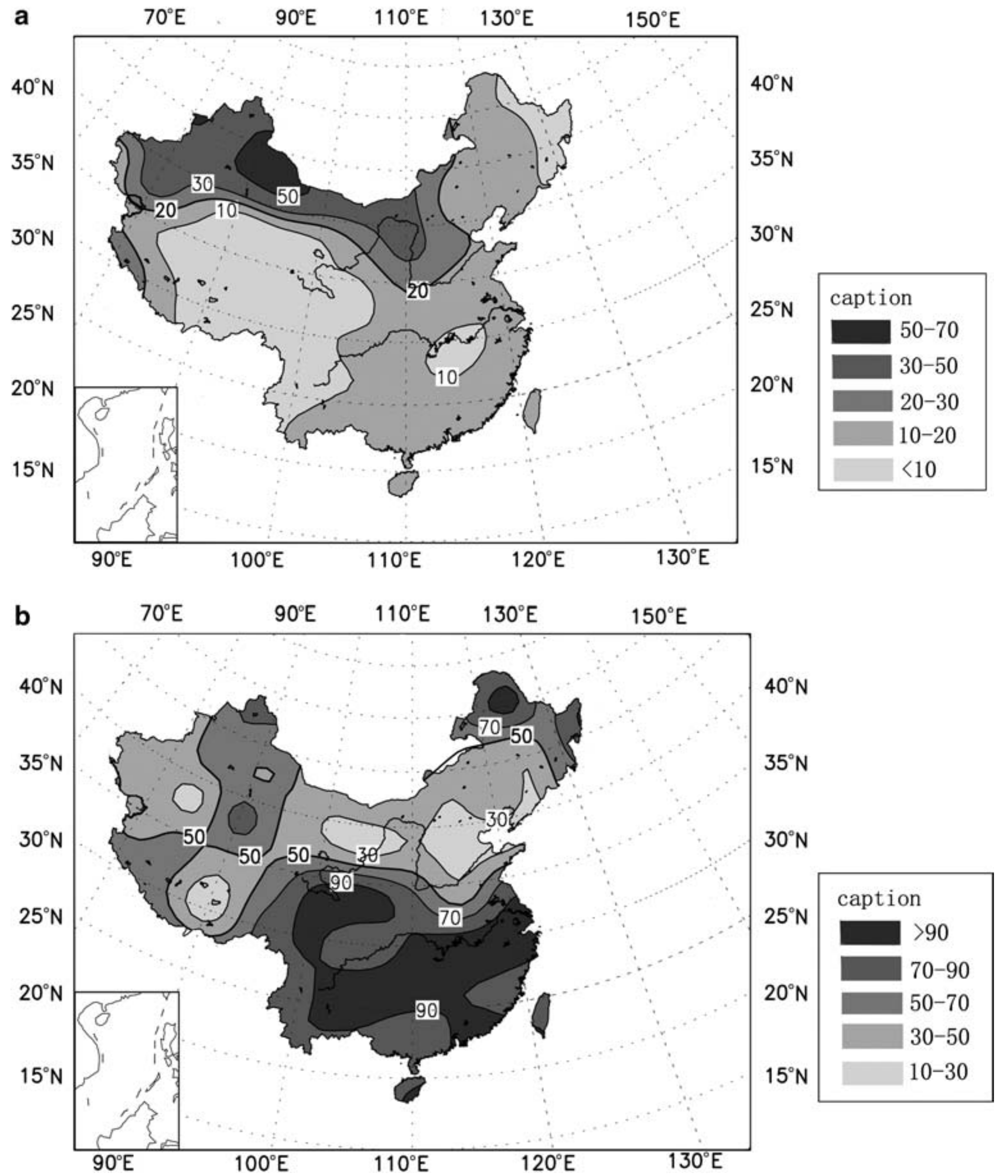

Fig. 9 **a** Standard deviation (in percentage) and **b** probability distribution (in percentage) with positive rainfall anomalies for the ensemble prediction of summer rainfall anomalies over China in 1999

parameterization schemes, radiation schemes etc.). Accordingly, additional efforts are necessary to improve seasonal predictive skill over the YRB. Specifically, it is proposed that the newly developed multimodel superensemble technique be incorporated into the IAP DCP-II system, as many studies have demonstrated that the superensemble approach can significantly increase the seasonal predictive skill (e.g., Krishnamurti et al. 1999).

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