Probabilistic Flood Prediction in the Upper Huaihe Catchment Using TIGGE Data

ZHAO Linna[1,2](赵琳娜), QI Dan[2*](齐 丹), TIAN Fuyou[2](田付友), WU Hao[1,2](吴 昊), DI Jingyue[1,2](狄靖月), WANG Zhi[1,2](王 志), and LI Aihua[3](李爱华)

1 *Public Meteorological Service Center, China Meteorological Administration, Beijing* 100081

2 *National Meteorological Center, China Meteorological Administration, Beijing* 100081

3 *Anhui Weather Modification Office, Anhui Provincial Meteorological Service, Hefei* 230031

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ABSTRACT

Based on the precipitation and temperature data obtained from THORPEX (The Observing System Research and Predictability Experiment) Interactive Grand Global Ensemble (TIGGE)–China Meteorological Administration (CMA) archiving center and the raingauge data, the three-layer variable infiltration capacity (VIC-3L) land surface model was employed to carry out probabilistic hydrological forecast experiments over the upper Huaihe River catchment from 20 July to 3 August 2008. The results show that the performance of the ensemble probabilistic prediction from each ensemble prediction system (EPS) is better than that of the deterministic prediction. Especially, the 72-h prediction has been improved obviously. The ensemble spread goes widely with increasing lead time and more observed discharge is bracketed in the 5th–99th quantile. The accuracy of river discharge prediction driven by the European Centre (EC)-EPS is higher than that driven by the CMA-EPS and the US National Centers for Environmental Prediction (NCEP)-EPS, and the grand-ensemble prediction is the best for hydrological prediction using the VIC model. With regard to Wangjiaba station, all predictions made with a single EPS are close to the observation between the 25th and 75th quantile. The onset of the flood ascending and the river discharge thresholds are predicted well, and so is the second rising limb. Nevertheless, the flood recession is not well predicted.

Key words: probabilistic hydrological prediction, TIGGE, variable infiltration capacity (VIC) model, Huaihe River

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1. Introduction

Land surface hydrological process is an important part of land surface interactive processes. The land surface hydro-meteorological forecasting has become a hot issue because of the coupling of meteorological and hydrological models, and is also the key point of flood forecasting. Deterministic flood forecasting based on the observed precipitation is the main foundation for decision-makers due to its high precision in spite of short forecast lead time. However, for some hydrological events, especially heavy flood events, deterministic hydrological forecasting is usually unable to provide sufficient precision and long lead time, and unable to satisfy the needs of flood control either (Krzysztofowicz, 2001). Thus, the uncertainty of the deterministic hydrological forecasting has attracted considerable attention and increasing efforts of research.

The uncertainty of hydrological forecasting originates mainly from the initial conditions, numerical model simplification, process of product generation, and so on. It is well known that the meteorological fields (rainfall, temperature, etc.) as the input forcing of hydrological models and the hydrological initial fields have some errors, and all of the errors related to the observations and the approximation of atmosphe-

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*Corresponding author: qidan@cma.gov.cn.

ric models and hydrological models are the sources of uncertainty for the objective forecast of hydro-meteorological processes. The complex uncertainty in hydrological forecasting always restricts the accuracy of flood control decision-making. The statistical decision theory points out that the decision-making is not optimal in the sense of math expectation without taking into account deterministic hydrological forecast uncertainty (Qian, 2004). Apparently, the policy-makers who need to do optimal flood control decision-making will meet trouble if they depend solely on certain hydrological forecast obtained from the determined input fields. Therefore, we need to develop a hydro-meteorological ensemble prediction system, which integrates all of forecast results from each model by using statistical methods.

It is well known that probabilistic forecasting (also called ensemble forecasting) could reduce the uncertainties in the atmosphere initial state and forecasting models. In the ensemble prediction system (EPS), since evolution of each ensemble member represents one possibility of the future weather status, the relative occurrence probability of a weather phenomena (such as the probability of heavy rain in a region) can be obtained by integrating all members' predictions, and consequently the relative occurrence probability of hydrological processes can be obtained. The precipitation forecast by the EPS is more valuable than that by a single model prediction system. The result of this methodology is more objective and quantitative than that by relying on experience alone or with a purely statistical probability prediction (Wang, 2005). Currently, there is a tendency to integrate the EPS into flood forecasting and warning systems. Some studies (Krzysztofowicz, 1998) related to the hydrological EPS have been conducted by the National Weather Service (NWS) of the United States, now called the National Centers for Environmental Prediction (NCEP), in order to develop "Probabilistic Quantitative Precipitation Forecasts (PQPFs) and Probabilistic River Stage Forecasts (PRSFs)." The probability forecasts of river stage have been issued since the 1990s. In addition to the issuance of regular forecasts, the 3 quantile (25%, 50%, 75%) water level prediction has also been provided to the common users and positive feedback has been obtained from the public (Krzysztofowicz, 1998). Recently, the European Flood Alert System (EFAS) has also been established based on a full set of 51 probabilistic forecasts from the EPS developed at the European Centre for Medium-Range Weather Forecasts (ECMWF, further abbreviated as EC) and on the medium-range weather forecasts from the German Weather Service (Deutsche Wetterdienst, DWD) since 2005, which provide 3–10-day probabilistic flood forecast products (Thielen et al., 2009). The probability forecasting has obtained more applications thereafter (Pappenberger et al., 2008; He et al., 2009).

2. Model, data and the research domain

2.1 Model and data descriptions

The variable infiltration capacity (VIC) hydrological model was co-developed by the Washington University, the University of California at Berkeley, and the Princeton University, of the United States. VIC is a spatially distributed hydrological model constructed on grids. The model participated in many projects such as the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) to study impacts of different climatic conditions on small-scale river basins (Abdula et al., 1996; Lohmann and Raschke, 1998; Nijssen et al., 1997). As one of the Soil-Vegetation-Atmosphere Transfers (SVATs) models, VIC can perform the energy and water balance simulation between air and land, and can also be carried out for water balance calculations. These make up for the shortage of energy balance in the traditional hydrological models. The VIC model has been used in the Mississippi, Columbia, Arkansas-Red, and other basins of the United States, and the Delaware basin of Germany to do runoff simulations. Some studies (Xie et al., 2007; Liang and Xie, 2001; Song et al., 2007) have also used the model on Weihe River, Yellow River, and Huaihe River basins of China, and good results have been achieved. In this paper, the latest version of the VIC with a new surface runoff parameterization by Liang and Xie (2001) and Xie et al. (2007) is employed. The spatial resolution of VIC is

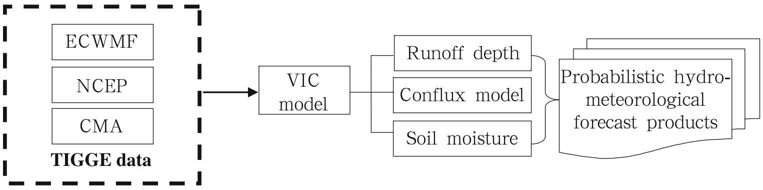

Fig. 1. The flow chart of probabilistic hydro-meteorological forecast with VIC.

15 km×15 km. Figure 1 shows the flow chart of probabilistic forecast with VIC adopted in the present study.

The meteorological forcing data are the precipitation and temperature data from the TIGGE database from 23 July to 3 August 2008. The EPS member forecasts are obtained from the EC, NCEP, and CMA (China Meteorological Administration) with lead time of 24 h. A detailed description of the data is presented in Table 1. The number of members of the EC ensemble is about twice of that of NCEP, and about three times of that of CMA. The EC ensemble has the highest horizontal and vertical resolutions among the three ensemble systems, while the NCEP ensemble system has the lowest horizontal and vertical resolutions. Only 1–3-day prediction data of precipitation and temperature are used in the experimental case.

Table 1. Comparison of the ensemble systems used in this study

	EC	NCEP	CMA
Country/Domain	Europe	United States	China
Number of ensemble members	51	21	15
Forecast length (day)	15	16	10
Perturbation method	SV (Singular Vectors)	ET (Ensemble Transform)	BV (Bred Vectors)
Horizontal resolution	TL399 (0–10 days) TL255 (11–15 days)	T126	T213
Number of vertical levels	62	28	31

2.2 Research domain

The Huaihe basin is located in East China. It is in the transitional region between the humid and semi-humid monsoon climates. The Huaihe catchment suffers from frequent drought and flood disasters. Since the upriver catchment is located in the Dabie and Tongbai mountains with high altitude and complex terrain conditions (Zhao et al., 2010), the river stream resulted from heavy precipitation in the upriver basin merges into the mainstream rapidly, which usually leads to rapid river stage increase, especially at Xixian and Wangjiaba stations. However, water flows slowly and floods also discharge slowly because the relatively flat terrain in the middle reaches of Huaihe basin, which frequently gives rise to the happening of water-logging and other flood disasters. Therefore, the hydrological characteristics of the main hydrological control stations on the upriver have important demonstrative significance. Thus, we selected the Huaihe basin, especially the upriver of the basin, as a research area. The flood forecasting at Xixian and Wangjiaba hydrological stations with runoff records are investigated in this paper.

2.3 Areal percentile precipitation

An established percentile method presented by Hyndman and Fan (1996) is adopted for the areal percentile precipitation. The equation is given as

$$Q_i(p) = (1-\gamma)A_{(j)} + \gamma A_{(j+1)}, \tag{1}$$

where j = int $(p \times n+(1+p)/3)$ and $\gamma = p \times n + (1+p)/3 - j$, p is the percentile, $Q_i(p)$ is the percentile areal precipitation, A is the array of the forecasted areal precipitation in ascending order, and n is the number of ensemble members. The areal precipitation is obtained by averaging the records of 19 observations or simulated precipitation values.

3. River discharge prediction

3.1 Performance of the EPSs at Xixian and Wangjiaba stations

Flood warnings are usually issued based on the hydrological predictions at some key points. Figure 2 shows the river discharge forecasts at Xixian station at the 3-day lead time. The 5th–99th percentile distribution of the EC-EPS is large and nearly brackets

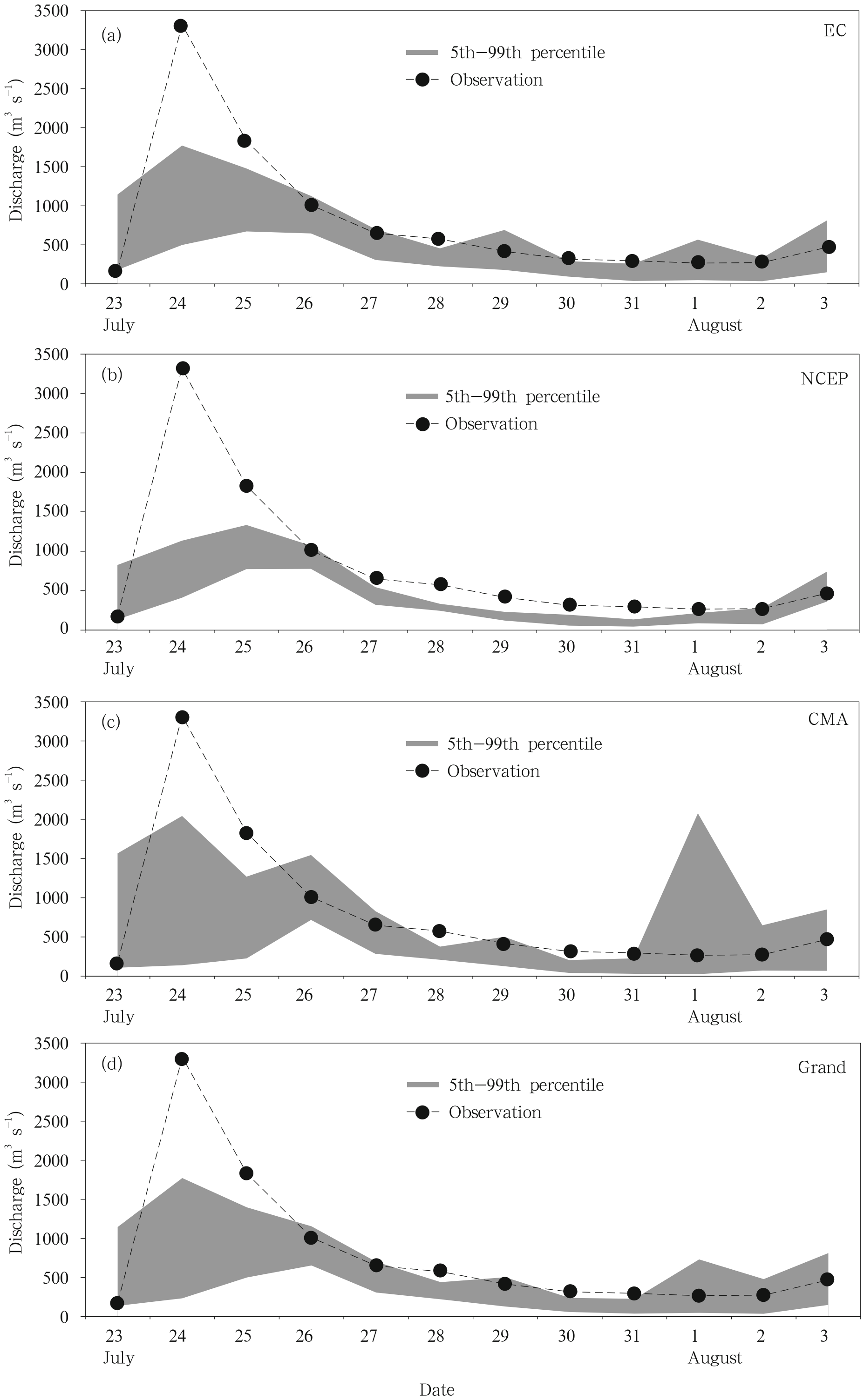

Fig. 2. River discharges from the observation and different EPSs at the 3-day lead time. The ordinate denotes river discharge, the grey zone is between 5th and 99th quantile, and the black circles indicate observed discharge at Xixian station. (a) EC-EPS, (b) NCEP-EPS, (c) CMA-EPS, and (d) Grand-EPS.

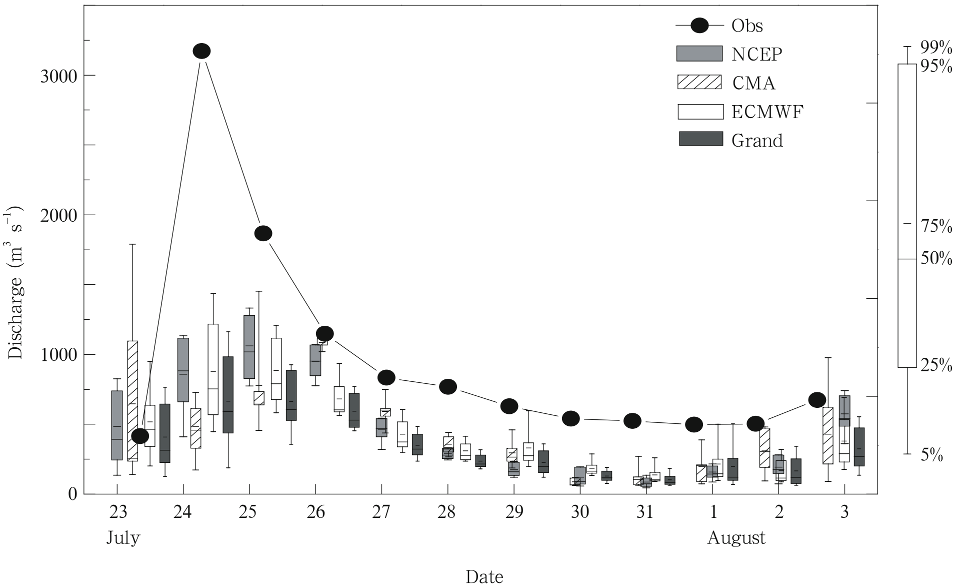

Fig. 3. Comparison of the three EPSs and the grand ensemble between 5th, 25th, 50th, 75th, 95th, and 99th percentile for the 3-day lead time runoff forecasts at Xixian station.

all discharge observations during the period 23 July–3 August 2008 except for the flood ascending period on 24 and 25 July (Fig. 2a). The NCEP-EPS and CMA-EPS (Figs. 2b and 2c) can bracket half of the observed discharges. Thus, the performance of the EC-EPS is the best among the three systems, which is consistent with the precipitation forecast results of the EPSs (Zhao et al., 2010). The performance of the Grand-EPS (Fig. 2d) is equal or better than that of EC-EPS. Both the single EC-EPS and the Grand-EPS can bracket most of the observations between 5th and 99th quantile. All of the EPSs did not obviously provide indicative significance for the Xixian flooding process (Fig. 3), especially in the first rising limb and the next recession limb, because most of the predictions occurred in the extreme area between 95th and 99th quantile. Generally, the main referenced inter-zone between 25th and 75th quantile is usually considered as a credible range in the EPS. However, it is clear that the forecast performance in the second rising limb on 1 August 2008 is better than the first rising limb for all of the EPSs.

Wangjiaba station is the outlet of the upper Huaihe River catchment. All of the EPSs predict the flood in good agreement with the observed discharge, which falls in the 5th–99th quantile except the NCEP-EPS (Fig. 4). The result is different from the discharge prediction at Xixian station in that the twice rising discharge thresholds at Wangjiaba station are captured nicely and the predictions of discharge are all nearly in the 25th–75th quantile (Fig. 5). It is a valuable reference for decision-making, but one deficiency is that the prediction in the recession limb is generally quicker than the observation. For the three EPSs (Fig. 5), the NCEP-EPS predicted discharge is generally smaller than the observation, while the EC-EPS and the CMA-EPS produce better predictions of discharge in the study period at Wangjiaba station, which provides helpful probabilistic hydrological forecasts for decision-making.

Figure 6 shows the ensemble forecasts of precipitation at Huaibin and Xixian stations by the ensemble systems at CMA, NCEP, EC, and by the grand ensemble. Note that Huaibin station is located at 32.45°N, 115.41°E and is the nearest station to Wangjiaba station. It is seen from Fig. 6 that the CMA-EPS largely underestimated the precipitation amount while the NCEP-EPS missed many precipitation events especially at Xixian. For most of the forecast days, the EC-EPS produced precipitation forecasts within the range of 5th–95th percentile, which are closest to the observation, so it outperformed the other two EPSs. The Grand-EPS production is the best since almost half of the forecasts are within the range of 25th–75th percentile. These results are in accordance with the results of the river discharge predictions. Obviously, the performance of the ensemble precipitation forecasts plays an important role in the forecasts of the river discharge.

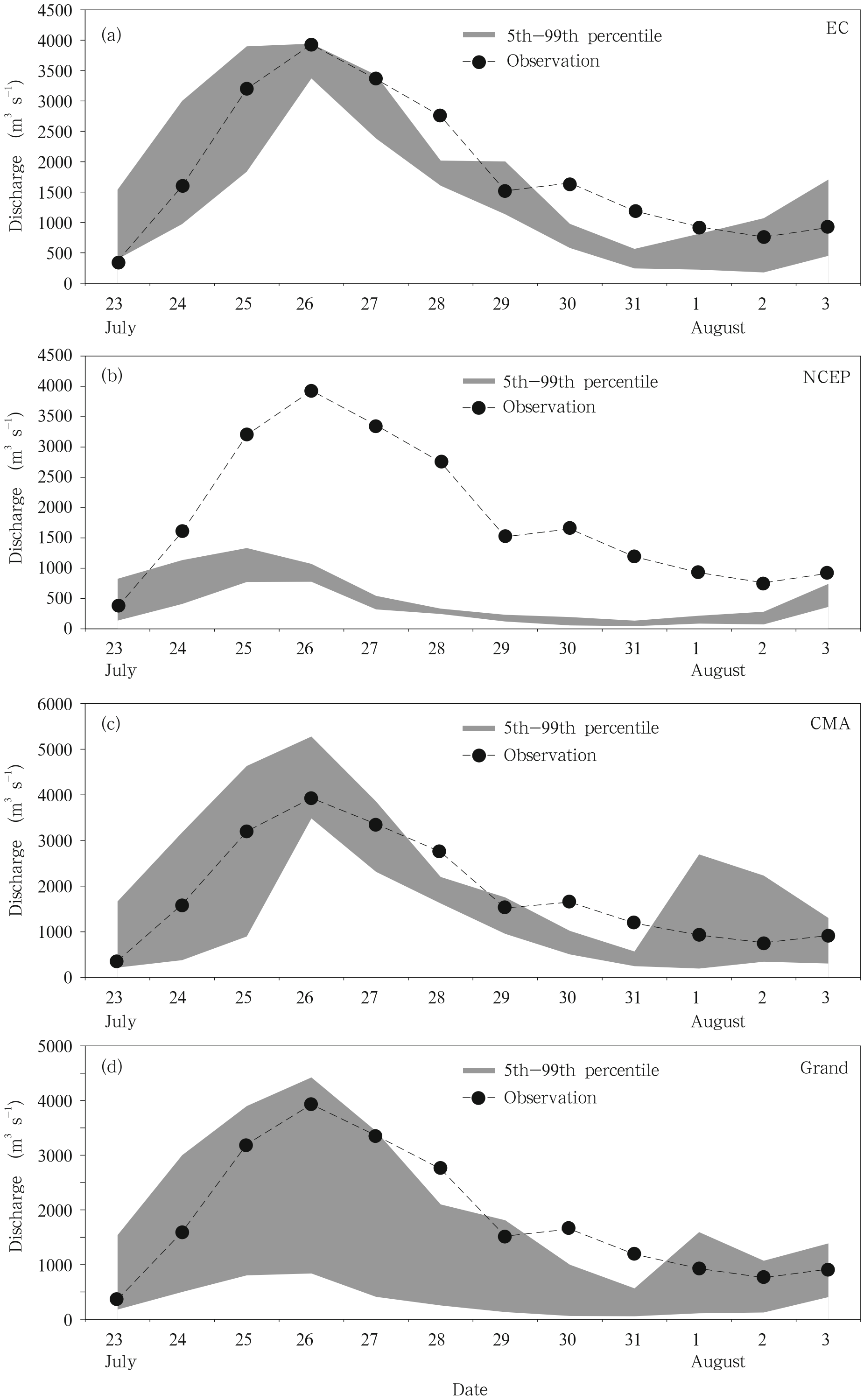

Fig. 4. As in Fig. 2, but for Wangjiaba station.

3.2 Evaluation of the EPSs at Xixian and Wangjiaba stations

We use the Nash-Sutcliffe index to evaluate the predictions of three single EPSs at Xixian and Wangjiaba stations. The definition of the Nash-Sutcliffe index is written as follows (Nash and Sutcdiffe, 1970):

$$\mathrm{NS} = 1 - \frac{\sum (Q_0 - Q_\mathrm{s})^2}{\sum (Q_0 - \overline{Q_0})^2}, \tag{2}$$

where Q_0 and Q_s are observed and predicted discharge, and $\overline{Q_0}$ is the time averaged observed discharge. A value of the Nash-Sutcliffe index close to 1 indicates a good agreement between observation and prediction (Thanapakpawin et al., 2007). Generally, if the Nash-Sutcliffe index is greater than 0.6, the

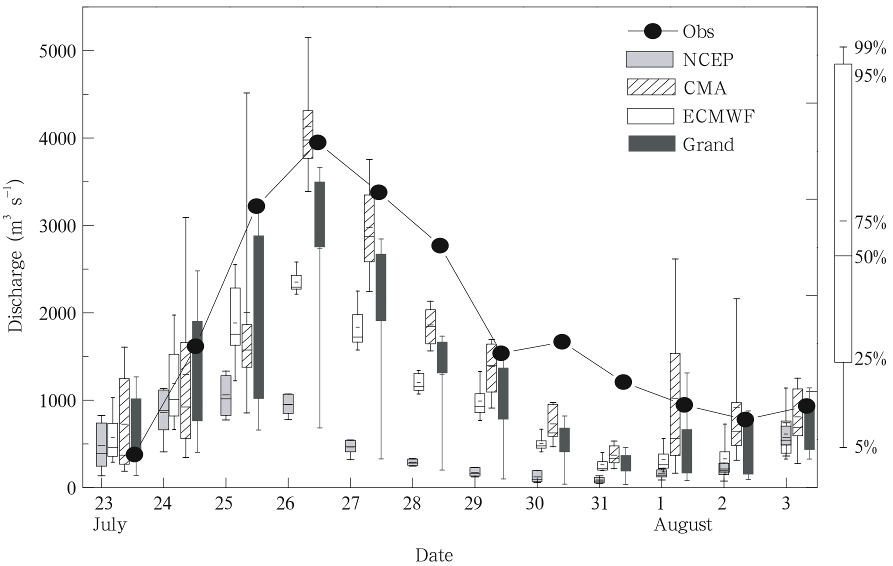

Fig. 5. As in Fig. 3, but for Wangjiaba station.

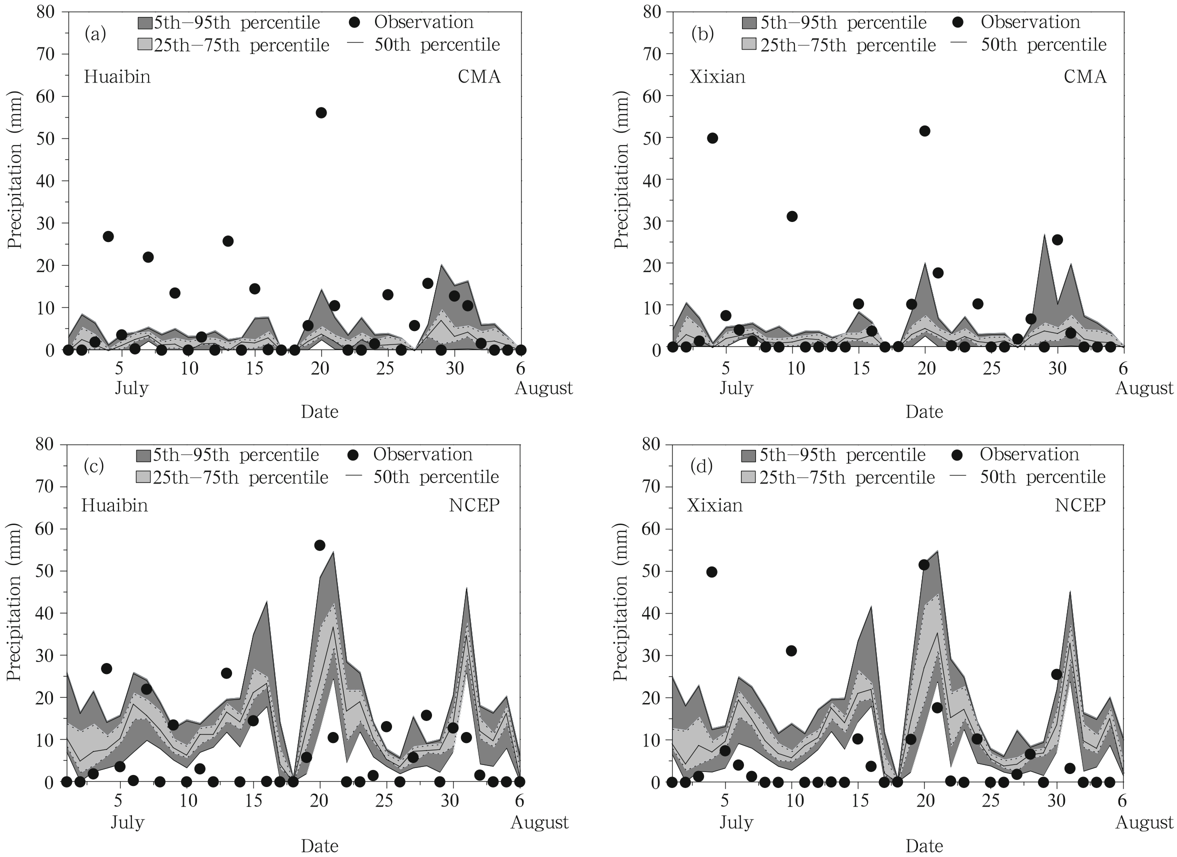

Fig. 6. Ensemble forecasts of precipitation at Huaibin (left panels) and Xixian (right panels) stations from (a) and (b) CMA-EPS, (c) and (d) NCEP-EPS, (e) and (f) EC-EPS, and (g) and (h) Grand-EPS.

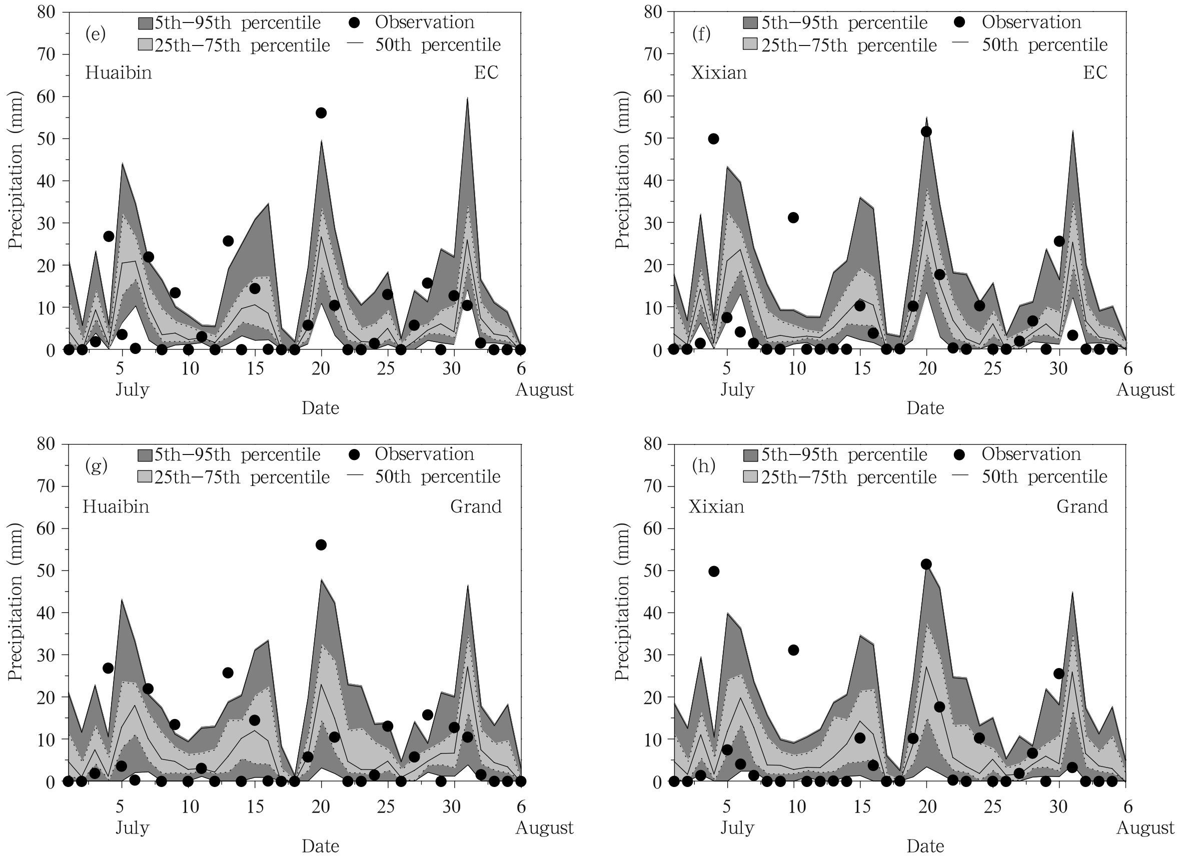

Fig. 6. (Continued.)

forecast is considered as being close to the observation (Bennis and Crobeddu, 2007). It is seen from Table 2 that the greatest NS value appears in the prediction of the EC-EPS, which is 0.97 for Wangiiaba station and 0.96 for Xixian station. The lowest NS value appears in the prediction of the NCEP-EPS. For Wangjiaba station, the average value of the Nash-Sutcliffe index in the EC-EPS is 0.68, which is greater than that of other EPSs.

Table 2. Nash-Sutcliffe index for Wangjiaba and Xixian stations

	Wangjiaba			Xixian		
	Maximum	Minimum	Average	Maximum	Minimum	Average
EC-EPS	0.97	0.54	0.68	0.96	–0.15	0.26
NCEP-EPS	–1.22	–1.47	–1.36	0.41	–0.08	0.21
CMA-EPS	0.74	0.28	0.51	0.76	–0.45	–0.13

4. Conclusions and discussion

In this study, the following conclusions can be drawn:

For the predictions of flood discharge by the three single EPSs, the performance of the EC-EPS is the best, while the NCEP-EPS is the worst, and the Grand-EPS is better than any of the single EPS. The performance of the EPSs at Xixian is not so satisfying, especially for the first onset of the rising limb, while the trend of the recession limb is well captured although it is lower than the observation. The EPSs' performance at Wangjiaba station is better than that at Xixian station. The predictions of all EPSs at Wangjinaba station have captured the onset of the rising limb correctly in terms of timing and river discharge thresholds for both the first and the second rising limb. The different performances of the EPSs at the two stations may be caused by the differences in the geographic location and topographical distribution. Xixian station is located in the upriver of the entire basin, where the topography is fairly complex, so there will be no enough time for this station to respond to the heavy rainfall. But Wangjiaba station, located at the exit cross-section of the catchment, has sufficient time to respond to the flood process.

Theoretically, ensemble systems are designed to capture all possible weather systems, but severe events might be entirely missed by a single EPS. In contrast, a Grand-EPS produces more reliable predictions of a flooding event and therefore brings significantly valuable results for the operational flood forecasting and warning service. In this study, the grand-ensemble forecast merging the single forecasts was conducted with equal weights, but how to assign a reasonable weight for each member to form the Grand-EPS is an issue deserving further studies.

Our results are based on the ensemble forecasts from the TIGGE archive, and the flood prediction of one severe flooding case in the Huaihe basin in July 2008 is chosen by using the VIC model. It is extremely difficult to carry out a statistically significant evaluation for flood events, but we believe that this work gives an encouraging indication that a multi-model ensemble can provide more valuable probability forecasts than a deterministic prediction for extreme flood events.

Probabilistic hydrological forecasting is foreseen as inevitable in the development of hydrological forecasting in future. As an important part of the decision-making system, the probabilistic hydrological forecasting is still rarely operationally used in China. As the probabilistic hydrological forecasting is a hot topic in the hydro-meteorological science, this study provides a good example for how to use the TIGGE achieve data to drive the hydrological model for probabilistic flood forecasts.

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