Development and Application of an Atmospheric-Hydrologic-Hydraulic Flood Forecasting Model Driven by TIGGE Ensemble Forecasts

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ABSTRACT

A coupled atmospheric-hydrologic-hydraulic ensemble flood forecasting model, driven by The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) data, has been developed for flood forecasting over the Huaihe River. The incorporation of numerical weather prediction (NWP) information into flood forecasting systems may increase forecast lead time from a few hours to a few days. A single NWP model forecast from a single forecast center, however, is insufficient as it involves considerable non-predictable uncertainties and leads to a high number of false alarms. The availability of global ensemble NWP systems through TIGGE offers a new opportunity for flood forecast. The Xinanjiang model used for hydrological rainfall-runoff modeling and the one-dimensional unsteady flow model applied to channel flood routing are coupled with ensemble weather predictions based on the TIGGE data from the Canadian Meteorological Centre (CMC), the European Centre for Medium-Range Weather Forecasts (ECMWF), the UK Met Office (UKMO), and the US National Centers for Environmental Prediction (NCEP). The developed ensemble flood forecasting model is applied to flood forecasting of the 2007 flood season as a test case. The test case is chosen over the upper reaches of the Huaihe River above Lutaizi station with flood diversion and retarding areas. The input flood discharge hydrograph from the main channel to the flood diversion area is estimated with the fixed split ratio of the main channel discharge. The flood flow inside the flood retarding area is calculated as a reservoir with the water balance method. The Muskingum method is used for flood routing in the flood diversion area. A probabilistic discharge and flood inundation forecast is provided as the end product to study the potential benefits of using the TIGGE ensemble forecasts. The results demonstrate satisfactory flood forecasting with clear signals of probability of floods up to a few days in advance, and show that TIGGE ensemble forecast data are a promising tool for forecasting of flood inundation, comparable with that driven by raingauge observations.

Key words: ensemble flood forecast, TIGGE ensemble predictions, Xinanjiang model, one-dimensional unsteady flow model, flood diversion and retarding, Huaihe River

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1. Introduction

As the severity of floods increases, there is an urgent need for more attention. Flood protection and awareness have continued to rise on the political agenda, accompanied by a drive to "improve" flood forecasting technologies (Parker and Fordham, 1996; DKKV, 2004; Demeritt et al., 2007; Pitt, 2007; Van Berkom et al., 2007; Cloke and Pappenberger, 2009; Bao et al., 2011a). The civil protection authorities and the public need adequate emergency response time, and the flood forecasting and control services are crucial to reducing the flood impacts. Most of the flood forecasting models and flood warning systems rely on precipitation inputs, which come initially from observed precipitation networks (Penning-Rowsell et al., 2000).

Actually, flood forecast lead time can be increased

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from a few hours to a few days with numerical weather prediction (NWP) models being incorporated into the flood forecasting model and flood warning systems. Flood forecasting uncertainties originate from precipitation inputs in most cases, so flood forecasting accuracy relies on NWP performance (Krzysztoofwicz, 1999; Bao, 2009). However, single deterministic weather forecast from NWP systems cannot track uncertainties and systematic biases and hence often fails to simulate or forecast weather variables and processes correctly (Bao et al., 2011a). Evolving over the last decade, the Ensemble Prediction Systems (EPSs) have been applied to simulating the effects on weather forecast of observation uncertainties, imperfect boundary conditions, data assimilation, and so on (Park et al., 2007). An EPS can be taken as a system based on a finite number of deterministic integrations and regarded as the only feasible method to predict probability density function beyond the range of linear error growth in meteorological prediction (Buizza, 2008). Part of NWP uncertainties originating from initial conditions and stochastic physical processes can be accounted for by EPS forecasts from each single weather center (Roulin, 2006). Other uncertainties in numerical implementations and data assimilation may be addressed with grand ensemble (GE) or combined multi-ensemble (ME) of EPSs from different weather centers (Goswami et al., 2007). When each model that participates in the EPS at different weather centers is integrated, the probabilistic nature of the ensemble precipitation forecasts is better retained (He et al., 2009, 2010; Bao et al., 2011a). Ensemble weather forecast products can be used for hydrometeorological forecast, hydrological forecast, and geological disaster-related weather forecast, and provide improved flood forecast and early flood warning as part of the uncertainties can be quantified (Cloke and Pappenberger, 2008; Bao, 2009).

The floods that took place in the last decade in China ranked the worst among recorded floods worldwide in terms of human fatalities and economic losses. The pilot Huaihe catchment located in central eastern China suffers from frequent floods. There exist usually many hydraulic projects, such as reservoirs, gates, dams, and, especially, flood diversion and retarding areas within the Huaihe River basin. Two-thirds of the catchment can be characterized as low lying flood plains. To forecast the flood hydrograph with high accuracy is not easy, especially when the flood diversion and retarding areas are being used (Bao et al., 2007, 2008, 2009, 2010; Hydrological Bureau of the Ministry of the Water Resource of China and the Yangtze River Commission, 2010).

The Huaihe River is well equipped with real-time meteorological and hydrological data recording infrastructure. The latter has made it possible to develop well calibrated hydrological models for the catchment. Weather forecasts, in particular precipitation, are often the limiting factors for reliable early flood warning. In order to improve the situation, China has made constant efforts in numerical weather prediction system development. The Global/Regional Assimilation and PrEdiction System (GRAPES) is a new NWP model developed by the China Meteorological Administration (CMA). This model has three-dimensional variation (3DVAR) data assimilation capability with a 4DVAR version in the pipeline (Zhuang et al., 2005). The China Heavy Rain Experiment, unlike the GRAPES project, emphasized research on new theory and methodology to improve heavy rain prediction (Xue and Liu, 2007). Further development of the GRAPES model is still undergoing. "XXT", a new hydrological model, has been integrated into the Noah land-surface model (LSM) of GRAPES (Xu et al., 2012). The aim is to improve the representation of the hydrological process in GRAPES for flood event prediction (Zhang et al., 2009).

To this end, this paper presents a case study using The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) data from four forecast centers, i.e., Canadian Meteorological Centre (CMC), European Centre for Medium-Range Weather Forecasts (ECMWF), UK Met Office (UKMO), and US National Centers for Environmental Prediction (NCEP), over the Huaihe River coupled with the Xinanjiang model (Zhao, 1992) and the one-dimensional unsteady flow model (Bao et al., 2011b; Bao and Zhao, 2011). The aims of this case study are 1) to develop an atmospheric-hydrologic-hydraulic flood forecasting model driven by the TIGGE data for early flood forecasts, which will perform simulations of rainfall-runoff processes and route complex channels over the flood diversion and retarding areas, and 2) to apply the newly developed model in the Huaihe catchment with flood diversion and retarding areas where its simulation results are compared with those of the original hydrologic-hydraulic model driven by the raingauge observations.

2. Case study area and data

The Huaihe River is located in the region 31°–35°N, 112°–121°E. The length of the main channel of the Huaihe River is 1000 km and the total area of the catchment is 1.912×10^5 km^2. Its mean annual precipitation and runoff depth are approximately 888 and 240 mm, respectively. The runoff coefficient ranges from 0.1 (northeast) to 0.6 (southwest). The spatial and temporal distributions of precipitation are very irregular and change from year to year. These may be attributed to the catchment location in the transitional area between the southern monsoon and the northern continental climate (Huaihe River Commission, 1999). The Huaihe River can be divided into the upper, middle, and lower streams. The area from Wangjiaba to Sanhe Gate is in the middle stream, where the channel has a gentle slope. The lower reaches below Sanhe Gate constitutes the lower stream of the Huaihe River. The target area for this study is the upper reaches of the Huaihe River above Lutaizi station, which drains an area of 8.86×10^4 km^2. Heavy rainfall usually occurs in the southwest of the river basin and is rapidly collected and carried from upstream through Wangjiaba station where the catchment transitions into low lying flood plains towards the northeast. The drainage area up to Wangjiaba station is regarded as the upper Huaihe River. It has a slope of 0.49‰ and an area of about 30672 km^2. The first key flood control gate of the catchment is located at Wangjiaba station. Behind this gate is the Mengwa flood retarding area with a design capacity of 750 million m^3 and a design maximum discharge of 1626 m^3 s^{-1}. The area usually serves as farmland of approximately 12000 hectares for a local population of about 157800 during drier periods. The retarding areas have been opened for diverting flood waters 15 times in the past 12 years. The water stage at Wangjiaba station is a key flooding indicator for the entire catchment and has been labelled by locals as the Huaihe River "barometer". It is therefore important to obtain a reliable discharge forecast at Wangjiaba station. The length of the channel from Wangjiaba to Lutaizi is 155.16 km. Four flood diversion areas and three flood retarding areas are inside the study area. There are three large tributaries: the Shi River and Pi River to the south of the Huaihe River, and the Shaying River to the north.

Observed hydrometeorological data were provided by the CMA, and TIGGE data were obtained from TIGGE-China. The EPS data were available from four centers in the TIGGE database with the majority from January 2007 onwards. The flood event that took place in July 2007 was hence selected as the high flow flood event in the study area. Table 1 lists the four weather centers and the numbers of ensemble forecasts. Each center provides one "central" unperturbed analysis generated by a data-assimilation procedure and a number of forecasts with perturbed initial conditions. All forecast members were assigned equal weights in this study.

Table 1. List of the meteorological forecast centers

Center	Center code	Ensemble members
CMC	babj	14+1
ECWMF	ecmf	50+1
UKMO	egrr	23+1
NCEP	kwbc	20+1

3. Development of the atmospheric-hydrologic-hydraulic model

A coupled atmospheric-hydrologic-hydraulic ensemble flood forecast model, driven by the TIGGE data, was developed for flood forecast over the Huaihe River with flood diversion and retarding areas. The hydrological model was used to forecast rainfall-runoff hydrograph, and the hydraulic model was used for channel flood routing. The Xinanjiang model (Zhao, 1992; Zhao and Liu, 1995) was used for the hydrological rainfall-runoff modeling. The one-dimensional unsteady flow model (Chow, 1959; Chow et al., 1988; Wu et al., 2008; Bao et al., 2011b; Bao and Zhao,

2011) was applied for the main channel flood routing. The non-linearity of the channel without cross-section data was taken care of by the non-linear Muskingum method, which had been applied successfully for flood operational routing of the Huaihe River in recent 10 years (Zhao, 1992; Bao, 2009). The input flood discharge hydrograph from the main channel to the flood diversion area was estimated with the fixed split ratio of the main channel discharge. The flood flow inside the flood retarding area was calculated as a reservoir with the water balance method. The Muskingum method was used for flood routing in flood diversion area (Li et al., 2008). Compared with the Muskingum method, the one-dimensional unsteady flow model of the Huaihe River with flood diversion and flood retarding areas had been proved to perform better (Bao et al., 2011b; Bao and Zhao, 2011).

4. Application and results

The majority of the weather centers delivered global ensemble prediction data from January 2007 onwards. The flood warning level at Wangjiaba station is 27.50 m and corresponds to a discharge of 2820 m^3 s^{-1}, and the flood assurance level at Wangjiaba station is 29.30 m and corresponds to a discharge of 5579 m^3 s^{-1} for the flood event in July 2007. When the water level is over the assurance level, the Mengwa gate ought to be opened and the Mengwa retarding area is used for flood retarding.

In flood forecasting of the Huaihe River, the discharge hydrographs of Wangjiaba, Jiangjiaji, Hengpaitou, and Fuyang hydrologic stations are forecasted by the Xinanjiang model, and the forecasts are taken as the input to the hydraulic model of the main channel of the Huaihe River. Wangjiaba hydrologic station is the last and most important station of the upper stream. According to the locations of hydrologic stations, raingauges, and natural river boundaries, the upper reaches of the Huaihe River above Wangjiaba station is divided into 10 sub-catchments. Because the outlets of six sub-catchments are reservoirs, the outflow of every reservoir after flood regulation is the input flow in flood forecasting, and discharge hydrographs of the other four sub-catchments: Bantai, Xixian, Huangchuan, and the sub-catchment between Bantai, Xixian, Huangchuan stations and Wangjiaba station, are forecasted with the coupled TIGGE-Xinanjiang model. Then, the flood discharge at Wangjiaba is combined with flow routing for Bantai, Xixian, and Huangchuan staions.

The outflow of every reservoir after flood regulation is the input flow in flood forecasting, but not every reservoir's runoff is included, so only the flood regulation of the flood diversion and retarding areas is described below. There are four flood diversion areas and three flood retarding areas in the test case. The flood diversion area is a pond or floodplain beside the main channel, with a gate that can control the input and output flow. The input flow from the main channel to the flood diversion area is the overflow of a temporarily broken dyke or a planned weir. The input flood is stored in the pond or floodplain. When the pond or floodplain fills, the flood flows to the main channel or next pond. The fixed split ratio method and the hydraulic method are used to deal with splitting flow into flood diversion areas. Actually, the fixed split ratio method has physical character and can be applied easilier, compared with the hydraulic method in flood forecast. For lack of channel information, the Muskingum method was used for flood routing of Pi River, Shi River, Ying River, and flood retarding areas. Taking into consideration the non-linearity of Pi River, Shi River, and Ying River, the non-linear Muskingum method was applied. More details about the hydraulic model of Huaihe River can be found in Bao et al. (2011b).

The catchment flow concentration time of Wangjiaba is about three days and channel flow concentration time from Wangjiaba to Lutaizi is two days. The normal time steps for rainfall data collection are 2 and 6 h at present, so a 6-h time step is used in flood forecasting.

4.1 Application in the Wangjiaba catchment of Huaihe River

The precipitation forecasts P_{f} were retrieved from four weather centers in the TIGGE archive (Table 1), i.e., CMC, ECMWF, UKMO, and NCEP. For the selected four centers, each provides one "central" unperturbed analysis and a number of forecasts with perturbed initial conditions. All forecast members were assigned equal weights (Park et al., 2007). The consequent inference is based on the principle of equal probability of selection which happens to have EPS as an acronym as well. The original medium-range forecasts were conducted on a 25 km× 25 km resolution (He et al., 2009; Bao et al., 2011a). They were interpolated to area averages to be used as inputs for the Xinanjiang model.

Figures 1a and 1b show the area mean P_{f} issued at 0800 BT (Beiing Time) 2 and 5 July 2007 and the resulting discharge forecast Q_{f} at Wangjiaba station, and Fig. 1c shows the area mean P_{f} issued on 5 July 2007 and the resulting Q_{f} at Xixian station using ECMWF data for the studied flood events. All ECMWF member forecasts issued on 2 July 2007 displayed the best agreement for the rainfall event that occurred on 3 July 2007. Similarly, the amount and timing of the rainfall event that took place between 7 and 9 July 2007 were best forecasted with 2-day lead time. For lead time longer than 2 days, the 51 ECMWF forecast members demonstrated a fairly consistent signal representing an intensive rainfall event, but one could not tell the exact date and time when it was to occur as the spread of forecast members was rather large or low. For example, the forecasts issued on 4 July 2007 indicated that a heavy precipitation event would possibly occur on 9 July 2007. Less than 35% of the forecast members predicted that it was to occur on 7 July 2007. The situation improved on 5 July 2007 when most forecast members clustered closer to each other than on the previous day of issue (over 80% of members agreeing on the occurrence of heavy rain on 9 July 2007). The progress of agreement amongst forecast members evolved from longer to shorter lead time demonstrates that the EPS forecasts become more predictable as it is getting closer to the actual event. In comparison with the observed discharge, the ensemble of Q_{f} was underestimated by approximately 20%–50% for all forecast members varying from day to day. It is worth pointing out that Q_{f} is not always the direct effect of P_{f} over the upper reaches of the Huaihe catchment as this region contains a large number of reservoirs for flood regulation. The results shown here took into consideration of the actual water release from the major impoundments in the region. This is the key reason why P_{f} variable hydrographs are not completely trackable by Q_{f} variable hydrographs in Figs. 1a and 1b.

The ensemble of Q_{f} was evaluated using a contingency table, where observations were compared with simulations. Possible outcomes in a contingency table (von Storch and Zwiers, 1999) are: (1) hit (H), i.e., the observed flood is correctly forecasted; (2) miss (M), i.e., the observed flood is not forecasted; (3) false alarm (FA), i.e., a flood event is wrongly forecasted; and (4) correct negative (CN), i.e., a nonoccurrence-event is correctly missed. The contingency table shows the forecast ability of the model to predict the individual events. The studied flood event is well predicted by all centers with a lead time of 10 days (see Figs. 2a–d for warning level and Figs. 3a–d for assurance level). In Figs. 2a (flood warning level) and 3a (flood assurance level), the probability of exceedance of the high warning threshold for each forecast center for 13 consecutive forecast dates is shown at Wangjiaba station. Figures 2a and 3a concentrate on the onset of the flood (3 July for warning level and 10 July for assurance level). The exceedance levels indicate that most EPS forecasts start to predict the forthcoming flooding in the forecasts issued from 1 to 9 July. The signal persists from forecast to forecast, which provides the necessary reassurance. From 3 July onwards, the signal is very strong. The mentioned points above are agreed with from the other figures. This means that there is an efficient flood warning several days in advance. However, making use of multi-center data from the TIGGE archive can assist the forecaster to make a better decision, since one does not have to rely on results from a single center.

4.2 Application in the upper reaches of the Huaihe River above Lutaizi station

Figure 4 shows that the observed flood hydrograph, especially discharge peak, is nearly ranged in the confidence interval of 90% among flood forecast results driven by four forecast centers' EPSs. In general, Q_{50} is very comparable with the $Q_{\mathrm{raingauge}}$ and Q_{obs} for ECMWF and UKMO ensemble forecasts. However, Q_{95} is very comparable with the $Q_{\mathrm{raingauge}}$ and Q_{obs} for CMC and NCEP ensemble forecasts. The accuracy of flood forecast driven by ECMWF and

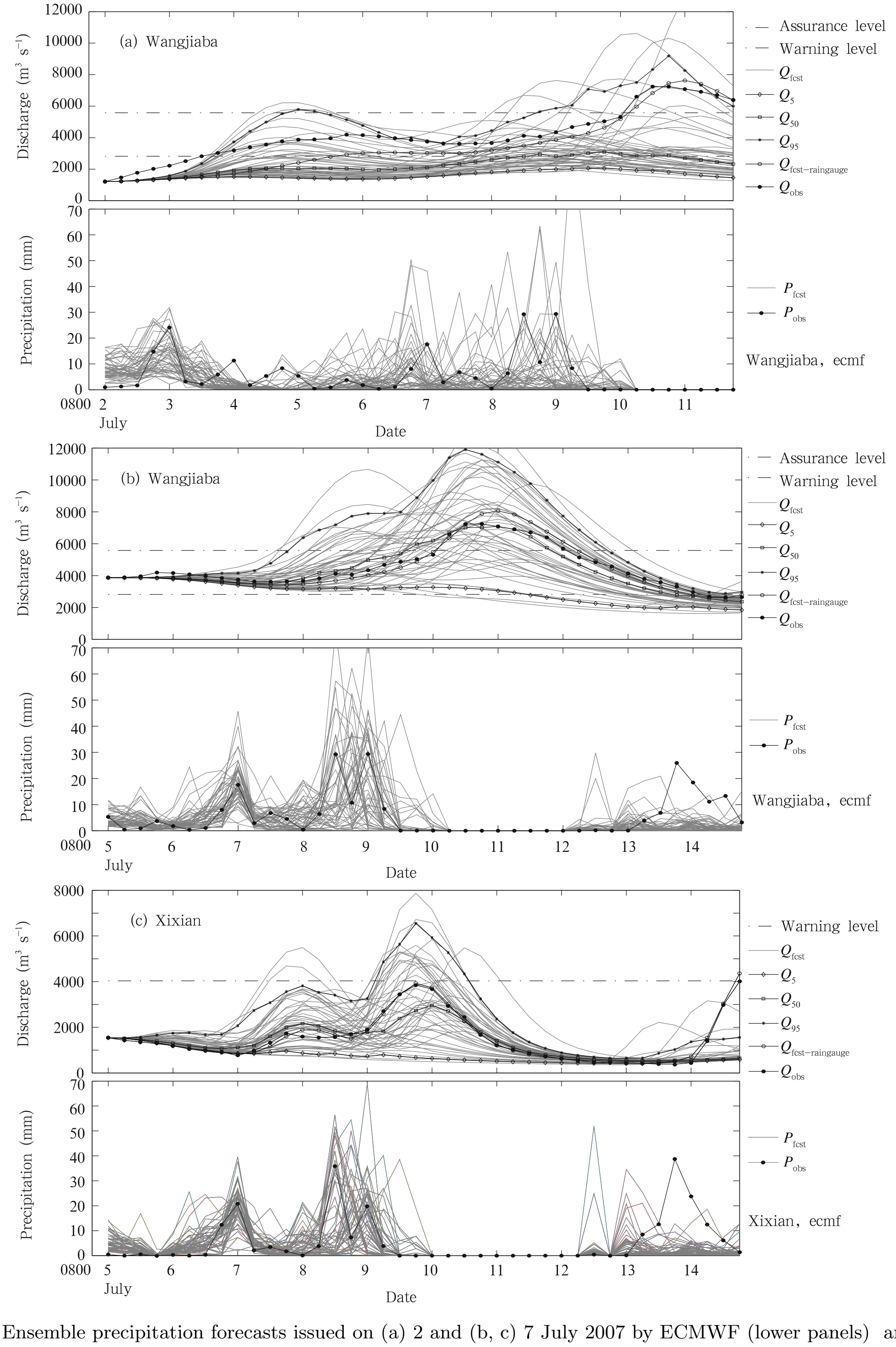

Fig. 1. Ensemble precipitation forecasts issued on (a) 2 and (b, c) 7 July 2007 by ECMWF (lower panels) and ensemble forecast discharges (upper panels) in comparison with observation. (a) and (b) Wangjiaba station, and (c) Xixian station.

UKMO data is better than that driven by the data from the other two centers. Therefore, in order to improve the accuracy of flood forecast, the weight factor should be applied respectively.

5. Conclusions and discussion

A coupled atmospheric-hydrologic-hydraulic flood forecast model driven by the TIGGE archive data was set up to study the potential benefits of using the TIGGE database in flood forecasting in the upper reaches of the Huaihe River above Lutaizi station during the 2007 flood season. The Xinanjiang model was used for the hydrological rainfall-runoff forecast. The one-dimensional unsteady flow model was applied to the main channel flood routing. The results

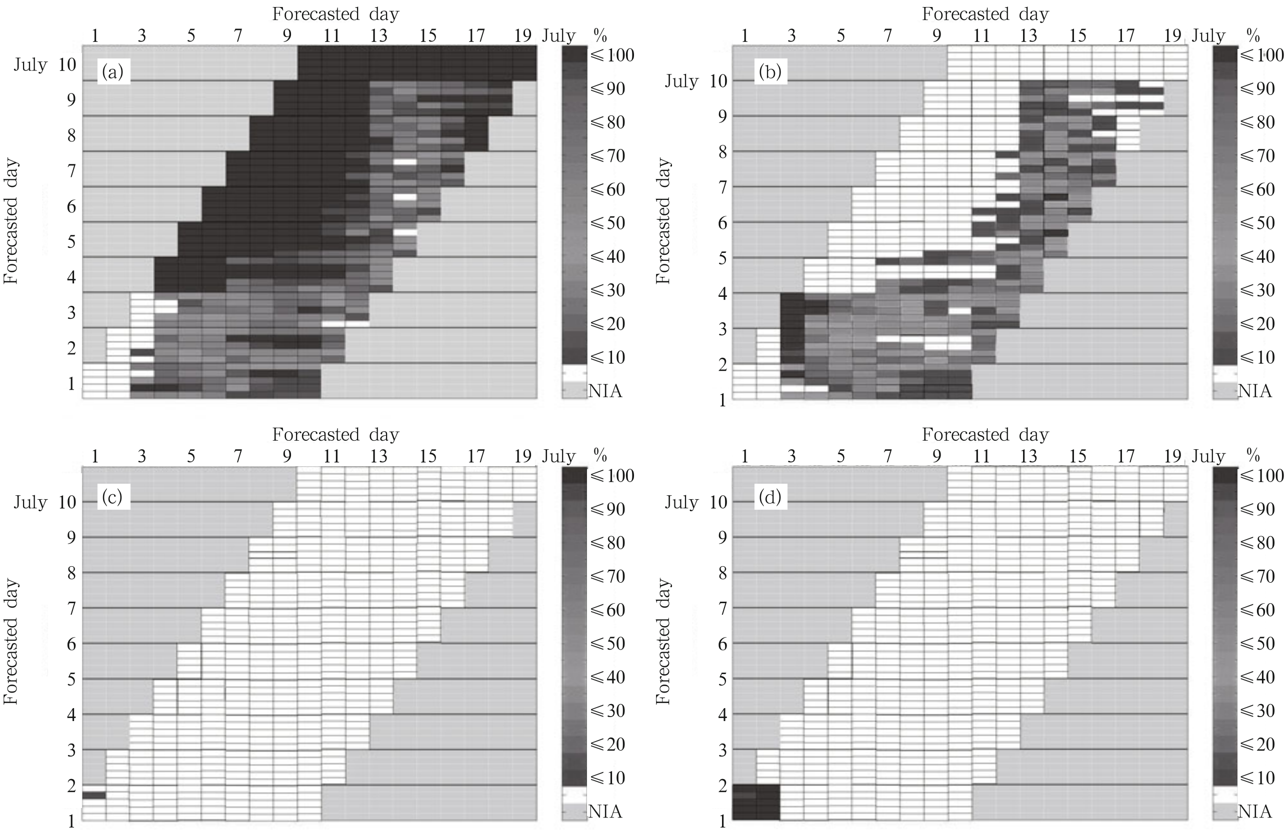

Fig. 2. Warning level of the studied flood event. (a) Hit, (b) miss, (c) false alarm, and (d) correct negative. The horizontal bars represent the ensemble of the four forecast centers.

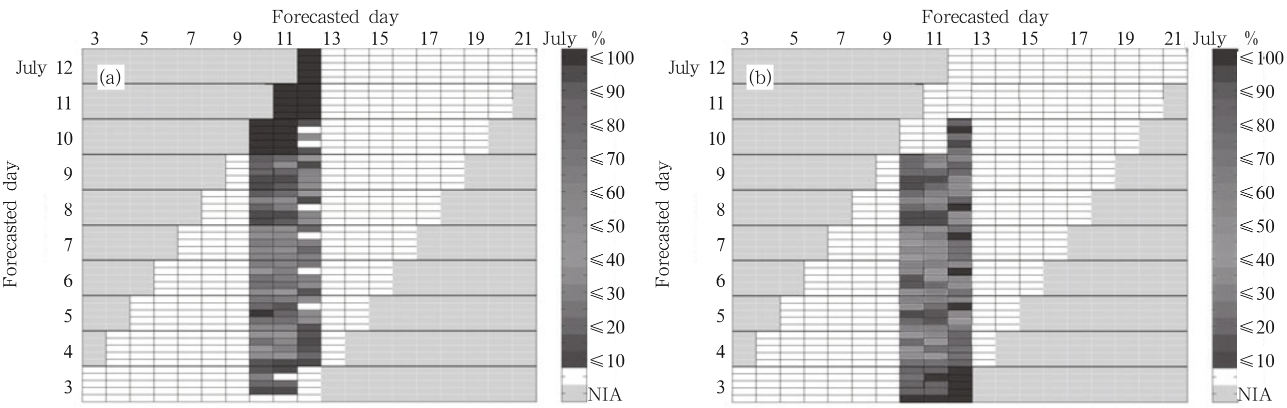

Fig. 3. As in Fig . 2, but for assurance level of the studied flood event.

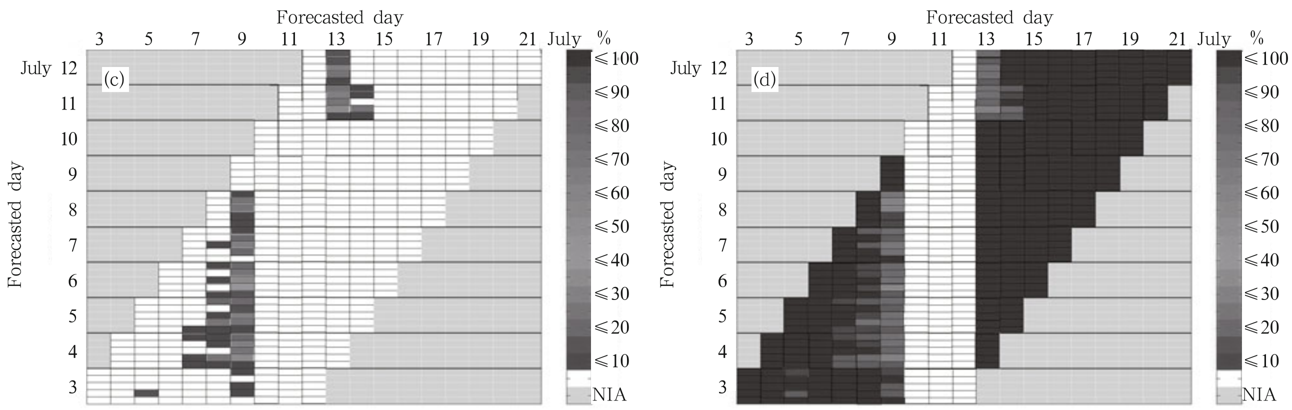

Fig. 3. (Continued.)

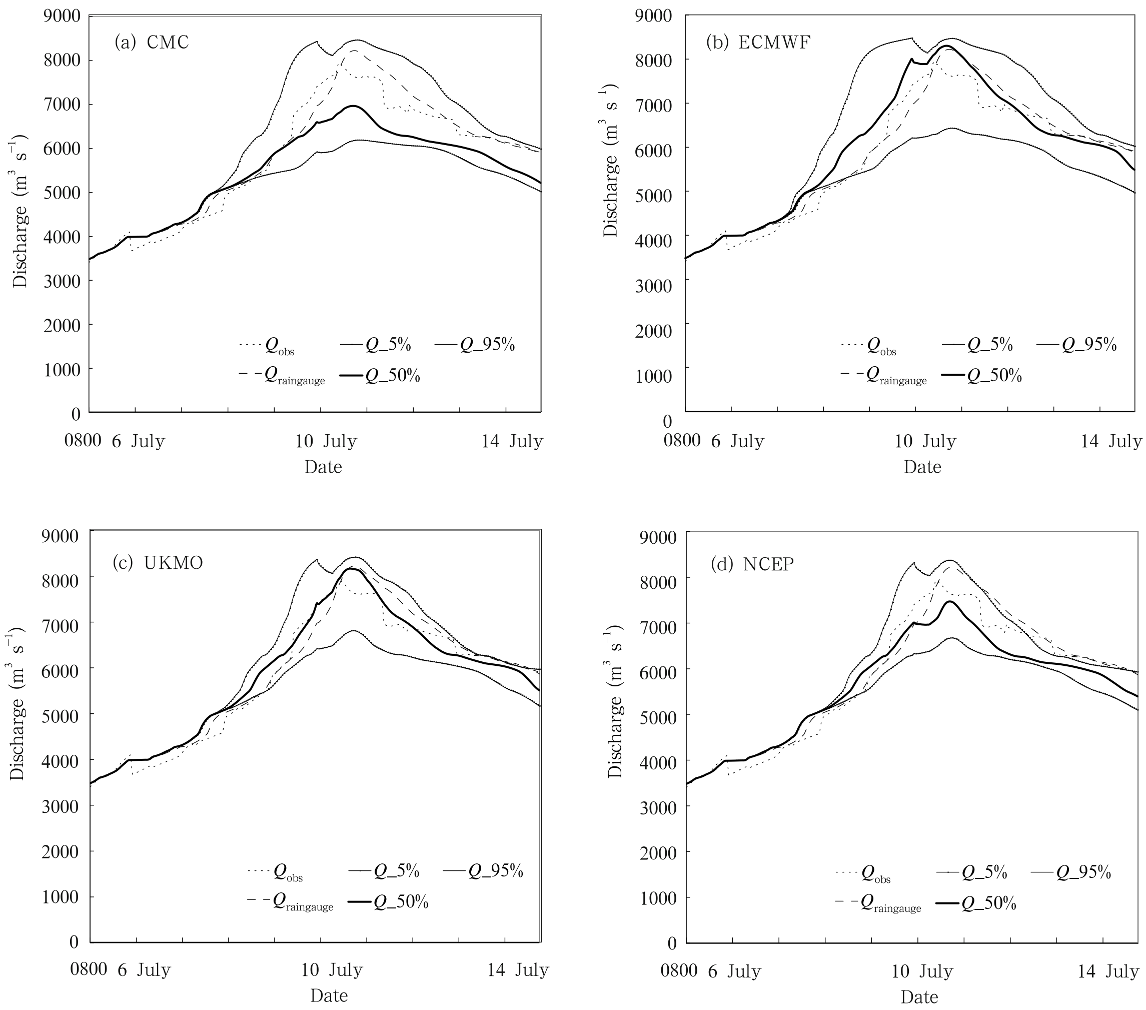

Fig. 4. Ensemble forecast discharges issued on 6 July 2007 from the coupled atmospheric-hydrologic-hydraulic model driven by the TIGGE data of the four centers (CMC, ECWMF, UKMO, and NCEP) in comparison with observation.

demonstrate that the TIGGE archive is a promising tool for producing forecasts of discharge comparable with the observed discharge and for issuing a fairly reliable flood forecasting and warning as early as a few days in advance. Currently, the existing operational forecast model produces forecasts 3 days in advance for the entire Huaihe River and 24 hours in advance for large scale reservoirs and sub-catchment outlets/stations in the catchment (Bao, 2009). With the TIGGE archive, the current lead time can be potentially improved, which provides great benefits for flood management and preparedness.

Techniques to integrate multimodel precipitation forecasts need to be developed correctly. The principle of equal weight coefficients for each ensemble forecast of selection was applied in this study. Actually, different weather center forecasts may be assigned different weight coefficients, which might improve the performance of the GE and ME. The precision of rainfall forecast affects an offset of the peak in terms of its timing and magnitude that may lead to partial failure in early flood forecasting. A spatial and temporal correction to the ensemble weather predictions to resolve discrepancies in the spatial distribution and timing should be developed for flood forecasting.

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