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Uncertainty assessment of early flood warning driven by the TIGGE ensemble weather predictions - A case study for the July–September 2008 floods in the Upper Huai catchment

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Abstract

We present a case study using the TIGGE database for flood warning in the Upper Huai catchment (ca. 30,672 km^2). TIGGE ensemble forecasts from 6 meteorological centres with 10-day lead time were extracted and disaggregated to drive the Xinanjiang model to forecast discharges for flood events in July-September 2008. The results demonstrated satisfactory flood forecasting skills with clear signals of floods up to 10 days in advance. The forecasts occasionally show discrepancies both in time and space. Forecasting quality could potentially be improved by using temporal and spatial corrections of the forecasted precipitation.

Introduction

Single deterministic weather forecasts from numerical weather prediction (NWP) systems do not take uncertainties and systematic biases into consideration and hence often fail to replicate weather events correctly. Ensemble Prediction Systems (EPS) have evolved over the last decade to simulate the effect on weather forecasts of observation uncertainties, model uncertainties, imperfect boundary conditions and data assimilation assumptions (Park *et al.*, 2007). An EPS is interpreted by Buizza (2008) as a system based on a finite number of deterministic integrations and regarded as the only feasible method in meteorology to predict probability a density function beyond the range of linear error growth. EPS can potentially benefit hydrologists and water managers (Thielen *et al.*, 2008), which has been demonstrated by Hydrologic Ensemble Prediction Experiment (HEPEX).

EPS forecasts from a single weather centre only account for part of the uncertainties originating from initial conditions and stochastic physics (Roulin, 2006). Other sources of uncertainties, including numerical implementations and/or data assimilation, can only be assessed if a grand ensemble (GE) of EPS from different weather centres are combined (Goswami *et al.*, 2007). This ensemble of weather forecasts can be coupled to catchment hydrology and provide improved early flood warning as some of the uncertainties can be quantified (Cloke and Pappenberger, 2008). The availability of twelve global EPSs through the 'THORPEX Interactive Grand Global Ensemble' (TIGGE) (Shapiro and Thorpe, 2004; Park *et al.*, 2007) offers a new opportunity for the design of a probabilistic flood forecasting framework. A prototype of such a framework was successfully demonstrated by Pappenberger *et al.* (2008) using 7 weather centres in the European Flood Alert System (EFAS) to hindcast the October 2007 flood event in the Danube basin in Romania. A study carried out for a meso-scale catchment (4062 km^2) in the Midlands region of England set up a coupled atmospheric-hydrologic-hydraulic cascade system driven by TIGGE ensemble forecasts to produce a probabilistic discharge and flood inundation forecast (He *et al.*, 2009). Both studies showed the TIGGE database is a promising tool for producing early flood warning within a probabilistic framework. The need to test TIGGE ensemble forecasts with other flood events in catchments with different hydrological and climatic regimes before giving TIGGE the benefit of the doubt is stressed in He *et al.* (2009) and Cloke and Pappenberger (2009). To this end, a case study was carried out using six TIGGE forecast centres in the Huai River catchment in China coupled with the Xinanjiang hydrological model.

The Huai River Catchment

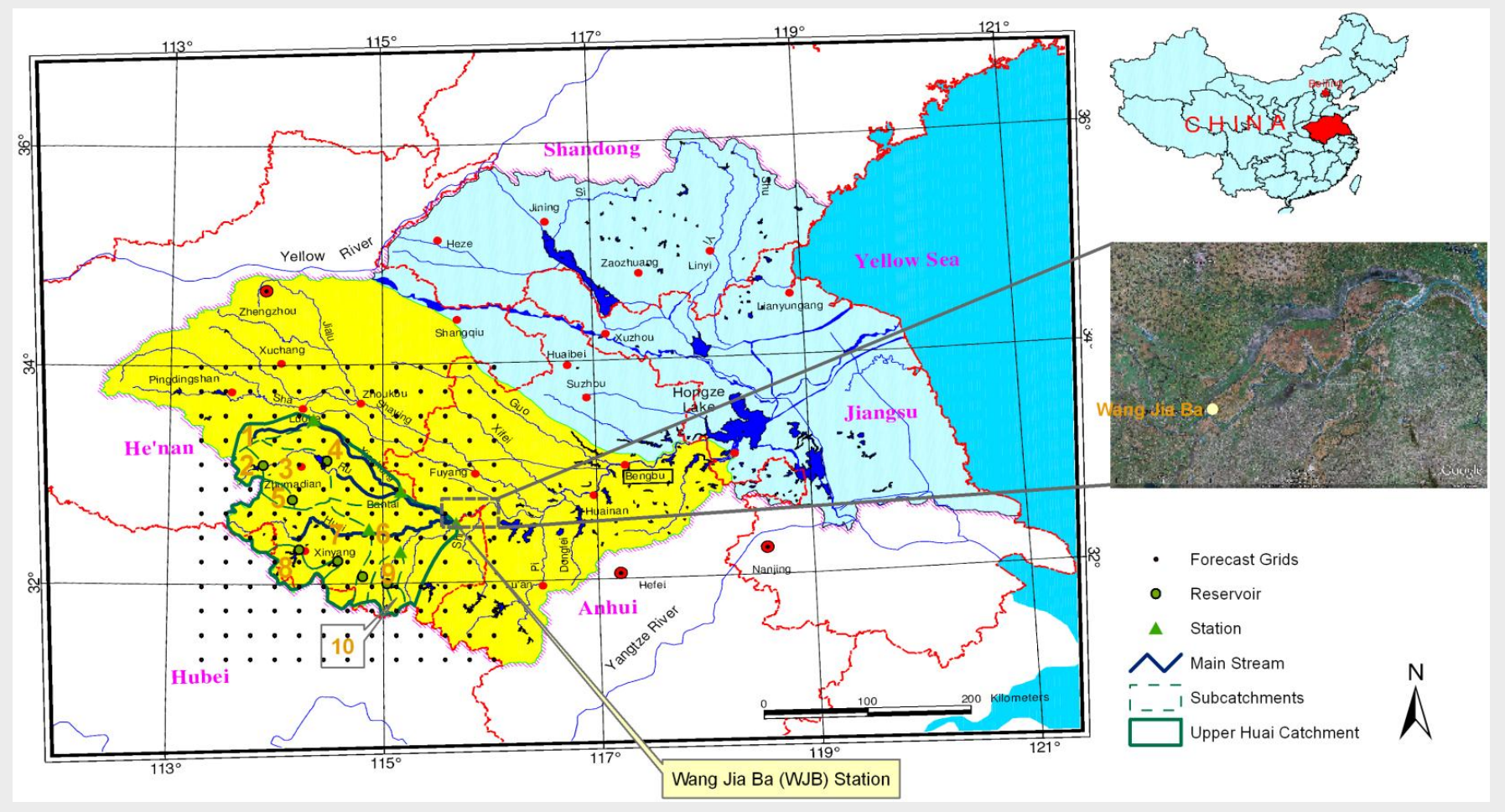

Figure 1. The location of the Huai River catchment in China (top right), the Upper Huai catchment (left), Mengwa flood retention zone (middle right)

The Huai River has a length of 1,078 km and a drainage area of ca. 174,000 km^2 (see Figure 1) and located mid-way between the Yellow and Yangtze Rivers. Its mean annual precipitation and runoff depth is approximately 888 and 240 mm respectively. The runoff coefficient ranges from 0.1 (northeast) to 0.6 (southwest).The dynamics of precipitation including spatial and temporal distribution is very irregular and changes from year to year. This is attributed to the catchment location in the transitional area between the southern monsoon and the northern continental climate (Huai River Commission, 1999).

The catchment is a very important economic region in China (Zhao, 1996). Its average population density is ca. 600 inh/km^2 (PCFCG 2001), more than four times the national average of 138 inh/km2. The catchment is vulnerable to flooding. Major catchment-wide floods have been recorded once every 5 years on the average and regional floods once every 2 or 3 years (Ningyuan, 1999). The period between 1 May and 31 September is officially regarded as the Huai River flood season, although large spring floods have occurred in April a number of times in the past years. Snowfall is rare and thus large floods are mainly driven by heavy rainfall.

The catchment incorporates a mountainous area in the southwest with the highest peak at 2153 m.a.s.l. Heavy rain usually falls in the southwest and is rapidly collected and carried from upstream through Wang Jia Ba (WJB) where the catchment transitions to low lying flood plains towards the northeast. The drainage area up to WJB is regarded as the Upper Huai catchment. It has a slope of 0.49‰ and an area of about 30,672 km^2. The first key flood control gate of the catchment is located at WJB. Behind this gate is the Mengwa flood retention zone (181km2 with an elevation of 20-26 m.a.s.l.) with a design capacity of 750 million m3 and a design maximum discharge of 1626 m3/s. The area, during drier periods, usually serves as farmland of approximately 12,000 hectares for a local population of about 157,800. The retention zone has been opened for diverting flood waters 15 times in the past 12 years. The water level at WJB is a key flooding indicator for the entire catchment and has been labelled by locals as the Huai 'barometer'. It is therefore important to obtain a reliable discharge forecast at WJB. Simulating the hydrology of the catchment is not an easy task as it is heavily engineered with more than 5,000 dams and numerous irrigation channels diverting water from one area to another (Baubion 2008). Complexities introduced by both an unconventional climate regime and man-made modifications make it a challenging task to forecast floods in the catchment. Nevertheless, the frequency and impact of floods resulting in significant damage to properties and human life have driven generations of engineers and researchers to take up such a challenge.

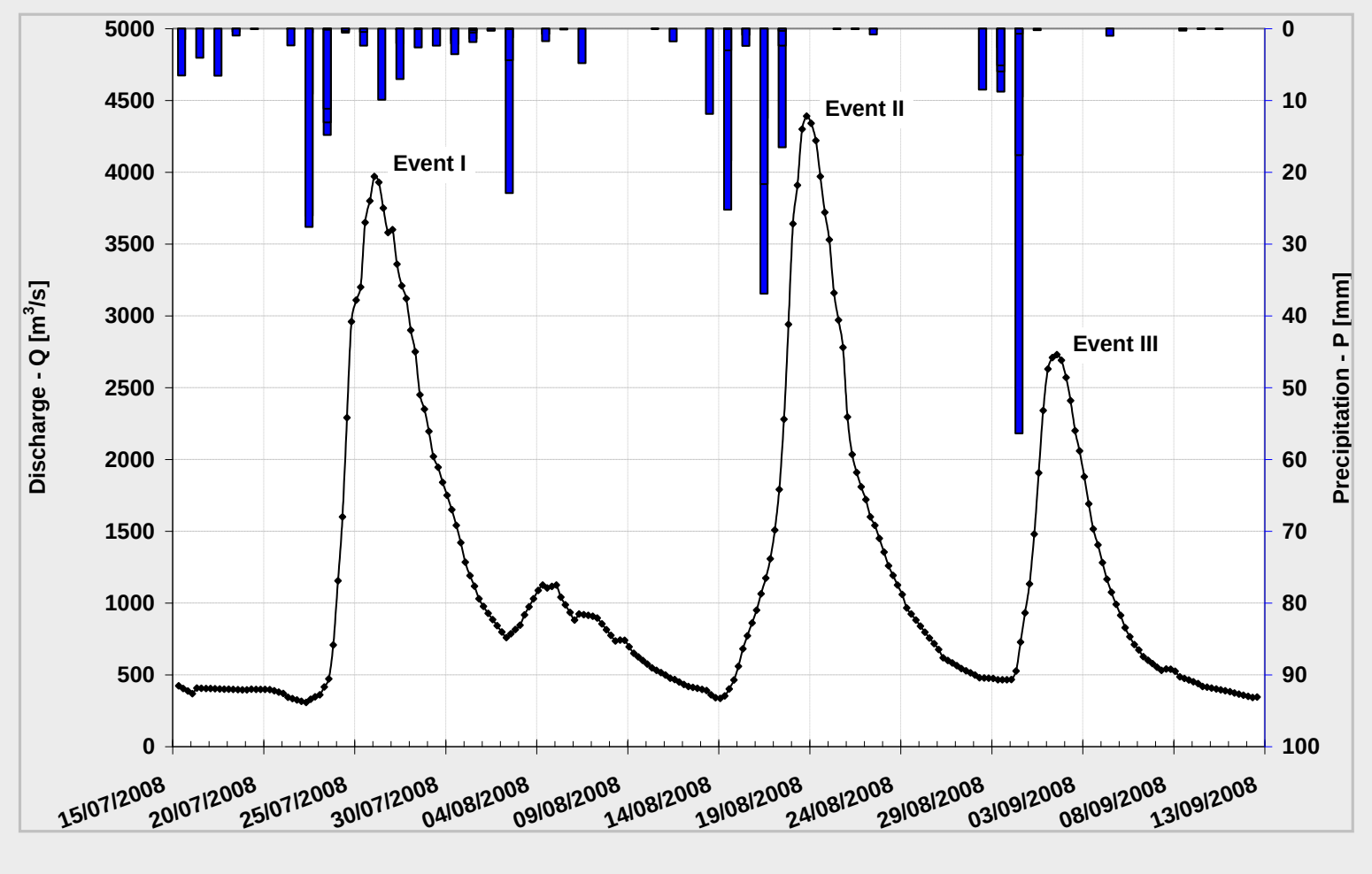

Figure 2.
Observed six hourly precipitation and discharge at WJB (15/07/2008-13/09/2008), three flood events are labelled as Event I, II and III.

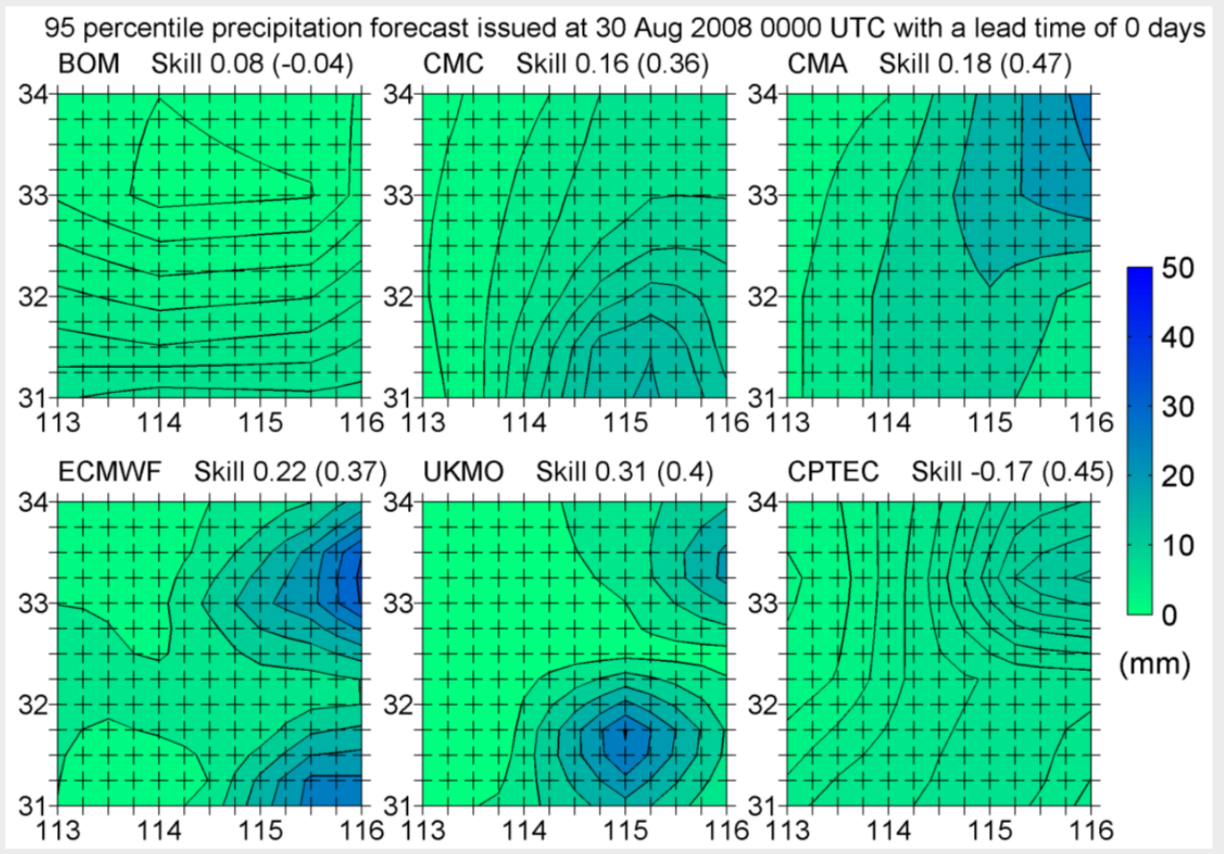

Figure 3. Composite precipitation map of the 5% forecasts with the largest total amounts for 30/08/2008. The maps show large spatial differences amongest centres

The July-September 2008 flood events

The majority of the weather centres delivered global EPS data to TIGGE from October 2007 onwards and so four flood events that took place in April and July-September 2008 can be possibly used for the case study. Three summer events were selected (see Figure 2). The flood warning level at WJB is 27.5 m.a.s.l. and corresponds to discharges of 3110, 3000, and 2730 m3/s for the three events respectively. The warning level was reached at 18:00 on 24/07/2008 for Event I and exceeded in the subsequent days. Event II was the highest in 2008 and reached the peak level of 4390 m3/s at 12:00 on 18/08/2008. Event III neared the warning level at 06:00 on 01/09/2008 but did not overtop it in the following days. Event III will be used as a benchmark to evaluate mainly against false alarms. The time used in this paper is the UTC time. The date is in the format of day/month/year.

Precipitation input evaluation

The precipitation forecasts Pf were retrieved from six weather centres in the TIGGE archive, namely the Australian Bureau of Meteorology (BOM), China Meteorological Administration (CMA), the Canadian Meteorological Centre (CMC), the European Centre for Medium-Range Weather Forecasts (ECMWF), the UK Met Office (UKMO), and Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) of Brazil. The forecasts from the Japanese Meteorological Agency (JMA) and National Centres for Environmental Prediction (NCEP) in the United States were excluded from this study due to an error that occurred during data extraction. For the selected six centres, each provides one 'central' unperturbed analysis and a number of forecasts with perturbed initial conditions. All forecast members were assigned equal weights (recommended by 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 are in ca. 25×25km resolution (see the forecast grids shown in Figure 1). They were interpolated to areal averages to be used along with observed temperature as inputs for the Xinanjiang model. Buizza (2008) pointed out that consistency between forecasts issued on consecutive days is a desirable property of a forecasting system, therefore we examined the feature by visually comparing P_f of the largest rainfall event in 2008 over the Upper Huai for 10 days. Figure 3 shows the 95 percentile of P_f issued at 00:00 on 30/08/2008. No centres displayed consistent P_f in terms of magnitude and spatial distribution. With regards to inter-centre comparison, both the magnitudes and the spatial distributions are notably different.

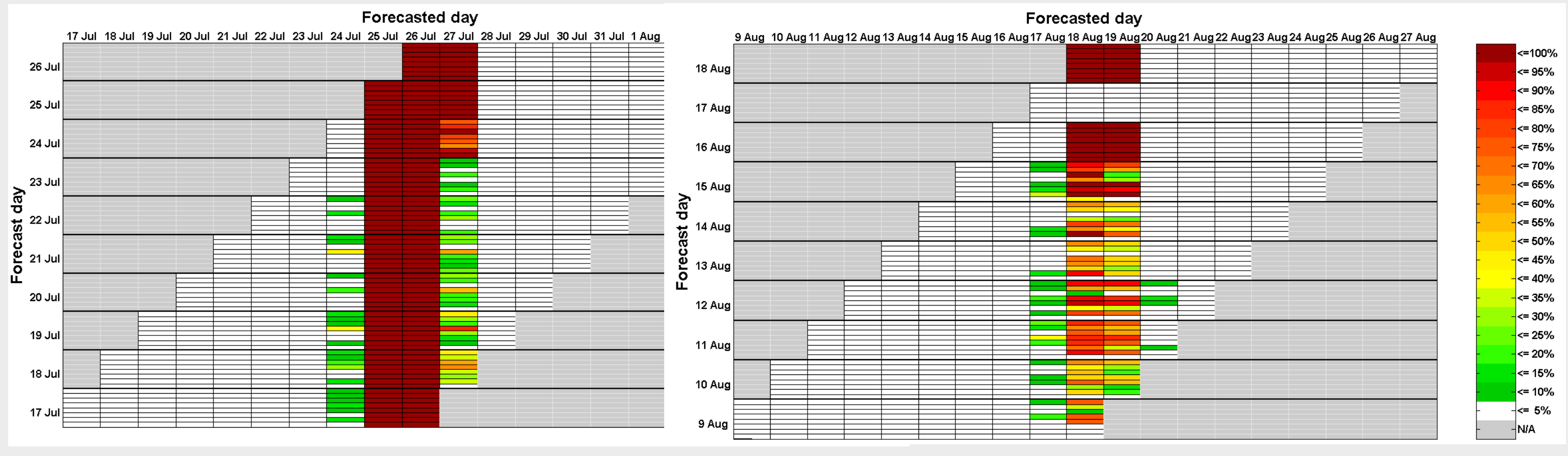

Figure 5. The hit table of the first two flood events. The eight horisontal bars from top to bottom represent the 6 centres (BOM, CMC, CMA, ECMWF, UKMO, CPTEC), the ensemble of the 6 centres and the ensemble of ECMWF/UKMO.

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Discharge simulation

The Xinanjiang model was conceptualized and established in the 1970's by Hohai University. It is a general purpose model for rainfall-runoff simulation, flood forecasting and water resources planning and management. Two basic concepts of the model are (1) runoff formation on repletion of storage; and (2) tension water capacity curve. The former concept is suitable for humid and semi-humid regions. Detailed information on its structure and applications can be obtained from Zhao (1984, 1992) and Zhao and Liu (1995). The Xinanjiang hydrological model was set up at the sub-catchment scale.

Figure 4 shows the area mean P_f issued at 00:00 on 10/08/2008 and resulting Q_f at WJB using ECMWF for Event II. All ECMWF forecast members issued on 13/08/2008 displayed the best agreement for the rainfall event occurred on 14/08/2008. Similarly, the amount and timing of the rainfall event took place on 16/08/2008 were best forecasted with 1-day lead time, i.e. 15/08/2008. For lead times longer than one day, 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 it was to occur as the spread of forecast members was rather large. For example, forecasts issued on 14/08/2008 indicated a large precipitation event would possibly occur from 15/08/2008 to 17/08/2008. Less than 40% of the forecast members predicted it was to occur on 16/08/2008. The situation improved on 15/08/2008 when most forecast members clustered closer to each other than on the previous day of issue (over 70% members agreeing on 16/08/2008), of which four members showed less than 5 mm difference from the actual peak rainfall amount on the day. The progress of agreement amongst forecast members evolved from longer to shorter lead times demonstrates the EPS forecasts become more predictable as it is getting closer to the actual event. In comparison to the observed discharge, the ensemble of Q_f was underestimated by approximately 20-50% for all forecast members varying from day to day. In general, Q95 is very comparable with the $Q_{sim\text{-}raingauge}$ and Q50 is just across or above the warning level.

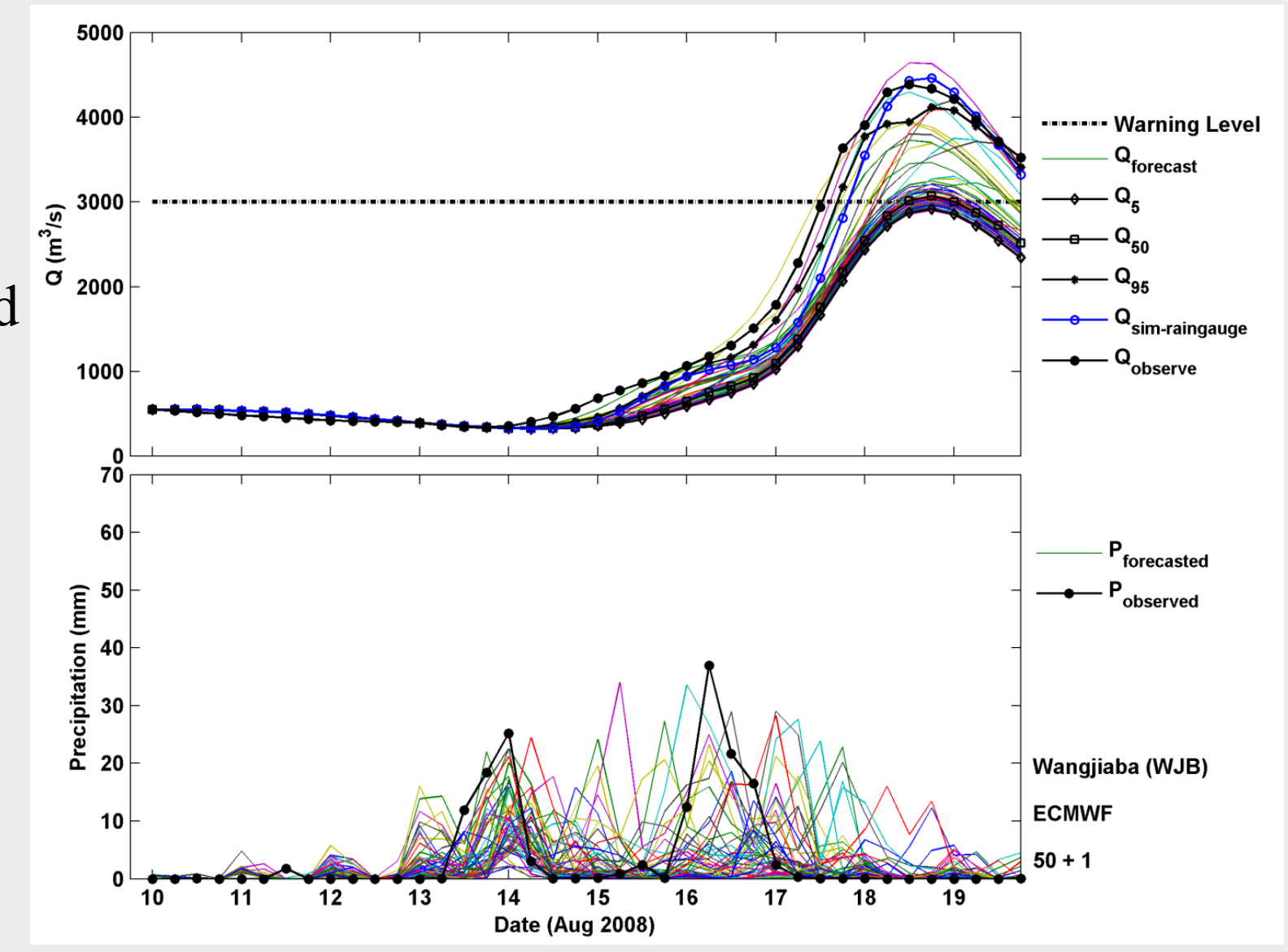

Figure 4. Area mean P_f issued at 00:00 on 10/08/2008 and resulting Q_f at WJB using ECMWF for Event II. The horizontal dashed line is the warning level.
Lines marked with diamonds, squares and stars represent the 5th, 50th and 95th percentile of the forecasted discharges respectively.
The lines marked with circles and the solid lines represent the observed and the forecasted values respectively.

Forecast performance evaluation

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), the observed flood is correctly forecasted, (2) miss (M), the observed flood is not forecasted, (3) false alarm (FA), a flood event is wrongly forecasted and (4) correct negative (CN), a non-event. The contingency table shows the forecasts ability to predict the individual events. Event I is well predicted by all centres with a lead time of 10 days (see Figure 5a). Event II is the largest, but it is not predicted by all centres (Figure 5b). This is due to a misrepresentation of the spatial precipitation pattern. However, making use of multi centres from the TIGGE archive can assist the forecaster make a better decision, since one does not have to rely on a single centre. Event III was a non event and no centres issued false alarm above 10% of all forecast members (figure not shown on this poster).

Conclusion and outlook

A coupled atmospheric-hydrologic cascade system driven by the TIGGE ensemble forecasts is set up to study the potential benefits of using the TIGGE database in early flood warning. The results demonstrate the TIGGE archive is a promising tool for (1) producing forecasts of discharge comparable with the observed discharge and (2) issuing a fairly reliable warning as early as 10 days in advance.

It is necessary to carry out a spatial as well as a temporal correction to the ensemble forecasts to resolve discrepancies in the spatial distribution and timing. The effect on the hydrology can be an offset of the peak in term of timing and magnitude that led to the partial failure in early warning of Event II. The study area has a large number of reservoirs for flood regulation, which presents both challenges and opportunities for using the TIGGE ensemble forecast. Reservoir water release plan can be potentially improved by having a reliable early forecast of precipitation. Future study needs to take into account of different reservoir operation rules and assess the benefit of using EPS.

Techniques to cope with multi-model forecasts need to be developed. Although it isn't the focus of this paper, it is worth noting the principle of equal probability of selection (EPS) ought to be applied to ensemble prediction systems (EPS) from different models with great caution as they have different error structures and cannot be easily combined (Cloke and Pappenberger, 2009).

Difficulties in communicating forecasts within a probabilistic framework could be more challenging than obtaining a well constructed probabilistic flood forecast. This has been clearly pointed out by Thielen et al. (2008) and Cloke and Pappenberger (2009) as a key challenge of an ensemble forecast system. The study was conducted together with the stakeholder, the Hydrological Bureau of Anhui Province, to allow an early involvement and efficient knowledge exchange. (Please refer to http://www3.interscience.wiley.com/journal/123333790/abstract?CRETRY=1&SRETRY=0 for the full paper.)

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