ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **11**: 132–138 (2010)
Published online 28 April 2010 in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/asl.270

Ensemble forecasting using TIGGE for the July–September 2008 floods in the Upper Huai catchment: a case study

Yi He,[1]* Fredrik Wetterhall,[1] Hongjun Bao,[2,3] Hannah Cloke,[1] Zhijia Li,[2] Florian Pappenberger,[4] Yuzhong Hu,[5] Desmond Manful[1] and Yingchun Huang[2]

[1] *Department of Geography, King's College London, London, UK*
[2] *College of Hydrology and Water Resources, Hohai University, Nanjing, China*
[3] *National Meteorological Centre, China Meteorological Administration, China*
[4] *European Centre for Medium-Range Weather Forecasts, Reading, UK*
[5] *Hydrological Bureau of Anhui Province, Hefei, China*

*Correspondence to:
Yi He, Department of Geography, King's College London, London, UK.
E-mail: yi.he@kcl.ac.uk*

Received: 22 September 2009
Revised: 8 February 2010
Accepted: 8 February 2010

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. Copyright © 2010 Royal Meteorological Society

Supporting information may be found in the online version of this article.

Keywords: **ensemble flood forecast; Upper Huai catchment; Xinanjiang model; TIGGE**

1. 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 a probability 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 the 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). The current limitation on computing power also makes GE particularly attractive because it offers an alternative to running a meteorological model with different sub-grid scale parameterisations as well as different representations of the underlying physics. This ensemble of weather forecasts can be coupled to catchment hydrology and provides improved early flood warning (Cloke and Pappenberger, 2008). The availability of 12 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 system. A prototype of such a system was successfully demonstrated by Pappenberger *et al.* (2008) using seven 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 that the TIGGE database can produce an improved early flood warning of up to 10 days ahead. This case study was carried out using six TIGGE forecast centres in the Huai River catchment in China coupled with the Xinanjiang hydrological model.

2. The Huai River catchment

The Huai River has a length of 1078 km and a drainage area of *ca* 174,000 km^2 (Figure 1) and is

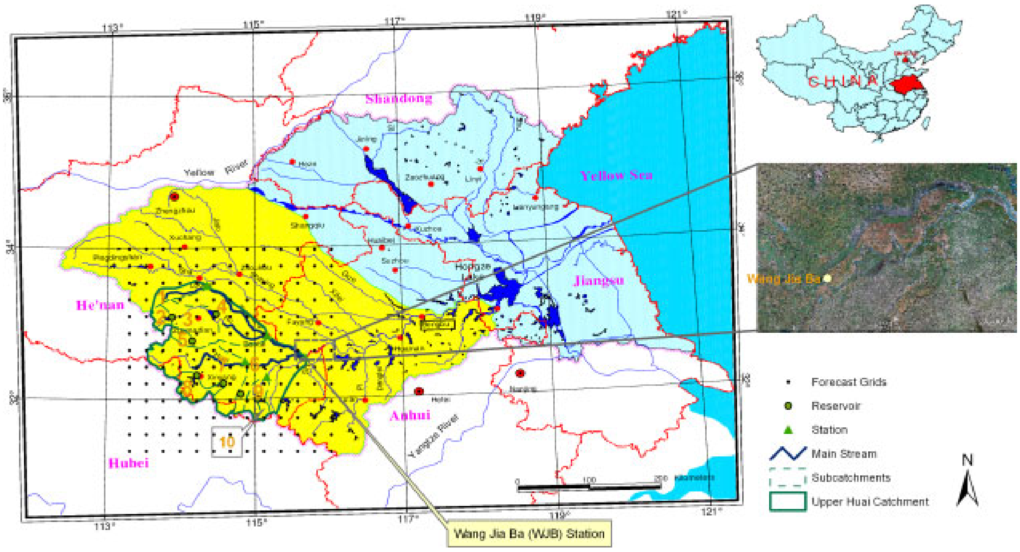

Figure 1. The location of the Huai River catchment in China (top right), the Upper Huai catchment (left) and Mengwa flood retention zone (middle right).

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/km^2. The catchment is vulnerable to flooding. Major catchment-wide floods have been recorded once in every 5 years on the average and regional floods once in 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 existing operational forecast system produces forecasts 3 days in advance for the entire Huai River catchment and 24 h in advance for large-scale reservoirs and sub-catchment outlets/stations in the catchment.

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 (181 km^2 with an elevation of 20–26 m.a.s.l.) with a design capacity of 750 million m^3 and a design maximum discharge of 1626 m^3/s. The area, during drier periods, usually serves as farmland of approximately 12,000 ha 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 5000 dams and numerous irrigation channels diverting water from one area to another (Baubion *et al*., 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.

3. Ensemble flood forecasting in the Huai

3.1. The July–September 2008 flood events

A majority of the weather centres have been delivering global EPS data to TIGGE continuously since October 2007. Four flood events that took place in April and July–September 2008 were possible to use for this case study. This study focused on the three summer events that took place from July to September 2008 (Figure 2). The flood warning level at WJB is 27.5 m.a.s.l. and corresponds to discharges of 3110, 3000 and 2730 m^3/s for the three events, respectively. The warning level was reached at 1800 UTC on 24

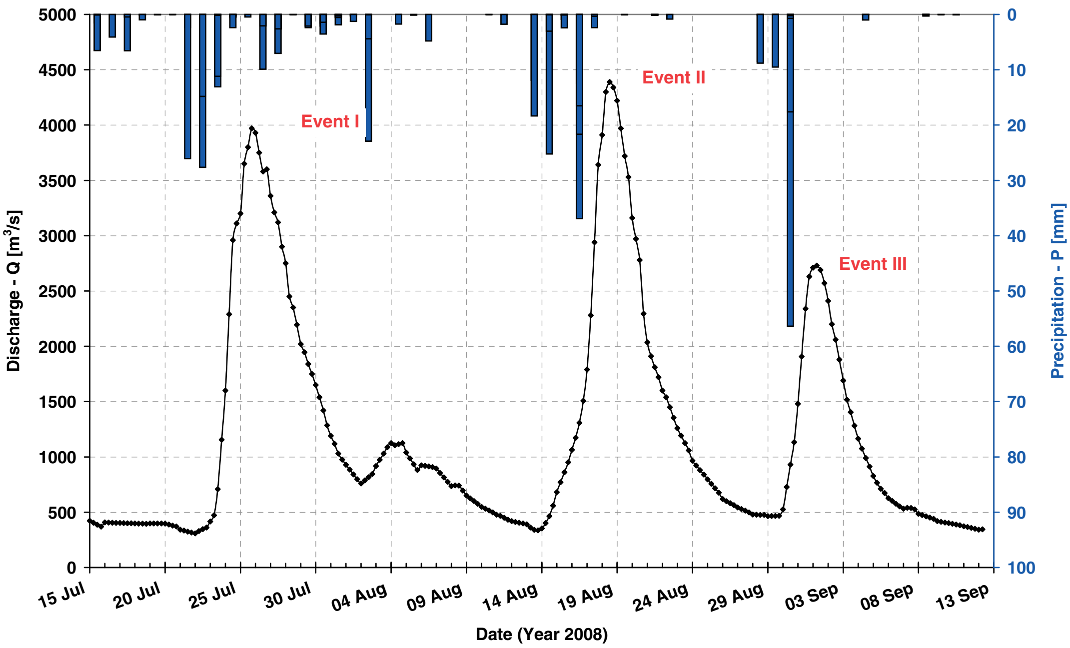

Figure 2. Observed 6-hourly precipitation and discharge at WJB (from 15 July 2008 to 13 September 2008), three flood events are labelled as Events I, II and III.

July 2008 for Event I and exceeded in the subsequent days. Event II was the highest in 2008 and reached the peak level of 4390 m^3/s at 1200 UTC on 18 August 2008. Event III neared the warning level at 0600 UTC on 1 September 2008 but did not overtop it in the following days. The three events can be regarded as 5-year flood events.

3.2. Precipitation input evaluation

The precipitation forecasts $\boldsymbol{P}_{\mathbf{f}}$ 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. The original medium-range forecasts are in *ca* 25 × 25 km 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 $\boldsymbol{P}_{\mathbf{f}}$ of the largest rainfall event in 2008 over the Upper Huai for 10 days. Figure 3 shows the 95th percentile of $\boldsymbol{P}_{\mathbf{f}}$ issued at 0000 UTC on 30 August 2008 (the *animation* online shows the 95th percentile of $\boldsymbol{P}_{\mathbf{f}}$ issued on 0000 UTC from 21 August 2008 through to 30 August 2008 for 30 August 2008). No centres displayed consistent $\boldsymbol{P}_{\mathbf{f}}$ in terms of magnitude and spatial distribution. With regard to inter-centre comparison, both the magnitudes and the spatial distributions are notably different. Continuous ranked probability skill scores (Hersbach, 2000) were calculated for the large precipitation event on 30 August 2008 for all lead times (Figure 3). A skill score of 1 means a perfect forecast, 0 no predictive ability and negative values means performance worse than the reference forecast, which in this study was randomly generated from the observed precipitation. The skill scores for the entire study period are indicated in brackets in Figure 3. Except BOM and CPTEC, the other four centres showed skillful forecasts with UKMO being the best for this particular event. CPTEC was skillful for the entire period, but not the event. This can be explained by the centre's constant under-estimation of precipitation, which can give high skills for the low-intensity periods between events, but no skill in the actual events. The skill scores should however be used with care because the studied period was very short.

3.3. Discharge simulation

The Xinanjiang model was conceptualized and established in the 1970s 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

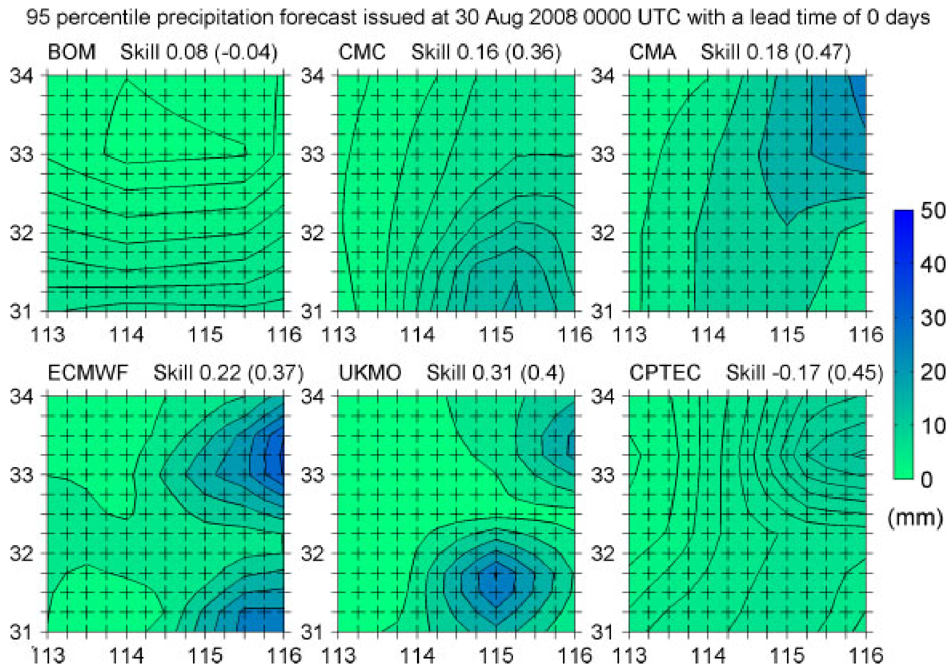

Figure 3. Composite precipitation map of the 5% forecasts with the largest total amounts for 30 August 2008. The maps show large spatial differences amongst centres (the *animation* (see Supplementary Information) shows the 95th percentile of P_f issued on 0000 UTC from 21 August 2008 through to 30 August 2008 for 30 August 2008). Skill scores for continuous ranked probability scores over the event is given for each centre, as well as over the entire study period (in brackets).

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 0000 UTC on 10 August 2008 and resulting Q_f at WJB using ECMWF for Event II (the *animation* online shows the period between 10 August 2008 and 19 August 2008). All ECMWF forecast members issued on 13 August 2008 displayed the best agreement for the rainfall event occurred on 14 August 2008. Similarly, the amount and timing of the rainfall event took place on 16 August 2008 were best forecasted with 1-day lead time, i.e. 15 August 2008. For lead times longer than 1 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 August 2008 indicated a large precipitation event would possibly occur from 15 August 2008 to 17 August 2008. Less than 40% of the forecast members predicted it was to occur on 16 August 2008. The ensemble spread decreased on 15 August 2008 when most forecast members clustered closer to each other than on the previous day of issue (over 70% members agreeing on 16 August 2008), of which four members showed less than 5 mm difference from the actual peak rainfall amount on the day. Disagreements between probabilistic and single forecasts can be used as an indication of potentially low predictability (Buizza, 2008) and vice versa. The progress of agreement amongst forecast members evolved from longer to shorter lead times demonstrates that 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, Q_{95} is very comparable with the $Q_{sim-raingauge}$ and Q_{50} is just across or above the warning level. It is worth pointing out that Q_f is not always the direct effect of P_f over the Upper Huai catchment as this region contains a large number of reservoirs for floods regulation. The results shown here took into consideration the actual water release from the major impoundments in the region.

3.5. Forecast performance evaluation

The ensemble of Q_f was evaluated using a hit table expressed in percentile representing how many forecast members correctly forecasted the event. An event is defined by the observed level exceeding the flood warning level indicated in Section 3.1. Event I was well predicted by all centres with a lead time of 10 days (Figure 5(a)). Event II was the largest, but it was not predicted by all centres (Figure 5(b)). This is possibly 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, because one does not have to rely on a single centre. Event III (Figure 5(c)) was a non-event and no centres issued false alarm above 10% of all forecast members.

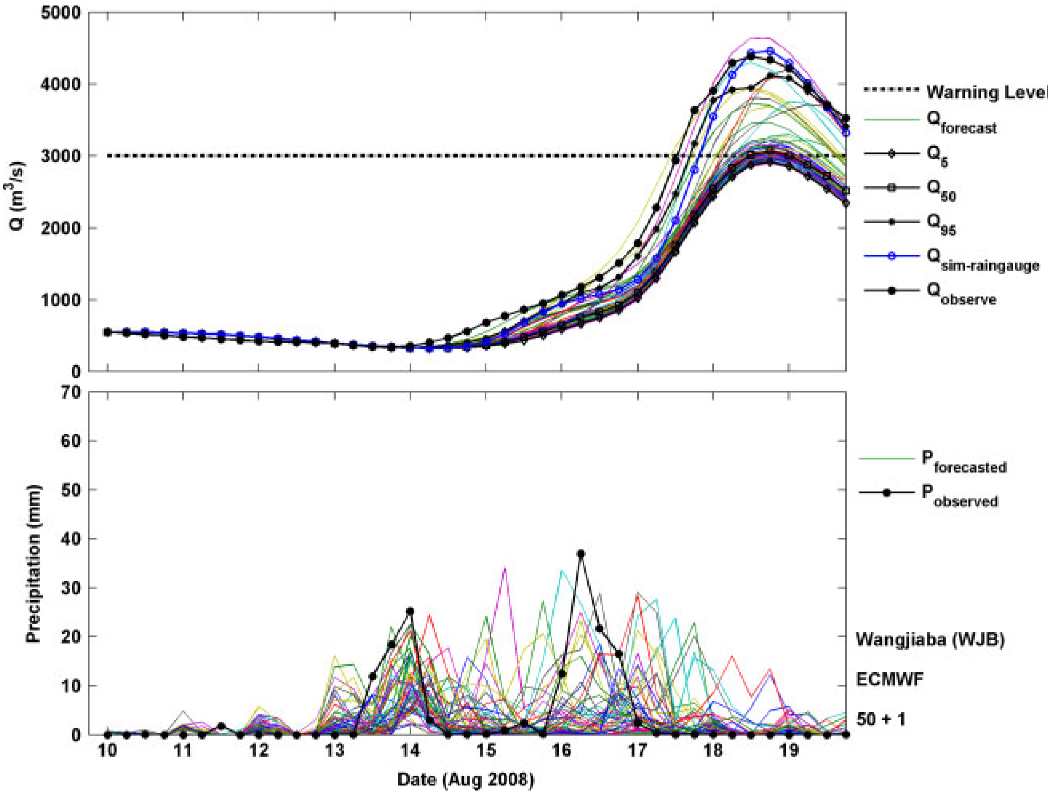

Figure 4. Area mean P_f issued at 0000 UTC on 10 August 2008 and resulting Q_f at WJB using ECMWF for Event II. The horizontal dashed line is the warning level. Lines marked with diamonds, squares and stars represent the 5th, 50th and 95th percentile of the forecasted discharges, respectively. The lines marked with circles and the solid lines represent the observed and the forecasted values, respectively (the *animation* (see Supplementary Information) shows the period between 10 August 2008 and 19 August 2008).

4. Conclusion and outlook

The article presents a case study using six forecast centres from the TIGGE archive for flood warning on the large-scale Upper Huai catchment (30,672 km^2) located in the east-central China. A coupled atmospheric–hydrologic cascade system driven by the TIGGE ensemble forecasts is set up to study the feasibility of using the TIGGE database in early flood warning in this region. The results demonstrating 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. With TIGGE archive, the current lead times (1–3 days) can be potentially improved, which holds great benefit for flood management and preparedness.

It is necessary to carry out a spatial as well as temporal correction of 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 and irrigation, which present 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 different reservoir operation rules and assess the benefit of using EPS.

Techniques to cope with multi-model forecasts need to be developed. Although it is not the focus of this article, it is worth noting the principle of equal probability of selection ought to be applied to 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. No conventional concept can be simply replaced by any new system, the same with the existing deterministic forecast. The study was conducted together with the stakeholder, the Hydrological Bureau of Anhui Province, to allow an early involvement and efficient knowledge exchange. Meteorologists and hydrologists can better understand the needs of the end users, and in return, end users can better accept new techniques as they actively participate in the development process.

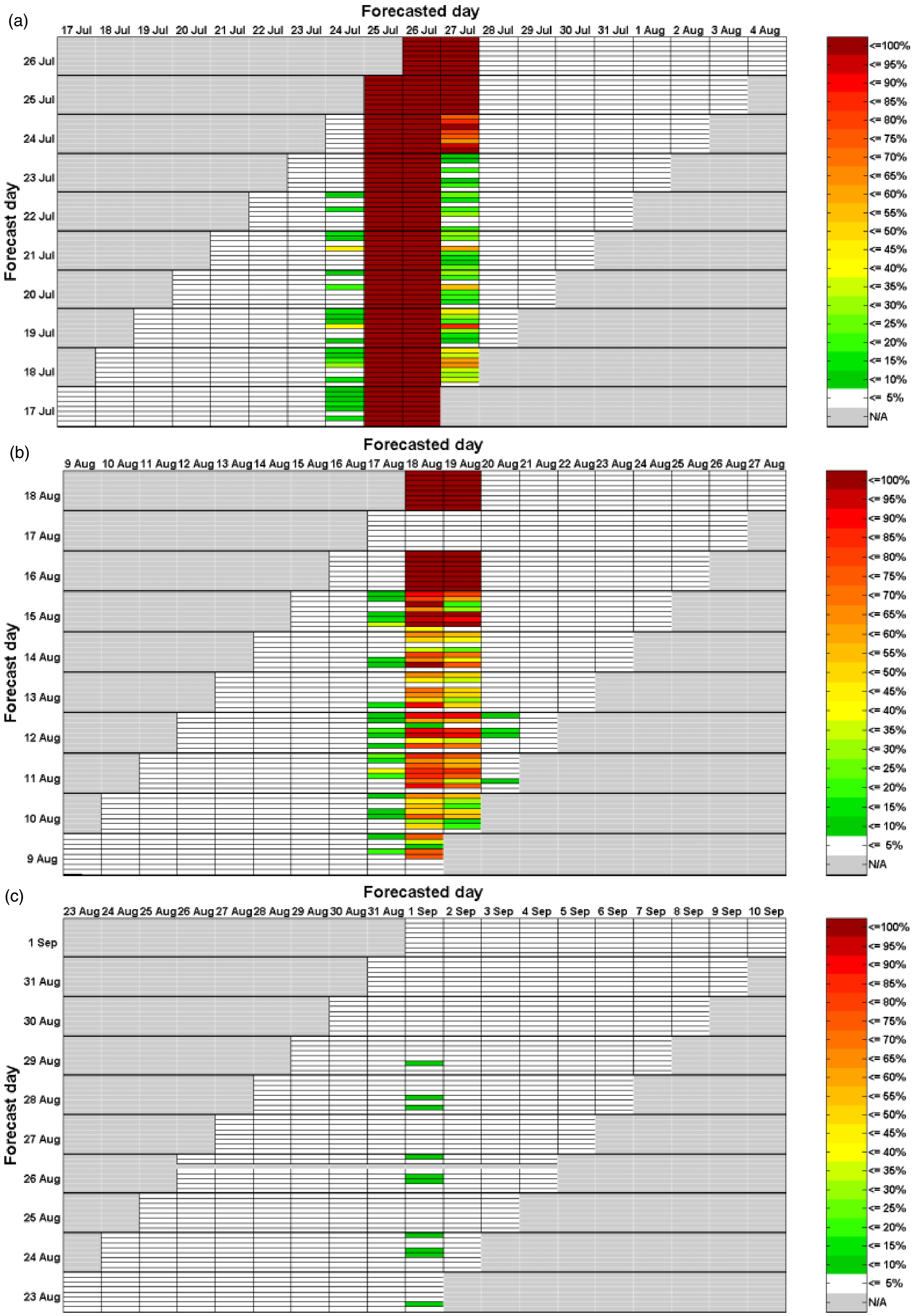

Figure 5. The hit table of the three flood events: (a) Event I, (b) Event II, and (c) Event III. The eight horizontal bars from top to bottom represent the six centres (BOM, CMC, CMA, ECMWF, UKMO and CPTEC), the ensemble of the six centres and the ensemble of ECMWF/UKMO.

Supporting information

Supporting information may be found in the online version of this article.

Acknowledgements

This work was funded by the Inovation China UK (ICUK) Development Fund and the NERC FREE programme (Grant number: NE/E002242/1). The TIGGE data were accessed through the European Centre for Medium-Range Weather Forecasts (ECWMF). The hydrological data were provided by the Hydrological Bureau of Anhui Province.

References

Baubion C, de Marsily G, Ledoux E, Li J-R, Xin J-F, Huang S-F. 2008. *Water resources assessment in the Huai River Basin: Hydrological modelling and remote sensing*. Proc. Dragon 1 Programme Final Results 2004–2007, Beijing, 21–25 April 2008.

Buizza R. 2008. The value of probabilistic prediction. *Atmospheric Science Letters* Special Issue: HEPEX Workshop: Stresa, Italy, June 2007, **9**: 36–42.

Cloke HL, Pappenberger F. 2008. Evaluating forecasts for extreme events for hydrological applications: an approach for screening unfamiliar performance measures. *Meteorological Applications* **15**: 181–197.

Cloke HL, Pappenberger F. 2009. Ensemble flood forecasting: a review. *Journal of Hydrology* **375**: 613–626.

Goswami M, O'Connor K, Bhattarai K. 2007. Development of regionalisation procedures using a multi-model approach for flow simulation in an ungauged catchment. *Journal of Hydrology* **333**: 517–531.

He Y, Wetterhall F, Cloke HL, Pappenberger F, Wilson M, Freer J, McGregor G. 2009. Tracking the uncertainty in flood alerts driven by grand ensemble weather predictions. *Meteorological Applications* Special Issue: Flood Forecasting and Warning, **16**: 91–101.

Hersbach H. 2000. Decomposition of the continuous ranked probability score for ensemble prediction systems. *Weather and Forecasting* **15**: 559–570.

Huai River Commission, Ministry of Water Resources. 1999. *Atlas Of Huai River Basin*. Science Press: Beijing, China, ISBN: 703007649.

Ningyuan. 1999. *Summary of Harnessing the Huai River*, Annual Report 1998, Huaihe River Commission, China.

Pappenberger F, Bartholmes J, Thielen J, Cloke H, Buizza R, de Roo A. 2008. New dimensions in early flood warning across the globe using grand-ensemble weather predictions. *Geophysical Research Letters* **35**: L10404. DOI: 10.1029/2008GL033837.

Park YY, Buizza R, Leutbecher M. 2007. *TIGGE: preliminary results on comparing and combining ensembles*. ECMWF TM 548, European Centre for Medium-Range Weather Forecasts (ECWMF): Reading, UK.

PCFCG – Participants of Chinese Flood Control Group (Li K-G, Wu D-X, Zhu C-B, Deng K-N, Hu Y-L, Sun F, *et al.*) 2001. Integrated River Basin Management for Flood Control in the Huai River Basin, final class report, IHE-Delft, the Netherlands.

Roulin E. 2006. Skill and relative economic value of medium-range hydro-logical ensemble predictions. *Hydrology and Earth System Sciences Discussions* **3**: 1369–1406.

Shapiro M, Thorpe A. 2004. THORPEX International Science Plan. WMO, WWRP, document, http://www.wmo.int/thorpex/publications.html.

Thielen J, J Schaake, R Hartman, R Buizza. 2008. Aims, challenges and progress of the Hydrological Ensemble Prediction Experiment (HEPEX) following the third HEPEX workshop held in Stresa 27 to 29 June 2007. *Atmospheric Science Letters* Special Issue: HEPEX Workshop: Stresa, Italy, June 2007, **9**: 29–35.

Zhao C-P. 1996. *Flood Control Series of Large Rivers in China, Volume: Huai River (in Chinese)*. China Water & Power Press: Beijing, China.

Zhao R-J. 1984. *Watershed Hydrological Modelling – Xinanjiang Model and Shanbei Model (in Chinese)*. China Water Resources and Hydropower Press: Beijing, China.

Zhao R-J. 1992. The xinanjiang model applied in china. *Journal of Hydrology* **135**: 371–381.

Zhao R-J, Liu X-R. 1995. The Xinanjiang model. In *Computer Models of Watershed Hydrology*, Singh VP (eds). Water Resources Pubns.

