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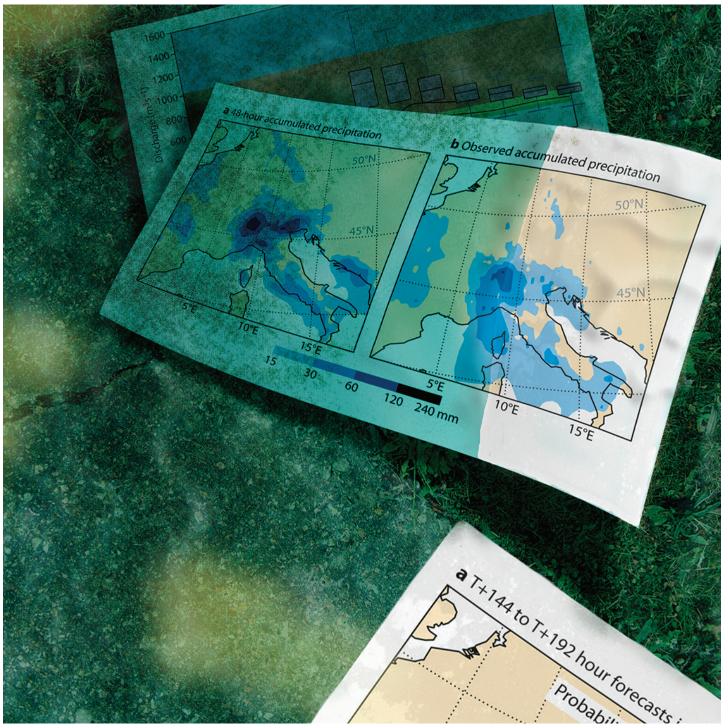

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EPS/EFAS probabilistic flood prediction for Northern Italy: the case of 30 April 2009

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Ensemble hydrological predictions generated by the European Union Joint Research Centre European Flood Alert System (JRC EFAS) driven by the ECMWF Ensemble Prediction System (EPS) have been used to assess the risk of flooding of the Po' river at the end of April 2009. This case illustrates the added value of using probabilistic flood predictions to signal the possible occurrence of flooding, and confirms statistically-based results published in the scientific literature. It shows that the key advantage of ensemble prediction systems, compared to systems that rely on one single forecast, is that they can be used not only to identify the most likely outcome, but also to assess the probability of occurrence of extreme/rare events.

Medium-range ensemble prediction systems are today part of the operational suite at many meteorological centres. Nine centres (in Australia, Brazil, Canada, China, England, Japan, Korea and the USA; see, for example, Buizza et al., 2008) run global, medium-range ensemble prediction systems, and many regional centres are running limited area ensemble prediction systems (e.g. in Australia, England, France, Germany, Italy, Norway and Spain). The past decade has seen an increased use of ensemble forecasts; see, for example, the work done within the DEMETER project on establishing the utility of coupled multi-model ensemble forecasts, in particular in the agriculture and health sectors; www.ecmwf.int/research/demeter/.

Another area where the value of an ensemble approach has been widely recognized is hydrology, which has seen several institutions developing and testing ensemble-based flood prediction systems that use ensemble weather forecasts as initial and boundary conditions (see, for example, the work done within the HEPEX project, *Thielen et al.*, 2008). One of these hydrological ensemble systems for flood prediction is EFAS, developed and successfully implemented by JRC in Ispra, Italy.

Probabilistic prediction of severe water level conditions with EPS/EFAS

The EPS/EFAS flood prediction system runs twice-a-day at JRC using forecasts of the weather variables required by the hydrological model to predict river discharge levels. EFAS probabilistic forecasts use data from the ECMWF EPS as initial and boundary weather conditions.

The ECMWF EPS

The EPS has changed several times since its implementation in 1992 (see *Palmer et al.,* 2007 for more details). Since 11 March 2008, the ECMWF EPS runs twice-a-day, at 00 and 12 UTC, with a variable resolution (*Buizza et al.,* 2006 and *Vitart et al.,* 2008). It includes 51 members: one starting from unperturbed initial conditions (defined by interpolating the high-resolution T799L91 analysis to the ensemble resolution) and 50 members starting from perturbed initial conditions.

The perturbed initial conditions are constructed as a linear combination of the perturbations with the fastest growth over a 48-hour period, provided by singular vectors computed with a T42L62 model and a total energy norm. The perturbed forecasts are integrated with a stochastic scheme designed to simulate the effect on forecast error of random model errors due to uncertainties in the parametrized physical processes (the stochastic physics).

The 00 UTC EPS is run at T399L62 resolution from day 0 to day 10 with persisted sea-surface-temperature anomalies, and then at T255L62 resolution from day 10 to day 15 (day 32 every Thursday at 00 UTC) coupled with an ocean model. Every Thursday the ensemble is extended to 32 days to cover the monthly forecast range. The 12 UTC EPS has the same configuration as that run at 00 UTC, but uses persisted sea-surface-temperature anomalies also between day 10 and 15, instead of a coupled ocean model.

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The JRC EFAS

The European Flood Alert System (EFAS) was launched in 2003 by the European Commission with the aim to increase preparedness for floods in trans-national European river basins (*Thielen et al.,* 2009; *Bartholmes et al.,* 2009). The system being developed has two main objectives:

- To complement European Member States activities on flood preparedness and to achieve longer early warning times.
- To provide the European Commission with an overview of ongoing and expected floods in Europe for improved international aid and crisis management in the case of large transnational flood events that might need intervention on an international level.

The EFAS prototype that is currently run operationally is set up for the whole of Europe on a 5-km grid. Twice daily it provides the national hydrological centres with medium-range ensemble flood forecasting information. In addition, when a high probability for flooding is forecast, the EFAS partners are alerted by e-mail and advised to monitor the development of the situation using the EFAS information system. Currently, forecasts with lead times of 3 to 10 days are achieved through the incorporation of ensemble and single forecasts:

- Two deterministic weather forecasts from ECMWF and the German Weather Service (DWD).
- Two sets of ensembles: the medium-range EPS from ECMWF (51 members, 10 days) and the shorter range COSMO-LEPS (16 members, 5 days) provided by the Regional Meteorological Service of Emilia-Romagna (ARPA-SIM), Bologna, Italy.

EPS/EFAS probabilistic predictions for 28–30 April 2009

To illustrate the value of EPS/EFAS probabilistic flood predictions in weather-related risk management, the severe meteorological and hydrological conditions that affected Northern Italy at the end of April 2009 are now discussed. For this example, only precipitation forecasts generated by the ECMWF EPS and the corresponding EPS-driven EFAS flood predictions have been used.

April 2009 was a rather wet period for Northern Italy. Towards the end of the month, river levels were quite high due to springtime rain and the beginning of the snow melting (Northern Italy witnessed very heavy snowfalls during winter 2008/09). On 29 April, Italian newspapers started listing the various damages due to the very high river levels caused by the heavy precipitation that hit this region on the 27th and 28th. It is interesting to read what was reported about this event in a local Italian news paper (VareseNews from Ispra).

> ***Po' river flood: the JRC forecast is confirmed***
> JRC predicted and communicated last Friday the high level reached by the Po river during these days. The news comes from JRC, which runs EFAS, the European Flood Alert System. On the 24th of April, EFAS personnel sent an alert message to the Italian Protection Agency, the Po' river Authority and other partner authorities. EFAS was predicting a high probability that the Po river would reach flood levels from the 27th of April, with peak levels between the 28th and the 29th. The warning was issued 4–5 days before the event, confirming the great potential of the EFAS-based warning system. Since Friday the 24th, EFAS partners could follow the sequence of EFAS predictions, updated every 12 hours, from the JRC web site, via the area that gives them restricted access to the EFAS forecasts (see Figure 1 for the original Italian article).

This newspaper article indicates that users are becoming increasingly familiar with the notion of a probabilistic forecast, and that decisions are made based on probabilistic forecasts.

Figures 2 and 3 show some of the consequences of the high river levels: in Alessandria, one of the main cities of Piemonte, over Northwestern Italy, some areas were flooded and some of the bridges were closed due to the extremely high level of the river Tanaro (Figure 2). In Piacenza, on 30 April one of the Po' river bridges collapsed causing accidents and casualties (Figure 3). The collapse has been linked to the water pressure associated with the extremely high levels of the Po'.

Verese News, 29 April 2009

Piena del Po: confermate le previsioni del Ccr

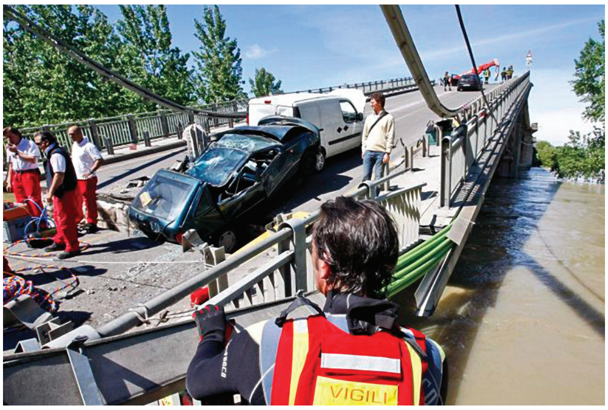
La piena del Po di questi giorni era stata prevista e annunciata dal Centro Comune di Ricerca (CCR, also named Joint Research Centre, JRC) di Ispra da venerdì scorso. Lo comunica lo stesso centro comunitario che rende nota l'attività svolta da EFAS, il sistema europeo di allerta sulle alluvioni ospitato all'interno dello stesso CCR. Il 24 aprile i responsabili di EFAS hanno inviato la notifica di allerta sulla piena del Po all'Istituto Superiore per la Protezione e la Ricerca Ambientale, alle autorità competenti per le acque del Po e alle organizzazioni nazionali partner per il grande fiume padano. Le previsioni di EFAS infatti prevedevano un'alta probabilità di alluvioni del Po' a partire dal 27 aprile, con un picco d'onda tra il 28 e il 29. L'avviso è stato emesso con 4–5 giorni di anticipo, il che conferma il grande potenziale di questo sistema di avvertimento preventivo. A partire da venerdì 24 inoltre i partner italiani dell'EFAS hanno potuto seguire l'andamento delle previsioni, aggiornate ogni 12 ore sull'area ad accesso riservato del sito Internet del sistema.

Figure 1 Extract from VareseNews of 29 April 2009 (see http://www3.varesenews.it/varese/).

La Stampa, 29 April 2009

La Regione Piemonte 'Stato di emergenza dopo la piena'. In tutto il Piemonte ci sono stati allagamenti e smottamenti di strade. Situazione difficile oltre che ad Alessandria anche nel Cuneese, nell'Astigiano e in Val d'Ossola. La presidente Mercedes Bresso ha chiesto lo stato di emergenza. Allerta per il Po' invece dalla Protezione civile dell'Emilia-Romagna, dove la piena e' attesa per oggi. La piena in Piemonte, dovrebbe avere una portata stimata sui 7.000 metri cubi al secondo.

Figure 2 Alessandria, 29 April 2009. The Tanaro river reaches extremely high levels (photo: A Contaldo, Photonews, available from http://torino.repubblica.it/)



La Repubblica, 30 April 2009

Crolla un'arcata, precipitano 4 macchine. Grave un automobilista ricoverato in rianimazione. Piena del Po', crolla ponte a Piacenza Le auto finiscono in acqua: 4 feriti Piena del Po', crolla ponte a Piacenza. Un'arcata ha ceduto alla furia della piena del fiume e l'asflato si è piegato verso l'acqua trascinando quattro auto. La strada si è piegata in una sorta di "v".

Figure 3 Piacenza, 30 April 2009. The collapse of one of the bridges across the Po' (photo: P Caridi, WordPress, available from http://peppecaridi2.wordpress.com/).

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Precipitation forecasts

River flooding was due to the heavy precipitation that affected this region between 27 and 29 April. On the 26th, the upper-level atmospheric flow was characterized by a deep trough positioned over Spain with a southwest-northeast axis that started funnelling hot, moist air towards Northwest Italy. The surface flow was characterized by a weak cyclonic circulation centred on the Balearic Islands. During the subsequent 48 hours, the upper-level trough moved slowly towards Italy with its axis gradually tilting from southwest-northeast towards south-north, and then towards a southeast-northwest direction, while at the surface the cyclonic circulation intensified. This upper level and surface circulation caused heavy precipitation over Italy, especially over the Po' Valley.

Figure 4 shows the areas of heavy precipitation (48-hour accumulated precipitation in excess of 15 mm) given by the 0–48 hour forecast produced by the ECMWF high-resolution model, and the corresponding observed precipitation. These two maps show that the whole of Italy was affected by heavy precipitation (note that the figures have shading starting from 15 mm, thus precipitation values between 1–15 mm are not shown), with very high values affecting Northwest Italy. Over this region, the observed precipitation and the 48-hour forecast show values between 30–60 mm, with a small area with values between 60–120 mm. Note, however, that care must be taken when comparing these with single, grid-point observations, since these two fields are defined on a 0.25° grid, and thus represent average values at this scale.

Hereafter, attention will focus on the probabilistic prediction of 48-hour accumulated precipitation exceeding these two values: 15 and 30 mm.

Figure 5 shows the EPS probabilistic forecasts of 48-hour accumulated precipitation exceeding 15 and 30 mm issued on the 25th (T+48 to T+96 hour) and 23rd (T+96 to T+144 hour). The corresponding forecasts issued on the 21st (T+144 to T+192 hour) and 19th (T+192 to T+240 hour) of April are given in Figure 6.

The EPS forecasts issued on the 23rd (Figure 5a) give probabilities of 40%–100% of precipitation exceeding both thresholds in the area where these amounts were observed. The probabilities issued two days earlier, on the 23rd (Figure 5b), are still correctly located and similar to those for the 15 mm threshold, but lower for the 30 mm threshold.

Forecast probabilities issued four days earlier, on the 21st (Figure 6a), are also correctly positioned for the 15 mm threshold, although they are now lower, 20%–40%, while the probabilities for the 30 mm threshold are positioned to the west of the area where this amount of rain was observed. This is an indication of a too slow propagation of the trough in the EPS forecasts. The forecast probabilities issued on the 19th (Figure 6b) give a 10%–20% probability that precipitation in excess of 15 mm could affect the Po' Valley, and signal that there is a 2–10% probability that precipitation could exceed 30 mm.

Although it is not possible to judge the quality of the EPS probabilistic precipitation forecasts from one case only (for this we refer the reader to published literature, see e.g. *Pappenberger & Buizza* (2008) and *Bartholmes et al.* (2009)), these maps indicate that the EPS gave good probabilistic forecasts up to T+192 hour, with a weaker signal also present at T+240 hour.

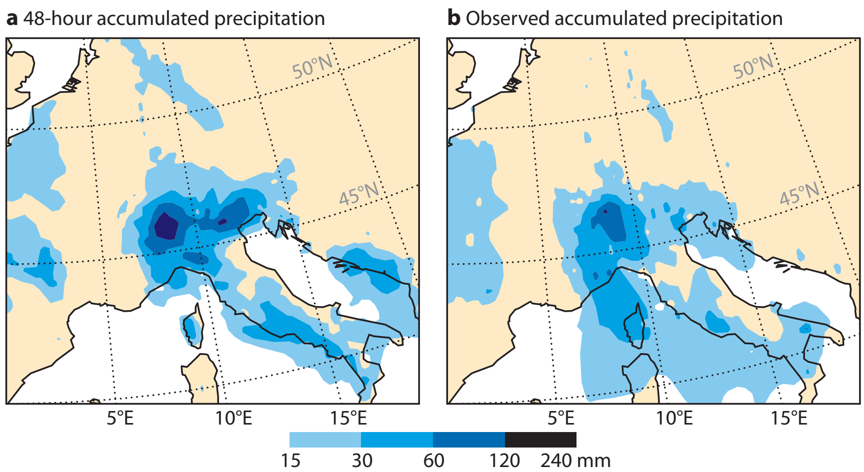

Figure 4 (a) The 0-48 hour forecast of accumulated precipitation in excess of 15 mm from the ECMWF high-resolution model (T799L91) issued at 12 UTC on 27 April and valid between 12 UTC on the 27th and 29th. (b) The 48-hour accumulated observed precipitation, computed by interpolating onto a regular grid the observations from SYNOP stations. The shading indicates the precipitation intervals specified in the legend.

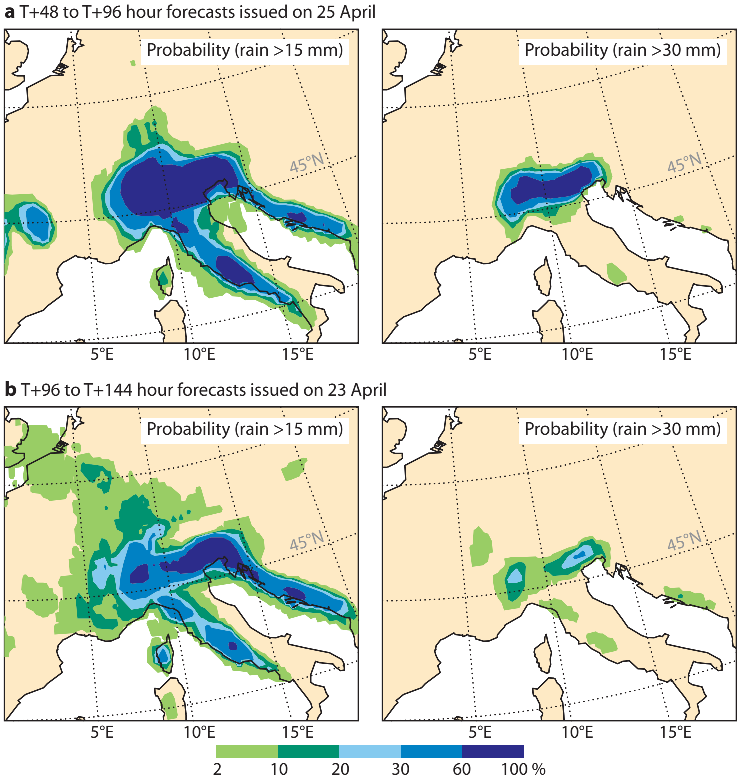

Figure 5 (a) T+48 to T+96 hour forecast probability of occurrence of precipitation in excess of 15 mm (left) and 30 mm (right) issued on 25 April. (b) The corresponding T+96 to T+144 hour forecast probability issued on 23 April. The shading indicates the probability intervals specified in the legend.

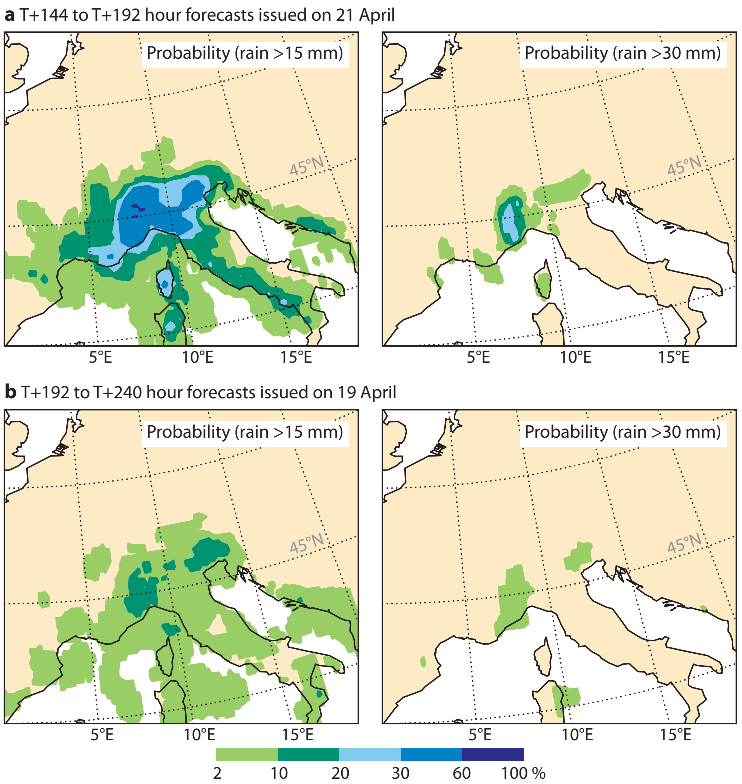

Figure 6 (a) The T+144 to T+192 hour forecast probability of occurrence of precipitation in excess of 15 mm (left) and 30 mm (right) issued on the 21 April. (b) The corresponding T+192 to T+ 240 hour forecast probability issued on 19 April. The shading indicates the probability intervals specified in the legend.

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Flood forecasts

EFAS gave the first indications of a possible flooding in the Po' river basin in the forecast issued at 12 UTC on 21 April. However, the number of ECMWF EPS members (and also of the single forecasts from the DWD and ECMWF high-resolution systems) exceeding alert thresholds were not persistent until the 00 UTC forecast from the 24th. On that date, both single high-resolution forecasts and the probabilistic forecasts simulated discharges exceeding the EFAS high-level threshold throughout the Po' catchment, and confirmed the earlier indications of a possible flooding from the previous forecasts. Hence, a flood alert was sent on the 24th to the Italian national authorities, informing them about the high risk of flooding in the Po' basin from 27 April until 2 May. The alert suggested that they should keep on monitoring the situation carefully using the subsequent forecasts on the EFAS web interface as well as on their national systems.

Figure 7 shows the spatial distribution of the number of ensemble members of the ECMWF EPS forecast (started at 00 UTC on 24 April) simulating discharges which exceed the high-level threshold. EFAS predicted increased, though not extreme, discharges for almost all tributaries within the Po' catchment. The increased flows were principally caused by the predicted heavy precipitation and only to a minor extent by snowmelt processes, despite the exceptionally large snow accumulations in the Southern Alps. However, the increase in discharge for the majority of tributaries resulted in significantly high flows in the main part of the Po'.

The temporal development of the EFAS/EPS forecasts for reporting points close to Alessandria (upper Po'), Piacenza (lower Po') and Ferrara is illustrated in Figure 8. The probabilistic forecast indicated that the highest risk of flooding would occur around 28 and 29 April in the upstream part of the Po', and around 29 April to 1 May for the downstream part. However, the start of the flooding on the 27th in the upper Po' and on the 28th in the lower Po' showed a varying number of ensemble members simulating discharges above the threshold level even with a lead time of two days. This was most likely caused by the temporal resolution of the EFAS simulations and/or the different initial conditions.

Figure 9 illustrates the added value of using probabilistic forecasts. Neither of the EFAS forecasts driven by the single, high-resolution forecasts (ECMWF T799L91 and DWD) could capture the likely high increase of discharge from the 27th onwards. Although both single forecasts lie within the uncertainty range predicted by the probabilistic forecasts, it was not until the 00 UTC forecast on the 26th that a significant exceedance of the alert level was predicted (not shown here).

Unfortunately, no discharge values are yet available for the location shown in Figure 9. Nevertheless, the observed water levels at a reporting station close to Alessandria (Figure 10) confirm the predicted peak on the 28th, although the EFAS forecasts simulate a longer-lasting exceedance of high alert levels. Note that alert levels between EFAS and national/local authorities cannot be compared directly as they were derived differently. Overall, the comparison of the forecasts with observations at other locations reported by ARPA-SIM after the flooding occurred indicated that EFAS predicted the high risk of flooding with a lead time of three to four days.

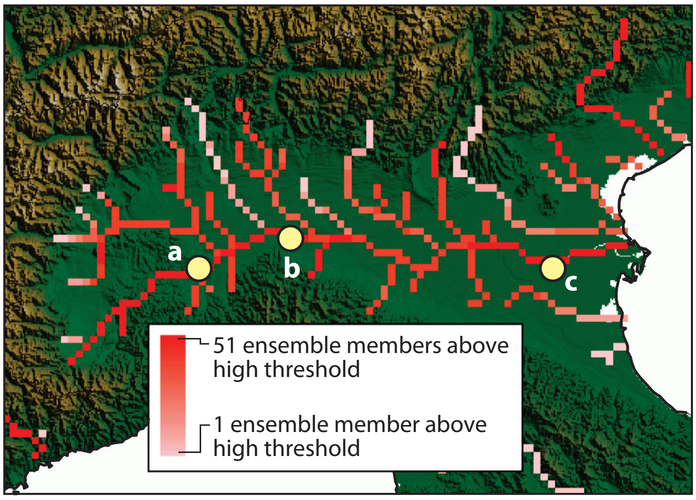

Figure 7 Number of ensemble members based on the ECMWF EPS forecast from 00 UTC on 24 April simulating discharges which exceed the EFAS high alert level for the Po river basin. The circles denote the locations of reporting points as used in Figure 8.

a Alessandria

Forecast day	22	23	24	25	26	27	28	29	30	01	02	03	04
2009042200					2	21	22	16	11	4			
2009042212					34	38	35	30	22	13			
2009042300						44	47	46	38	30	24		
2009042312					45	48	48	46	40	33	24		
2009042400					8	44	46	45	45	40	32	25	
2009042412					31	40	38	36	31	21	16	15	
2009042500					6	29	31	23	21	10	6	4	3
2009042512					42	45	40	37	34	25	21	15	9

b Piacenza

Forecast day	22	23	24	25	26	27	28	29	30	01	02	03	04
2009042200							19	18	4	1			
2009042212						21	32	21	10	3			
2009042300						4	38	43	27	10			
2009042312						44	48	42	22	6	3		
2009042400						23	44	46	43	23	1	1	
2009042412						36	41	39	28	6	2	5	
2009042500						8	43	40	25	4			
2009042512						44	47	42	34	7	2		

c Ferrara

Forecast day	23	24	25	26	27	28	29	30	01	02	03	04	05
2009042200							20	26	28	20			
2009042212						17	37	40	37	18			
2009042300						13	43	46	40	29			
2009042312						35	42	44	40	31	11		
2009042400						31	46	45	44	35	14		
2009042412						51	51	51	49	41	20	4	
2009042500						3	47	51	51	51	42	15	3
2009042512						40	51	51	51	49	29		

Figure 8 Temporal evolution of the ECMWF EPS ensemble members exceeding the EFAS high alert level for a location close to (a) Alessandria, (b) Piacenza and (c) Ferrara. The column on the left denotes the date and time of the forecast. The colour scale indicates the number of ensemble members above the high alert level (see also Figure 7), and can be used to compute the probability of occurrence of high-alert conditions.

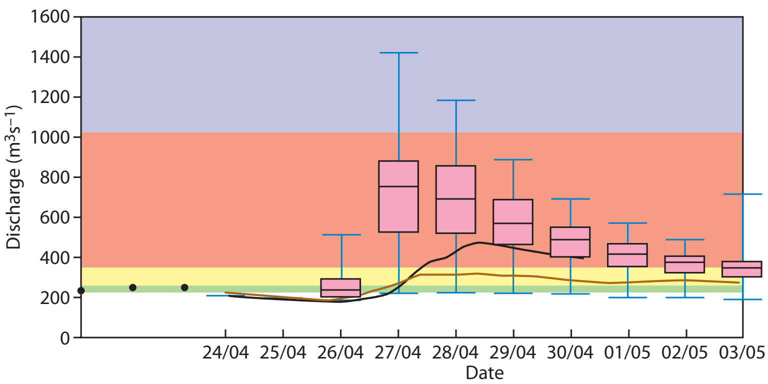

Figure 9 Hydrograph for the reporting point close to Alessandria (see also top panel of Figure 7) for the 00 UTC forecast on the 24 April. The black dots denote the discharge as simulated based on observed data. The black and brown solid lines denote the predicted discharge using the single high-resolution forecasts from the DWD and ECMWF, respectively. Note that the DWD forecast ends at T+168 hour. The Box-Whisker plots denote the predicted discharges using the ECMWF EPS forecasts. The background colours correspond to the low (green), medium (yellow), high (red) and severe (purple) alert levels.

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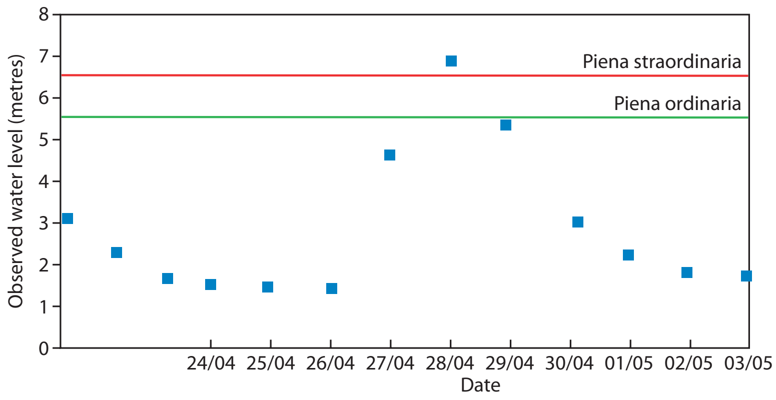

Figure 10 Daily averaged observed water levels at a reporting point close to Alessandria. Green and red solid lines denote the ordinary and extraordinary alert levels (piena ordinaria and piena straordinaria) as used by the Piemonte regional authorities.

EPS/EFAS future changes

One of the key advantages of ensemble prediction systems compared to systems that rely on one single forecast is that they can be used not only to identify the most likely outcome, but also to assess the probability of occurrence of extreme/rare events. The EPS/EFAS discharge prediction for Alessandria illustrated that this was actually the case for the situation that occurred on 28–30 April.

Work is progressing to continuously improve the ECMWF EPS and the JRC EFAS systems.

It is planned that ECMWF will introduce three key modifications to the EPS that are expected to further improve its quality.

- The scheme used to simulate the effect of model errors is going to be upgraded.
- The methodology followed to generate the EPS initial conditions is going to be modified to include an ensemble data assimilation system.
- The EPS resolution during the first 10 days will be increased from 50 to about 30 km. In parallel to this change the resolution of the single high-resolution and of the data-assimilation system will also be increased.

These changes are expected to further improve the quality of EPS probabilistic forecast. Results from this work will be reported in due course.

In the near future EFAS is expected to improve its performance significantly through the assimilation of data from higher-density station networks, which are now collected in real time through the EU-FLOOD-GIS data collection system running at the JRC. This will improve the calibration of the system, the determination of critical thresholds and the calculation of initial conditions.

While case studies will remain an important part of the verification of the skill of the system to predict medium to major floods, a newly developed skill score module is now being implemented pre-operationally to monitor the skill of the probabilistic forecasts at regular intervals. In addition to the constant improvement of EFAS as an early flood warning system in Europe, it is also investigating which other products from EFAS could be made available to the partners and researchers in general (e.g. European soil moisture maps, low flow calculations or flood monitoring).

Furthermore, feasibility studies are currently ongoing to test if EFAS methodologies can be transferred to African basins, where climatology is different than in mid-latitude Europe, and where an early warning system needs to satisfy different requirements. If successful, an extension to a global application could be envisaged.

Further Reading

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