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Monthly-, medium-, and short-range flood warning: testing the limits of predictability

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ABSTRACT: This paper describes a case study that explores the limits of the predictability of floods, by combining forecasts with multiple spatial and temporal resolutions. Monthly, medium- and short range numerical weather prediction (NWP) data are input to the European Flood Alert System for a flood event that affected rivers in Romania in October 2007. The NWP data comprise ensembles and deterministic forecasts of different spatial resolutions and lead times from different weather prediction models. Results are explored in terms of the individual NWP components as well as the ensemble. In this case study, ensembles of monthly weather forecasts contribute only marginally to the early warning, although some indication is given as early as 3 weeks before the event. The 15-day medium-range weather forecasts produce early flood warning information 9 to 11 days in advance. As the event draws nearer and is in range to be captured by the higher resolution ensemble forecasts, the spatial extent of the event is forecast with much more precision than with the medium-range. A novel post-processing method for the calculation of river discharge is applied to those stations where observations are available, and is able to correct for time-shifts and to improve the quantitative forecast. The study illustrates how a combination of forecasts and post-processing improves the lead time for early flood warnings by 2 to 3 days, while remaining reliable also in the short-range. Copyright © 2009 Royal Meteorological Society

KEY WORDS ensemble flood forecasting; discharge post-processing; early flood warning; skill scores; ARMAXSS; COSMO-LEPS; ECMWF; EFAS

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1. Introduction

The skill of weather prediction has steadily improved over the past years through higher resolution models, improved physics, remote sensing data and better data assimilation methods. The skill of predicting intense precipitation has, however, remained low and has barely increased over the past decade (Hamill *et al.*, 2007). Pappenberger and Buizza (2008) have found no long term trend of precipitation skill for the Danube area, but it is worth pointing out that more positive trends have been detected in routine evaluations of the ECMWF operational, high-resolution forecasts of more extreme precipitation thresholds. As Richardson *et al.* (2008) have documented, 12-month running average equitable threat scores of operational, high-resolution forecasts over Europe verified against synop station data have been continuously improving, especially for the prediction of 5 and 10 mm day^{-1} thresholds. McBride and Ebert (2000) have shown that for seven global weather forecasting models tested over Australia the skill falls dramatically for rainfall occurrence thresholds greater than 10 mm day^{-1}, implying that the models are much better at predicting the occurrence of rain than they are at predicting the magnitude and location of the peak values. Error and uncertainty significantly increase at longer lead times.

Most hydrological services therefore rely either on observations only or on short-term deterministic rainfall forecasts of up to 2 days or less, because the unpredictable degree of uncertainty at longer lead times renders the results unreliable and therefore not useful for decision-making (Demeritt *et al.*, 2007). Lately, however, the hydrological community is increasingly looking at the use of ensemble prediction systems (EPS) instead of single (deterministic) forecasts for flood warning times beyond 48 h. EPS have already become an integral part of operational weather forecasts over the past years (Molteni *et al.*, 1996; Buizza *et al.*, 1999, 2007b; Palmer and Hagedorn, 2006). They are designed to give a measure of the predictability of the weather and the uncertainty in the model solution for lead times up to 2 weeks, which would be considered well outside the range of predictability for deterministic models.

In 1999 the 'European Flood Forecasting System' (EFFS, 1999–2003) project became the first European research project to address early flood warning based on EPS (de Roo, 2003; Kwadijk, 2003; Gouweleeuw *et al.*, 2004, 2005; Bartholmes and Todini, 2005; Pappenberger *et al.*, 2005). The findings clearly showed the great potential for using EPS to increase flood early warning time, but equally highlighted the need for: further research on the interpretation of the

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results; sufficient events for statistical analysis; post-processing of the 'raw' output; and ways to communicate the results to end users and decision-makers. In the light of these results the European Commission created the European Flood Alert System (EFAS). In 2004 the 'Hydrological Ensemble Prediction Experiment' (HEPEX, see http://hydis8.eng.uci.edu/hepex) followed as an international initiative to foster interdisciplinary dialogue between the meteorological and hydrological communities (Schaake *et al*., 2006, 2007; Thielen *et al*., 2008) and to promote ensemble prediction systems for floods, droughts and general water management on short, medium and seasonal scales. Since then, EPS-based research has become a dominant feature of hydrological research and applications on all time scales (see publications on research projects, such as: Mesoscale Alpine Programme Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events (MAP D-PHASE), (Zappa *et al*., 2008); Prevention, Information and Early Warning (PREVIEW), (Buizza *et al*., 2007a; Bogner and Kalas, 2008); and other research projects on ensembles, including: Roulin *et al*. (2007); Bartholmes *et al*. (2009); Hopson and Webster (2008); Olsson and Lindstrom (2008); Thirel *et al*. (2008). See also the full review by Cloke and Pappenberger, 2008a).

While the number of research projects on EPS has increased rapidly, the implementation of EPS in operational hydrological services has been much slower (Cloke and Pappenberger, 2008a). Apart from practical problems such as the need for intensive computing power facilities or the mismatch between meteorological grid spacing and hydrologically relevant units, there are other more fundamental issues. Probabilistic forecasting needs to be assessed statistically over a sufficient number of events and not only on a case study basis. Treating events with high return periods makes it, however, unlikely that a sufficient number of events is available to determine the reliability of the forecasts, even if 'hindcasts' over a sufficiently long time period were systematically provided with the same model and parameterization.

The use of probabilistic flood forecasting for risk assessment and risk-based decision-making in flood warning is still one of the greatest challenges for the scientific community. The responsibility of the modellers to interpret the probabilistic results and to communicate them efficiently to end-users (in research, operational forecasting centres or the public) and decision-makers, is even greater than for the classical deterministic approaches. This challenge is present in the majority of European operational forecasting centres, as highlighted in the recent report of the EXCIFF initiative (Exchange Circle for International Flood Forecasting, 2005).

In this paper, the performance of EFAS when using EPS at different spatio-temporal resolutions is studied in respect to hydrological predictions (Pappenberger *et al*., 2008 and Cloke and Pappenberger, 2008b). Monthly weather forecasts, global EPS and limited-area EPS (LEPS) are evaluated for a flood event that took place in Romania in 2007 and that has already been the subject of research with multiple EPS (Pappenberger *et al*., 2008). Clearly the results of this study can only be indicative since the results are based on one flood event only. In order to test the conclusions, longer time series need to be evaluated and the limits of the approach further tested with flood events at different spatial and temporal scales. In Section 2 of this paper, a brief description of EFAS and its set-up, data inputs and methodologies, is presented. In addition, a novel method for discharge EPS post-processing is proposed that aims at rendering the results more useful for decision-makers. A brief description of the case study is given in Section 3. Section 4 describes briefly the rainfall forecast fields, the resulting flood forecast information at the different lead times, and the possible improvements after application of the novel post-processing routine. Conclusions are drawn in Section 5.

2. Description of EFAS set-up, input data and methodology used in this study

2.1. European flood alert system (EFAS) set-up

The aim of the European Flood Alert System (EFAS) is to increase preparedness for floods in trans-national European river basins. Since 2005 EFAS has been providing local water authorities and the European Commission with early flood warning information up to 10 days in advance based on EPS and deterministic forecasts from different weather services (so-called 'poor man's ensembles') The investigation of probabilistic flood forecasting results with case studies and statistical analyses as well as their effective communication to flood forecasters as early warning information, are the predominant tasks of EFAS (Ramos *et al*., 2007; Bartholmes *et al*., 2009; Thielen *et al*., 2009; Younis *et al*., 2008). EFAS incorporates operationally available global and limited area model EPS as well as deterministic forecasts from different meteorological models. This multi-model approach ensures that forecasts are based on different numerical implementations, data assimilation schemes and grid resolutions, which can have a substantial impact in generating the full spectrum of possible solutions. This is particularly important at the 'tails' of the distributions, where the extreme rainfall events that cause flooding are captured (Pappenberger *et al*., 2008).

The operational EFAS has been developed on two main pillars. The first is the state-of-the-art meteorological input data including several EPS and deterministic forecasts. The meteorological data used in the study are described in Section 2.2. The second pillar of EFAS is a strong geographical information system (GIS) component designed to make effective use of the existing spatial data sets relevant for hydrological processes and to provide estimates of stream flow and other information at any point along the river system. The LISFLOOD model is a dynamic GIS-based hydrological rainfall-runoff-routing model (van der Knijff and de Roo, 2006; van der Knijff *et al*., 2008). It is a hybrid between a conceptual and physical rainfall-runoff model combined with a routing

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module in the river channel. Whenever possible, model parameters are derived from physical information, e.g. soil maps and land-use maps The remaining parameters are calibrated based on discharge observations (Pappenberger *et al.*, 2004; Mo *et al.*, 2006; van der Knijff and de Roo, 2006; Feyen *et al.*, 2007).

EFAS results are explored on an event basis when critical flood warning levels are exceeded. Four warning levels (low, medium, high and severe) are derived from a 16-year reference (1990–2006) LISFLOOD simulation driven by weather observations. The highest simulated discharge represents the highest critical threshold (severe) and the 99% quantile, the second highest critical threshold (high), the medium warning level is defined by 98% quantile and the low warning level by the 97% quantile. A flood event is defined when the discharge exceeds at least the high threshold. Results are viewed as time series representations of flood hazard exceedances at point locations as well as combined flood hazard maps (Ramos *et al.*, 2007).

EFAS aims to forecast fluvial floods that are mostly caused by large synoptic scale weather phenomena such as widespread severe or prolonged precipitation that numerical weather prediction models are likely to capture consistently as the event approaches. While this principle of 'Let's wait and see the next forecast' is often intuitively used when results are uncertain, Bartholmes *et al.* (2009) have demonstrated statistically that introducing the principle of temporal 'persistence' (whereby a river pixel is flagged at 'risk of flooding' only if the event is forecast on three consecutive 12-hourly forecasts) considerably increases the skill of the flood forecast. For this study this implies that control points with detailed information on river pixels are only created if an event has been forecast twice within 24 h by forecasts based on VAREPS (Variable Resolution EPS) or VAR.

For this study EFAS was set up for the entire Danube river basin with a spatial grid resolution of 5 × 5 km. Time steps vary depending on the input data as indicated in Section 2.2. Only the 1200 forecasts are evaluated for this study. Although the model is run for the entire Danube, the case study analysis is restricted to Romania, the country affected by the flooding of October 2007.

2.2. Input data for this study

Meteorological station data of precipitation, temperature and estimated potential evaporation are derived from the meteorological data archive of the AGRICULTURE unit at the DG Joint Research Centre (http://www.agrifish.jrc.it). This database holds meteorological data from about 1000 stations reporting regularly across Europe from 1974. These data are extracted, interpolated and used to calculate the initial conditions at the start up of the flood forecast situation. For Romania about 22 rainfall stations are available.

Hydrological station data have been provided by the Romanian hydrological services as average daily data (0600–0600). These data have been used for comparison and post-processing of the discharge output as described in Section 2.4. The weather forecast data-sets used for this study are listed in Table I. The longest-range forecasts are the monthly forecasts provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). They are available once a week every Thursday, have a lead time of 30 days and contain 51 ensembles. The medium-range VAREPS, also provided by ECMWF, are provided twice a day and have a lead time of 15 days. Both monthly and VAREPS forecasts have staggered temporal and spatial resolutions. The shortest range EPS forecasts are COSMO-LEPS provided by ARPA-SIM (Marsigli *et al.*, 2001, 2008). COSMO-LEPS has a lead time of 5 days and a total of 16 members. The spatial resolution is 10 km throughout. In addition to the three sets of EPS the two deterministic weather forecasts from ECMWF and the German Weather Service (DWD) are also used. The DWD input data is a composite consisting of data from the regional model (Lokal Modell) with a spatial resolution of 7 km for the first 3 days, and the global model (Global Modell) with a spatial resolution of 40 km for the remaining 4 days.

2.3. Updating of river flow with the ARMAXSS model

EFAS is grid-based and there provides warnings along rivers also at locations at which no measurements are available. Remotely sensed river information could be used to update river discharges (Schumann *et al.*, 2005; Matgen *et al.*, 2007). However, current operational subsystems rely predominantly on point measurements. Since the latter are also available to the EFAS forecast system, the updating procedure is implemented for those river pixels only where observations are available. The method is mainly based on the idea to decompose the discharge data (observed and simulated) at multiple scales and construct a state-space model at each scale.

The wavelet transformation decomposes the time series into different resolution levels and provides a way of analyzing a signal in both time and frequency domains (e.g. Carmona *et al.*, 1998). The reason this decomposition has been applied is that the difference between observed and simulated discharge will be caused by different time-scale processes (e.g. snowmelt processes can last for several weeks while flash floods occur within a time-scale of a few hours). An Auto-Regressive Moving Average with Exogenous Input (ARMAX) model in state-space form, also called dynamic linear model (DLM), is applied for updating the state variables at each scale. State-space models have been introduced in Kalman (1960) and Kalman and Bucy (1961), and an excellent treatment of ARMAX models and their equivalent state-space form is given by Shumway and Stoffer (2006). More details about this error correction method can be found in Bogner and Kalas (2008).

Table I. Specification of the meteorological forecasting data used for this study.

Acronym	Provider	Lead time in days	Spatial resolution	Ensemble members	Forecasting frequency	Forecasts processed for this study	EFAS time step
MON (part of VAREPS)	ECMWF	30	*ca.* 40 km (T399/L62) for the first 10 days, and *ca.* 80 km (T255/L62) for days 11–30)	50 and 1 control run	Every Thursday of the month	27 September 2007 1200 4 October 2007 1200 11 October 2007 1200	Daily
VAREPS	ECMWF	15	*ca.* 40 km (T399/L62) for the first 10 days, and *ca.* 80 km (T255/L62) for days 11–15)	50 and 1 control run	Twice daily	Daily 1200 from 1 October 2007 until 31 October 2007	Daily
COSMO-LEPS	ARPA-SIM	5	10 km	16 (no control)	Once daily	Daily 1200 from 1 October 2007 until 31 October 2007	6 hourly
DWD	German weather service (DWD)	3	7 km	1	Twice daily	Daily 1200 from 1 October 2007 until 31 October 2007	Hourly

3. The October 2007 floods in Romania

In October 2007 the Danube river basin received above average rainfalls in the Balkan region and Romania (Figure 1(a)), compared with the EFAS reference period (1990–2004). Consequently, the hydrological regime of almost all Romanian rivers was above the monthly mean multi-annual values. In the last 10 days of the month the precipitation regime exceeded the normal values for the whole month due to the high instability of the weather and torrential rainfall, especially during the days 20–24 October. Figure 1(b) also clearly demonstrates that there is not a linear relationship between excess of rainfall and flood hazard. While a relatively large region in south-eastern Europe received higher than average rainfalls, flooding was only observed in Romanian tributaries to the Danube.

Flooding levels were exceeded on 23–25 October in the middle and lower basin of the Olt river, in the upper basin of the Jiu river and in the lower basin of the Siret. Flood attention levels were exceeded on many rivers across the country (Figure 2(a)). Localized flooding was also observed in tributaries of the rivers Somes and Tisza. A second event affected the country just a few days after the initial flooding and affected particularly the north-west of the country. Figure 2(b) illustrates that when LISFLOOD is driven by observed weather data, and after the EFAS flood thresholds are applied, the event is reproduced very well. The figure shows that the EFAS high threshold corresponds roughly to the national flood level. At a few places the EFAS high level was only just exceeded, e.g. in the Jiu, while in reality the flood level was not quite reached.

4. Presentation of results

4.1. Observed and forecast rainfall fields

4.1.1. Observations

The total rainfall from 20 to 25 October 2007 as estimated from the observed data available for this study, is shown in Figure 3(a). Due to the coarse raingauge network the spatial rainfall pattern shown here is quite coarse. The whole country was affected by rainfall and the main centres of high rainfall accumulates are in the southwest, northwest and east of the country.

4.1.2. Monthly rainfall forecasts

Rainfall probabilities of monthly rainfall forecasts (MON) from 4 October 2007, 3 to 4 weeks before the flood event, show a high probability of exceeding the 100 and 150 mm rainfall thresholds along the Adriatic coast. In Figure 3(a) data exceeding the 100 mm threshold are shown as shaded areas while those exceeding the 150 mm are shown as contour lines. The country borders are also shown. For Romania there is a 20–30% probability of exceeding the 100 mm threshold in the western part of the country but only few EPS accumulated rainfalls exceed 150 mm (Figure 3(b)).

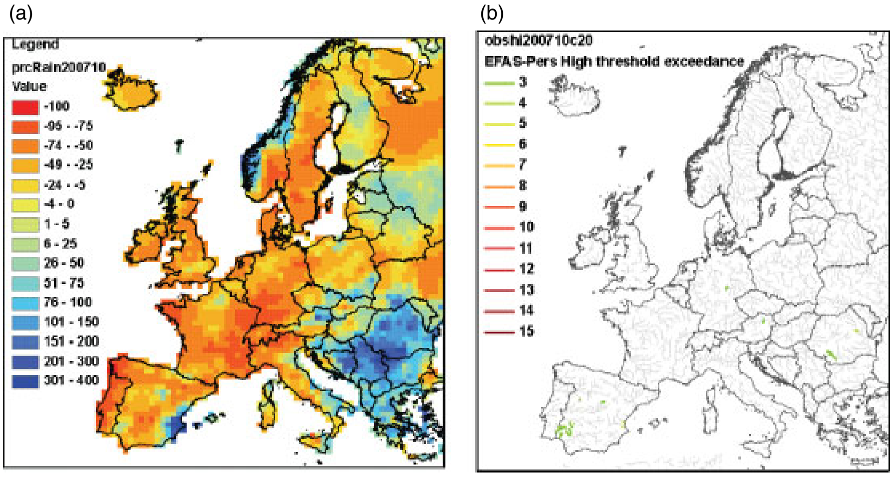


Figure 1. European map showing difference in precipitation in percentage for October 2007 in comparison to long term average from 1990 to 2004 (a) and number of days that the EFAS high alert was exceeded during this month when driving the model with observed meteorological data (b).

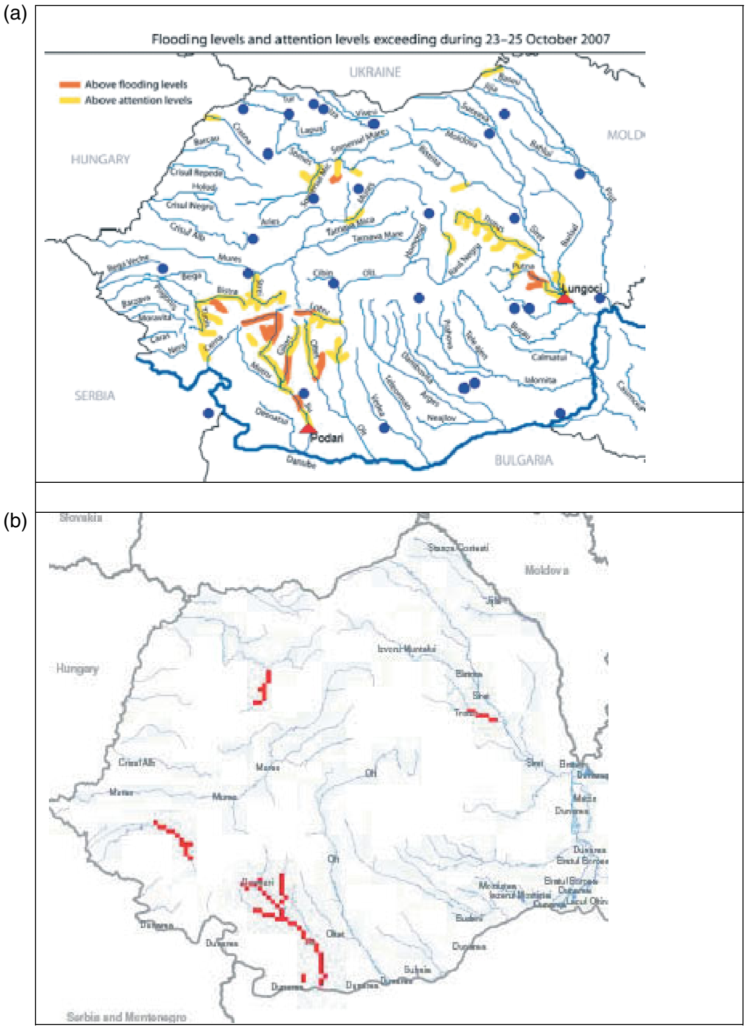


Figure 2. Flooding as reported by the Romanian water authorities from 23 to 25 October 2007 [Courtesy of Institutul National de Hidrologie si Gospodarire a Apelor]. Exceedence of flood levels are shown in red and of flood attention levels in green. (a) River pixels, shown in red, where EFAS simulations exceeded the EFAS high threshold for the same period (b).

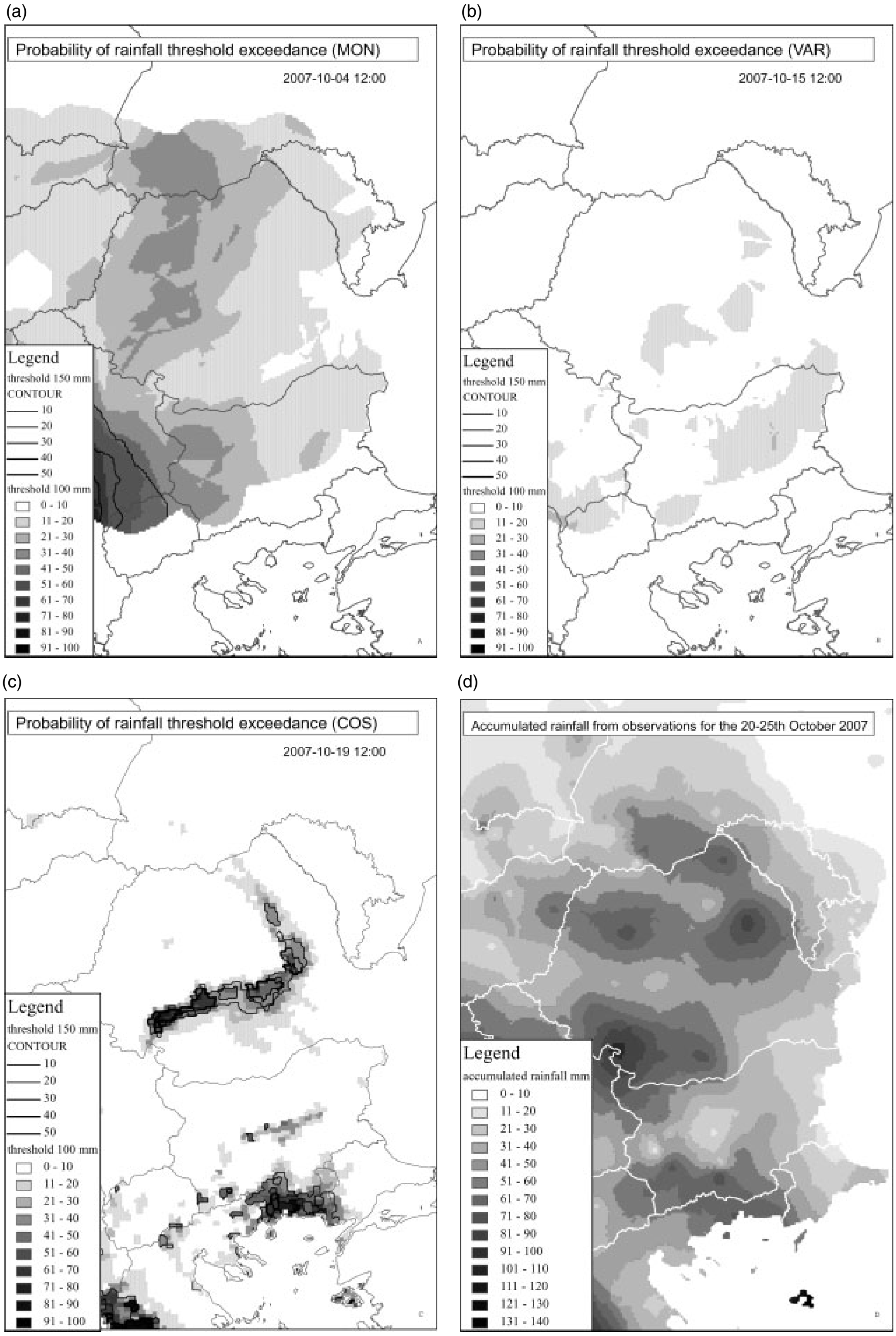


Figure 3. The accumulated rainfalls from 20 to 25 October 2007 as derived from gauge observations available for this study (www.agrifish.jrc.it) (a). Probabilities of MON20071004 1200 forecasts to exceed the 100 (shaded) and 150 (contoured) mm accumulated rainfalls over the 30 day period (b), of VAR20071015 1200 forecasts to exceed the 100 (shaded) and 150 (contoured) mm accumulated rainfalls over the 15 day period (c), of COS20071019 1200 forecasts to exceed the 100 (shaded) and 150 (contoured) mm accumulated rainfalls over the 5 day period (d).

4.1.3. Medium-range rainfall forecasts

Figure 3(c) shows the percentages of EPS members exceeding 100 and 150 mm over the full forecasting period for the VAREPS forecast of 15 October 2007. For better visual comparison, the same accumulation thresholds as for the monthly forecasts (Figure 3(b)) are chosen, despite the different forecasting periods. Rainfall probabilities from VAREPS on 15 October 2007, 7 to 9 days before the flooding, show up to 15% probability for rainfall accumulates to exceed 100 mm 15 day^{-1} and

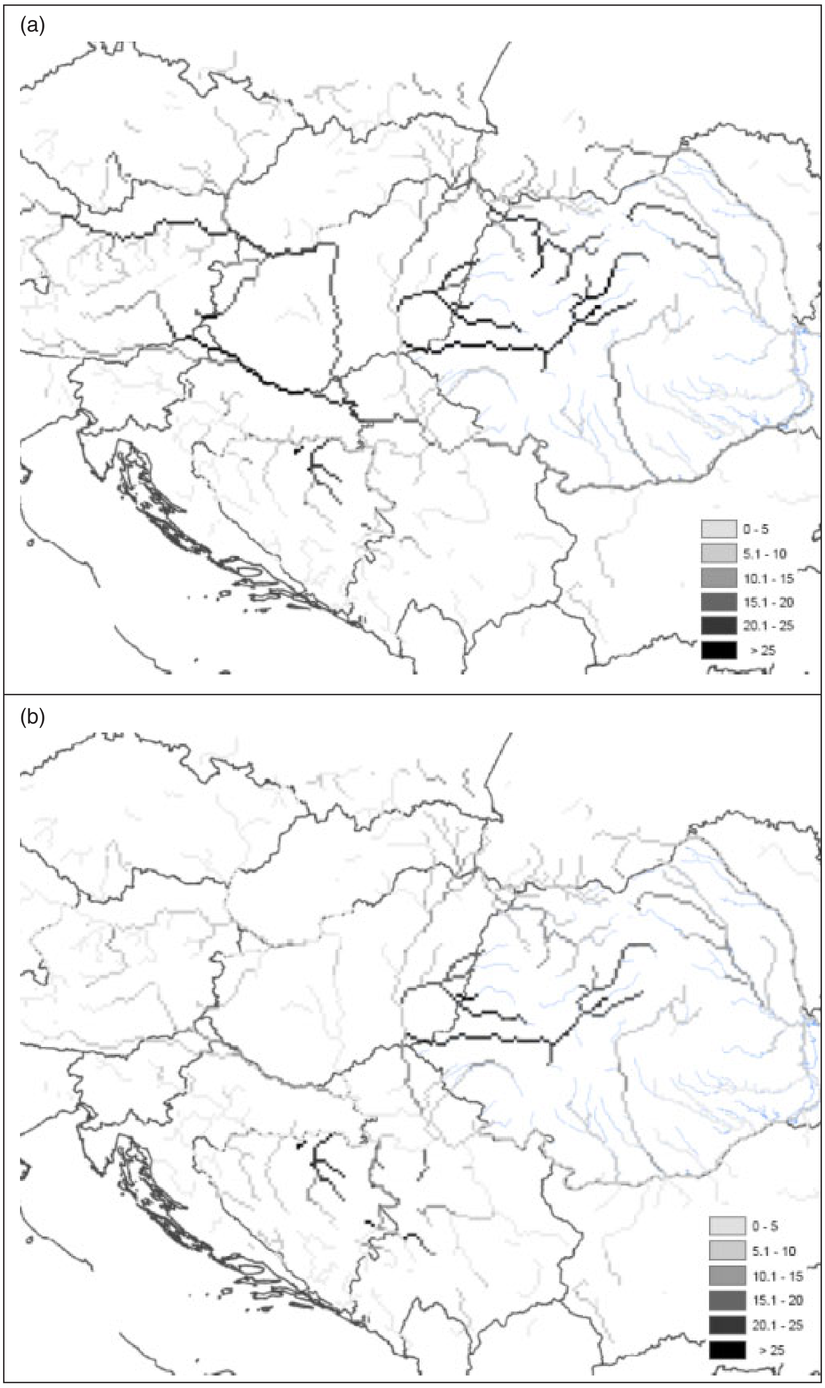


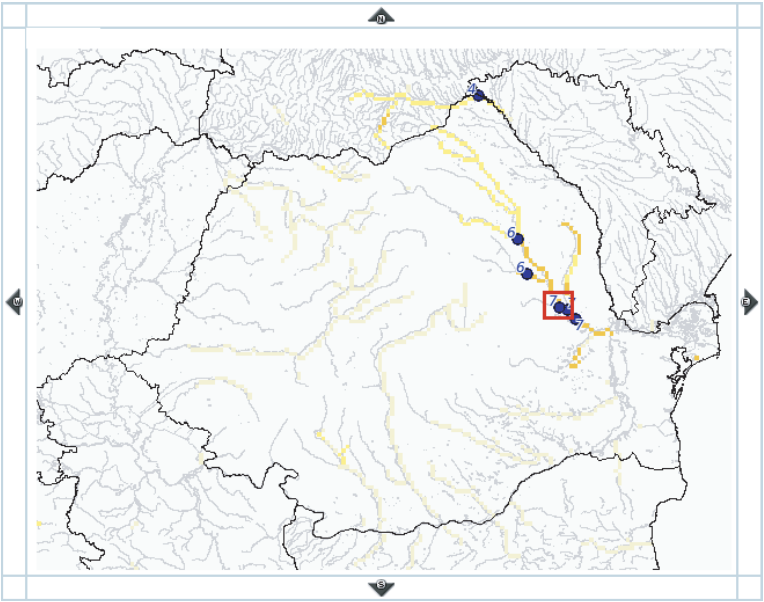
Figure 4. Overview map of percentage of maximum number of monthly EPS exceeding the EFAS high alert on 2007092712 forecasts (a) and 2007100412 forecasts (b). This figure is available in colour online at www.interscience.wiley.com/ma

about 5% probability of exceeding 150 mm 15 day^{-1} in the southwest (Jiu, Olt, and Mures catchments) and east (Siret) of Romania, thus capturing the region of later flood events correctly but with a low probability. Consistent with the monthly forecasts, much higher probabilities are simulated along the Adriatic coast, but flooding was not reported there. Two days later and thereafter, from the forecast of 17 October 2007 onwards (not shown), the probabilities increase considerably up to 33% for the 100 mm 15 day^{-1} and to 15% for the 150 mm 15 day^{-1} thresholds, while the regions of heavy rainfalls are more sharply defined for the Siret and the Jiu.

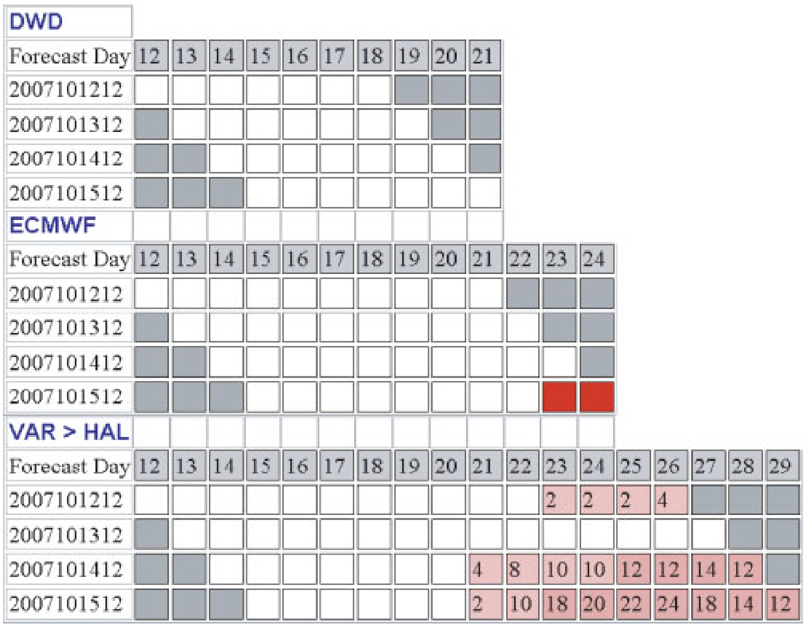
4.1.4. Short-range rainfall forecasts

Results from COSMO-LEPS reflect the higher spatial variability of the rainfall fields due to the higher grid resolution. Although already present in the COSMO-LEPS forecasts from 18 October 2007, it is the rainfall probabilities from 19 October 2007 that show clearly a high probability of rainfall exceeding the 100 and 150 mm thresholds for a hook-shaped region across Romania that

(a)



(b)



DWD										
Forecast Day	12	13	14	15	16	17	18	19	20	21
2007101212								▨	▨	▨
2007101312	▨								▨	▨
2007101412	▨	▨								▨
2007101512	▨	▨	▨							

ECMWF													
Forecast Day	12	13	14	15	16	17	18	19	20	21	22	23	24
2007101212											▨	▨	▨
2007101312	▨											▨	▨
2007101412	▨	▨											▨
2007101512	▨	▨	▨									🟥	🟥

VAR > HAL																		
Forecast Day	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
2007101212												2	2	2	4	▨	▨	▨
2007101312	▨																▨	▨
2007101412	▨	▨								4	8	10	10	12	12	14	12	▨
2007101512	▨	▨	▨							2	10	18	20	22	24	18	14	12

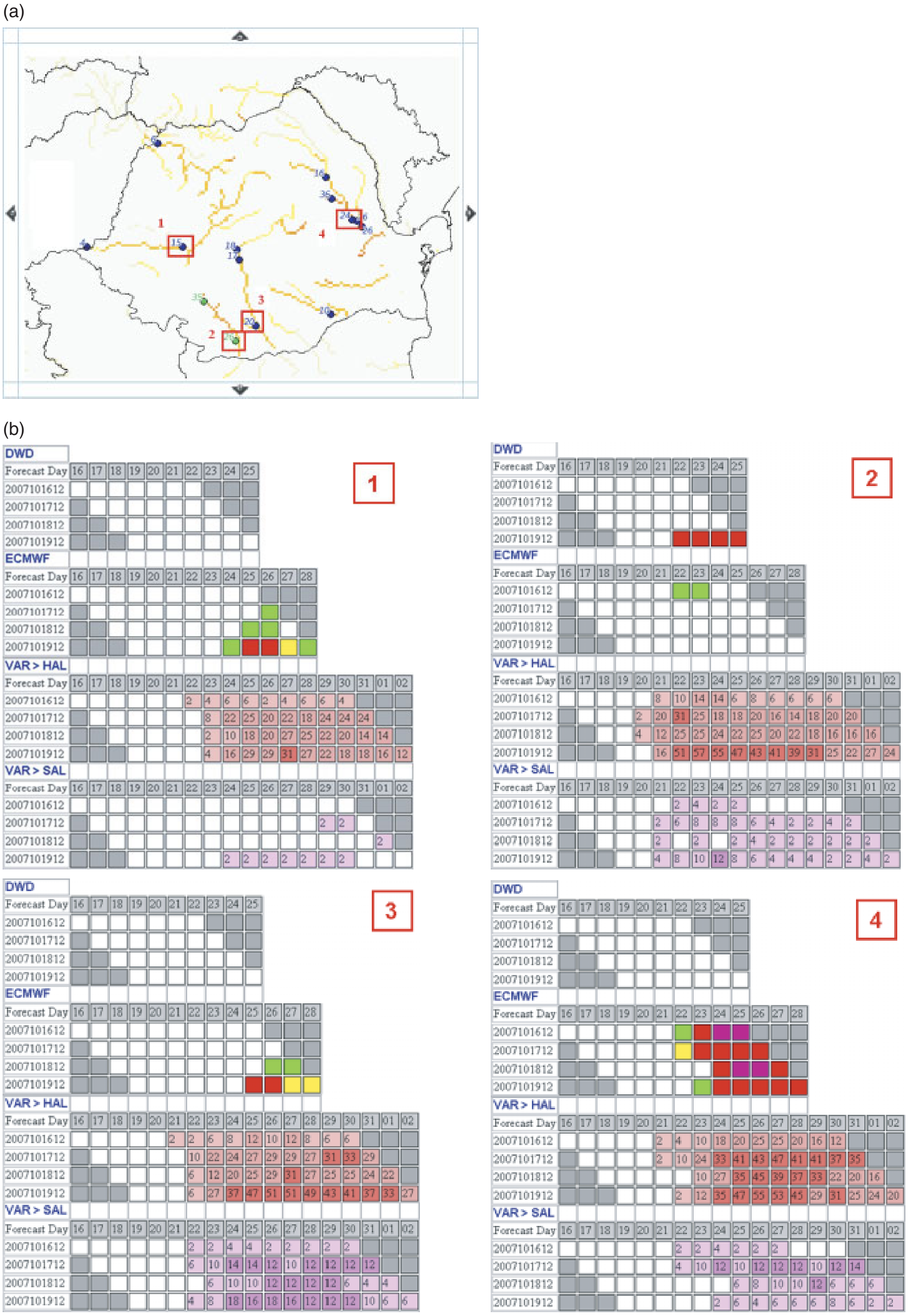
Figure 5. (a) Flood probability map from VAR20071015 1200 (b) and history diagrams of current and previous forecasts for the station highlighted with a red square for the DWD, ECMWF deterministic and VAREPS. Shown are the highest threshold exceedances for each day (green = low threshold exceeded, yellow∼medium, red∼high and magenta∼severe). For VAR the percentage of EPS exceeding the EFAS high alert (VAR>HAL) and the EFAS severe alert (VAR>SAL) are shown.

closely follows the terrain of the Carpathian Mountains. According to COSMO-LEPS there is a probability of more than 50% that a rainfall total of 150 mm will be exceeded over the next 5 days in the upstream parts of many tributaries to the Danube including the Jiu and Olt, but also the Arges and Siret (Figure 3(d)).

4.2. Flood forecasting

4.2.1. Monthly flood forecasts

The earliest monthly forecast that could have captured the event was that of 27 September 2007, 3 weeks before the event (lead time 27 days). Figure 4 illustrates the highest number of EPS members exceeding the EFAS high alert threshold during the 4 week period. It is noticeable that almost throughout the catchment the threshold is exceeded by 5–10% of the EPS members. This is due to the rapidly increasing spread in EPS after the second week of forecast and should therefore not be translated into a flood probability. Instead those river stretches where a significantly higher number of EPS members exceed the EFAS high threshold should be considered. In this forecast there are two areas of possible flooding: firstly the upper Danube and parts of the Sava,



1

DWD

Forecast Day	16	17	18	19	20	21	22	23	24	25
2007101612								▨	▨	▨
2007101712	▨								▨	▨
2007101812	▨	▨								▨
2007101912	▨	▨	▨							

ECMWF

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28
2007101612											▨	▨	▨
2007101712	▨										🟩	▨	▨
2007101812	▨	▨								🟩	🟩		▨
2007101912	▨	▨	▨						🟩	🟥	🟥	🟨	🟩

VAR > HAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612							2	4	6	6	2	4	6	6	4	▨	▨	▨
2007101712	▨							8	22	25	20	22	18	24	24	24	▨	▨
2007101812	▨	▨						2	10	18	20	27	25	22	20	14	14	▨
2007101912	▨	▨	▨					4	16	29	29	31	27	22	18	18	16	12

VAR > SAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612																▨	▨	▨
2007101712	▨													2	2		▨	▨
2007101812	▨	▨															2	▨
2007101912	▨	▨	▨						2	2	2	2	2	2	2			

2

DWD

Forecast Day	16	17	18	19	20	21	22	23	24	25
2007101612								▨	▨	▨
2007101712	▨								▨	▨
2007101812	▨	▨								▨
2007101912	▨	▨	▨				🟥	🟥	🟥	🟥

ECMWF

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28
2007101612							🟩	🟩			▨	▨	▨
2007101712	▨											▨	▨
2007101812	▨	▨											▨
2007101912	▨	▨	▨										

VAR > HAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612						8	10	14	14	6	8	6	6	6	6	▨	▨	▨
2007101712	▨				2	20	31	25	18	18	20	16	14	18	20	20	▨	▨
2007101812	▨	▨			4	12	25	25	24	22	25	20	22	18	16	16	16	▨
2007101912	▨	▨	▨			16	51	57	55	47	43	41	39	31	25	22	27	24

VAR > SAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612							2	4	2	2						▨	▨	▨
2007101712	▨					2	6	8	8	8	6	4	2	2	4	2	▨	▨
2007101812	▨	▨				2		2		2	4	2	2	2	2	2	2	▨
2007101912	▨	▨	▨			4	8	10	12	8	6	4	4	4	2	2	4	2

3

DWD

Forecast Day	16	17	18	19	20	21	22	23	24	25
2007101612								▨	▨	▨
2007101712	▨								▨	▨
2007101812	▨	▨								▨
2007101912	▨	▨	▨							

ECMWF

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28
2007101612											▨	▨	▨
2007101712	▨											▨	▨
2007101812	▨	▨									🟩	🟩	▨
2007101912	▨	▨	▨							🟥	🟥	🟨	🟨

VAR > HAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612						2	2	6	8	12	10	12	8	6	6	▨	▨	▨
2007101712	▨						10	22	24	27	29	29	27	31	33	29	▨	▨
2007101812	▨	▨					6	12	20	25	29	31	27	25	25	24	22	▨
2007101912	▨	▨	▨				6	27	37	47	51	51	49	43	41	37	33	27

VAR > SAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612							2	2	4	4	2	2	2	2	2	▨	▨	▨
2007101712	▨						6	10	14	14	12	10	12	12	12	12	▨	▨
2007101812	▨	▨						6	10	10	12	12	12	12	6	4	4	▨
2007101912	▨	▨	▨				4	8	18	16	18	16	12	12	12	10	6	6

4

DWD

Forecast Day	16	17	18	19	20	21	22	23	24	25
2007101612								▨	▨	▨
2007101712	▨								▨	▨
2007101812	▨	▨								▨
2007101912	▨	▨	▨							

ECMWF

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28
2007101612							🟩	🟥	🟪	🟪	▨	▨	▨
2007101712	▨						🟨	🟥	🟥	🟥	🟥	▨	▨
2007101812	▨	▨							🟥	🟪	🟪	🟥	▨
2007101912	▨	▨	▨					🟩	🟥	🟥	🟥	🟥	🟥

VAR > HAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612						2	4	10	18	20	25	25	20	16	12	▨	▨	▨
2007101712	▨					2	10	24	33	41	43	47	41	41	37	35	▨	▨
2007101812	▨	▨						10	27	35	45	39	37	33	22	20	16	▨
2007101912	▨	▨	▨				2	12	35	47	55	53	45	29	31	25	24	20

VAR > SAL

Forecast Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02
2007101612							2	2	4	2	2	2				▨	▨	▨
2007101712	▨						4	10	12	10	12	12	12	10	12	14	▨	▨
2007101812	▨	▨								6	8	10	10	12	6	6	6	▨
2007101912	▨	▨	▨						2	6	4	6	6	6	8	6	2	2

alert (VAR>SAL) are shown.

Figure 6. (a) Flood probability map from VAR20071019 1200 (b) and history diagrams of current and previous forecasts for the station highlighted with a red square for the DWD, ECMWF deterministic and VAREPS. Shown are the highest threshold exceedences for each day (green = low threshold exceeded, yellow∼medium, red∼high and magenta∼severe). For VAR the percentage of EPS exceeding the EFAS high alert (VAR>HAL) and the EFAS severe alert (VAR>SAL) are shown.

and secondly the Romanian tributaries to the Tisza, in particular the Koroes and Mures. The highest percentage of EPS members exceeding the EFAS high alert threshold is 38% in the Sava (Figure 4(a)).

One week later, in the forecast of 4 October (lead time 20 days), the event in the upper Danube is no longer forecast, while for the Romanian tributaries to the Tisza the event remains visible in the maps (Figure 4(b)), and

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percentages of almost 70% are reached. In addition to the overview maps, the monthly results are summarized as weekly information. These suggest that the flood peaks and flood extents would be biggest in the fourth week of October (i.e. 21–28).

4.2.2. *Medium-range flood forecasts*

VAREPS are identical with the monthly forecasts for the first 15 days. Therefore, in line with the results from the monthly forecasts, the flood simulations based on VAREPS (hereafter VAR) from 4 October 2007 do not yet indicate any particular flood hazard. A few EPS members exceeding the EFAS high alert are simulated within the normal spread of EPS towards the end of the forecasting period. The first indication for flooding shows up in VAR from 14 October, but according to EFAS persistence rules (Thielen *et al.*, 2009; see also Section 2.1), only in the following forecast of 15 October those river pixels again exceeding the EFAS high threshold are marked at risk of flooding (Figure 5). The forecast from 15 October shows that mostly the Siret river basin is forecast (persistently) at risk of flooding starting with a low probability from 21 October onwards, and has the highest probability of more than 50% for 24–25 October. On 15 October the EPS information is supported for the first time by the deterministic ECWMF forecasts (EUD).

In the subsequent days, although the forecast rainfalls shift daily the centre of heavy precipitation across Romania, flooding remains forecast predominantly for the Siret from the 24 October 2007 onwards. The forecasts suddenly change on the 19 October 2007 when all major rivers in the country are forecast with a probability of more than 50% to be at risk of flooding (Figure 6).

Figure 6 illustrates that from 16 October onwards for all rivers flood threshold exceedences are simulated with at least five EPS for 22–23 October onwards and that the number of EPS in VAR exceeding the thresholds is mostly increasing. The highest number of EPS exceeding the thresholds is simulated for 26 October. In particular for Olt and Siret there is also a considerable number of EPS exceeding the EFAS severe alert. Except for the Siret, the deterministic ECMWF forecasts (EUD) do not support the VAR information. Visualization of the hydrographs (an example is given for Olt, Point 3 from Figure 7) shows that almost 50% of all EPS just exceed the EFAS high alert and that 25% of all EPS get close to or exceed the EFAS severe alert level.

EUD-based forecasts simulate potential flooding mostly east of the Olt (included) and the central-northern parts of the country with Mures and Tisza tributaries. The Jiu is not simulated at risk of flooding at all by EUD. On 21 October the EUD-based forecast indicate potential flooding only for parts of the Siret while the signal disappears entirely for all other rivers.

On 24 October flooding is forecast within the next 2 days for the lower parts of the Siret and Jiu, while other rivers previously forecast at risk of flooding such as the Mures, Olt or Ialomita, do not show up any more. Tributaries to the Tisza in the northwest of the country are forecast with a second peak for the 2–3 November, and thus a second flood event.

4.2.3. *Short-range flood forecasts*

The first flood forecast based on COSMO-LEPS (hereafter COS) that captured the event may have been that from 19 October. Figure 8 shows the overview maps of EPS above EFAS severe flood threshold for both COS (right) and VAR (left) for 19 and 21 October. The areas at risk of exceeding the EFAS severe alert (flooding very likely) are much more sharply defined by COS than VAR. COS in particularly identifies the Jiu river with 16 out of 16 EPS exceeding the EFAS severe flood threshold. For Olt and Siret only smaller tributaries are identified with around 25% probability. Results from VAR are, in contrast, much more widely spread across Romania and the whole Danube basin. With VAR the region simulated at risk of flooding is shifted eastwards, affecting the Olt rather than Jiu.

The first day that the DWD-based forecasts could capture the flood event was on 17 October onwards. The first day that DWD-based results exceeded the EFAS high alert was on 19 October in the Jiu. A day later all major tributaries to the Danube, Jiu, Olt, Ialomita, Arges and Siret exceed the EFAS high alert threshold. On 22 October even the severe alert threshold is exceeded in the Jiu. The bi-polar distribution of the flooding for the Jiu in the west and Siret in the east is, therefore, well captured by the DWD-based forecasts.

4.3. Summary of uncalibrated outputs

The analysis of the discharge predictions (Sections 4.2.1 to 4.2.3) clearly show that flood forecasts based on EPS can considerably increase the flood early warning time, compared with the deterministic forecasts. Furthermore, it suggests that the use of multiple weather forecasts and EPS at different lead times and resolutions can be beneficial compared with single EPS. For this study there were not sufficient monthly EPS to draw conclusions on their performance. From an initial analysis they would appear, however, to be useful for a general outlook or trend, if interpreted cautiously. More research is needed in this regard. In contrast, VAR provided in this case a convincing early flood warning lead time of 7 to 8 days, that flooding is likely to occur in one or several Romanian tributaries to the Danube. This early warning is confirmed in subsequent forecasts. In terms of quantitative results, however, VAR simulates flooding that is too widespread, while underestimating the peak in those rivers where flooding did occur. From the 19 October onwards COS provided quantitatively better results than VAR and would have allowed a flood forecaster to pinpoint the rivers at risk of flooding.

4.4. Improving flood forecasts through post-processing

At the Lungoci station on the Siret river the hydrological model simulates the discharge quite well and the error

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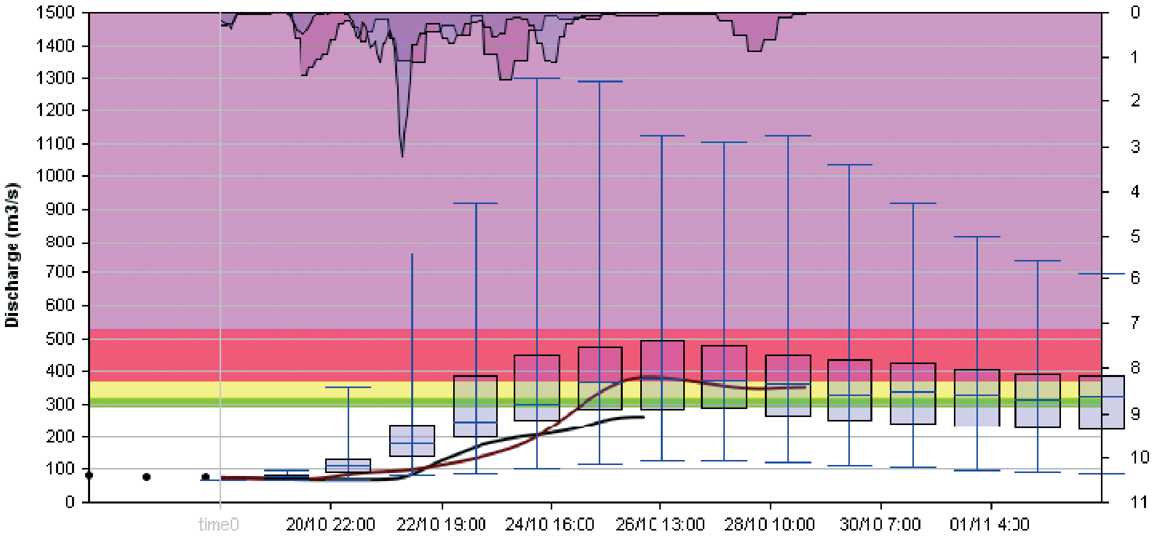

Figure 7. Hydrographs for point 3 in Figure 4. Shown are box-plot diagrams of discharges calculated with VAREPS as input with indication of min and max, 25–50 and 75% quantiles. In addition the hydrographs based on the deterministic DWD (black line) and ECMWF forecasts (brown line) are shown. EFAS thresholds are indicated in colour with green (low flood thresholds), yellow (medium), red (high) and magenta (severe). At the top with inverse distance the upstream rainfalls forecast with DWD and EUD are indicated.

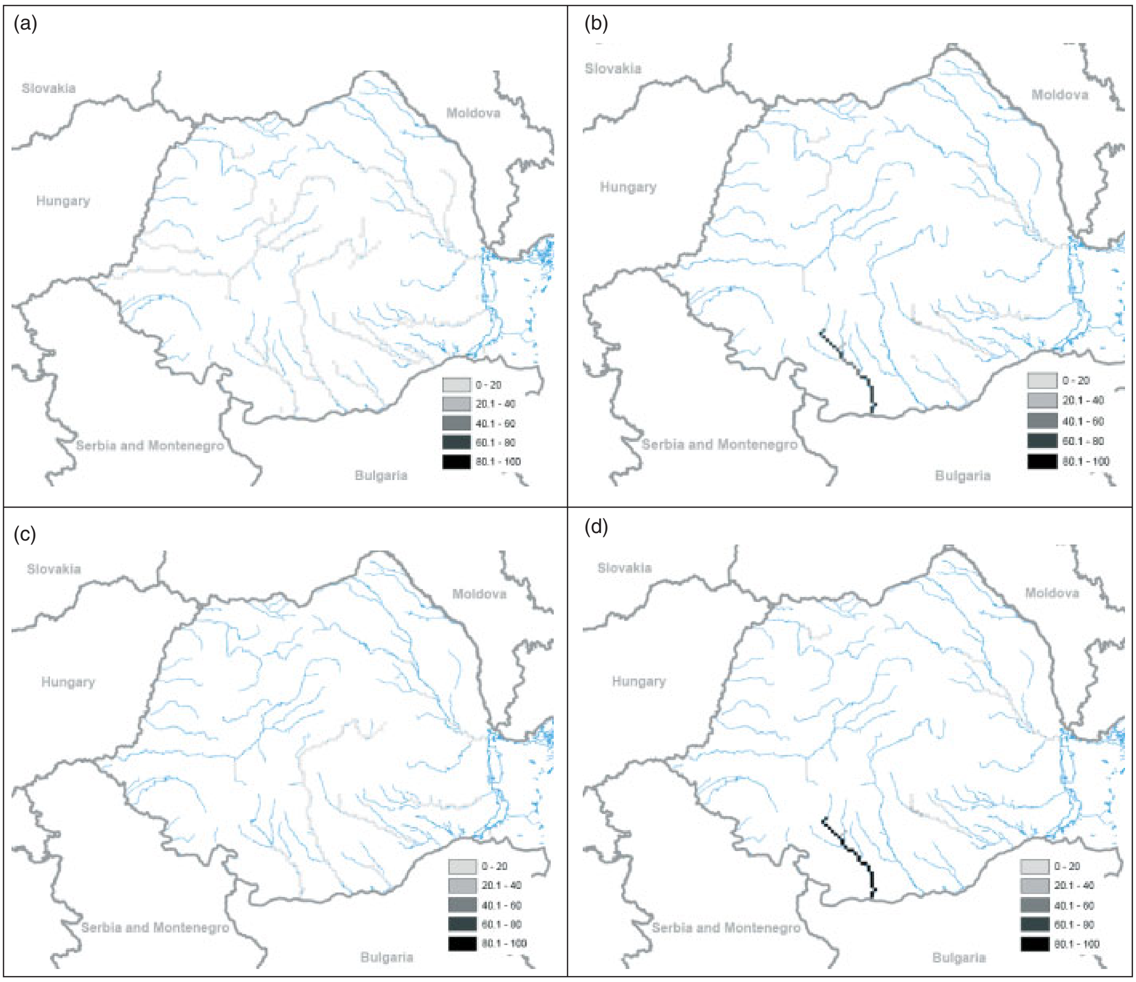

Figure 8. Overview maps of EPS above EFAS severe threshold for (a) VAR on 19 October 2007 1200, (b) COS on 19 October 2007 1200, (c) VAR on 21 October 2007 1200, and (d) COS on 21 October 2007 1200.

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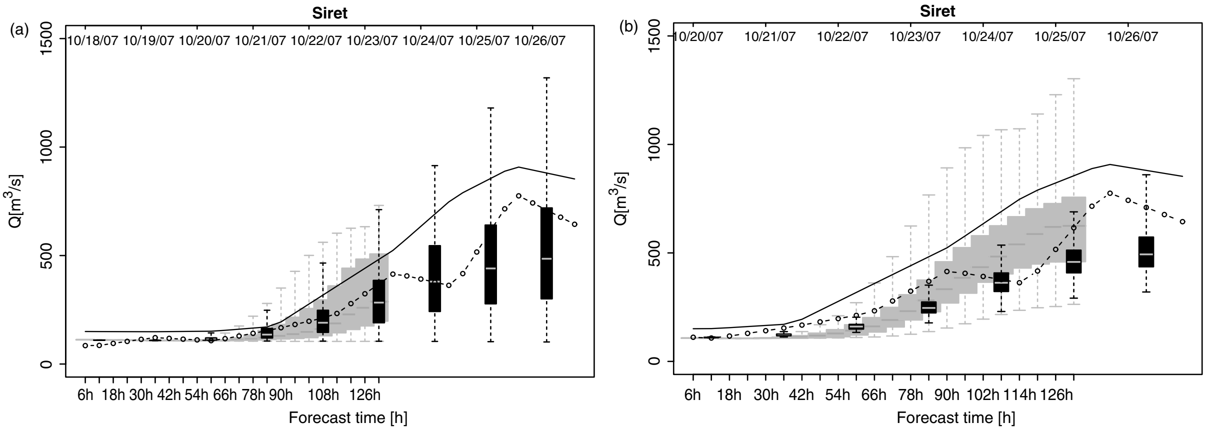

Figure 9. Forecast for the Siret river at the station Lungoci from the 17 and 19 October 2007. ▬ COSMO ▬ VAREPS ——— simulated -○- observed.

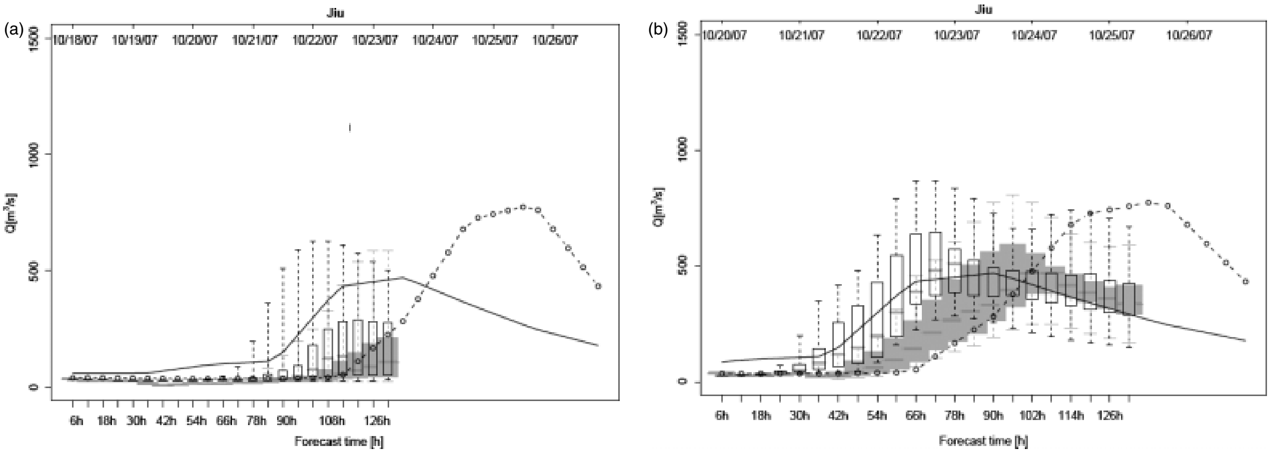

Figure 10. Forecast for the Jiu river at the station Podardi from the 17 and 19 October 2007 with and without error corrected COSMO-LEPS. ▬ COSMO-corr ▭ COSMO ——— simulated -○- observed.

between observed and simulated discharge, taking the observed precipitation data as input, is negligible. Therefore, any correction of the ensemble members would not improve the forecast quality. In Figure 9 the results of the COSMO-LEPS and the VAREPS are shown, indicating a possible flood event almost 9 days ahead. The observed discharge is covered by the spread of both EPS and the timing and peak discharge of the flood is forecast almost perfectly.

A big discrepancy between the observed and simulated peak discharge exists, however, in the Jiu river. The reason there is such a big shift in the timing of the flood peak in October 2007 has not yet been clarified. In addition the possible causes for the underestimation must be analyzed in order to improve the flood forecasting system. It should be mentioned that the error correction methodology described above is just an additional tool to improve the system by the application of statistical methods. In Figure 10 the results for the Podardi station on the Jiu river are shown, taking the 16 ensemble members of the COSMO-LEPS as input to the LISFLOOD model and correcting each of the 16 predicted discharge series by the described methodology. A first indication of the possibility of a flood occurrence can be seen almost 7 days ahead (Figure 10(a)). In Figure 10(b) one can see how the applied methodology improved the timing of the peak. The negative time shift could be eliminated and therefore the flood event of October 2007 would have been forecast quite well almost 4 to 5 days ahead, although the peak discharge is still underestimated (Figure 10).

5. Conclusions

A seamless forecasting suite for floods using multiple long-, medium- and short-range weather forecasts as input, is presented for a widespread event in Romania with locally severe flooding. The approach is driven by multiple spatio-temporal scaled inputs as well as multiple weather forecasting models and ensemble prediction systems. The early flood warning approach explored here is based on threshold exceedence and takes into account the persistence of the signals to decrease significantly the number of false alarm rates without significantly corrupting hit rates.

Results for this case study show conclusive probabilistic flood forecasts that complement each other at different lead times and resolutions. While the potential benefits of monthly forecasts must be investigated further with longer time series and statistical analysis, the results suggest that they can indicate the tendency of areas at risk of flooding 3 to 4 weeks in advance. Clear localization of the event in space and time seems to be beyond the scope of these forecasts. In contrast, the 15-day VAREPS forecasts implemented in 2007 at ECMWF show qualitative and quantitative good results. They allow the forecasting, with a high probability, of a flood event with an early warning lead time of 7 to 9 days. The forecasts indicate, however, a more widely spread flooding than actually occurred. Those forecasts driven with the higher-resolution limited-area model EPS (COSMO-LEPS) allow, 4 days before the event, a comparatively good identification of the areas most at risk. These results are persistent throughout the forecasts. In comparison with the deterministic forecasts which show rather intermittent behaviour and little consistency between the DWD and ECMWF forecasts, the probabilistic results are much more coherent and complement each other.

Overall, the paper has shown how flood forecasting at different temporal and spatial scales can produce a seamless suite of forecasts ranging from qualitative early warning information to quantitative reliable short-term information. For the case study presented, the benefit of using ensembles compared with deterministic forecasts is clearly demonstrated for the medium range, but also short ranges up to 5 days. Furthermore, there is a clear indication that post-processing of discharge ensembles can reduce the uncertainty bounds further to a more meaningful level for decision-making.

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