ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **9**: 80–87 (2008)
Published online 19 May 2008 in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/asl.183

MAP D-PHASE: real-time demonstration of hydrological ensemble prediction systems

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Received: 21 December 2007
Revised: 28 March 2008
Accepted: 28 March 2008

Abstract

Mesoscale Alpine Programme Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events (MAP D-PHASE) is a forecast demonstration project aiming at demonstrating recent improvements in the operational use of end-to-end forecasting system consisting of atmospheric models, hydrological prediction systems, nowcasting tools and warnings for end-users. Both deterministic and ensemble prediction systems (EPSs) have been implemented for the European Alps (atmospheric models) and a selection of mesoscale river basins (hydrological models) in Central Europe. A first insight into MAP D-PHASE with focus on operational ensemble hydrological simulations is presented here. Copyright © 2008 Royal Meteorological Society

Keywords: **MAP D-PHASE; ensemble prediction systems; flood; heavy precipitation**

1. Introduction

The operational use of ensemble prediction systems (EPSs) for probabilistic forecasting to assess uncertainty involved in forecasting precipitation is an established practice in the atmospheric modeling community since the last decade. EPSs are operationally used to quantify uncertainty involved in weather forecasting, including the forecast of space and time distributions of precipitation (e.g. Molteni *et al*., 1996; Palmer, 2000). Uncertainty analysis is a 'hot' topic in hydrology (e.g. Pappenberger and Beven, 2006). The quantification of hydrological forecast uncertainty resulting from the uncertainty of quantitative precipitation forecasts is an emerging research field, with first attempts of transferring the probabilistic information from atmospheric EPS into the hydrological models (Krzysztofowicz, 2001; Bartholmes and Todini, 2005; Pappenberger *et al*., 2005; Siccardi *et al*., 2005; Verbunt *et al*., 2007; Thielen *et al*., 2008).

As the first Research and Development Project of the WMO World Weather Research Program (WWRP), the *Mesoscale Alpine Programme* MAP has seen three phases: a development phase (Binder and Schär, 1995), a field phase in the fall of 1999 (Bougeault *et al*., 2001), and an analysis phase that yielded a wealth of novel scientific contributions in the fields of alpine meteorology (Benoit *et al*., 2002; Volkert and Gutermann, 2007) and mountain hydrology (Bacchi and Ranzi, 2003; Ranzi *et al*., 2007).

One of the most relevant, high-impact and best-studied aspects of weather during the MAP was certainly heavy precipitation and the associated flooding. Following an invitation of the WWRP, the MAP community launched a fourth phase in order to demonstrate concrete advances in operational high resolution and ensemble forecasting of meteorological and hydrological extremes in Alpine regions (Rotach and Arpagaus, 2006). In the following, we highlight basic aspects of MAP D-PHASE, a scientific project at the borderline between fundamental and applied research. The structure and very first outcomes of this research effort in (ensemble) operational meteorology and hydrology are shown. The nonexhaustive selection of models and examples focus on the authors' own contributions to MAP D-PHASE.

2. MAP D-PHASE

2.1. Background

The fourth stage of MAP runs under the acronym MAP D-PHASE (http://www.map.meteoswiss.ch/

d-phase), which stands for ***D****emonstration of* ***P****robabilistic* ***H****ydrological and* ***A****tmospheric* ***S****imulation of flood* ***E****vents in the Alpine region*. Specifically, an end-to-end forecasting system for Alpine flood events has been implemented to demonstrate state-of-the-art forecasting of precipitation-related extreme events. On the atmospheric side, the system consists of probabilistic forecasting based on EPSs with a lead-time of a few days, followed by short-range, high-resolution deterministic forecasts. For over 60 catchments with areas ranging from 100 to 36 000 km^2, hydrological models are coupled to the output of the atmospheric models. The whole system is completed with real-time nowcasting and high-resolution observational information. Over 30 atmospheric and hydrological models participated in D-PHASE.

Furthermore, large efforts are needed in order to establish improved communication of uncertainty between the modelers and the warning agencies on the one hand, and between the warning agencies and the task forces who are responsible for flood mitigation on the other hand. Therefore, a large number of practitioners applied as D-PHASE 'observers'. They will be actively involved in the project evaluation.

The demonstration period lasted from June to November 2007 and has been termed the D-PHASE Operations Period (DOP). This period encompasses the 'standard' MAP Special Observing Period in the fall season (Bougeault *et al*., 2001), when severe floods are more frequent on the southern side of the Alps (Malguzzi *et al*., 2006), and the preceding summer season, when convective events can often produce flood hazards on the northern side. The former ensures that full advantage can be gained from the improvements and developments during MAP, and the latter is motivated to benefit from synergies and common interests with the ***C****onvective and* ***O****rographically induced* ***P****recipitation* ***S****tudy* (COPS), the field phase of the international 'Quantitative Precipitation Forecast' research project covering areas in southwestern Germany and northeastern France (Wulfmeyer *et al*., 2008).

2.2. Organization

The lead of the project has been provided by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss (www.meteoswiss.ch) that coordinated the activities of a large number of partners and end-users in different countries (Table I). Four working groups (WGs) have been established:

- *WG Hydrology and End-Users* groups different levels of (end-) users, which may be 'actors' (such as forecasters) or 'observers' (such as civil protection agencies and hydropower companies), or both. End-user workshops have been held at different stages of the project. Feedback questionnaires have been compiled and will be evaluated by social scientists.

Table I. Some numbers about MAP D-PHASE

Affiliated countries	17
Affiliated institutions	120
Known users of www.d-phase.info	357
Modelers and forecasters	175
End-users among them	166
Number of deterministic NWPs	23
Number of high-resolution deterministic NWPs (grid size $<5 \times 5$ km^2)	11
Number of ensemble NWPs	7
Number of hydrological models	7
Number of nowcasting platforms	4
Number of meteorological target areas	74
Number of hydrological impact areas	60
Data stored in the data archive by 30 November 2007	~13 TB
Questionnaires sampled for end-user feedback analysis	50

- *WG Verification* takes care of the evaluation protocols and is responsible for the validation and verification methodology to be adopted.
- *WG Data Interface* deals with data handling and common formats of atmospheric and hydrologic model output as well as observational hydro-meteorological data. It also defines all data flows, including timing (i.e. 'when what data needs to be where') and technical requirements. In collaboration with all other WGs it defines the parameter list necessary both to drive the hydrologic models and to conduct verification.
- *WG Data Policy* takes care of all the legal matters related to the exchange of data.

Among several national and transnational companion initiatives supporting MAP D-PHASE, it is worth pointing at the COST Action 731 ('Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast Systems'), which has been signed by over 20 countries (http://www.cost.esf.org/index.php?id = 205&action_number = 731). COST 731 started in 2005 and will last until 2010. The action focuses on the quantification and propagation of uncertainty in hydro-meteorological forecast chains including decision making.

2.3. Visualization and warnings

Throughout the D-PHASE forecasting chain, experimental warnings have been issued and visualized on a novel visualization platform (VP) (Figure 1) that represents, together with the data archive, the 'heart' of the project. This password protected platform allowed forecasters and end-users to compare results from various atmospheric and hydrological models in order to improve their basis and background knowledge for potential decisions.

The VP issued alerts for target areas (hydro-meteorological entities of a fairly large geographical extent) as well as impact areas (hydrological entities related to a river runoff gauging station displayed by a 'Hydro-Box'). For the atmospheric models, alerts are based on 3, 6, 12, 24, 48, and 72 h accumulated precipitation, whereas for the hydrological models, alerts

DOI: 10.1002/asl

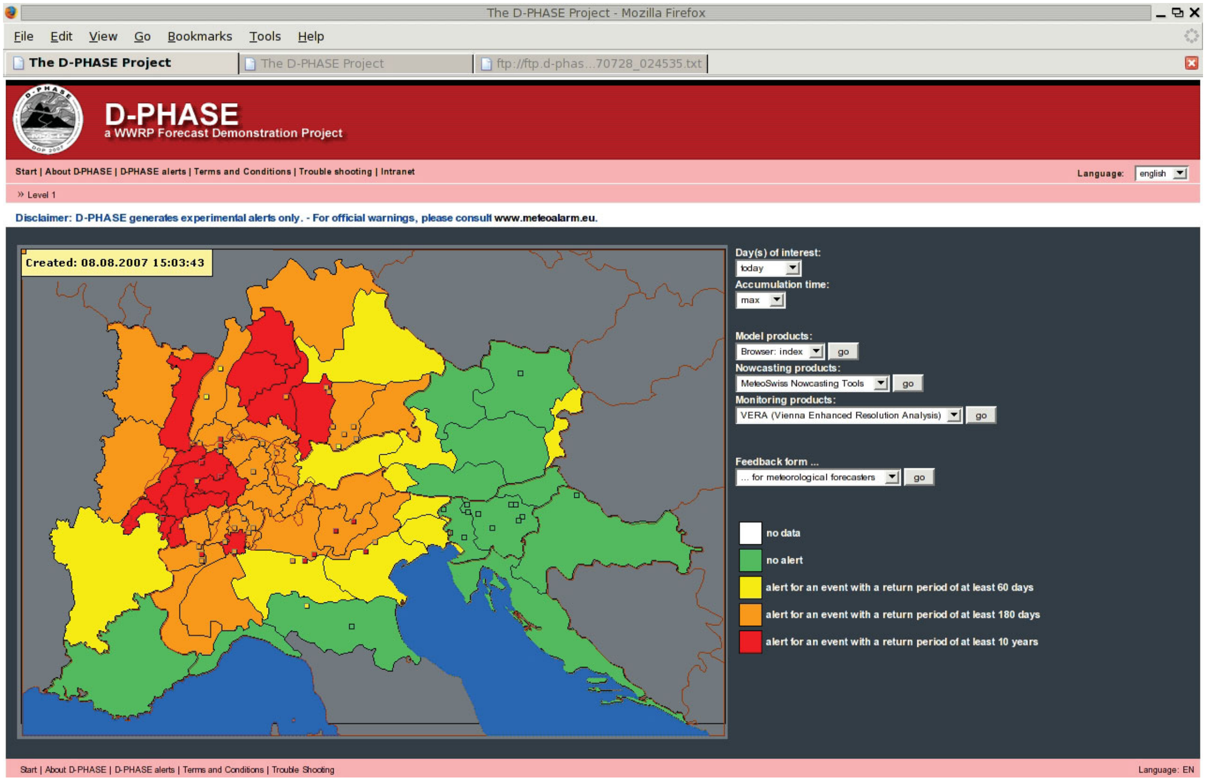

Figure 1. Level 1 of the D-PHASE visualization platform, which gives an overview (in alert colors) of the warning status in the entire Alpine region. Shown, is the example of experimental alerts from atmospheric models issued one day ahead of the 8–9 August 2007 floods, which largely affected Switzerland. Red alert corresponds to a return period of more than 10 years.

are based on the hourly river runoff forecasts. Alert maps and tables are available for today, tomorrow, or for days 3 to 5. Alerts for target areas and impact areas are displayed with colors:

- Green means that no alert is issued by any of the models:
- The attention level (WL1, yellow) is visualized as soon as any of the models pass the first warning level (WL), either for area mean precipitation or river discharge. WL1 'warns' for events having a return period of 60 days;
- The alert level (WL2, orange) warns for events with a return period of 180 days;
- The alarm level (WL3, red) warns for events with a return period of 10 years.

Concerning the warnings issued from each atmospheric and hydrological EPS chain, it was decided to issue an alert if 33% of the ensemble members exceed WL1, WL2 or WL3 at a particular time step.

All defined thresholds were derived from discussions between modelers and end-users during the implementation of VP.

Finally, VP was linked to four experimental nowcasting systems. One of the most requested elements of the VP were the radar nowcasting applications. These include real-time monitoring of the evolution of precipitation systems, quantitative estimates of precipitation amounts, and characterization and extrapolation of severe convective cells.

2.4. Data archive

In the frame of COPS and D-PHASE, an outstanding collection of observation and forecast model data has been successfully archived at the World Data Center for Climate (WDCC) in Hamburg. An extensive metadata description is combined with each item in the database, which is essential in identifying and handling the data on a long-term perspective.

Data analysis efforts often require a synopsis of different data sources, thus, a straightforward subset of formats has been agreed on. For atmospheric forecast model data the common data format is *GRIB1 (http://www.nco.ncep.noaa.gov/pmb/codes/GRIB1/)*, while observation data and hydrological model data are stored in *netCDF (http://www.unidata.ucar.edu/software/netcdf/)* format wherever possible. Pictures and forecast model alerts are stored as *jpg* or *png* and *xml*, respectively.

The archiving of the D-PHASE data has been performed and maintained in a close-to-operational mode throughout the whole DOP.

3. MAP D-PHASE and operational hydrology

3.1. Overall goals

Operationally forecasting flood events in the Alps using high-resolution (ensemble) numerical modeling in connection with hydrological modeling has

DOI: 10.1002/asl

been decided to become one of the major focuses of D-PHASE. A new generation of flood warning systems is able to provide deterministic and probabilistic discharge estimations for short-term (1–2 days) and mid-term (3–5 days) lead times. Various hydrological prediction systems have been deployed in different catchments (Table I). For each catchment, in which an end-user participated, one or more hydrological models have been implemented.

However, we would like to anticipate that no MAP D-PHASE contributor was obviously able to implement its hydrological model in all basins and couple it with all available deterministic and ensemble numerical weather prediction (NWP) models.

3.2. Deterministic and ensemble nowcasting

Initial conditions for hydrological modeling are sources of uncertainty in hydrological forecasting. Initial conditions are usually taken from continuous deterministic near-real-time model runs based on interpolated station data. Initial conditions can be improved by assimilation of real-time meteorological and hydrological models (Refsgaard, 1997). Recent studies deal with the assimilation of discharge data, snow cover information and soil moisture.

Within D-PHASE, new ways have been explored in order to investigate the sensitivity of flood forecasts to the data sources providing the meteorological forcing for the hydrological model systems. An innovative setup coupling distributed hydrological modeling and ensemble rainfall radar information has been tested. In spite of significant improvements in quantitative precipitation estimation from radar platforms (Germann *et al*., 2006b) in the last decade, the residual uncertainty is still relatively large for hydrological applications.

A novel promising solution to express this residual uncertainty is to generate an ensemble of radar precipitation fields by combining stochastic simulation and detailed knowledge of the radar error covariance structure (Germann *et al*., 2006a). A prototype system coupling the MeteoSwiss Radar Precipitation Ensemble Generator with the semi-distributed hydrological model, PREVAH (Precipitation-Runoff-EVpotranspiration-Hydrological response unit model, Gurtz *et al*., 2003), was running during D-PHASE for the Verzasca catchment (186 km^2, Ticino, Switzerland, Wöhling *et al*., 2006).

Figure 2 shows possibly the first real-time radar ensemble hydrology coupling experiment worldwide. Both rain gauge-driven and radar-driven runoff simulations for an eight-day period in August 2007 show similar evolution. The spread of the ensemble provides an estimate of the sensitivity of runoff to uncertainties in operational radar precipitation fields. A qualitative examination of all events collected so far reveals similar performance of radar-driven and rain gauge-driven runoff as compared to observed runoff. This is an impressive result when considering the difficulties in radar rainfall estimation in complex terrain on one hand, and the dense rain gauge network on the other. As a next step, we will investigate the spread of the radar-driven runoff as compared to the spread of precipitation amounts on input. This allows quantifying the sensitivity of runoff of Verzasca river to uncertainties in the radar precipitation estimates. Furthermore, comparison with observation-based ensembles (Ahrens and Jaun, 2007) is envisaged.

3.3. Deterministic forecasting

The deterministic hydrological forecasts are driven by operational and experimental weather forecast models from several agencies. The meteorological model output available on the model specific grid spacing

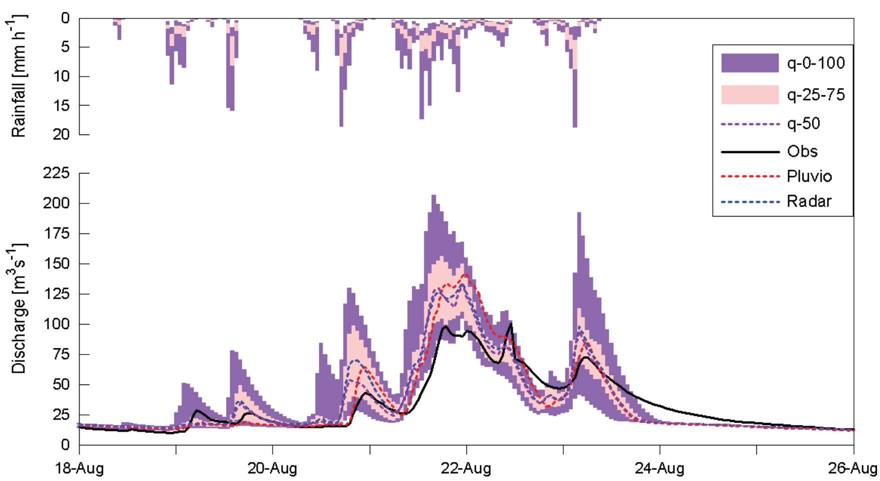

Figure 2. Ensemble hourly runoff nowcasting with PREVAH in the Verzasca catchment in August 2007. Black line: observed discharge. Dotted red line: simulation forced by interpolated rain gauge data. Dotted blue line: simulation driven by the deterministic radar. Purple and pink areas, and dotted purple line: runoff driven by radar ensemble. Purple areas: full ensemble spread (q-0-100). Pink areas: interquartile range (q-25–75). Dotted purple line: median value of the nowcasting ensemble (q-50). For the hourly rainfall plot, only data from the radar ensemble generator are shown.

DOI: 10.1002/asl

is then further processed to meet the requirements of the hydrological models (Jaun *et al*., 2008). Depending on the driving meteorological model deterministic hydrological forecasts with a forecast horizon of 24–72 h are available.

Figure 3 shows a hindcast experiment (in forecast mode) with COSMO-2 (the deterministic NWP at 2×2 km^2 resolution run by MeteoSwiss; Kaufmann *et al*., 2003) used as input for FEWS/HBV model of the Swiss Federal Office for Environment. COSMO stands for Consortium for Small Scale Modelling, while FEWS/HBV stands for Flood Early Warning System/Hydrologiska Byrns Vattenbalansavdelningels. The high-frequent updating of COSMO-2 and temporal overlapping of the various deterministic forecasts introduces an 'ensemble dimension' to the obtained plots.

After a large overestimation in the morning, the system is able to narrow the magnitude of the flood peak better with every subsequent run while the timing of the flood remains too late. This experiment demonstrates the advantage of frequently updated short-term forecasts with high resolution compared to previous work (e.g. Ahrens *et al*., 2003).

3.4. Ensemble prediction systems

Several meteorological EPSs are operationally available at the global scale. One of the European Centre for Medium Range Weather Forecast (ECMWF), Molteni *et al*., 1996), which is simply called 'VAREPS', is currently operated at a horizontal resolution of roughly 50×50 km^2 and consists of 51 members. The spread of the ensemble members during the forecast horizon (3–5 days) represents the initialization uncertainty of the meteorological model. These large-scale numerical models are not accurate at modeling local weather, because local sub-grid scale features and dynamics are not resolved. Dynamical downscaling methods are therefore applied in the local ensemble prediction system COSMO Limited-area Ensemble Prediction System (COSMO-LEPS) (Marsigli *et al*., 2005), developed by ARPA-SIM within the COSMO consortium. The 'COSMO-LEPS' is nested into the EPS of ECMWF. COSMO-LEPS considers the last two EPS forecasts for a total of 102 members. Since the procedure is expensive in terms of computational time, it is not feasible to downscale the full global ensemble for everyday operational applications. Therefore, a subsample of 16 representative ensemble members only is assigned by cluster analysis (Molteni *et al*., 2001). Within each of the resulting 16 clusters, a representative member is selected and dynamically downscaled to a spacing of 10×10 km^2 providing a forecast horizon of up to 132 h. The computational costs to implement the coupling between the atmospheric EPS and the hydrological model system are comparably low. The hydrological EPS calculates results for a specific EPS member within a few minutes on a standard desktop computer.

Figure 4 shows an example of a probabilistic hydrological forecast for the Verzasca basin forced by COSMO-LEPS. In order to allow for cross-comparison with the radar ensemble generator the same event as in Figure 2 is presented. The observed runoff is well captured by the ensemble interquartile range. Single ensemble members show very poor timing in predicting the flood peak. Flood volumes are also missed. On the other hand, the 75% quartile shows very good agreement with the observed discharge.

The lead-time of deterministic COSMO-2 NWP is too short to detect the main event. COSMO-2 is the only model to show a good forecast for the small pre-event on 20–21 August 2007. The need

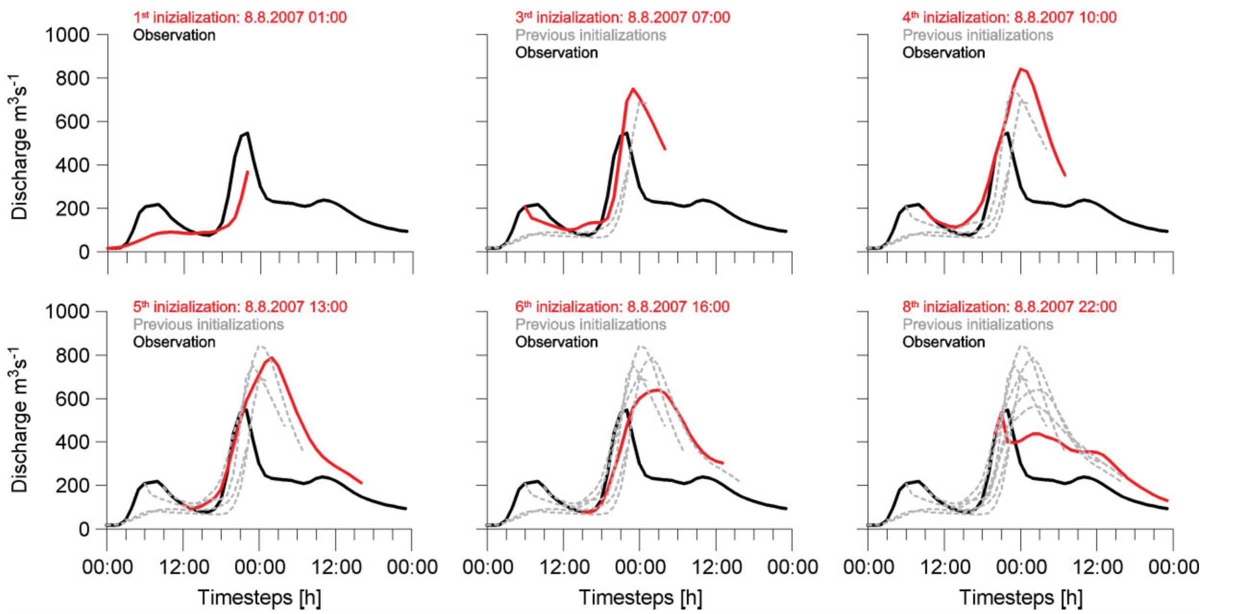

Figure 3. Hindcast for a major flooding for the 'Kleine Emme' river basin using FEWS/HBV driven by COSMO-2 during MAP D-PHASE for 8 August 2007. Forecasts are updated every 3 h.

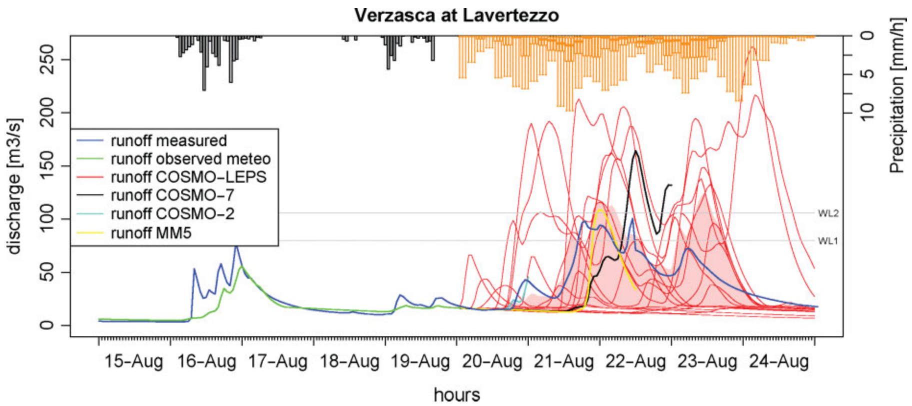

Figure 4. Hydrological forecast, starting 20 August 2007 for the Verzasca basin, in southern Switzerland. The 16 ensemble members (red) are shown with corresponding interquartile range (Q25–Q75). Additionally, three deterministic runs are shown: COSMO-7 (black), COSMO-2 (turquoise), and MM5 (yellow). The observed runoff is shown in blue, and a run forced by interpolated pluviometer data is shown in green. Spatially interpolated observed precipitation (catchment mean) is plotted from top (grey bars), as well as forecasted ensemble precipitation (orange whisker-plots).

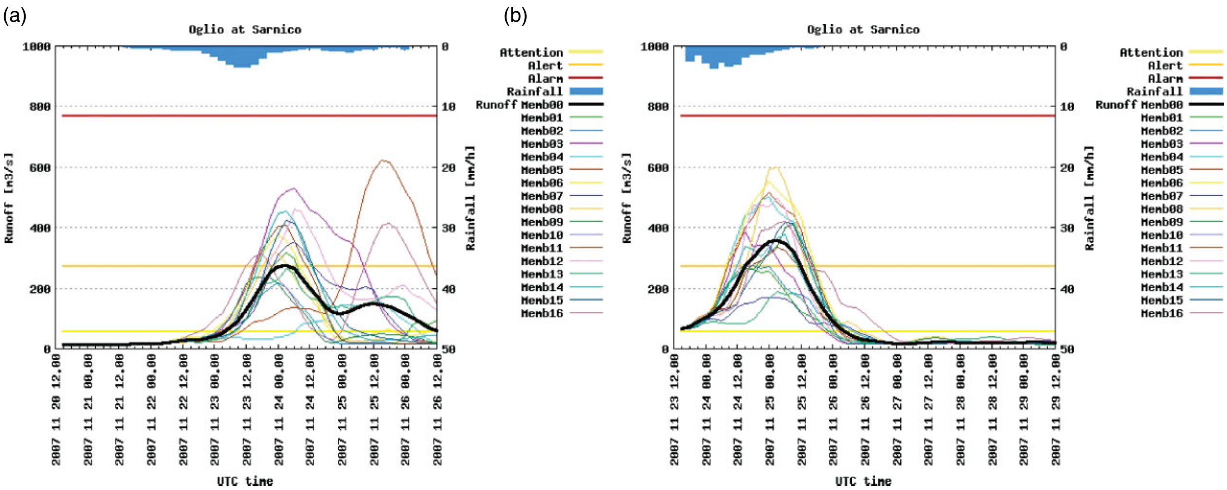

Figure 5. The hydrological ensemble prediction of the 24 November flood in the Oglio basin (Central Italian Alps). In (a) and (b), the forecasts based on the 21 November 1200 UTC and 23 November 1200 UTC runs are represented. Above each figure, the hyetograph of the ensemble mean of the COSMO-LEPS model forecasts is shown. Below the figure, the 17 hydrographs computed by the DIMOSOP hydrological model are plotted. The thick black line represents the hydrograph resulting from the ensemble mean rainfall, the other lines represent the 16 members.

for considering uncertainty becomes evident as the second deterministic simulation driven by COSMO-7 (the deterministic NWP at 7×7 km^2 resolution run by MeteoSwiss) misses the timing of the runoff peak completely. The MM5 model (the deterministic NWP at 15×15 km^2 resolution run by IMK-IFU) overperforms the COSMO-7 in this particular case. The spread of the ensemble can be interpreted as the uncertainty (stemming from the meteorological forecast) of the deterministic hydrological simulation, given that the deterministic and probabilistic runs are based on the same model chain. This is of course not entirely true for the simulations shown in Figure 4 because of different grid spacing.

In Figure 5, relative to the meteorological forcing of the DIMOSOP (for DIstributed hydrological MOdel for the Special Observing Period, Ranzi *et al.*, 2003) model with the 16 COSMO-LEPS members, the effect of the time horizon of the forecast on the hydrological ensemble predictions is shown. The small flood which actually occurred on 24 November in the Oglio basin, in the Central Italian Alps, was already anticipated by the 20 November 12 : 00 UTC meteorological forecast (Figure 5(a)). COSMO-LEPS forecasts were available around 00 : 00 UTC of the following day and the flood forecasts can be made available, as a term of reference, after 3 h of computational time of a 2 GHz dual processor laptop computer for 17 runs of a 436×622 cells domain over a time horizon of 6 days. The correct timing of the rainfall event became clear, however, only in the 22 November 12 : 00 UTC run and more accurate in the 23 November 12 : 00 UTC run, shown in Figure 5(b).

4. Conclusions and outlook

In this contribution, the MAP D-PHASE end-to-end forecasting system for (ensemble) meteorological and hydrological applications was briefly introduced. Different deterministic and ensemble approaches in hydrological forecasting and nowcasting have been implemented and will be evaluated.

As shown above, 'ensemble information' on model uncertainties can be obtained from local hydrological and atmospheric EPS, from frequently updated deterministic runoff forecasts, and even from nowcasting systems consisting of hydrological models coupled to new sophisticated ensembles quantitative precipitation estimates derived from rainfall radars.

While a detailed evaluation process of all the results for the various catchments and models will take its time, some 'highlights' showing a representative cross-section of the potential of the various hydrological approaches have been presented.

However, these first examples already show improvements and new possibilities available in hydrological forecasting as compared to previous forecast (Benoit *et al.*, 2002) and hindcast (Ahrens *et al.*, 2003) experiments.

Most important, first end-user feedback is generally very encouraging. The experimental warning on the VP provided valuable information on rainfall and flood events with some days in advance. Even localized storms were predicted by some high-resolution models, at least.

However, there is a broad feeling that the approach of probabilistic forecasting in hydrology is still quite novel and will require careful training and communication efforts to the end-user. Some years will be needed in order to build up the know-how of the practitioners and also within the hydrological forecasting agencies in order to finalize the practical applications of these new end-to-end operational flood forecasting tools.

The data archive at WDCC provides a precious opportunity to access all relevant data. This collection of model and observation data is unique in terms of details of different valuable data sources and data size of a single experiment. We expect large national and international scientific interest in this dataset for a long time as a source of data for transdisciplinary research in hydrological, atmospheric, and other related sciences.

Acknowledgements

The authors are thankful to colleagues of the COPS field program for a very fruitful collaboration, especially with respect to operating the data archive. The wizard, Gerhard Kittel, who programmed the visualization platform in practically no time, is especially thanked, as well as all the countless modelers, forecasters, end-users and other contributors. WWRP of WMO is thanked for their support as a Forecast Demonstration Project.

References

Ahrens B, Jaun S. 2007. On evaluation of ensemble precipitation forecasts with observation-based ensembles. *Advances in Geosciences* **10**: 139–144.

Ahrens B, Jasper K, Gurtz J. 2003. On ALADIN precipitation modeling and validation in an Alpine watershed. *Annales Geophysicae* **21**: 627–637.

Bacchi B, Ranzi R. 2003. Hydrological and meteorological aspects of floods in the Alps: an overview. *Hydrology and Earth System Sciences* **7**: 784–798.

Bartholmes J, Todini E. 2005. Coupling meteorological and hydrological models for flood forecasting. *Hydrology and Earth System Sciences* **9**: 333–346.

Benoit R, Schar C, Binder P, Chamberland S, Davies HC, Desgagne M, Girard C, Keil C, Kouwen N, Luthi D, Maric D, Muller E, Pellerin P, Schmidli J, Schubiger F, Schwierz C, Sprenger M, Walser A, Willemse S, Yu W, Zala E. 2002. The real-time ultrafinescale forecast support during the special observing period of the MAP. *Bulletin of the American Meteorological Society* **83**: 85.

Binder P, Schär C (eds). 1996. *The Mesoscale Alpine Programme: Design Proposal*. MAP; 77 [Available from MAP Programme Office, c/o MeteoSwiss, CH-8044 Zürich, Switzerland. http://www.map.meteoswiss.ch/map-doc/proposal.htm].

Bougeault P, Binder P, Buzzi A, Dirks R, Houze R, Kuettner J, Smith RB, Steinacker R, Volkert H. 2001. The MAP special observing period. *Bulletin of the American Meteorological Society* **82**: 433–462.

Germann U, Berenguer M, Sempere-Torres D, Salvade G. 2006a. Ensemble radar precipitation estimation – a new topic on the radar horizon. In *Proceedings 4th European Conferences on Radar in Meteorology and Hydrology*, Barcelona, 18–22 September 2006, 559–562.

Germann U, Galli G, Boscacci M, Bolliger M. 2006b. Radar precipitation measurement in a mountainous region. *Quarterly Journal of the Royal Meteorological Society* **132**: 1669–1692.

Gurtz J, Zappa M, Jasper K, Lang H, Verbunt M, Badoux A, Vitvar T. 2003. A comparative study in modelling runoff and its components in two mountainous catchments. *Hydrological Processes* **17**: 297–311.

Jaun S, Ahrens B, Walser A, Ewen T, Schär C. 2008. A probabilistic view on the August 2005 floods in the upper Rhine catchment. *Natural Hazards and Earth System Sciences* **8**: 281–291.

Kaufmann P, Schubiger F, Binder P. 2003. Precipitation forecasting by a mesoscale numerical weather prediction (NWP) model: eight years of experience. *Hydrology and Earth System Sciences* **7**: 812–832.

Krzysztofowicz R. 2001. The case for probabilistic forecasting in hydrology. *Journal of Hydrology* **249**: 2–9.

Malguzzi P, Grossi G, Buzzi A, Ranzi R, Buizza R. 2006. The 1966 "century" flood in Italy: A meteorological and hydrological revisitation. *Journal of Geophysical Research-Atmospheres* **111**: D24106.

Marsigli C, Boccanera F, Montani A, Paccagnella T. 2005. The COSMO-LEPS mesoscale ensemble system: validation of the methodology and verification. *Nonlinear Processes in Geophysics* **12**: 527–536.

Molteni F, Buizza R, Palmer TN, Petroliagis T. 1996. The ECMWF ensemble prediction system: Methodology and validation. *Quarterly Journal of the Royal Meteorological Society* **122**: 73–119.

Molteni F, Buizza R, Marsigli C, Montani A, Nerozzi F, Paccagnella T. 2001. A strategy for high-resolution ensemble prediction. I: definition of representative members and global-model experiments. *Quarterly Journal of the Royal Meteorological Society* **127**: 2069–2094.

Palmer TN. 2000. Predicting uncertainty in forecasts of weather and climate. *Reports on Progress in Physics* **63**: 71–116.

Pappenberger F, Beven KJ. 2006. Ignorance is bliss: or seven reasons not to use uncertainty analysis. *Water Resources Research* **42**: W05302. DOI: 10.1029/2005WR004820.

Pappenberger F, Beven KJ, Hunter NM, Bates PD, Gouweleeuw BT, Thielen J, de Roo APJ. 2005. Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European Flood Forecasting System (EFFS). *Hydrology and Earth System Sciences* **9**: 381–393.

Ranzi R, Bacchi B, Grossi G. 2003. Runoff measurements and hydrological modelling for the estimation of rainfall volumes in an alpine basin. *Quarterly Journal of the Royal Meteorological Society* **129**: 653–672.

Ranzi R, Zappa M, Bacchi B. 2007. Hydrological aspects of the Mesoscale Alpine Programme: findings from field experiments and simulations. *Quarterly Journal of the Royal Meteorological Society* **133**: 867–880.

Refsgaard JC. 1997. Validation and intercomparison of different updating procedures for real-time forecasting. *Nordic Hydrology* **28**: 65–84.

Rotach MW, Arpagaus M. 2006. Demonstration of probabilistic hydrological and atmospheric simulation of flood events in the alpine region (D-PHASE). In *Proceedings Second THORPEX International Scientific Symposium*, Landshut, 4–8 December 2006, 54–55.

Siccardi F, Boni G, Ferraris L, Rudari R. 2005. A hydrometeorological approach for probabilistic flood forecast. *Journal of Geophysical Research-Atmospheres* **110**: 1–9.

Thielen J, Bartholmes J, Ramos M-H, de Roo A. 2008. The European flood alert system – Part 1: concept and development. *Hydrology and Earth System Sciences Discuss. J1 – HESSD* **5**: 257–287.

Verbunt M, Walser A, Gurtz J, Montani A, Schar C. 2007. Probabilistic flood forecasting with a limited-area ensemble prediction system: selected case studies. *Journal of Hydrometeorology* **8**: 897–909.

Volkert H, Gutermann T. 2007. Inter-domain cooperation for mesoscale atmospheric laboratories: the Mesoscale Alpine Programme as a rich study case. *Quarterly Journal of the Royal Meteorological Society* **133**: 949–967.

Wöhling T, Lennartz F, Zappa M. 2006. Technical note: updating procedure for flood forecasting with conceptual HBV-type models. *Hydrology and Earth System Sciences* **10**: 783–788.

Wulfmeyer V, Behrendt A, Bauer HS, Kottmeier C, Corsmeier U, Adrian G, Blyth A, Craig G, Schumann U, Hagen M, Crewell S, Di Girolamo P, Flamant C, Miller M, Montani A, Mobbs S, Richard E, Rotach MW, Arpagaus M, Russchenberg H, Schlüssel P, König M, Gärtner V, Steinacker R, Dorninger M, Turner DD, Weckworth T, Hense A, Simmer C. 2008. The Convective and Orographically-induced Precipitation Study: A research and development project of the world weather research program for improving quantitative precipitation forecasting in low-mountain regions. *Bulletin of the American Meteorological Society*; in press.

DOI: 10.1002/asl