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A COMPARISON OF TWO APPROACHES FOR STATE UPDATING WITH THE PARTICLE FILTER IN A NORDIC WATERSHED

Olivier Chimi Chiadjeu[1], Marie-Amélie Boucher[2], André St-Hilaire[1], and Fateh Chabana[1]*

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Abstract:

Given the non-Gaussian and non-linear processes included in hydrologic models, on existing data assimilation algorithms, sequential Monte Carlo methods known as particle filters appear as one of the best tools for data assimilation. Given that particle filters rely on a large number of simulation runs at each step, their usage necessarily leads to ensemble rather than deterministic forecasts. Hydrologists usually use direct or indirect approach for particle sampling. In the direct approach, the particles are sampled through model states. In the indirect approach, the particles are sampled through the perturbation of meteorological observations. Here, the CEQUEAU hydrological model is then used in simulation mode to compute the state variables corresponding to each perturbation of meteorological observations.

The aim of this study is to compare both approaches for particle sampling. To assure the diversity of particles during the simulation and for large noise on models states, previous studies showed that, modified Auxiliary Sampling Importance Resampling (ASIR) if the best algorithm for data assimilation in this context. Applied on two watersheds, five states of the CEQUEAU model are updated by the assimilation of the observed streamflows. To evaluate our simulation, we compare the mean of ensemble simulation with observed streamflow using the Nash-Sutcliffe coefficient for deterministic forecast. We also used the mean of the Continuous Ranked Probability Score for ensemble forecast (MCRPS). On 28 years of simulations, the average Nash-Sutcliffe coefficient value increased from 0.87 to 0.96 on the first watershed and from 0.22 to 0.89 on second watershed using the direct approach. For the indirect approach, the Nash-Sutcliffe coefficient increased from 0.87 to 0.90 on the first watershed and from 0.22 to 0.89 on second watershed. MCRPS confirmed the trend for the ensemble forecast. Having shown that the water budget is preserved with the direct approach, the results show that this latter approach for sampling particles is much more efficient than indirect approach. In the case of the direct approach, simulated values of streamflow were in good agreement with observed streamflows.

Keywords:

Ensemble Forecast, Particle Filter, CEQUEAU Model, Data assimilation.

A COMPARISON BETWEEN STREAMFLOW ENSEMBLE FORECASTS OF AN EXTREME HYDROLOGICAL EVENT USING INPUTS FROM THE ECMWF AND GEFS ENSEMBLE WEATHER MODELS

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Abstract:

This work examines the effect of uncertainty from ensemble weather prediction models, namely ECMWF (European Center for Medium Range Weather Forecast) and GEFS (Global Ensemble Forecast System), on streamflow hydrological predictions for an extreme hydrological event, Hurricane Irene.

An automated hydrological ensemble prediction framework was implemented using GIS and a regional scale hydrological model (HEC-HMS). The upland hydrologic framework was applied to the Hudson River Basin, USA (~36,000 km2) using gridded precipitation data from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR), and was validated against streamflow observations from the United States Geologic Survey (USGS). Forced by 125-member precipitation ensemble, the automated framework now runs operationally every 6 hours to predict hourly ensemble streamflow discharges from the Hudson and its tributaries that feed into the New York Harbor Observing and Prediction System (NYHOPS), with a 96-hr forecast horizon. NYHOPS was developed at Stevens Institute of Technology's Davidson Laboratory to generate marine and coastal forecasts for the New York Harbor, Atlantic Coast, and Hudson River region through in-situ monitoring equipment and hydrodynamic modeling. A probabilistic comparison between streamflow predictions during Hurricane Irene generated by forcing the hydrologic model with 51 ECMWF meteorological members versus 21 GEFS meteorological members is presented. The visual and statistical comparison offers interesting perspectives on the spatio-temporal resolution of meteorological inputs that are used in this hydrological ensemble prediction system.

Keywords:

ECMWF, GEFS, Irene, Streamflow Ensemble Forecasts, Uncertainty

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ACCOUNTING FOR COMBINED EFFECT OF INITIAL CONDITION AND MODEL UNCERTAINTY IN SEASONAL FORECASTING THROUGH DATA ASSIMILATION

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Abstract:

Uncertainties are unfortunate yet inevitable parts of any forecasting system. Within the context of seasonal hydrologic predictions, these uncertainties can be attributed to three causes: imperfect characterization of initial conditions, an incomplete knowledge of future climate and errors within computational models. In currently available forecast products, only a partial accounting of uncertainty is performed, with the focus primarily on meteorological forcing. For example, the Ensemble Streamflow Prediction (ESP) technique uses meteorological climatology to estimate total uncertainty, thus ignoring initial condition and modeling uncertainty. Here we propose a method to account for all threes sources of uncertainty, providing a framework to reduce uncertainty and accurately convey persistent predictive uncertainty. In order to manage all three sources of uncertainty, this study combines ESP with ensemble data assimilation, to quantify initial condition uncertainty, and sequential Bayesian combination, to quantify model errors. This gives a more complete description of seasonal hydrologic forecasting uncertainty. Results from this experiment suggest that the proposed method increases the reliability of probabilistic forecasts, particularly with respect to the tails of the predictive distribution. The presentation also intends to address latest advances in using data assimilation to account for nonstationarity in catchment behavior as pertains to operational forecasting.

Keywords:

Data assimilation, Model Uncertainty, Initial Condition, ESP

AN EXCHANGEABLE CONSTRUCTION FOR ENSEMBLE FORECASTS POST-PROCESSING

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Abstract:

Probabilistic forecasting aims at producing a predictive distribution of the quantity of interest instead of a single best guess estimate. With regard to river flow forecasts, the main sources of uncertainty are due (a) to the unknown future rainfalls and temperatures (input uncertainty), (b) to the inadequate representation of the rainfall-runoff transformation by the deterministic model in use (hydrological uncertainty). Our strategy is first to model them separately and then to combine the input uncertainty and the hydrologic uncertainty into the total uncertainty. This communication will focus on meteorological uncertainty.

Input uncertainty is nowadays taken into account using members of a meteorological ensemble, i.e. scenarios which represent the possible multiple trajectories of the meteorological system on a short to medium range. Such forecasts are considered as inputs to the rainfall-runoff model. However, ensemble forecasts are often a biased and under-dispersed sample of a probabilistic prevision.

To post-process ensemble members in order to recalibrate the forecasts, we develop a model based on the hypothesis of exchangeability, a key property when dealing with any ensemble-based forecasting system. This model has the advantage of being easily adapted to include several sources of (ensemble) forecasts. We apply it to ensemble forecasts of temperature, river flow and precipitation occurrence, and we present solutions to adapt it to precipitation ensemble forecasts.

Our work focuses on series of forecasts routinely issued by two hydro-electricity producers in France and in Québec. We finally compare the results of our statistical elaborations to their present operational forecasting systems.

Keywords:

Exchangeability, Probabilistic Forecasts, Post-Processing, Ensemble Weather Forecasts

AN OPERATIONAL HYDROLOGICAL ENSEMBLE PREDICTION SYSTEM IN THE WINNIPEG RIVER BASIN

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Abstract:

The Lake of the Woods Control Board (LWCB) is a Canadian board which regulates the water levels of Lake of the Woods and Lac Seul, and the flows in the Winnipeg and English Rivers downstream of these lakes to their junction, for the benefit of all users and interests. The LWCB has been operationally using the WATFLOOD hydrologic model since 2014 to daily forecast reservoir inflows in the Winnipeg River Basin. WATFLOOD is a physically based model that uses grouped response units (GRUs) to speed up computation time. Currently the operational forecasting framework captures meteorological uncertainty by using the North American Ensemble Forecast System (NAEFS) as precipitation and temperature forcing data. All 21 meteorological ensembles are fed into WATFLOOD and results are post processed and manually bias corrected. This forecasting framework has proved to be a valuable tool to regulators in the basin.

The LWCB has sought to improve the forecasting framework in order to account for hydrological model uncertainty and reservoir level uncertainty. Hydrological model uncertainty occurs because of simplification of model processes in the hydrological model and the inability to measure and assimilate hydrologic state variables at the time of forecast. Reservoir level uncertainty occurs on large reservoirs when wind setup disproportionately biases water level gauges on the windward side of the reservoir, thus affecting reservoir inflow calculations.

In order to account for hydrological uncertainty, 11 different model calibrations were configured using Ostrich, an automated calibration program. The historic calibration periods were varied in order to obtain models that are calibrated to a variety of hydrological periods (i.e. wet, normal or dry). Each model calibration is run in hindcast mode using observed data, and in forecast mode using the NAEFS ensemble data. Computation time is reduced by executing the simulations in parallel. The inflow forecasts are automatically bias corrected using varying lookback periods to account for calculated reservoir inflow error caused by wind setup. Probabilities are calculated from these ensemble inflow forecasts that account for meteorological, hydrological and reservoir level uncertainty. These forecasts are produced on a daily basis. Forecast skill and reliability for the first season of inflow forecasts are analyzed and compared with the current operational model that only captures meteorological uncertainty.

Keywords:

Forecast, Ensemble, Operational, Probabilistic

ASSESSING THE ECONOMIC VALUE OF AN ENSEMBLE HYDROLOGICAL FORECAST: CASE OF THE MONTMORENCY RIVER

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Abstract:

The snow-dominated Montmorency watershed (1150 km2), situated in southern Québec, Canada, experiences near-annual flooding in vulnerable inhabited areas. Operational streamflow forecasts for the Montmorency River are issued by the Direction de l'Expertise Hydrique (DEH) department of the Ministère du développement durable, de l'environnement et de la lutte aux changements climatiques of the Quebec Government. The DEH uses Environment and Climate Change Canada's deterministic meteorological forecasts, along with the spatially distributed, physics-based HYDROTEL model (Fortin et al. 2004), to produce a 5-day horizon, 3h time step forecast. The DEH adds a 50% confidence interval around the forecasts. This interval is derived from a statistical analysis of past forecast errors (Huard, 2013). Upon receiving DEH's forecast, Quebec City's civil security bureau can choose to engage in active protection and surveillance measures if upcoming water levels threaten residents' security.

The present study aims at comparing the operational forecasting platform with an ensemble hydrological forecasting system driven by Environment and Climate Change Canada's meteorological ensemble forecast (hereafter "the new system"). The new system also accounts for the uncertainty on the model's four state variables with the Ensemble Kalman Filter (or EnKF, Evensen, 2003). The period under study spans from 2011 to 2014, which coincidentally saw two major flood events requesting residents' evacuation (March 2012 and April 2014). Hydrological forecast performance is assessed using statistical tools such as the CRPS, reliability diagram, spread-skill diagram and the logarithmic score. Results show that the new system based on meteorological ensemble forecasts outperforms the operational system in terms of forecast resolution, although at the expense of reliability. In an attempt to overcome this loss of reliability in the new system, the EnKF was implemented. This effectively allowed for improvement of the reliability with negligible loss of resolution.

The basic cost-loss ratio is inapplicable to the problem of floods in the Montmorency watershed, as well as in many flood management situations. The cost-loss ratio assumes a risk-neutral decision-maker, which is unlikely in this type of situation. In addition, the current emergency system offers no protection against material damages, as assumed with the cost-loss ratio. Here the economic value of both forecasting systems is assessed using a Constant Absolute Risk Aversion (CARA) utility function. This utility function depends on the streamflow forecasts, the damages and the cost of emergency measures as well as on the level of risk aversion of the decision maker. The latter is allowed to vary. Water-level and related flooding and damage curves are used to assess material losses. Historic of recent floods and associated expenses are used to evaluate costs of evacuation operations and to appraise intangible value of public protection.

Keywords:

Flood Forecasting, Economic Value, CARA Utility Function, Cost-Loss Ratio, Risk Aversion

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ASSESSING THE POTENTIAL OF OVER-THE-LOOP SHORT-TO-MEDIUM RANGE ENSEMBLE FORECASTS USING SHERPA

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Abstract:

Many if not most national operational short-to-medium range streamflow prediction systems rely on a forecaster-in-the-loop approach in which some parts of the forecast workflow are automated, but others require the hands-on-effort of an experienced human forecaster. This approach evolved out of the need to correct for deficiencies in the models and datasets that were available for forecasting, and often leads to skillful predictions despite the use of relatively simple, conceptual models. On the other hand, the process is not reproducible, which limits opportunities to assess and incorporate process variations, and the effort required to make forecasts in this way is an obstacle to expanding forecast services – e.g., though adding new forecast locations or more frequent forecast updates, running more complex models, or producing forecast ensembles and hindcasts that can support verification. In the last decade, the hydrologic forecasting community has begun develop more centralized, ‘over-the-loop’ systems. The quality of the new forecast products will depend on their ability to leverage research in the areas of remote sensing, earth system modeling, parameter estimation, data assimilation, statistical post-processing, weather and climate prediction, verification, and uncertainty estimation through the use of ensembles. Currently, practitioners in both operational streamflow forecasting and water management have little experience with the strengths and weaknesses of the over-the-loop outcomes, even as the systems are being rolled out in major operational forecasting centers.

There is a need both to evaluate these forecasting advances and to demonstrate their potential in a public arena, raising awareness in forecast user communities and development programs alike. To address this need, the National Center for Atmospheric Research is collaborating with the University of Washington, the Bureau of Reclamation and the US Army Corps of Engineers to create a fully automated, real-time ‘System for Hydromet Ensemble Research and Prediction Applications (SHERPA). We present early hindcast and verification results from SHERPA for short to medium range streamflow forecasts in a number of US case study watersheds.

Keywords:

Ensemble Streamflow Forecasting, Hindcasting, Verification, Over-The-Loop Paradigms

BENCHMARKING DIFFERENT APPROACHES FOR HARNESSING PREDICTABILITY IN CLIMATE AND HYDROLOGIC INITIAL CONDITIONS FOR SEASONAL STREAMFLOW FORECASTING

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Abstract:

A number of forecasting centers around the world offer seasonal streamflow predictions using methodologies that span a wide range of data requirements and complexity. In the western United States, two primary approaches have been employed for operational purposes: (i) future streamflow volumes are regressed on in situ observations (e.g. rainfall, snow water equivalent); and (ii) hydrologic models predict the future evolution of simulated initial watershed moisture states when forced by an ensemble of historically observed weather sequences for the forecast period (i.e. the Ensemble Streamflow Prediction, ESP, method). Neither of these methodologies uses analyzed or forecasted climate information, which is a major potential source of seasonal streamflow prediction skill. The operational community needs to understand better the potential benefits both of additional predictor information (such as climate) and of alternative methods and datasets, such as hybrid dynamical/statistical approaches. Though substantial increases in complexity and data usage are possible, their marginal benefits to forecast skill versus simpler and less intensive methods remain relatively unquantified.

In this work, we provide a systematic intercomparison of various seasonal streamflow forecasting techniques, including: (1) dynamical approaches such as ESP, with post-processing, (2) statistical regression schemes using climate information and/or initial hydrologic conditions, (3) an ESP trace weighting scheme based on analog climatic conditions, and (4) hierarchical, hybrid combination of dynamical and statistical forecasts. These methods and data are tested for predicting spring runoff volumes at case study basins located in the US Pacific Northwest, and results obtained for several initialization times are evaluated in terms of accuracy, probabilistic skill and reliability. Preliminary results suggest that hierarchical approaches that merge multiple predictions provide a powerful framework that can leverage different predictability sources at different times of year. We find also that the relatively limited hindcast periods available from seasonal precipitation forecasts provide the greatest challenge to their utilization in streamflow forecasting; thus at present the use of longer-record climate reanalyses and indexes may be a more robust strategy.

Keywords:

Seasonal Streamflow Forecasting, Climate Information, Initial Conditions, Hybrid Methods

CAN POST-PROCESSED METEOROLOGICAL ENSEMBLE FORECASTS OUTPERFORM A SOPHISTICATED ANALOG MODEL FOR OPERATIONAL STREAMFLOW FORECASTING?

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Abstract:

While many end-users now recognize the potential benefits of probabilistic and ensemble forecasts, many operational agencies resort to analogs or statistical models rather than meteorological ensemble forecasts. Meteorological ensemble forecasts for precipitation and temperature are often biased, and they only convey a small portion of the total predictive uncertainty into the system. One of the many possibilities to overcome those difficulties is to post-process the raw streamflow ensembles obtained at the end of the forecasting chain, after the meteorological ensemble forecasts have been fed as inputs to a hydrological model. Regarding analogs or statistical models, they can be calibrated to account for the total uncertainty of the hydrological forecasting problem in a lumped fashion. In this study, the HSAMI global conceptual model was used in combination with precipitation a temperature ensemble forecasts to issue 1-day to 9-day ahead daily streamflow forecasts for three watersheds in the province of Québec (Canada). Those three watersheds are managed by Hydro-Québec for hydro-power production. Meteorological ensemble forecasts from ECMWF, NCEP and MSC were obtained from the TIGGE database. In order to improve raw streamflow forecasts, two post-processing strategies, namely Bayesian model averaging (BMA) and weighted kernel dressing, are applied and compared. This comparison is based on the CRPS, the rank histogram and the spread-skill diagrams, but also on the visual appreciation of hydrographs. It is shown that weighted kernel dressing and BMA provide comparable results in terms of overall performances, with a few specificities. BMA is very efficient at reducing biases. It also improves reliability in general, except that it can generate very important over-dispersion of peak flows during the spring freshet. The BMA results also depend strongly on the choice of a specific probability function to be fitted to the raw streamflow forecasts. Weighted kernel dressing is not prone to over-dispersion, but is not very efficient on its own at reducing bias. For this reason, separate bias correction is applied. Both post-processing methods allow for great improvement over raw forecasts. However, further comparison with the operational analog system currently used by Hydro-Québec, with and without human forecaster influence, reveals that analogs are superior to post-processed streamflow forecasts on many occasions, for all three watersheds. For two out of three watersheds, it is shown that the day-to-day expertise of the human forecaster cannot be matched by any concurrent method tested in this study. According to the authors, post-processing often feels like a never-ending quest for perfection that leads to more questions than answers. Hopefully this talk will be an occasion to share and discuss some of those questions in the light of the results briefly described above.

Keywords:

Post-Processing, Kernel Dressing, Bayesian Model Averaging, Analog Forecasts, Influence of Human Forecaster

COMPARISON OF ENSEMBLE VERIFICATION METRICS ON DAILY MEAN FLOWS AND MONTHLY PEAK FLOWS

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Abstract:

Probabilistic skill score has been used as an ensemble verification tool in several probabilistic weather forecasting and flood forecasting studies (Atger 1999; Demargne et al 2010; Franz et al 2002). The main objective of the study is to evaluate and compare model performance statistics on ensembles of daily flows and maximum monthly flows. The notable aim is to see for which type of ensemble flows the model performance statistics are better and whether alternative metrics are needed for peak flows.

The model was first calibrated and validated in a case study area of Little Don Valley River basin located in Humber - Don Valley Watershed. Ensembles of daily stream flow were generated from multiple parameter sets of a conceptual rainfall-runoff model SAC-SMA by using Monte-Carlo simulation. A Nash-Sutcliffe model efficiency index of 0.6 for calibration and 0.5 for validation were chosen as an objective criteria to screen out behavioral model parameters from 200000 Monte-Carlo random optimization sample size. As such, 689 behavioral parameter combinations of SAC-SMA model parameters (19 model parameters) has been retained which has generated 689 ensembles daily streamflow for 20 years from May 1975 to August 1995. In addition to daily stream streams flows, same number of ensembles of maximum monthly streamflows were produced.

The generated ensemble streamflows mimicking the observed discharge characteristics and dynamics were verified by four selected model performance statistics and ensemble verification metrics using NOAA's Ensemble Verification System (EVS) software tool (Brown et al. 2010). Reliability Diagram, Relative Operating Characteristic curve (ROC), Mean Continuous Ranked Probability Score (CRPS) and Rank Histogram are computed separately for daily stream flows and monthly peak flows at 75th, 80th, 90th and 95th percentile of daily mean and monthly peak flows respectively which are considered as event thresholds. Reliability Diagram indicated that for large daily flow thresholds ensemble probabilities overestimated the observed frequency which is associated with a high bias and errors in the ensembles for large stream flow simulation. Whereas Reliability Diagram of monthly peak ensemble flows showed mostly underestimation of observations. Similarly, the other model performance statistics were also estimated and compared between daily mean flows and monthly peak flows. The study revealed the presence of conflicting differences in the ensemble verification metrics when evaluating mean ensemble flows with respect to peak ensemble flows.

Keywords:

Ensemble Verification, Skill Score, Reliability Diagram, Daily flow, Peak flow

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COMPARISON OF KALMAN FILTER TYPE AND VARIATIONAL DATA ASSIMILATION APPROACHES FOR OPERATIONAL HYDROLOGY

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Abstract:

Data assimilation (DA) is a valuable technique to improve the system state of hydrological models at forecast time as the initial condition of subsequent forecasts. It combines ground and remotely sensed observations and model simulations together with their corresponding uncertainties to identify the optimum or true state. One of the most commonly applied techniques in operational hydrology is the Ensemble Kalman Filter (EnKF). It is a typical representative of a sequential DA approach in which the co-variance matrix gets approximated and updated at every time step. In contrast, a variational DA technique such as the Moving Horizon Estimation (MHE) is referred to as simultaneous due to its concurrent assimilation in a finite assimilation horizon. Besides these two extremes, many intermediate methods and hybrids exist.

A lot of these methods have been already applied successfully to assimilate ground and remotely sensed observations (Liu et al., 2012). However, there have been only few studies comparing these approaches for hydrological applications. The purpose of this study is to classify and compare several methods such as the EnKF, Asynchronous EnKF, Particle Filter and MHE in application to a simple HBV-style conceptual hydrological model. The performance of the different approaches is assessed in hindcasting experiments. Furthermore, we discuss the pros and cons of each approach in terms of the implementation effort, the computational costs and scalability as well as other aspects relevant for its operational application in flow forecasting systems.

Keywords:

Data Assimilation, Kalman Filter, Variational Methods

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CRITICAL FLOOD EVENT PREDICTION BASED ON MULTIPLE METEOROLOGICAL SCENARIOS FROM TIGGE PROPAGATED INTO DIFFERENT HYDROLOGICAL CONCEPTUAL MODELS AND NEURAL NETWORKS CONFIGURATIONS - STUDY CASE: LA MOJANA, COLOMBIA.

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It is clear the social and economic impact that floods have had in Colombia, accentuated in the last decade. This work seeks to explicitly assess the uncertainty associated with rainfall-runoff complex process as a key tool in decision-making processes. To this end it was taken as study area the region of La Mojana, highly hit by the 2010-2011 floods with around 100,000 homeless. This region covers an area of about 500,000 hectares of which 25,000 hectares of cultivated land were flooded.

In this work, we elected the upper basin zone which determines the dynamics of the flood to simulate what would have been the basis of an early warning system based on probabilistic forecasts. Thus, the system simulated up to ten days in advance weather scenarios from models from Canada, USA, Brazil and central Europe into three conceptual hydrological models and three models based on different configurations artificial neural network.

Hydrologic modeling with conceptual hydrological models GR4J, HBV, SIMH and artificial neural networks were activated daily with different prediction horizons. For this, we compared two hydrological ensemble prediction systems, first one is based on hydrological models previously calibrated with historical records, and the second one, corresponds the calibration directly based on the first three forecast meteorological horizons; here these horizons are considered the most critical scenarios for decision making given the characteristics of bias and reliability of the TIGGE database in the study area.

The results show the gain of using probabilistic methodology to operate an early warning system. Additionally, direct calibration with the first three horizons in hydrological prediction models is more advantageous than the conventional method based on observed historical records with subsequent spread of probabilistic weather system. In conclusion, the methodology set shows that the critical events of the great flood of 2010 in the Mojana could foresee at least three days in advance, which would have greatly minimized the impact of such events.

DEVELOPMENT AND IMPLEMENTATION OF A PROBABILISTIC MEDIUM-RANGE FORECASTING SERVICE FOR WATERWAY TRANSPORT ON THE RIVER RHINE

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Abstract:

Inland waterway transport is an important even though often neglected economic sector relying on hydrological forecasts in order to increase its operating efficiency. The water-level is the main hydrological driver for shipping along the European inland waterways as it sustainably affects the availability of the waterways as well as the load capacity of vessels and thus transportation costs. Most of the current navigation-related forecasts offer lead-times of a few days and allow for optimizing the load of upcoming trips. But, at least for the German waterways, forecast products supporting decisions with longer handling time (e.g. timing of a specific trip, selection of the appropriate vessel type or mode of transport etc.) are missing. Therefore, the Federal Institute of Hydrology (BfG) being in charge to develop, operate and maintain the transportation-related forecasting systems for the navigable rivers in Germany, has tackled the issue of medium-range water-level forecasts within the last years and is now technical ready to offer probabilistic water-level forecasts up to 10 days for the River Rhine being one of the world's most frequented waterways.

The existing operational forecasting system for the River Rhine has been extended in two ways: on the one hand a 68-member hydro-meteorological ensemble composed of the COSMO-LEPS as well as ECMWF's high-resolution (HRES) and ensemble forecast (ENS) is used to force the hydrological forecasting chain consisting of the semi-distributed hydrological model HBV (covering approx. 168.000 km²) and a one-dimensional hydrodynamic Sobek model (simulating nearly 900 river kilometer). On the other hand, statistical post processing modules, adapted / optimized by the Computational Statistics group at HITS, have been added to the forecasting system (Figure 1). In order to receive well-calibrated and sharp inflows to the hydrodynamic model the flow forecasts generated by HBV are initially post processed using ensemble model output statistic (EMOS). As hydrodynamic models can't use predictive distributions as boundaries conditions ensemble copula coupling (ECC-T) is subsequently applied to obtain discharge trajectories out of the post processed predictive distributions. Here the spatio-temporal interaction of the different tributaries of the raw ensemble is preserved. As a final step the water-level ensemble generated by the hydrodynamic model is again post processed by EMOS.

We will present current results and different forecasting products from the aforementioned forecasting system for the River Rhine. In addition to the added value (related to forecast skill) of the applied post processing techniques in comparison to the raw ensemble we also intend to demonstrate the economic benefit of the new medium-range probabilistic forecasts by coupling a simulation based cost-structure model of inland waterway transport with the hydrological forecast output.

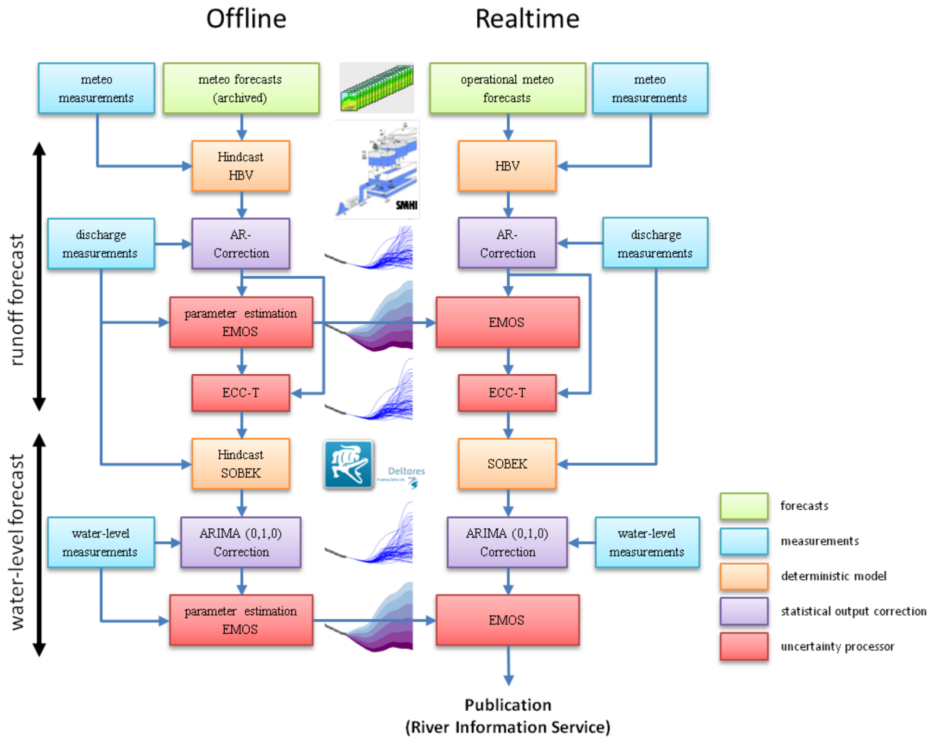

Figure 1: Operational forecasting workflow to generate probabilistic water-level forecasts for the Rhine

Keywords:

Ensemble Calibration, Inland Waterway Transport, Medium-Range Water-Level Forecast, Probabilistic Forecast, Statistical Post Processing

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DEVELOPMENT OF A GRIDDED METEOROLOGICAL ENSEMBLE FORECAST PROCESSOR AT US NATIONAL WATER CENTER

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Abstract:

The Meteorological Ensemble Forecast Processor (MEFP) is a key component of the Hydrologic Ensemble Forecast Service (HEFS) developed by the US NWS National Water Center. It can produce precipitation and temperature ensemble forecasts on a basin-average basis for lead times ranging from 6 hours up to 9 months. Past evaluations indicate that the MEFP is capable of producing reliable precipitation and temperature ensembles and preserving the forecast skill in the input forecast sources. In order to serve the National Water Model initiative at the NWC, an augmented version of the MEFP is being developed to produce ensemble forecasts on a gridded basis. In this presentation, we describe the science enhancements made to the gridded MEFP, including the use of real-time ensemble members as the basis for performing the Schaake Shuffle, and we report preliminary verification results of the ensemble forecasts from the gridded MEFP in terms of reliability and spatiotemporal consistency.

Keywords:

Ensemble forecasting, Precipitation, Schaake Shuffle.

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DO WE (STILL) NEED ENSEMBLE PREDICTIONS?

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Abstract:

Hydrological and meteorological ensemble predictions have undergone a tremendous and rapid evolution over the last decades. The first meteorological ensembles at ECMWF were produced in November 1992 and in 1999 they were used for the first time in hydrological applications. Resolution has increased from over 240km to 18km globally today for the meteorological ensemble. Forecast skill for hydrological relevant variables such as precipitation has increased by 1 day a decade and is now deemed skilful until a lead time of 6 days. River discharge shows an increase in skill of 1.3 days per decade (as it integrates over several variables as well as temporal and spatial domains). Today, global flood forecasting systems produce predictions several weeks ahead. Paired with this increase in skill, there has been a considerable improvement in the representation of uncertainty with ensemble spread continuously improving in reliability. Higher resolution meteorological models, improved pre-processing of inputs, better hydrological and hydraulic models, advanced post-processing, progress in system-wide uncertainty representation and enhanced data assimilation (in particular in hydrology) are promising pathways to improve hydro-meteorological forecasts even further in the future. New observations and increased computer power (including new ways to utilize it) will lead to ever more certain forecasts and will possibly increase sharpness, meaning a reduced width in ensemble distribution. These improved forecasts increasingly lead to improved decisions - although the up-take of probabilistic forecasts for decision making is arguably currently not at the same pace as technical improvements.

Users are key elements to justifying operational forecasts and any associated value. Thus, it is not surprising that the necessary forecast skill, including any properties with respect to sharpness, is ‘user’ led. Traditionally, we have asked questions on what is the maximal acceptable spread or the minimal acceptable skill. However, given all the advances made, maybe it is time to develop a vision on the contrary properties. This means we need to ask what is the maximal skill which is useful (and hence should be provided) for an application or user. For example, a perfect precipitation forecast for 2 months ahead is great, but if one is only concerned with a reservoir which is operated on a weekly time scale, and there are no significant other downstream uses, than a perfect 3-week forecast may be entirely sufficient.

A similar argument can be made for the minimal spread an ensemble forecast exhibits. If ensembles are indistinguishable from each other (e.g. they collapse to a ‘single line’) and become so certain (whilst adequately representing all uncertainties), which can be particularly the case if a meteorological ensemble has been fed through a hydrological system with high memory, then running 1 instead of 52 ensemble members may be entirely sufficient. If ensemble members are slightly indistinguishable, then one needs to ask the question of how many ensemble members are required (e.g. 5-10 may be sufficient for estimating the mean).

Initially, these arguments may be seen as a prediction of demise for ensemble forecasting and this flourishing discipline. However, it is the contrary. Through these advances, new frontiers are discovered:

I. skill and spread vary significantly, not only with individual variables (such as precipitation or temperature), but also with the type of the event as well as the location. Even average skill increases may not be an accurate reflection of skill for extreme or high impact events. In addition, particular (additional) uncertainty representation may only be required in one certain geographical region (e.g. because response is dominated by a certain soil type), but a global hydrological model may not be able to accommodate changing

regional configurations. This requires research and development, including new scores to advance and measure performance of sub samples.

II. Using a forecast and developing a forecast is an interlinked cycle. A user may often only design an application given a certain capability (and such a capability could be forecast skill). Unless new capabilities are at least visible on the horizon, users may not even consider developing applications. Thus similar to the chicken and egg issue, one may need to create the chicken (egg?) in terms of a skilful and sharp longer-range forecast so that an egg (chicken?) can develop.

It has to be pointed out that even with ever increasing computer power, better observations etc., we are still a long way away from the scenario outlined in this abstract. Expect high certainty in extended-range forecasts may still be a something for the distant future. However, inevitably, these arguments will be made, in particular as we boast with increasing skill whilst requesting increased resources to improve it.

EFFICIENT UNCERTAINTY ANALYSIS IN STREAMFLOW PREDICTION FOR RESERVOIR OPTIMIZATION

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Abstract:

One of the fundamental aspects of reservoir management for hydropower generation is the necessity to adequately predict inflows to the system. This is typically achieved by using a hydrologic model which is calibrated for the watershed. Weather forecast time-series are then fed into the model to simulate future discharge rates. However, streamflow prediction is subject to many different sources of uncertainty, which can lead to a large spread in the predicted hydrographs. Weather forecasts, hydrologic model structures and parameterizations as well as the catchment's initial conditions all add uncertainty to the predicted flows.

As such, decisions regarding reservoir management are based on uncertain and biased inputs. Furthermore, the reservoir optimization process requires probabilistic estimates of the forecasted inflows to maximize expected hydropower production. In cases where the predicted inflows are under-dispersed (or over-dispersed), the more extreme predictions are weighted more heavily, thus skewing the decision process. This leads to non-optimal reservoir management and can also increase reservoir vulnerability. In this context, improving our understanding of the overall uncertainty is essential. However, attempts to isolate and estimate the independent sources of uncertainty have yet to yield satisfactory results.

Existing methods to estimate uncertainty in hydrologic prediction require the assumption of model error distributions, such as the general likelihood uncertainty estimation (GLUE) method. Our work is a novel approach which attempts to estimate the overall uncertainty in inflow prediction without the need for particular assumptions. Instead, the uncertainty is conditioned to the model, its parameters and to a given weather sequence. This allows estimating uncertainty for short to medium forecasting ranges. The method's efficiency resides in the analysis of observed uncertainty on past forecast scenarios, which is performed by evaluating the prediction error over time in hindcasting mode. Preliminary tests on a catchment in Québec, Canada show promising results.

Keywords:

Prediction Error, Uncertainty, Under-dispersion, ESP.

ENSEMBLE FLOW FORECASTING FOR HYDROPOWER OPERATIONS

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Abstract:

In November 2015, utilities from the CEATI group gathered at Indian Wells, CA for a hydropower conference focusing specifically on "inflow forecasting and uncertainties on predicting supply" (http://www.ceati.com/events/conferences/hop2015-hydropower-2015/). Utilities presented their inflow forecast system and discussed best approaches, and possible improvements including coordination with hydropower operations. They also showed interest in probabilistic inflow forecasting. Outcomes of the conference include the need to understand state-of-the-art flow forecasting for hydropower utilities, and understand the role of verification. The presentation summarizes the outcomes of the conference; we expose the present challenges faced by the industry to develop their own flow forecast system, and the additional steps to engage in a probabilistic forecasting that would be optimized for hydropower over the US electricity grid. What are the remaining gaps in the integrated modeling leading to decision making for hydropower operations while under uncertainty? We discuss HEPEX opportunities to support the hydropower industry.

Keywords:

Hydropower, Probabilistic Forecast, End-users.

ENSEMBLE STREAMFLOW FORECASTING ACTIVITIES WITH WRF-HYDRO

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Abstract:

This poster presents the current and planned ensemble streamflow forecasting activities with the operational version of the WRF-Hydro model (Gochis et al., 2014; as implemented at the National Weather Service's National Water Center). Beginning in the summer of 2016, daily 16-member 30-day ensemble streamflow forecasts will be produced operationally using CFSV2 (Saha et al., 2014) climate forecasts bias corrected using the NLDAS2 meteorological analyses. Preliminary analyses of these ensemble forecasts will be presented.

Next, short-term 'convection-permitting' ensemble forecasts are also being investigated using two different forcing forecast data sets: 1) time-lagged 18-hr, High Resolution Rapid Refresh (HRRR-Benjamin et al, in press) operational and experimental forecasts, and 2) NCAR, 10-member, 48-hr ensembles (Schwartz et al., 2015). The HRRR and the NCAR models are both convection-allowing versions of the WRF weather forecast model. The HRRR forecasts are available operationally real time and offer a direct pathway to operational implementation of short-term, ensemble streamflow forecasting. The NCAR ensembles are more experimental but likely offer a more robust description of forcing uncertainty for the WRF-Hydro model. We investigate bootstrapping new ensemble members from the 10-member NCAR ensemble to account for storm position errors. Assessment of WRF-Hydro hydrologic model uncertainty is also included.

Keywords:

Operational Streamflow Forecast Convection Climate

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ENSEMBLE WATER TEMPERATURE FORECASTING: ACCOUNTING FOR UNCERTAINTY ASSOCIATED WITH METEOROLOGICAL INPUTS

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Abstract:

High water temperatures are known to put pressure on aquatic organisms such as salmonids. In some hydrological systems, mitigation strategies (e.g. cool water releases) are used to protect local fish populations based on short term water temperature forecasts (Huang et al., 2011). While various uncertainty sources are known to affect thermal modelling, their individual impact on water temperature forecasts remain poorly understood. Few studies took interest in uncertainty in water temperature forecasting within last few years (e.g. Pike et al. 2013; Bal et al., 2014; Hague and Patterson, 2014) while none of them clearly considered the uncertainty of the meteorological inputs that is propagated within the hydrothermal modelling framework. The aim of this project is to explicitly characterize uncertainty resulting from meteorological inputs by feeding ensemble meteorological forecasts to a hydrological and thermal model cascade. The resulting forecasts are then compared to deterministic forecasts. Daily ensemble temperature forecasts were produced for the Nechako River between 2009 and 2014 during the months of July and August for one day to five day horizons (hz), and compared to previously emitted operational deterministic forecasts. Preliminary results demonstrate that ensemble forecast showed better general performances than its deterministic counterpart. More precisely, they improved the prediction of a biologically meaningful temperature exceedance threshold of 20°C for a 5-day forecast. Brier scores of 0.21 (hz = 5 days) was obtained through ensemble forecasts while the same metric was 0.32 (hz = 5 days) for the deterministic forecast. Continuous Ranked Probability Scores (CRPS), for the ensemble forecasts, and mean absolute errors (MAE), for the deterministic forecasts, were calculated and compared. Overall, CRPS's were lower than the MAE's for the same forecasting horizons apart from hz 1, indicating the superiority of the ensemble forecasts for all but the shortest term horizon. The mean uncertainty induced by meteorological inputs ranged between 0.48°C for a one-day forecast to 1.4°C for a 5-day forecast.

Keywords:

Water Temperature, Ensemble forecasts, Threshold Exceedance, Uncertainty

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EVALUATING THE IMPACT OF BIASED PRECIPITATION ON MULTIVARIATE DATA ASSIMILATION FOR STREAMFLOW PREDICTIONS

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Abstract:

The Ensemble Kalman Filter (EnKF), a popular data assimilation approach in hydrology, can be used to update state variables, providing improved initial states for hydrological forecasts. However, the EnKF relies on unbiased model and observation errors in order to guarantee optimal results; an assumption not often met in hydrological modeling, especially in snow-dominated regions where precipitation gauges are known to undercatch snowfall. Using state augmentation to include a bias parameter has been shown to reduce the streamflow bias, but this approach assumes that model parameters are adequate to begin with, which is not necessarily the case, especially if they have been calibrated using model input assumed to be biased. The present study assesses the performance of various data assimilation configurations on ensemble streamflow predictions when precipitation input is biased in a synthetic experiment simulating the Nechako watershed located in British-Columbia, Canada. These configurations involve data assimilation of snow water equivalent and streamflow observations, and state vector augmentation to include a bias parameter and some model parameters. Results show that including key parameters in the state vector yields considerable improvement of various metrics, such as the bias, the continuous probability rank score and Nash-Sutcliffe efficiency over a range of forecast horizons. However, combining some of these key parameters can degrade the overall performance, highlighting the importance of performing a state vector configuration analysis when using the EnKF.

Keywords:

Ensemble Kalman Filter, Hydrological Modeling, Bias Correction, Ensemble Forecast, Snow Accumulation and Melt

EVALUATING THE U.S. NATIONAL WEATHER SERVICE HYDROLOGIC ENSEMBLE FORECAST SERVICE (HEFS) IN THE MIDDLE ATLANTIC REGION FOR FLOOD AND DROUGHT APPLICATIONS

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Abstract:

U.S. National Weather Service River Forecast Centers (NWS RFCs) produce water forecasts for public safety during floods and for many other applications during all flow conditions. Many users need uncertainty information to take full advantage of these forecasts. The Middle Atlantic River Forecast Center (MARFC) currently uses three different ensemble forecast techniques to produce forecast uncertainty information for different customers. Extended Streamflow Prediction (ESP) techniques predict flow volumes during the next 30 to 90 days by running past climate scenarios through our hydrologic models (Day, 1985). The Meteorological Model Ensemble Forecast System (MMEFS) produces 7-day river forecasts by running raw meteorological ensemble output through our hydrologic models (Adams and Ostrowski, 2010). MMEFS is currently used for situational awareness to give an early indication of flood potential in our region. The Hydrological Ensemble Forecast Service (HEFS) provides the newest set of tools to RFCs, adding powerful capabilities to bias correct meteorological forcing input to our hydrologic models (pre-processing) and bias correct hydrologic model output (post-processing) to produce more accurate forecast ensembles (Demargne et al., 2014).

Along with other NWS Offices, MARFC is evaluating HEFS tools and identifying methods to implement HEFS to enhance operational services. In this study, we investigate several questions that will help us make decisions about further operational implementation. Does the HEFS output improve on MMEFS as a tool for flood potential awareness in the 7-day time frame? If so, will HEFS consistently show improvements over all spatial scales? Can HEFS provide improved seasonal volume estimates relative to those historically provided by ESP?

While traditional verification techniques and hindcasting studies have already shown the potential benefits of HEFS forecasts, it is often difficult to understand the true value of forecasts for decision making using aggregated verification metrics (e.g. Mean Absolute Error, Brier Skill Score, etc.). Therefore, in this study, we augment traditional verification analysis with case studies. In these studies, we evaluate new HEFS-based graphical products that are comparable to ESP and MMEFS graphical products already familiar to decision makers in our region. For example, we look at whether HEFS can improve region-wide flood potential awareness maps relative to MMEFS-based maps for recent flood events. We also use hindcasting to explore whether HEFS-based weekly volume and 90-day exceedance probability maps could improve upon the ESP graphics available during the 2002 drought in the Susquehanna River Basin. Results are still being evaluated and will be presented at the conference.

Keywords:

Ensemble Hydrologic Forecasting, HEFS, ESP, MMEFS

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EXPLOITING THE NOVEL CANADIAN METEOROLOGICAL ENSEMBLE REFORECASTS FOR THE POST-PROCESSING OF THEIR ENSEMBLE FORECASTS

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Abstract:

Biases and dispersion errors of meteorological ensemble forecasts can be minimized through a statistical post-processing of the output data. Performing this task for ensemble forecasts of the Canadian Meteorological Centre (CMC) has always been a challenge due to the lack of a reforecast dataset. Recently, CMC published an eighteen-year-reforecast dataset, which contains 4 nonexchangeable members and extends up to 32 days. It has been used to post-process the 20-member real-time ensemble forecasts of precipitation and temperature for 18 Québec watersheds. It was not possible to apply a standard probabilistic post-processing technique, like the Bayesian Model Averaging (BMA), because of the limited ensemble size (4) of the reforecasts. Therefore, only the bias has been corrected here, based on the distribution based scaling (DBS) technique. DBS models has thus been developed based on the available reforecasts, and applied to the 20-member operational forecasts. A detailed verification by season for the 4-member reforecasts and for the 20-member forecasts is presented in this study to evaluate the impact of our downscaling method for each season. Results show much improvements of the performance in the spring and summer seasons, in contrast with the autumn and winter periods where the improvement is smaller.

Keywords:

Post-Processing, Reforecast, Ensemble Meteorological Forecasts, Distribution Based Scaling, Bias.

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FLOOD FORECASTING FOR RIVERS OVER COLD REGIONS USING GRACE SATELLITE OBSERVATIONS

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Abstract:

Peak river flow or flood forecasting for rivers over cold regions where the discharge is predominately governed by snowpack accumulation and melting remains a challenge. A cold-region peak river flow forecasting model is developed using the observations from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. The model forecasts peak river flows by simulating peak surface runoff from snowmelt and the corresponding baseflow from groundwater discharge. Peak surface runoff from snowmelt is predicted using a temperature index model. Baseflow is predicted using a first order differential equation model. Streamflow measurement is used for model calibration. The model was applied to the Red River and Mackenzie River basins. The predicted peak river flows were found to compare well with the observed values at downstream hydrometric stations. The results also quantified the hysteresis between the maximum snowmelt and the peak river flows, or the travel time for the snowmelt water to reach the hydrometric stations. The model is relatively simple and only needs GRACE and temperature inputs for peak river flow forecasting. It can be readily applied to other cold-region basins after calibration, and could be particularly useful over regions with minimal data.

Keywords:

Flood, Forecast, GRACE Satellite, Model, Cold Region.

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FORECASTING AT QUEBEC PROVINCIAL GOVERNEMENT FOR FLOOD PREDICTION AND DAM MANAGEMENT – AN OVERVIEW OF THE CURRENT OPERATIONAL METHODS AND CHALLENGES PRODUCING FORECAST UNCERTAINTIES

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Abstract:

The Quebec government's forecasting team focus on producing hydrological forecast for flood prediction and public dam management mainly in the southern part of the province of Québec. Current R&D activities include the replacement of the forecasting system as well as the development of a forecasting benchmark for a better assessment of new methods on the quality of the forecast for end-users. The selection of an optimal method for producing useful and relevant uncertainty assessment is one of these new methods and is the current main challenge for the team. The selection should take into account the operational computational limitations, the availability of forecasters for adding values to automated procedures, and the limited interest and capacity of end-users to include uncertainties in their decision processes. The presentation will elaborate on current performances of the system and will present some methods currently analysed with academia and institutional collaborators (ex.: Abaza and al., 2014 and 2015ab, Thiboult et al., 2015).

Keywords:

Operational Forecasting, Benchmark, Uncertainties

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FROM METEOROLOGICAL TO HYDROLOGICAL POSTPROCESSING: THE QUEST FOR AN EFFECTIVE APPROACH

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Abstract:

Ensemble Streamflow Prediction (ESP) has been used to capture the uncertainty in hydrologic predictions. However, ESP is prone to bias due to the uncertainty in forcing data, initial condition, and model structure that are not yet properly characterized. Bias-correcting or in general post-processing the climate forecast has been found necessary before inclusion of these forcing data in operational hydrologic forecasting systems. This presentation aims to: 1) introduce a practical approach for Ensemble Post-Processing (EPP) to reduce the uncertainty arising from the forcing data and 2) evaluate the efficacy of post-processing the hydrologic forecasts in enhancing the reliability and skill of such forecasts. The North American Multi-Model Ensemble (NMME) consisting of 99 ensemble members are taken as forcing data. Different scenarios are designed to assess the effect of postprocessing of meteorological and hydrological forecasts individually and in combination to identify the effectiveness of these methods in operational forecasting for the basins located in the Western United States.

Keywords:

Bias correction, NMME, ESP, Post-Processing

FROM SEASONAL FORECASTS TO SCENARIOS OF CLIMATIC VARIABILITY

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Abstract:

Seasonal forecasts have been shown to be of use in informing water resources managers, with forecasts showing skill over climatology for lead times reaching up to 4-5 months, depending on the geographic location, as well as the parameter being forecasted. Additional to the information this provides, water resource managers may, however, be interested in longer term outlooks. Rather than using these as forecasts, these represent possible future scenarios and can be applied as a stress test, given the current water resources situation and the variability of the climate. In this paper we present a novel technique to develop such scenarios. A nearest neighbour sampling technique (Beersma & Buishand, 2003; Peters et al., 2005) is applied to sample analogues from the climate record based on the Mahalonobis distance of a vector of normalized indices relevant to the climate. This method is extended by conditioning the samples using the values of the indices at the start of the scenario, or forecast start time. An ensemble of possible scenarios, conditional on the current condition is developed through a bootstrap.

We apply the method to estimating groundwater recharge due to rainfall in the Valle del Cauca region in Colombia. This is an important parameter in sustainably managing the groundwater resources in the area, which are exploited for irrigating the extensive sugar cane crops. Climate variability is strongly influenced by the El Niño Southern Oscillation, and the indices we consider in the resampling technique include the Standardised Precipitation Index (SPI), and the Southern Oscillation index (SOI). Results show that using the proposed sampling strategy, realistic scenarios can be developed, conditional on the current climatic conditions in the area. We show that the sampled scenarios have skill in the first months, and then seamlessly becoming scenarios that represent the climatic variability, including possible worst case scenarios. This can provide water resource managers in the Valle region with clear insight into the possible development over the forthcoming months, as well as the possible impact, should extreme climatic conditions prevail.

Keywords:

Drought, Seasonal Forecasts, Climate Variability Scenarios, Analogues, Sampling

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HYDROLOGIC ENSEMBLE PREDICTION: ENHANCING SCIENCE, OPERATION AND APPLICATION THROUGH HEPEX

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Abstract:

HEPEX (Hydrologic Ensemble Prediction Experiment) was established in March 2004 at a workshop hosted by the European Centre for Medium Range Weather Forecasts (ECMWF), co-sponsored by the US National Weather Service (NWS) and the European Commission (EC). Over its more than 10 years of existence, HEPEX and the community it represents have continuously worked to promote and advance the science of hydrologic ensemble prediction as well as operational systems and water management applications. Through workshops and conference sessions, HEPEX has connected the research community, forecasters and forecast users and facilitated the exchange of ideas, data, methods and experience. In particular, the establishment of an online blog portal has greatly enhanced community interaction and knowledge sharing (www.hepex.org). HEPEX has now a strong and active community of nearly 400 researchers and practitioners around the world. In this poster, we present an overview of recent and planned HEPEX activities, and highlight opportunities to further progress ensemble prediction science, operation and application.

Keywords:

Ensemble Prediction, Operational Systems, Water Management, Community Building

HOW DO I KNOW IF I'VE IMPROVED MY CONTINENTAL SCALE FLOOD EARLY WARNING SYSTEM?

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Abstract:

Flood early warning systems mitigate damages and loss of life and are an economically efficient way of enhancing disaster resilience. The European Flood Awareness System (EFAS) is a pan-European flood early warning system (EWS) providing probabilistic warnings up to 15 days ahead of a flood event. Here, a new strategy for evaluating the implementation of scientific improvements to EWS is presented, which considers the skill of river discharge variables and the monetary value of warnings. The combination of a multi-forcing ensemble of EFAS flood forecasts is evaluated. It is found that a fully combined multi-forcing ensemble is to be recommended for operational forecasting and warning. However, there are spatial variations in the optimal forecast combination between different river catchments. Adding more than 2 NWPs to the multi-forcing ensemble does not bring further benefit. The use of the CRPS with lagged ensembles is recommended to reflect both skill and monetary value.

HOW MUCH CAN WE IMPROVE THE HYDROLOGICAL FORECASTING SKILL IN SNOW DOMINATED REGIONS VIA SNOW DATA ASSIMILATION?

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Abstract:

Accurate prediction of spring melt runoff is an important need for hydropower reservoir management in Sweden. The predicted spring flood volume is used to optimise the hydropower production during the current winter while still be able to fill up the reservoirs until next year and/or to reach a minimum required level at a certain date. In an effort to improve spring flood forecasting, SMHI in close collaboration with the hydropower industry has been incorporating information from snow observations of various types (manual snow depth observations at weather stations; manual snow water equivalent observations in points or along survey lines, ground-penetrating-radar surveys from snow mobile or helicopter, as well as satellite based observations of snow covered area and snow water equivalent) and use those in hydrological modelling. The most common method to assimilate snow observations in operational hydrological models has been to modify the meteorological forcing data (manually or semi-automatic) during some time-window up to the forecast date to minimize the difference between observed and simulated snow water equivalent. Recently, more advanced data assimilation methods such as Ensemble Kalman filter have also been used in similar efforts. The main causes of failure to systematically improve the seasonal forecasts have been attributed to on one hand the problem to translate point or line survey data into representative sub-basin average values, or on the other hand how to downscale satellite based data to the sub-basin scale, especially in mountain areas. In here, we evaluate methods for updating hydrological models by use of: 1) operational snow depth measurements from SMHI, 2) satellite based data on snow water equivalent and snow cover area from EU FP7 project CryoLand, and 3) pre-operational manual observations of snow depth, snow density and snow water equivalent located close to hydropower reservoirs in the Swedish mountain area, operated by hydropower management company Vattenregleringsföretagen AB.

Results show that assimilation of snow information improved spring melt forecasts in most of the study areas and study years. It was mainly manual observations of snow water equivalent and satellite based data on fractional snow cover area that where useful for improving the forecasts. However, model updating with snow data does not always lead to improved simulations of river discharge and reservoir inflow probably due to: 1) the uncertainty in the weather forecast/climatological forecast is more important than the uncertainty in the snow conditions at the start of the forecast, 2) the updating methods do not take into account systematic representation errors in the assimilated snow information in an adequate way, and 3) the manual snow observations are most sparse and the satellite based data is most uncertain in the mountain areas that are most interesting for spring melt runoff predictions from a hydropower management perspective.

Keywords:

Snow Observations, Remote Sensing, Data Assimilation, Spring Melt Runoff Forecasts

IMPACT OF BETTER FORECASTS ON A DECISION MODEL FOR HYDROPOWER

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Abstract:

The needs of hydropower operational systems for accurate and reliable weather forecasts cover a wide range of space and time scales: short-range forecasts (from a few hours up to 2-3 days ahead) that are used for flood protection of the population living downstream of the facilities and for the security of installations, medium-range forecasts (up to 7-15 days ahead) that are used for the optimisation of hydropower production, long-range (months ahead) streamflow forecasts that are used for water resources management and planning.

Since the operation of hydropower systems, including the management of water reservoirs, is impacted by weather and climate variability and extremes, it is essential to quantify how operations and management rules are sensitive to improved predictability of hydrometeorological events at different time and space scales. This study proposes a preliminary investigation on how 7-day ahead deterministic and ensemble streamflow forecasts of different quality might impact economic gains of energy production. It is based on a heuristic model developed by Irstea and EDF for the optimisation of energy production (Zalachori, 2013) and applied in South-Eastern French catchments. Through a synthetic experiment, inputs of different quality are used to assess the sensitivity of the decision model to forecast quality. Relationships between forecast quality and economic value are discussed.

This work is part of the IMPREX project, a research project supported by the European Commission under the Horizon 2020 Framework programme, with grant No. 641811 (http://www.imprex.eu)

Keywords:

Hydropower, Extreme Events, Forecast Value, Economic Gain

Reference

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IMPACT OF DYNAMICAL DOWNSCALING ON LAND SURFACE MODEL FORCINGS

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Abstract:

Extremes in the water cycle, such as drought and flood, threaten the sustainability of water resources and cause significant impacts on society that will likely increase due to growing populations and a changing climate. Reducing the impact of extreme events requires preparations enabled by reliable and relevant predictions of streamflow and other hydrologic variables at seasonal time scales. Climate predictions from Global Climate Models (GCMs) can provide seasonal predictions of climate that can aid in predicting the local aspects of the hydrologic system, however the GCM spatial resolution is typically too course for application at the local level where the prediction is needed to ensure a society resilient to extremes. Therefore, a common practice is to downscale the climate predictions to finer spatial resolutions. One way of downscaling the GCM output is through dynamical downscaling using a regional climate model that can provide predictions at scales consistent with the hydrologic application. There are still many questions about the utility of dynamical downscaling and the results are dependent on model physics, model setup (e.g. boundary conditions, nudging) and as a result the overall validity of dynamically downscaling has not been fully demonstrated to date.

NASA has recently sponsored an intra-agency downscaling project to better understand the validity of dynamical downscaling. As part of this project, several 10-year simulations of the NASA Unified Weather Research and Forecast (NU-WRF) model that vary in resolution and large scale nudging were used to downscale MERRA-2 reanalyses over the continental U.S. In addition, a high resolution globally downscaled run was also produced by the NASA Global Modeling and Assimilation Office (GMAO) called the MERRA replay. This work leverages these model runs in order to understand the impact of model resolution, nudging and domain on the forcing variables needed to make seasonal streamflow predictions using hydrologic models. The precipitation, daily minimum and maximum temperature and wind speed from these model runs are analyzed and compared against the original outputs from the MERRA Reanalysis as well as gauge data over the Central Great Plains. The results suggest that the local impacts due to resolution are less than those due to the type of nudging and model, although there is some improvement with an increase in spatial resolution. Furthermore, the spatial variability of precipitation from the model runs ranges from underestimating to overestimating the gauge based data and suggests that some model configurations may not be representative of reality. The impacts of these findings relative to seasonal streamflow prediction and possible ways forward are also discussed.

Keywords:

Downscale, Seasonal Prediction, Precipitation, Temperature, Wind

IMPROVING HYDROLOGIC PREDICTION THROUGH STATE UPDATING

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Abstract:

Data assimilation (DA) holds considerable potential for improving hydrologic predictions. However, advances in hydrologic DA research have not been adequately or timely implemented in operational forecast systems to improve the skill of forecasts for better informed real-world decision making. Several challenges exist (see Liu et al., 2012). The objective of this paper is to highlight several recent studies on basin and continental scale data assimilation using distributed hydrologic models that touch upon these challenges including application of streamflow data assimilation using different algorithms, combined streamflow/snow data assimilation and the development of a generic linkage of OpenDA and the open source hydrologic package Openstreams/Wflow based on the (emerging) standard Basic Model Interface (BMI) as advocated by CSDMS using cross-platform webservices (i.e. Apache Thrift).

Keywords:

Uncertainty, Noise, Data Assimilation, Skill Scores.

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INVESTIGATING THE RELATIONSHIP BETWEEN PRECIPITATION INPUT AND MODEL PARAMETER DISTRIBUTION DURING CALIBRATION: INITIAL RESULTS FROM 72 CANADIAN BASINS

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Abstract:

Model calibration is an important step in any hydrological forecasting system and is an important potential source of structural model errors. To investigate the impact of precipitation forcing on model parameter calibration and parameter distributions, the Mac-HBV model was calibrated using a Markov Chain Monte Carlo algorithm known as MT-DREAM$_{(ZS)}$ with three different precipitation products in 72 Canadian reference hydrometric basins. Precipitation was derived from a classic inverse-distance weighting (IDW) approach, from the ANUSPLIN derived CanGRD daily precipitation product and from the Canadian Precipitation Analysis (CaPA). The median Nash-Sutcliffe Efficiencies (NSE) were 0.79, 0.82 and 0.38 for CaPA, CanGRD and IDW respectively during the calibration period. The difference in model performance (NSE) when calibrated with CaPA or CanGRD was less than 10% in 50 basins, 5% in 39 basins and 1% in 13 basins. Despite the similar performance during the calibration period, in all cases the similar performance (within 1%) was achieved with markedly different distributions of most parameters.

During validation 49, 53, and 21 basins were within 80% of the calibration NSE for CaPA, CanGRD and IDW respectively and 41 basins had NSE values below zero. An investigation of basin characteristics and parameter distributions will be used to elucidate the strengths and weaknesses of the precipitation products. Since each of these precipitation products are only available as an analysis, a forecast experiment with each parameter set and NWP precipitation forecasts during the validation period will also be used to examine operational forecast skill.

Keywords:

CaPA, CanGRD, DREAM, Parameter Uncertainty, Calibration.

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INVESTIGATING QUALITY AND VALUE OF DISSIMILAR STREAMFLOW FORECASTING SYSTEMS

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Abstract:

Floods are among the most devastating natural hazards, both in terms of human and economic loss. One of the main purposes of the hydrometerological sciences is to build operational and efficient tools, such as Early Warning Systems (EWS), which aim to prevent and mitigate losses that adverse events may cause (Rogers and Tsirkunov, 2011; Pappenberger et al., 2015). In the scientific literature, most streamflow forecasting systems are assessed according to their quality (bias, accuracy, skill, reliability, etc.). More rarely, their economic value is investigated (Boucher et al., 2012).

This study assesses the quality and the value of five different ensemble forecasting systems, which differ by the amount of total predictive uncertainty they are expected to decipher and, thus, by their complexity. The forecasting systems rely on tools that quantify and reduce the predictive uncertainty. For this purpose, meteorological ensemble forcing, hydrological multimodel approach and the Ensemble Kalman filter are used to decipher meteorological, structural and parameter, and initial conditions uncertainty, respectively. The EWSs are subsequently assessed with several criteria of forecast quality (NSE, Normalized Root-mean-square error Ratio) and with the Relative Economic Value (REV), in a cost-loss and flood mitigation situation on 20 watersheds.

Results show that every EWS systematically provides an economic gain over the “no warning” case, regardless of the forecasting horizon and the catchment. The different tools applied to quantify uncertainty confer to the forecast a higher quality, which is also reflected in the REV. The most complex EWS, the one that deciphers more sources of uncertainty, also provides hydrological forecasts with the best quality and the highest REV. However, a clear relationship between forecast quality and value could not be detected when considering all EWS investigated. The need for further investigation is discussed.

Keywords:

Forecast quality, Economic value, Uncertainty, Ensemble forecasting, Decision making

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METEOROLOGICAL ENSEMBLE FORECAST VERIFICATION STUDY AT THE CATCHMENT SCALE OVER QUEBEC, CANADA.

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Abstract:

Uncertainty in short to medium range meteorological forecasting can be quantified using ensemble forecasts (Leutbecher and Palmer, 2008). The added value of ensemble forecasts is already well established for short and medium range lead times (Cloke and Pappenberger, 2009). However, an extended forecast verification exercise has not been realised at the catchment scale on the province of Quebec, Canada. Consequently, a pre-operational testing system of the NAEFS forecasts (Toth et al., 2006) has been operating at Hydro-Québec since May 2015. The purpose of such system is to evaluate the added value of using ensemble forecasts for operational hydrological forecasting at Hydro-Québec.

This article presents the results of an ensemble forecast verification study conducted over 52 operational Hydro-Québec catchments, all located between 44°N and 55°N. The meteorological forecasts archive comes from the TIGGE database (Swinkank et al., 2015). Three meteorological variables used as input for the Hydro-Québec operational hydrological model to compute inflow forecasting were assessed: total precipitation, maximum temperature and minimum temperature. The verification metrics used in this experiment were selected for their ability to evaluate the reliability and resolution of ensemble forecasts. In particular, skill scores were considered using the climatology as forecast reference in order to determine the relative performance of these ensemble forecasts.

Keywords:

Ensemble Forecasts, Verification, Skill Score, Reliability.

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MULTIVARIATE STATISTICAL POSTPROCESSING OF ENSEMBLE FORCASTS OF PRECIPITATION AND TEMPERATURE OVER FOUR RIVER BASINS IN CALIFORNIA

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Abstract:

Hydrological forecasts strongly rely on predictions of precipitation amounts and temperature as meteorological inputs to hydrological models. Ensemble weather predictions provide a number of different scenarios that reflect the uncertainty about these meteorological inputs, but are often biased and underdispersive, and therefore require statistical postprocessing. In hydrological applications it is crucial that spatial and temporal (i.e. between different forecast lead times) dependencies as well as dependence between the two weather variables is adequately represented by the recalibrated forecasts.

We present a study with temperature and precipitation forecasts over four river basins over California that are calibrated with a variant of the nonhomogeneous Gaussian regression method (Gneiting et al., 2005) and the censored, shifted gamma distribution approach (Scheuerer and Hamill, 2015) respectively. The Schaake Shuffle (Clark et al., 2005) and recently proposed variants of it are used to generate forecast trajectories with realistic spatial and temporal dependence structures, and their respective strengths and weaknesses are evaluated and compared via state-of-the art multivariate verification techniques.

Keywords:

Meteorological Forcing, Multivariate, Postprocessing, Reforecasts.

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OPERATIONAL HYDROLOGIC-HYDRAULIC ENSEMBLE PREDICTION SYSTEM IN URBAN WATERSHEDS: RUNOFF AND COMBINED SEWER OVERFLOW (CSO) FORECASTS IN THE CITY OF HOBOKEN, NJ

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Abstract:

This work investigates the utility of ensemble weather forecast precipitation inputs for the prediction of hourly runoff and combined sewer overflow in a highly urbanized watershed. The study encompasses the City of Hoboken, NJ. Hoboken's development at the Hudson Riverfront over the past two centuries has led to a bowl-shaped relief and an impervious coverage of 94%, leading to chronic flooding during wet weather that can overwhelm its combined sewer drainage network that collects both sewage and urban runoff.

A state-of-the art operational forecast platform using the US Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) was developed to provide hydrologic-hydraulic representation of Hoboken's stormwater system. Hoboken was divided into a number of sub-catchment areas that receive precipitation from an ensemble of weather prediction models and generate runoff to the routing component. The latter transports this runoff through a system of pipes and hydraulic connections in order to forecast discharge, with up to 96 hours lead time, at seven combined sewer overflow (CSO) outfalls located along the Hudson River.

The framework was forced with precipitation forecasts from 125 weather ensemble members that include the European Center for Medium range Weather Forecasting (ECMWF), Global Ensemble Forecast System (GEFS), Short-Range Ensemble Forecast (SREF), Canadian Meteorological Centre (CMC) and the North American Mesoscale Forecast System (NAM).

This work shows that ensemble modeling provides useful information about uncertainties associated with the meteorological inputs. The framework has several important perspectives in the context of stormwater best management practices and prediction, including the continuous simulation of pollutant loads and backwater flow conditions.

Keywords:

Ensemble Prediction System, Stormwater, Combined Sewer Overflow, SWMM, Weather models

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OPPORTUNITIES AND CHALLENGES OF TRANSITIONING TO AN INFLOW FORECAST SYSTEM OF HIGHER COMPLEXITY AT BC HYDRO

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Abstract:

BC Hydro's inflow forecast system has been undergoing major redevelopment over the last few years to accommodate a growing demand for better ensemble forecasting capability. The new system, which is built on the Deltares FEWS platform, incorporates both short-range and long-range ensemble forecasting capability and significantly improves on the predecessor in terms of data visualization and forecast model configuration. While the UBC Watershed model remains the core engine, the transition from elevation bands to hydrologic response units as the basic modeling block offers the ability to assimilate data with finer spatial resolution. Some other new features include the ability to perform automated data loading, forecast updating, hindcasting, verification and web-based reporting. This presentation will discuss the opportunities offered by these improvements and the challenges of data assimilation and computational efficiency that come with increasing spatial discretization in an operational environment.

Keywords:

BC Hydro, Ensemble Forecasting, Inflow Forecasting, UBC Watershed Model, Deltares FEWS

POST-PROCESSING AND VERIFICATION OF MONTHLY HYDROLOGICAL FORECASTS IN SWITZERLAND

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Abstract:

In Switzerland a drought awareness system has been developed in order to inform the public about water scarcity and its environmental impact at present and how the situation will possibly change within the next days ahead (www.drought.ch). In Spring 2015 the system has been enhanced by incorporating monthly weather forecasts and deriving hydrological predictions relevant for water and agricultural management. These forecasts for the next 32 days consists of 50 members of the Ensemble Prediction System from ECMWF and one control run and are available twice per week.

Besides the process of downscaling in order to overcome the gap between meteorological and hydrological model resolutions (grid cells of 50km, resp. 500m length), which will be accomplished using Quantile Mapping approaches, the post-processing of the outcome of the hydro-meteorological model chain is important for improving the quality of the prediction system and for deriving predictive probability density functions. Therefore, different methods have been tested with varying complexity ranging from simple Autoregressive processes to more complex methodologies combining wavelet transformations and Quantile Regression Neural Networks (QRNN) and including the derivation of predictive uncertainties (Bogner and Pappenberger, 2011; Bogner et al., accepted).

Regarding the practical evaluation of the forecast two major problems arise: at the moment the available series of monthly forecast are limited to one season only and on the other hand the forecasts are aggregated to predefined political regions, which most often do not correspond to hydrological catchments, thus no direct verifying measurements are available. However, for all these regions long term simulations have been calculated driven by observed meteorological input data, which could be referred to as climatology. For these reasons the Geometric Mean Relative Absolute Error (GMRAE) is used to measure out-of-sample forecast performance (see Fig. 1). It is calculated using the relative error between the benchmark model (i.e., climatology) and the currently selected forecast model (e.g. a GMRAE of 0.54 indicates that the size of the current model's error is only 54% of the size of the error generated using the climatology for the same data set). Since the GMRAE is based on a relative error, it is less scale sensitive than the MAPE and the MAE and therefore allows the comparison of different regions and variables.

At gauging stations, the preferred verification measures are the two alternatives forced choice score (2AFC), which reflects the forecast performance in discriminating between different observation (Mason and Weigel, 2009) and the Continuous Ranked Probability Score (CRPS), which compares the forecast probability distribution with the observation and addresses the sharpness and the reliability and can be interpreted as a general version of the Mean Absolute Error (Gneiting et al., 2005). First verification results of the monthly forecast for the very dry Summer 2015 in Central Europe show some clear signal of potential water scarceness in Switzerland already beginning of June for the next couple of weeks. Although these first results are quite promising further analysis have to be carried out with longer forecast periods.

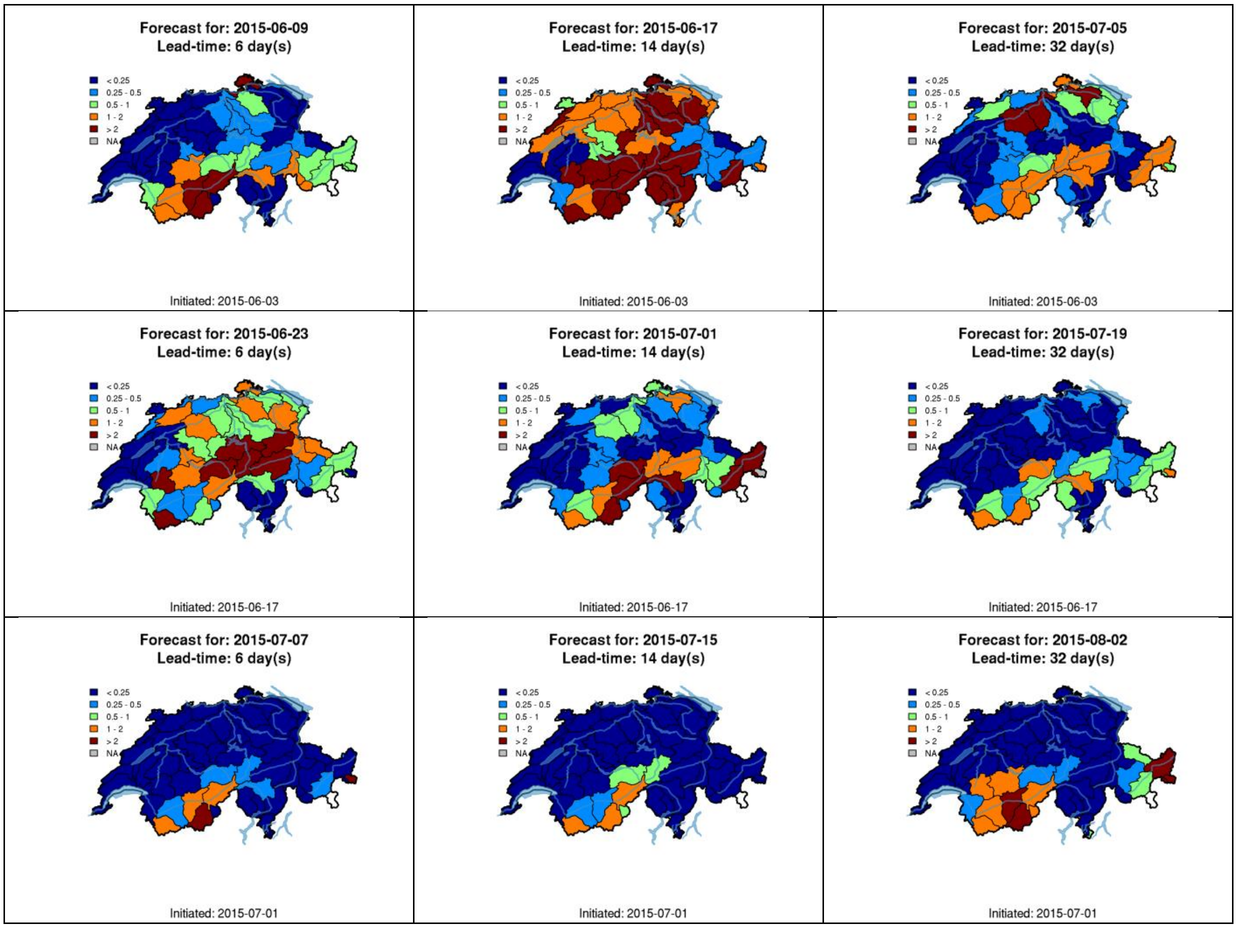

Figure 1: Forecast verification of the surface runoff aggregated to regional areas applying the Geometric Mean Relative Absolute Error (GMRAE) measure for three different lead-times (columns) and three different initializations (rows).

Keywords:

Monthly Forecast, Post-Processing, Forecast Verification

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POST-PROCESSING ENSEMBLE PRECIPITATION FORECASTS USING GEOMETRIC MODEL COMBINATION

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Abstract:

Forecasts of precipitation from deterministic and ensemble numerical weather prediction (NWP) models are being increasingly used for hydrological forecasting applications. Forecasts from ensemble NWP models typically have lower errors than those produced by deterministic NWP models, but are still susceptible to bias and over confidence. Statistical post-processing has been demonstrated to reduce errors in deterministic precipitation forecasts and reliably quantify forecast uncertainty. However, methods of post-processing ensemble NWP forecasts that use more than just ensemble summary statistics are still in their infancy.

This poster describes the extension of a Bayesian forecast post-processing approach (Robertson et al., 2013), which has been applied to deterministic precipitation forecasts (Shrestha et al., 2015), to deal with forecasts from an ensemble NWP model. When applied to deterministic NWP forecasts, the Bayesian forecast post-processor models the joint distribution of NWP precipitation forecasts and corresponding observations using a log-sinh transformed bivariate normal distribution. Zero and very small values of precipitation are treated as censored data. A post-processed ensemble forecast is produced by conditioning the joint distribution on the NWP forecast value and taking samples from the conditional distribution. Separate models are fitted to data for each forecast location and lead time, and the Schaake shuffle (Clark et al., 2004) used to ensure that ensemble forecasts have appropriate space-time correlations.

The extended Bayesian post-processing approach combines probability density forecasts produced by post-processing different NWP ensemble members. We adopt a geometric combination approach, rather than the more commonly used arithmetic combination, which has the advantage of producing post-processed forecasts with thinner tails and a single mode. Model parameters for the joint distribution are inferred using a composite likelihood function.

Using the extended post-processing approach, we show the fitted model describes the marginal distributions of and correlation between the raw NWP forecasts and the observations. Under cross-validation, post-processed forecasts are shown to have lower bias than the raw ensemble NWP forecasts and more reliability quantify forecast uncertainty.

Keywords:

Post-Processing, Precipitation, Ensemble Numerical Weather Predictions, Verification, Forecast Reliability.

PRESERVING THE SPACE-TIME DEPENDENCE STRUCTURE IN HYDRO-METEOROLOGICAL FORECASTS: A CASE STUDY WITH ANALOGUE DERIVED PQPF

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Abstract:

Preserving the space-time dependence structure in meteorological forcing ensembles is a major concern in Hydrological Ensemble Prediction Systems (HEPS). This is particularly important to prevent concomitant flood events to which industrial and civil safety are very sensitive. In this study we focus on Probabilistic Quantitative Precipitation Forecasts (PQPF) derived with an analogue method (Obled et al, 2002) applied on several catchments of the French Upper Rhone basin. The prediction horizon is 5 days with a 6-hour time step. Because analogue dates are selected independently for given locations and given lead times, forecasts need to be reordered so as to construct an ensemble of traces that are physically coherent. We applied different reordering methods such as the Schaake shuffle (Clark et al., 2004) and the ensemble copula coupling (Schefzik et al., 2013). The former approach gives to any ensemble the rank dependence structure from randomly selected historical observations, while the latter picks the dependence structure from raw ensembles issued an ensemble prediction system. An adaptation of the Schaake shuffle is also proposed, where historical observations are selected by the analogue method having been applied on the whole study basin. It therefore replicates on the forecast the space-time rank dependence structure that has been observed on past days with similar large scale atmospheric patterns. A twostep verification was carried out in order to assess the benefit of the aforementioned reordering methods. Firstly, multivariate analyses of PQPF against precipitation observations were conducted. Secondly, PQPF for each catchment were used as input of rainfall-runoff models, providing hydrologic ensemble traces at the confluence point. The verification against simulated streamflows thereby isolates the effect of the meteorological ensemble dependence structure on streamflows.

Keywords:

Probabilistic Quantitative Precipitation Forecasting, Analogues, Schaake Shuffle, Rhone River.

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PROCESSING OUTPUTS FROM A LAND-DATA ASSIMILATION SYSTEM IN ORDER TO GET ENSEMBLE STREAMFLOW PREDICTIONS FOR FREE: DO WE GET MORE THAN WHAT WE PAID FOR?

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Abstract:

Operational numerical weather prediction (NWP) systems benefit tremendously from accurate initial conditions of surface characteristics (Belair et al., 2003). Environment and Climate Change Canada provides 48-h weather forecasts every six hours at a resolution of 2.5-km on a domain covering all of Canada with the exception of the arctic archipelago. This forecasting system is known as the High-Resolution Deterministic Prediction System (HRDPS, Mailhot et al., 2014). Initial conditions of soil moisture, soil temperature, and snow depth are provided by the Canadian Land Data Assimilation System (CaLDAS, Carrera et al., 2015), which relies on an ensemble Kalman filter (EnKF) procedure. Hence, although the weather forecasting system is deterministic, a 24-member ensemble of initial conditions and 6-h forecasts is available every 6-h at each grid point. During the model integration phase of CaLDAS, the embedded land-surface model generates surface runoff and ground water recharge at each model time step and for each member. These fields can be aggregated spatially and temporally in order to convert them into streamflow predictions. In this presentation, we compare two methods for estimating streamflow at a single location from CaLDAS outputs: a unit hydrograph approach similar to the one used by the GR4J lumped hydrological model, and a 1-km scale distributed routing model (WATROUTE). Similar results are obtained with both approaches. While it can be argued that the distributed model offers more flexibility for taking into account control structures and provides more information on streamflow throughout the watershed, a non-negligible amount of effort is required to set up and run this model. The unit hydrograph approach can be implemented as a simple post-processing system of standard NWP outputs; hydrological forecasts are produced with minimal effort. Limitations of this system include the simplistic representation of the land-surface in the atmospheric model, the fact that streamflow observations are not assimilated by the EnKF, and that hydrological forecasts are only available at specific locations. The first issue is currently being addressed: the legacy two-layer land-surface model ISBA is being replaced by the multi-layer SVS land-surface model (Alavi et al., 2016), itself coupled to the WATDRAIN hillslope model (Soulis et al., 2011). This major update should permit the assimilation of streamflow observations in CaLDAS by adjusting deep soil moisture estimates, with the unit hydrograph constituting the observation operator. If this approach is successful, then not only can we get hydrological forecasts virtually for the price of a weather forecast, but potentially better weather forecasts as well.

Keywords:

Numerical Weather Prediction, Land Surface Model, Land Data Assimilation System, Unit Hydrograph

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PROGRESS TOWARD ENSEMBLE FLOOD AND 7-DAY STREAMFLOW FORECASTING SERVICES FOR AUSTRALIA

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Abstract:

Australian streamflow forecasting services have traditionally focussed on flood events and only been available when anticipated or observed rainfall is significant. Most of these services are based on event models that are initialised at the commencement of a flood. These models produce accurate estimates of flood levels once a hydrograph has commenced rising, but are limited in their ability to forecast flooding at long lead times. Flood forecasting services have recently been augmented by a 7-day forecasting service to support water resources management. The service issues forecasts derived from continuous hydrological models, real-time rainfall and streamflow observations and raw precipitation forecasts from the global ACCESS numerical weather prediction (NWP) model. Forecasts of daily streamflow totals out to 7 days are available to the public, while registered users can access forecast hydrographs at hourly time steps. The ultimate aim is for these services to issue ensemble forecasts.

Developing and verifying ensemble flood and short-term streamflow forecasting methods for Australia is challenging. Many of the rivers that supply water resources and pose flooding hazards are ephemeral, ceasing to flow for long periods each year. This reduces the effective length of streamflow records, and hence available verification data. In addition, the record length and spatial coverage of hourly rainfall observations are often limited. Rain gauge records with spatial densities sufficient to calibrate hydrological models are often available for only 10 years or fewer. Australian NWP models are rapidly evolving and archives of forecasts from an individual model version rarely exceed 4 years.

This presentation will discuss the progress in developing and verifying methods for ensemble flood and 7-day streamflow forecasting services in Australia. Key research findings that will be highlighted in the presentation include:

- Generating reliable ensemble streamflow forecasts is essential to explicitly model the uncertainty in forecast rainfall and hydrological modelling processes.
- Choosing an effective precipitation post-processing method results in much greater increases in streamflow forecast performance than using an ensemble of NWP models
- To correctly represent hydrological uncertainty in forecasts, error models must be able to: i) handle the skewed and heteroscedastic nature of residuals; ii) correct strongly conditional bias; iii) account for autocorrelation in residuals; iv) use appropriate parametric distributions to represent residual to ensure reliable ensemble forecasts; and v) propagate errors correctly so that uncertainty is correctly represented at long lead times
- Hydrological error modelling in ephemeral catchments is especially difficult, and requires a combination of statistical techniques to ensure reliable ensemble forecasts.

Keywords:

Streamflow Forecasts, Verification, Forecast Reliability.

SEASONAL FORECASTING OF RIVER DISCHARGE IN THE UPPER YELLOW RIVER BASED ON THE DISTRIBUTED GRID AND PHYSICAL PROCESS BASED VIP MODEL AND BEYOND

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Abstract:

Vegetation Interface Processes (VIP) Model, a grid-based, physical process-based eco-hydrological model, is used to forecast the seasonal flow at the outlet (Tangnaihai Gauge) of upper Yellow River with the control area of 121,972 km2. The model runs in hourly and 1 km resolution from 1971 to 2001 driven by the EU WATCH forcing data. The monthly model performance reaches 0.72 (NSE) and -5.38% (PBIAS). Projections are from five GCM models including GFDL-esm2m, HADgem2-es, IPSL-cm5a-lr, Miroc-esm-chem and NORESm1-m. In order to evaluate the accuracy of the seasonal forecasting results, a mock seasonal-forecast is done starting from January 1, 2007, at two initial conditions including the observed and simulation results from January 1, 2005 onwards. Weekly, monthly and seasonally forecasting results are compared (ensembled) with the observed, routine seasonal forecasting results by the local operational sectors, as well as the exploring forecasting results based on geophysical factor such as polar motion, respectively. The ensemble forecasting results are for the reference for the water resources management of Yellow River, especially for improving the operational seasonal forecasting skill of the Longyang Reservoir, which is located 133 km downstream of the Tangnaihai station.

Keywords:

VIP Model, Seasonal Forecasting, Polar Motion, Upper Yellow River

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SEASONAL HYDROLOGICAL PREDICTABILITY AND THE NMME-BASED FORECASTING OVER THE YELLOW RIVER BASIN IN CHINA

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Abstract:

Climate change has fundamentally affected terrestrial hydrological cycle, with an increasing risk of hydrological extremes that challenges the water resource management. This calls for an effort of mitigation and adaptation, where the latter might be an effective approach for a timely action to reduce the risk. Nevertheless, a well-planned adaptation cannot be achieved without a reliable prediction of the future. In terms of terrestrial hydrology, a basic question is how to manage the water resources that is adaptive to climate change, especially to the extreme events. In other words, how to predict the future hydrology at a lead time that is not only long enough for taking an action, but also reliable for an effective adaptation is a big concern both for science and application.

In this presentation, an experimental seasonal hydrological forecasting system over the Yellow River basin in northern China is introduced. The system makes use of the North American Multimodel Ensemble (NMME) seasonal climate prediction, a spatial downscaling and bias correction method that is used to transfer global climate prediction of meteorological forcings for driving a land surface hydrological model and a routing model, where the hydrological models are calibrated grid by grid at a 0.25-degree resolution over a 752,000 km^2 drainage area, by using the reference runoff disaggregated from the naturalized streamflow. In addition, a hydrological post-processor is incorporated to correct the hydrological modeling errors that cannot be calibrated, such as the human interventions in terms of irrigation and inter-basin water diversion, which are very common over the Yellow River basin.

The hydrological part of the system is used to conduct Ensemble Streamflow Prediction (ESP) and reverse ESP-type simulations, and the natural hydrological predictability in terms of initial hydrological conditions (ICs) and meteorological forcings is assessed over the Yellow River. The assessments conditional on the surface and subsurface water state variables, and the dry/wet conditions are also investigated. A set of 6-month seasonal hydrological hindcasts during 1982-2010 by connecting with multiple NMME climate forecast models are performed. The climate-model-based forecasting is comparing with the ESP approach to explore the added values from climate forecast models, especially when the effects of human interventions are implicated considered.

Keywords:

Seasonal Hydrological Forecasting, Drought, Predictability, VIC, NMME

SWIFT2: SOFTWARE FOR CONTINUOUS ENSEMBLE SHORT-TERM STREAMFLOW FORECASTING

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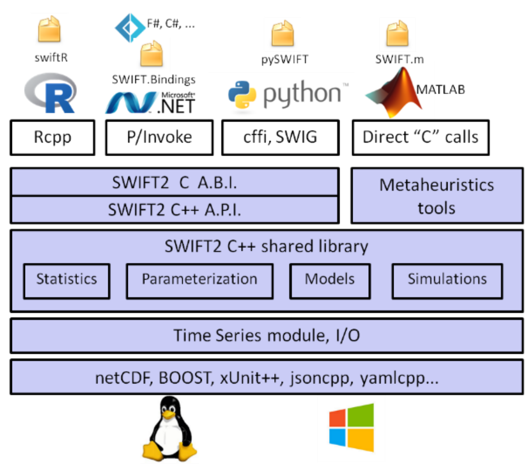
Abstract:

Research undertaken through the Water Information Research and Development Alliance (WIRADA) has laid the foundations for continuous deterministic and ensemble short-term forecasting services. One output of this research is the software Short-term Water Information Forecasting Tools version 2 (SWIFT2).

SWIFT2 is developed for use in research on short term streamflow forecasting techniques as well as operational forecasting services at the Australian Bureau of Meteorology. The variety of uses in research and operations requires a modular software system whose components can be arranged in applications that are fit for each particular purpose, without unnecessary software duplication. SWIFT2 modelling structures consist of sub-areas of hydrologic models, nodes and links with in-stream routing and reservoirs. While this modelling structure is customary, SWIFT2 is built from the ground up for computational and data intensive applications such as ensemble forecasts necessary for the estimation of the uncertainty in forecasts. Support for parallel computation on multiple processors or on a compute cluster is a primary use case. A convention is defined to store large multi-dimensional forecasting data and its metadata using the netCDF library.

SWIFT2 is written in modern C++ with state of the art software engineering techniques and practices. A salient technical feature is a well-defined application programming interface (API) to facilitate access from different applications and technologies. SWIFT2 is already seamlessly accessible on Windows and Linux via packages in R, Python, Matlab and .NET languages such as C# and F#. Command line or graphical front-end applications are also feasible.



This poster gives an overview of the technology stack, and illustrates the resulting features of SWIFT2 for users. Research and operational uses share the same common core C++ modelling shell for consistency, but augmented by different software modules suitable for each context. The accessibility via interactive modelling languages is particularly amenable to using SWIFT2 in exploratory research, with a dynamic and versatile experimental modelling workflow. This does not come at the expense of the stability and reliability required for use in operations, where only mature and stable components are used.

Keywords:

Software, Ensemble Streamflow Forecasts, Modelling Framework, Interoperability

SYSTEMATIC PAIRING OF ENSEMBLE INITIAL CONDITIONS AND ENSEMBLE FORECASTS IN AN AUTOMATED HYDROLOGIC FORECAST SYSTEM

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Abstract:

In a hydrologic ensemble prediction system that incorporates both uncertainty in initial hydrologic conditions (IHCs) and in hydrometeorological predictions, the total number of hydrologic simulations required to represent all possible combinations of ensemble members can become computationally prohibitive. Informed resampling of the full uncertainty space, however, can reduce the number of ensemble members required for prediction. The System for Hydromet Ensemble Research and Prediction Applications (SHERPA), developed by the National Center for Atmospheric Research, University of Washington, US Army Corps of Engineers, and US Bureau of Reclamation, is a fully automated system for hydrologic prediction for short-term to seasonal applications. SHERPA employs the methodology of Newman et al. (2015) to generate an ensemble of historical hydrometeorological forcings to represent uncertainty in the interpolation of station observations of precipitation and temperature. These forcings are used spin up the hydrological model's initial soil moisture and snow water equivalent conditions. Short-range hydrologic ensemble predictions use quantitative temperature and precipitation predictions from the Global Ensemble Forecast System (GEFS). In order to save on computation time, while maintaining a realistic representation of uncertainty in the hydrologic predictions, we develop a method based on particle filters to sample the combined IHC and meteorological forecast uncertainty. We test this method in several basins in the Pacific Northwest that are important to water resources management. The hydrologic behavior of these basins spans a range of sensitivity to snow storage. The resampling based on particle filter methods is tested against 1) an ideal resampling: all possible ensemble member pairings (resulting in the number of IHC ensemble members times the number of meteorological forecast ensemble members), and 2) a naïve resampling: pairings based on random sampling. The a posteriori forecast distributions and computational costs of predictions at lead times of 1 to 7 days for each method are compared.

Keywords:

Initial State, Uncertainty, Particle Filter, Automation, Short-Term Prediction

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THE GAME OF MAKING DECISIONS UNDER UNCERTAINTY: HOW SURE MUST ONE BE?

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Abstract:

Probabilistic hydrometeorological forecasting is now widely accepted to be more skillful than deterministic forecasts, and is increasingly being integrated into operational practice. Provided they are reliable and unbiased, probabilistic forecasts have the advantage that they give decision makers not only the forecast value, but also the uncertainty associated to that prediction. Though that information provides more insight, it does now leave the forecaster/decision maker with the challenge of deciding at what level of probability of a threshold being exceeded the decision to act should be taken. According to the cost-loss theory, that probability should be related to the impact of the threshold being exceeded. However, it is not entirely clear how easy it is for decision makers to follow that rule, even when the impact of a threshold being exceeded, and the actions to choose from are known. We will address the challenge of making decisions based on probabilistic forecasts through a game to be played with the audience. We will explore how decisions made differ depending on the known impacts of the forecasted events. Participants will be divided into a number of groups with differing levels of impact, and will be faced with a number of forecast situations. They will be asked to make decisions and record the consequence of those decisions. A discussion of the differences in the decisions made will be presented at the end of the game, with a fuller analysis later posted on the HEPEX web site blog (www.hepex.org).

Keywords:

Probabilistic Forecast, Decision-Making, Forecast Value, Cost-Loss Ratio

THE HYDROLOGICAL ENSEMBLE PREDICTION IN FEILAIXIA BASIN

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Abstract:

Meteorological ensemble forecasts, their pre- and hydrological post-processing, and multimodel combination approaches are different components of an integrated ensemble hydrological prediction system. Which part of the system plays the most important role in the skill metrics of the hydrological ensemble forecasts? How to quantify and decrease the uncertainty and increase the skill metrics of the integrated system? In this presentation, we will address those questions via a case study. A hydrological ensemble prediction system (HEPS) developed at Beijing Normal University is used for the purpose, which includes several pre- and post-processing approaches and contains different hydrological models. Using hindcasts generated by meteorological ensemble forecasting systems (e.g., GEFS, TIGGE), HEPS can create ensemble hydrological predictions. The case study will involve Feilaixia basin in South China. This study is intended to quantify the uncertainty due to different components, such as meteorological ensemble forecasts, pre-processing of those forecasts, and hydrological post-processing approaches and hydrological model. Although the accuracy of meteorological ensemble forecasts is still limited, pre- and post-processing approaches often help generate ensemble forecasts with reasonable skill metrics.

Keywords:

Multimodel, Ensemble Prediction, GEFS, Feilaixia.

THE PEAK BOX GAME – TWO YEARS AND 250 PARTICIPANTS LATER

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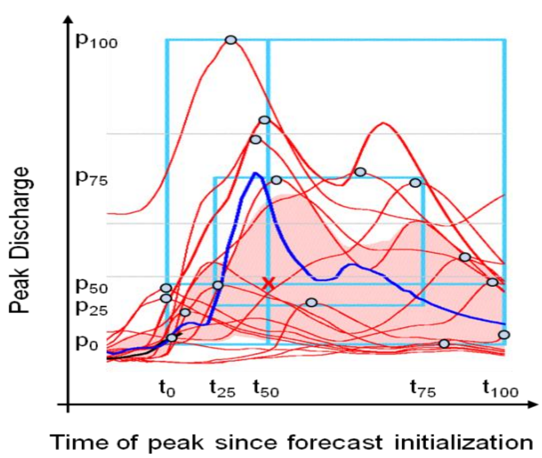
Abstract:

In many situations the wisdom of the crowds (Galton 1907) demonstrated to be superior to the estimation of single individuals. This is maybe one of the reasons why operational hydro-meteorological services are more and more recognizing the added value given by ensemble prediction systems. A crowd of members has more wisdom than a single model output.

Two years ago we presented the peak box game at the HEPEX workshop. In the game the participants compete with the Peak-Box by estimating the peak and timing of the observed outcome of a given ensemble forecast. The Peak-Box defines the "best estimate" of a flood events' timing and magnitude by framing the discharge peaks of all members of an ensemble forecast and taking their median in timing and magnitude (Figure 1). This visual solution should provide support in the assessment of actions relying on accurate estimation of peak-timings and peak-flows.



Peak-box estimate:

- Mark the highest peak of each member
- Draw boxes limited by quantiles in timing and magnitude of the peaks
- "Best estimate": Intercept of median in peak timing and in peak magnitude (**x**)

Figure 1: The Peak-Box approach suggested by Zappa et al. (2013).

Since the first game played at EGU 2013 roughly 250 participants handed in their estimates. All together they are a pretty good ensemble, and better then the single estimates. However, if the single estimates have to compete with the estimate made by the Peak-Box approach they lose. These results nicely show that the wisdom of the crowds applies for hydrological forecasting and makes the advantage of ensembles obvious to any sceptic.

Keywords:

Ensemble Forecasting.

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TOWARDS IMPROVED ERROR MODELLING FOR SHORT-TERM STREAMFLOW FORECASTING IN AUSTRALIA

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Abstract:

Operational short-term streamflow forecasting services in Australia are currently all deterministic. The Bureau of Meteorology, Australia's lead agency for flood forecasting and warning, has sought to transition the current deterministic forecasting to ensemble forecasting to quantify uncertainty and allow risk-based decision making.

We have developed an approach, called Error Reduction and Representation in Stages (ERRIS), to quantify the hydrological model uncertainty in forecasts as well as to reduce forecast error. ERRIS establishes statistical models (called error models) that describe biases and persistence in the forecast error time-series. ERRIS consists of a sequence of simple error models rather than a single complicated one. This approach improves computational efficiency and avoids possible parameter interference. ERRIS consists of four stages: (1) hydrological model simulation and data transformation; (2) non-linear bias-correction conditional on the simulated streamflow; (3) a restricted autoregressive model; (4) residual distribution adjustment with a mixture Gaussian distribution.

We test ERRIS on hourly data to lead-times of 48 hours. We show that when flows are receding, forecast uncertainty tends to be much lower than when flows are rising. This required an additional refinement to ERRIS: at Stage 4, we categorise flows as either rising or falling, and apply different distribution parameters to each category.

ERRIS performs well in perennial catchments, producing very accurate forecasts at short lead times. As forecast uncertainty grows at longer lead times, the forecast uncertainty is reliably quantified. The ensemble is generally reliable at all lead times, demonstrating: i) that the mixture Gaussian distribution (Stage 4) is capable of representing the peaky distribution of residuals after the autoregressive model is applied (Stage 3) and ii) that uncertainty is correctly propagated through the forecast.

Australia extends across arid and semi-arid zones and many Australian rivers are ephemeral. Long periods of zero flow are challenging not only for effective hydrological modelling but also for statistical error modelling. We will discuss the prospects for continued improvement of ERRIS for application to ephemeral rivers.

Keywords:

ERRIS, Hydrological Uncertainty, Statistical Error Modelling

TOWARDS PROBABILISTIC FLOOD FORECASTING IN FRANCE

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Abstract:

The French flood forecasting network includes 19 regional Flood Forecasting Centres (FFC) and a national centre (SCHAPI; Tanguy et al., 2005), responsible for the flood warning map publication on the Vigicrues website (www.vigicrues.gouv.fr). The local FFCs are in charge of short-term forecasting, based on hydrological and hydraulics models fed with a limited number of meteorological scenarios, provided by Meteo-France and, at three local FFCs, by the analog approach (Marty et al., 2012), similarly to a poor-man ensemble approach. The national centre provides 1-week ahead survey, based on EFAS (Thielen et al., 2009) and SIM-PE (Coustau et al., 2013) ensemble prediction systems.

The SCHAPI and FFCs are setting up their operational forecasting systems to explicit uncertainty inherent to the forecasts. The paradigm in short-term hydrological forecasting is currently shifting from being deterministic to probabilistic. The deterministic models used by FFCs are supplemented by two new tools (Berthet et al., 2016):

- OTAMIN, a tool designed by IRSTEA to assess the deterministic model uncertainty and provide a 'first guess' to forecasters;
- EXPRESSO: an interactive tool which helps forecasters to express the human expertise and to produce the 'final' uncertainty assessment.

In near future, probabilistic meteorological forecasts are expected to be increasingly used for flood forecasting in France. Several projects are carried out to demonstrate the benefits of such an approach:

- The CHROME project's purpose is to design a short-term hydrological ensemble forecasting system adapted to mid-sized Mediterranean basins: first results confirm the interest of a hydrological multi-model approach combined with meteorological ensemble.
- Recent results from the ANALOGUES project highlight that the analog sorting approach is suitable to provide probabilistic precipitation forecasts at basin scale. This project aims to spread the method to the whole French territory, and to combine it with ensemble predictions.
- On smaller time and space scales, the 3rd project deals with the development of a flash flood warning system adapted to small ungauged basins, based on a simplified hydrological model and merging precipitation estimation from radar and high-resolution ensemble forecasts.

Providing probabilistic hydrological predictions remains a great challenge for human forecasters as well as for numerical prediction systems. Key issues need to be addressed in the next years:

- How to adapt deterministic semi-distributed prediction chains of local FFCs to benefit from probabilistic meteorological forecasts and data assimilation?
- Is the coupled hydro-meteorological model SIM-PE suitable to provide accurate forecasts on snow-influenced basins?

- How to propagate downwards forecasts and its uncertainty, and keep consistency in hydrological forecasts at basin and sub-basin scale?
- How to adapt the human forecasters role with the use of such hydrological prediction systems?

Keywords:

Operational Forecasting, Hydrological Forecasting, Predictive Uncertainty, Flood Warning

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TOWARDS TIMELIER, SUB-SEASONAL TO SEASONAL STREAMFLOW FORECASTS IN AUSTRALIA TO BETTER MEET USER NEEDS

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Abstract:

The Australian Bureau of Meteorology releases seasonal streamflow forecasts each month, giving ensembles of total flow volume for the three months ahead. The forecasts are based on the Bayesian joint probability (BJP) modelling approach using catchment wetness and climate predictors. User surveys and case studies have established the value of the service for decision making in water resources management. However, stakeholder engagement activities also reveal that forecast users want improved forecast products and services including: (1) timelier forecast release and (2) sub-seasonal forecasts, with seasonal totals broken into monthly totals.

The call for timelier forecasts is in response to a systematically delayed forecast release schedule. Normally, the seasonal streamflow forecasts are released approximately 7 business days into the forecast period. This is due the time required to obtain model input data, run several hundred forecasting models and develop a communication strategy. The need for timelier forecasts is made more pressing by the call for sub-seasonal forecasts. Sub-seasonal forecasts, particularly for the first month, are more likely to be used for operational decision making, and thus delays in forecast release will diminish the value of the forecasts.

This study comprises two activities: (1) investigation of ways to issue timelier BJP seasonal streamflow forecasts and (2) application of BJP to issue ensemble forecasts for each month in the season. For both activities, a common period from 1981 to 2011 is specified for model establishment, historical references and verification. Results are produced using leave-five-years-out cross validation.

The key findings for the timelier seasonal forecast investigation are:

- Using a consistent model set up for N-days lead time forecasts, it is estimated that forecasts with up to 7-days lead time incur no cost of reliability and only a small skill penalty compared to 0-day lead time forecasts.
- Several climate indices currently used in operational models are not compatible with early release forecasts. Hence, climate predictors are restricted to SST climate indices that are able to be calculated from daily data.

The key findings for monthly BJP forecasts investigation are:

- BJP is robust and able to efficiently produce reliable and skillful ensemble streamflow forecasts for each month in a season.
- Aggregates of monthly BJP forecasts and direct seasonal BJP forecasts are similarly skillful and reliable, thus indicating BJP properly models the temporal pattern of streamflow.
- The latest version of the BJP model works efficiently for all tested cases, although monthly forecasting involves more computation due to an increase in the numbers of predictands.

The results of this study demonstrate that it is possible for BJP seasonal streamflow forecasts in Australia to better meet user needs, by being available earlier, and having higher temporal resolution.

Keywords: Sub-Seasonal, Operational Forecasting, User Needs, Forecast Verification, Bayesian Joint Probability

UNDERSTANDING THE STATISTICAL STRUCTURE OF GCM ENSEMBLE FORECASTS

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Abstract:

GCM climate forecasts are increasingly used as inputs to hydrological models for ensemble streamflow forecasting. GCM forecast ensembles are produced at different lead-times. How does forecast bias and ensemble spread change with lead-time? How consistent are the forecasts with observations in overall direction? Does the ensemble spread contain useful information about the real uncertainty of the forecasts? Answering these questions will inform how GCM ensemble forecasts can be most effectively utilised. For example, should a large ensemble with forecasts going back many lead-times be used, or should only the most recent forecasts be used? Should forecasts with different lead-times be valued differently? What kind of ensemble calibration method is needed for extracting the most information from GCM ensemble forecasts? In this presentation, we present results of an exploratory analysis of the NOAA CFSv2 hindcasts of Nino3.4. Ensemble forecasts show clear systematic drift over lead-time. In general, forecast ensemble spread increases with lead-time. The forecast ensemble mean correlates well with observations, but there is little correspondence between forecast ensemble spread and the departure of observation from forecast ensemble mean.

"UPGRADED" METEOROLOGICAL FORCING FOR OPERATIONAL HYDROLOGICAL ENSEMBLE PREDICTIONS: CHALLENGES, RISKS AND CHANCES

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Abstract:

The real challenge in operational hydrological ensemble predictions is mostly not the calibration and setup of the different models involved in the prediction chain. In our experience the monitoring of the data-flow and the archiving of the simulations are the most demanding task of the routine operation of such a system (e.g. Addor et al., 2011; Andres et al., 2015). The analysis of the archived data allows for verification of the systems and this is often the real fun part of the task (e.g. Liechti et al., 2013). The two real challenges linked with the deployment and maintenance of real-time systems are: A) the switch from a safe calibration environment to a real-time environment, where only part of the data available during calibration can be accessed. And B) the change in version ("Upgrade") of models such as the numerical weather predictions and of "observed" data products such as the weather radar QPE.

We base our experience on real-time applications running in Switzerland since 2007 (https://hydro.slf.ch/sihl/chysghl/). In this contribution we present the problems that one can bump into when putting is "perfectly" running offline predictions system into true operations. We focus here first on the aspects of the environment hosting the system (FEWS and an own solution) and the data source available for precipitation in real-time (Andres et al., 2016).

The second part of the contribution will be focussed on the efforts needed to cope with changes in the forcing data. We experienced in 2011 a change in the weather radar network that led to inhomogeneity in the operational series of simulated ensemble hydrological predictions evaluated in Liechti et al. (2013). The modernization of the Swiss weather-radar network started in 2011 and will be completed in 2016. We expect to have a new series of homogeneous input for hydrology in 2017.

Starting in September 2015 a new probabilistic NWP model is available in Switzerland. The COSMO-E model with 21 members and 2.2 km resolution is meant to replace COSMO-LEPS (16 members, 7 km resolution) in summer 2016. We used COSMO-LEPS since 2008 for real-time forecasts for the Sihl river (Addor et al., 2011). We have a homogenous time series of model runs dating back from 2010. We are now in a phase where both NWP are run in parallel. Results from comparison of the outcomes of our HEPS with both forcing will be discussed (Figure 1).

From a scientific point of view such changes in forcing data are only a marginal chance to improve an operational HEPS and represent a high risk, since users might lose trust in the forecasts and even more dangerous, lose their "gut feeling" about taking decisions using ensembles. Personally we are still very reluctant in trusting the QPE produced with the new generation of weather radars.

While the scientific issues could be solved by requesting (but probably not getting) reforecasts from the meteorological service, users issues can only be managed by tailored training. Thus, for the period February to October 2016 we will maintain two operational visualisation platforms and comment on a regular basis on the difference between the two systems.

Keywords:

Real-time HEPS, Change In Data Flow, NWP, QPE

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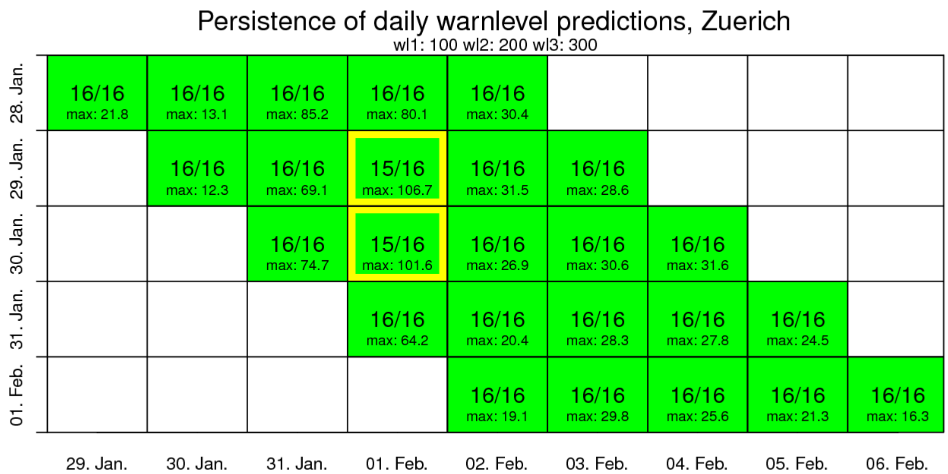

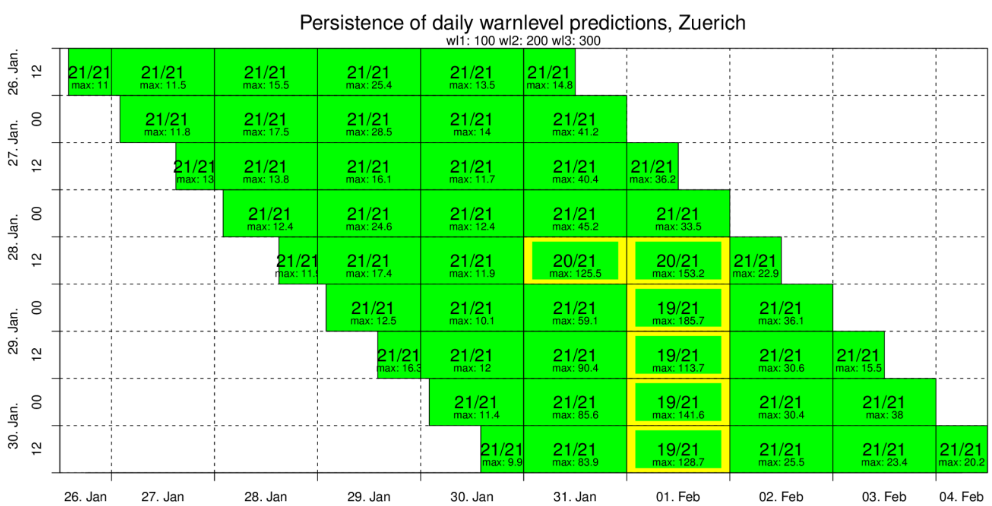

Figure 1: Persistence plots of PREVAH-FLORIS COSMO-LEPS (top panel) and PREVAH-FLORIS COSMOE (bottom panel). Since 2007 we received 16 COSMO-LEPS members daily and could realize forecasts with lead time of up to 132 hours. Since October 2015 we also receive COSMOE forecasts. COSMOE has 21 members, is updated twice daily and has a lead time of up to 120 hours.

VARIATIONAL DATA ASSIMILATION BY MOVING HORIZON ESTIMATION AND A PROBABILISTIC POOL OF CONCEPTUAL HYDROLOGICAL MODELS

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Abstract:

Hydrological forecasts are an essential input for decision makers to attain efficient, anticipatory water management. The forecast skill reflects several sources of uncertainties. These result from the meteorological forcing, the hydrological model structure and its parameters. In this context, data assimilation aims to improve the state estimation at forecast time by combining near real-time observations and model simulations. In a probabilistic mode, data assimilation also tries to represent structural and parametric model uncertainty or uncertainty in the historical forcing.

Operational hydrological forecasting systems usually implement sequential data assimilation techniques of the Kalman Filter type for state estimation. They rely on the direct computation or approximation of a covariance matrix and its propagation in time. A bottleneck of the sequential approach is the consideration of large time lags in connected processes, for example between the snow accumulation in winter and the spring runoff. For these applications, variational assimilation methods such as Moving Horizon Estimation (MHE) (aka 4DVAR) appear a more suitable choice. These implement simultaneous changes in model inputs and states over several time steps (Alvarado-Montero et al., submited). The original MHE is a deterministic approach using a single deterministic model. In this study, we extend it to a probabilistic approach by the use of a model pool to represent structural and parametric model uncertainty (Velázquez et al.,2011).

We present an assessment of a probabilistic MHE in application to three river basins Germany, Poland and Turkey. The assimilated data consists of observed streamflow at gauges and remotely sensed snow water equivalent, snow coverage and soil moisture. The model uncertainty is represented by a pool of conceptual rainfall-runoff models of different model structures and parameters sets. The assimilation window extends up to 6 months into the past using either daily or hourly simulation time steps. The lead-time performance of streamflow, snow and soil moisture quantities is analysed by hindcasting experiments and shows the added value of the probabilistic approach above its deterministic counterpart.

Keywords:

Data Assimilation, Moving Horizon Estimation, Multi-model

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VERIFICATION AND COMPARISON OF SEASONNAL METEOROLOGICAL ENSEMBLE FORECASTS FOR LONG-TERM HYDROPOWER PLANT MANAGEMENT IN NORDIC WATERSHEDS

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Abstract:

Hydropower managers have to take decisions for reservoir management at different time scale. Short-term meteorological forecasts are routinely used as inputs for hydrological model. Dynamical meteorological forecasts also exist for long-term forecasting horizons, but in practice, most operational agencies involved in water management rely on climatology-based approaches such as Extended Streamflow Predictions (ESP, Day, 1985) for lead times longer than a few (5 to 10) days. In any case, longer lead-times are associated to large uncertainties and a probabilistic or ensemble framework is required. ESP consider historical meteorological time series as potential future scenarios. This kind of forecasting system accounts for the natural variability of climate and hydrological initial conditions to predict future inflows through a hydrological model. Alternatively, the members of dynamical meteorological forecasts describe the uncertainty related to the initial conditions of the climatic model. As these two kinds of system rely on different approaches, the aim of this study is to compare their performances. Meteorological forecasts for 10 watersheds managed by Hydro-Québec are compared to the current ESP-type forecasting system they use operationally. Watersheds' area span from 4000 to 37 000 km2 and they are all Nordic watersheds for which snowmelt forecasting is a crucial operation. Dynamical meteorological forecasts comprise total precipitation and temperature and were produced by the European Centre Medium Range Weather Forecasts' (ECMWF) System 4 model. Real-time forecasts are available from 2012 to 2015 and the verification set is completed by hindcasts for the 1981-2011 period. One forecast is issued each month, for a 7-month forecasting horizon with daily time steps and a 0.75° horizontal resolution. Hydro-Quebec's ESP forecasting system is based on a record of 50 years of daily observations from ground stations. The comparison is performed using the Continuous Ranked Probability Score (CRPS, Matheson and Winkler, 1976), the ignorance score (Roulston and Smith, 2002), and the reliability diagram. Globally, results show similar performances for both systems (ESP vs ECMWF's System 4). However, forecasts from the ECMWF's model lead to noticeably improved skill for day-1 to day-15 compared to ESP. In practice, this could translate in extending the current operational definition of "short-term" from 5-day to 15-day, before connecting to climatology. Nevertheless, the ESP system exhibits skill and slightly outperforms the ECMWF's forecasts in many situations for long-range forecasts. Further comparison of the CRPS for both systems shows that the respective level of skill for the ECMWF's System 4 and ESP change over throughout the year. For cumulative precipitation forecasts issued in fall, ECMWF's System 4 performs slightly better (lower CRPS) than climatology for several watersheds. The ESP system is reliable and sometimes shows overdispersion whereas ECMWF suffers from under-dispersion in most cases.

Keywords:

Seasonal Ensemble Forecast, Climatology, Extended Streamflow Predictions, Long-range Forecasts,

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VERIFICATION OF MULTI-MODEL PRECIPITATION FORECASTS FOR OPTIMAL DECISION MAKING IN WATER MANAGEMENT

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Abstract:

End users responsible for water management make use of a variety of different precipitation forecasts as input for their hydrological and hydraulic models. These differ in both forecast horizon (short versus medium range) and forecasting approach (deterministic models versus probabilistic ensemble systems). In Belgium, the Royal Meteorological Institute provides precipitation forecasts based on the deterministic Alaro and the European Centre for Medium Range Weather Forecasting (ECMWF) HIRES models, the limited area model ensemble prediction system GLAMEPS, and the ECMWF ensemble prediction system ENS. We have noted an increasing interest of end users for guidance in when to use the different precipitation forecasts and how to best combine all available information. In this work, we try to address the question of how to combine our precipitation forecasts in an optimal way to enable the best decision making for end users involved in water management.

We perform a verification study of a pre-alert/alert system that makes use of Alaro and GLAMEPS during the first 2 days, and the ECMWF forecasts for the following 3 to 10 days, making use of two years of archived precipitation forecasts at point locations and over catchments (Ourthe and Dijle in the Meuse and Escaut basins respectively). We make a comparison with a system that uses ECMWF forecasts only. We use common verification measures for probabilistic forecasts and also consider economic value using a cost/loss model. We also perform some experiments where the deterministic model is added as an extra member to an ensemble, with a higher weight that depends on the lead time (Rodwell, 2006). Finally, we also perform a hydrological validation, where the precipitation forecasts are used as input to the RMI hydrological model SCHEME.

Preliminary results show that the use of GLAMEPS, which often has a larger spread during the first days, slightly improves the spread-skill relationship compared to ECMWF ENS. The Alaro model can also be used as an extra ensemble member, with an optimal “weight” of ca. 15 members during the first day. Verification results show that the forecasts at medium range (3-10 days) have value in generating early warnings for severe precipitation events.

Keywords:

Ensemble Precipitation Forecasts, Verification, Seamless Forecasting, Hydrological Ensemble Predictions, Economic Value.

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