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Programme at a glance

	Day 1 - 6 February 2018 (Tue)
8.15 – 9.00:	Registration and coffee; put up posters
9.00 – 9.45:	Workshop open
9.45 – 10.25:	**Keynote: Hannah Cloke (University of Reading)**
10.25 – 10.55:	Coffee break
10.55 – 12.35:	Session 1 – Regional to Global Scale Forecasting
12.35 – 13.40:	Lunch break
13.40 – 14.30:	Session 2 - Hydrological modelling and data assimilation for ensemble prediction
14.30 – 14.50:	Coffee break
14.50 – 16.00:	Session 2 (continued) - Hydrological modelling and data assimilation for ensemble prediction
16.00 – 17.30:	**Poster Session 1 - 20 posters (with drinks)**

	Day 2 - 7 February 2018 (Wed)
8.30 – 9.00:	Coffee; put up posters
9.00 – 9.50:	Session 3 - Subseasonal forecasting: bridging medium-term and seasonal horizons
9.50 – 10.30:	**Keynote: Dasarath Jayasuriya (Jaya) (Bureau of Meteorology)**
10.30 – 11.30:	Group Photo and Coffee break
11.30 – 12.20:	Session 4 - Ensemble Weather Prediction
12.20 – 13.30:	Lunch break
13.30 – 14.35:	Session 5 - Floods: risk, forecasting and warning
14.35 – 14.55:	Coffee break
14.55 – 16.00:	Session 5 (continued) - Floods: risk, forecasting and warning
16.00 – 17.30:	**Poster Session 2 - 20 posters (with drinks)**

19.30:	Dinner - Clyde hotel

	Day 3 - 8 February 2018 (Thu)
8.30 – 9.00:	Coffee
9.00 – 9.50:	Session 6 – Seasonal streamflow forecasting
9.50 – 10.30:	**Keynote: Matthew Bethune (Murray-Darling Basin Authority)**
10.30 – 11.15:	Coffee break
11.15 – 12.20:	Session 7 - Operational hydrometeorological forecasting services
12.20 – 13.30:	Lunch break
13.30 – 14.50:	Session 8 - Applications of ensemble prediction: hydropower and reservoir operations
14.50 – 15.20:	Coffee break
15.20 – 16.50:	**Plenary Discussion: Maria-Helena Ramos (IRSTEA) & Ilias Pechlivanidis (SMHI)**
16.50 – 17.00:	Workshop close

Programme – Day 1 (Tue 6 Feb)

8.15 – 9.00:	Registration and coffee; put up posters
9.00 – 9.30:	Workshop open – Welcome from local organizers, sponsors and HEPEX co-chairs
9.30 – 9.45:	Welcome to country
9.45 – 10.25:	**Hannah Cloke (University of Reading) - Fly me to the moon: a review of ensemble flood forecasting 10 years on (Keynote) (Chair: QJ Wang, University of Melbourne)**
10.25 – 10.55:	Coffee break
	Session 1 – Regional to Global Scale Forecasting (Chair: Maria-Helena Ramos, IRSTEA)
10.55 – 11.15:	**Qiuhong Tang (Chinese Academy of Sciences) - A Hydrological Monitoring And Seasonal Forecast System Using Satellite And Climate Model Data Over China (Invited)**
11.15 – 11.30:	Micha Werner (IHE-Delft/Deltares) - Are global models skillful in forecasting floods, drought, and their impacts in data scarce areas?
11.30 – 11.45:	Louise Arnal (University of Reading/ECMWF) - Skilful seasonal forecasts of streamflow over Europe?
11.45 – 12.00:	Calumn Baugh (ECMWF) - Using global ensemble forecasts to issue flash flood warnings
12.00 – 12.15:	Andy Wood (NCAR) - Exploring The Application Of Ensemble Prediction Methods Across Regional Forecasting Domains
12.15 – 12.35:	**Florian Pappenberger (ECMWF) - Earth System modelling @ECMWF – Implications for HEPEX and hydrology (invited)**
12.35 – 13.40:	Lunch break
	Session 2 - Hydrological modeling and data assimilation for ensemble prediction (Chair: Nathalie Voisin, PNNL)
13.40 – 14.00:	**Hamid Moradkhani (Portland State University) - Recent Developments In Evolutionary Data Assimilation And Model Uncertainty Estimation For Hydrologic Forecasting (Invited)**
14.00 - 14.15:	Albrecht Weerts (Deltares/Hydrology and Quantitative Water Management group) - Improving hydrological modelling/predictions for the Rhine River in the framework of the IMPREX project
14.15 – 14.30:	Tomoki Ushiyama (ICHARM-PWRI/Kyoto University) - Comparison Of Ensemble Flood Forecasts From Two Regional Ensemble Prediction Systems: Simple Downscaling Of Global EPS And Regional Data Assimilation
14.30 – 14.50:	Coffee break
	Session 2 (continued) - Hydrological modeling and data assimilation for ensemble prediction (Chair: Julien Lerat, Bureau of Meteorology)
14.50 – 15.10:	Bastian Klein (German Federal Institute of Hydrology) - Impact of hydrological model uncertainty on predictability of seasonal streamflow forecasting in the River Rhine basin
15.10 – 15.25:	**François Anctil (Université Laval) - Impact Of Data Assimilation On The Usage Of Multiple Models (Invited)**
15.25 – 16.00:	Recap (Schalk Jan van Andel, IHE-Delft) & Discussion
16.00 – 17.30:	**Poster Session 1 - 21 posters (with drinks)**

2018 HEPEX Workshop

Breaking the barriers

6-8 February 2018, Melbourne, Australia

Programme – Day 2 (Wed 7 Feb)

8.30 – 9.00:	Coffee; put up posters
	Session 3 - Subseasonal forecasting: bridging medium-term and seasonal horizons (Chair: Andy Wood, NCAR)
9.00 – 9.20:	**Luis Samaniego (UFZ-Helmholtz Centre for Environmental Research) - Lessons Learnt From The EDgE Seasonal Hindcast Experiment (Invited)**
9.20 – 9.35:	Andrew Schepen (CSIRO) - Is It Better To Post-Process Seasonal Rainfall And Temperature Forecasts At Daily Or Monthly Time Steps?
9.35 – 9.50:	Fredrik Wetterhall (ECMWF) - Merging of extended- and seasonal-range forecasts to improve subseasonal to seasonal hydrological forecasts
9.50 – 10.30:	**Dasarath Jayasuriya (Jaya) (Bureau of Meteorology) - Viewing Ensembles through the Eyes of the End-user (Keynote) (Chair: Andy Wood, NCAR)**
10.30 – 11.30:	Group Photo and Coffee break
	Session 4 - Ensemble Weather Prediction (Chair: Christel Prudhomme, ECMWF)
11.15 – 11.35:	**Céline Cattoën-Gilbert (NIWA) - Post-Processing Precipitation Forecasts From A High Resolution Convective-Permitting Weather Model For National Scale Short-Term Flow Forecasting In New Zealand (Invited)**
11.35 – 11.50:	Tom Pagano (Bureau of Meteorology) - Operational Weather Verification at the Australian Bureau of Meteorology
11.50 – 12.05:	QJ Wang (University of Melbourne) - A seasonally coherent calibration (SCC) model for post-processing numerical weather predictions
12.20 – 13.30:	Lunch break
	Session 5 - Floods: risk, forecasting and warning (Chair: David Robertson, CSIRO)
13.30 – 13.50:	**Rebecca Emerton (University of Reading/ECMWF) - Complex Picture for Likelihood of ENSO-Driven Flood Hazard (Invited)**
13.50 – 14.05:	Maria-Helena Ramos (IRSTEA) - Contribution Of Ensemble Forecasting Approaches To Flash Flood Nowcasting At Gauged And Ungauged Catchments
14.05 – 14.20:	Agathe Boronkay (Bureau of Meteorology) - The use of radar-based rainfall observations and forecasts to provide enhanced flood forecasts and warnings In Australia
14.20 – 14.35:	Li Liu (Zhejiang University) - The Role Of Hydrological Ensemble Prediction In Forecasts Of Flood And Its Components Over The Upper Brahmaputra Basin, China
14.35 – 14.55:	Coffee break
	Session 5 (continued) - Floods: risk, forecasting and warning (Chair: Micha Werner, IHE-Delft/Deltares)
14.55 – 15.10:	Schalk Jan van Andel (IHE-Delft) - Does event-based verification lead to different results from equal-interval verification?
15.10 – 15.25:	Vincent Boucher (Université Laval) - Confidence in flood warning system and the value of ensemble forecasts
15.25 – 16.00:	Recap (Louise Arnal, University of Reading/ECMWF) & Discussion
16.00 – 17.30:	**Poster Session 2 - 20 posters (with drinks)**

19.30:	Dinner - Clyde hotel

Programme – Day 3 (Thu 8 Feb)

8.30 – 9.00:	Coffee
	Session 6 – Seasonal streamflow forecasting (Chair: Fredrik Wetterhall, ECMWF)
9.00 – 9.20:	**Louise Crochemore (SMHI) - Skill sensitivity in Europe and site-specific diagnostics based on catchment characteristics (Invited)**
9.20 – 9.35:	Shaun Harrigan (CEH) - Improving seasonal prediction of UK winter streamflow
9.35 – 9.50:	Daehyok Shin (DH) (Bureau of Meteorology) - The Operational Seasonal Streamflow Forecasting Service For Australia: Assessment And Communication Of Forecast Quality At The National Scale
9.50 – 10.30:	**Matthew Bethune (Murray-Darling Basin Authority) - Hydrologic models to support decision making in the Murray Darling Basin (Keynote) (Chair: Fredrik Wetterhall, ECMWF)**
10.30 – 11.15:	Coffee break
	Session 7 - Operational hydrometeorological forecasting services (Chair: Aizhong Ye, Beijing Normal University)
11.15 – 11.35:	**Young-Mi Min (APCC) - Current Status Of The Operational Multi-Model Ensemble Prediction System And Climate Service Activities At APEC Climate Centre (Invited)**
11.35 – 11.50:	Narendra Tuteja (Bureau of Meteorology) - Opportunities and challenges in delivering water availability forecasts – sharing the Australian experience
11.50 – 12.05:	Ilias Pechlivanidis (SMHI) - An Operational Pan-European Seasonal Hydro-Climatic Forecasting Service
12.05 – 12.20:	Charlie Pilling (UK Met Office) - Improving Operational Decision Making And Services: Collaboration In Science, Systems And Communication
12.20 – 13.30:	Lunch break
	Session 8 - Applications of ensemble prediction: hydropower and reservoir operations (Chair: James Bennett, CSIRO)
13.30 – 13.50:	**Samuel Monhart (ETH/WSL) -Hydrometeorological ensemble predictions in Switzerland: Using streamflow forecasts to improve hydropower reservoir operations (Invited)**
13.50 – 14.05:	Hae Na Yoon (Seoul National University) - A Theoretical Study On Adjustment Of Reservoir Operating Rules Using Ensemble Streamflow Forecasts
14.05 – 14.20:	Thomas Chubb (Snowy Hydro) - Use Of Artificial Neural Networks In Short-Term Streamflow Forecasting For The Snowy Mountains Scheme
14.20 – 14.35:	Sabrina Celie (Compagnie Nationale du Rhône) - A First Use Case Of Operational Ensemble Discharge Forecasts For Hydropower Production On The Rhone River: Evaluation Of Several Post-Processing Methods s
14.35 – 14.50:	Nathalie Voisin (PNNL) - Sensitivity of power system operations to water availability: insight for designing ensemble hydro-meteorological forecasts
14.50 – 15.20:	Coffee break
15.20 – 16.50:	**Plenary Discussion: What's next in hydrological ensemble prediction? (Led by Maria-Helena Ramos, IRSTEA, & Ilias Pechlivanidis, SMHI)**
16.50 – 17.00:	Workshop close

Poster Session 1 (Tue 6 Feb 16:00-17:30)

Presenter	Title
François Anctil (Université Laval)	On The Incidence Of Meteorological And Hydrological Processors: Effect Of Resolution And Reliability Of Hydrological Ensemble Forecasts
Louise Arnal (University of Reading/ECMWF)	The 2013/14 Thames Basin Floods: Do Improved Meteorological Forecasts Lead To More Skilful Hydrological Forecasts At Seasonal Timescales?
James Bennett (CSIRO)	Long-range Streamflow Forecasts in Drylands
David Bretreger (University of Newcastle)	Assimilating P-Band Microwave Soil Moisture Observations To Improve Root Zone Soil Moisture Estimation
Bapon Fakhruddin (Tonkin + Taylor)	Medium range Ensemble flood forecasting in Waikato River Basin, New Zealand
Prasantha Hapuarachchi (Bureau of Meteorology)	Developing An Ensemble 7-Day Streamflow Forecast Service For Australia
Jiawei Hou (ANU)	Potential for enhanced flow forecasting through Satellite-based River Gauging
Yuan Li (Monash University)	Soil Moisture Assimilation For Ensemble Streamflow Prediction
Alberto Meucci (University of Melbourne)	Wind and Wave Climate: Design Sea State from Ensemble Forecasts
Valentijn Pauwels (Monash University)	Estimation Of The Observation Bias For Remotely Sensed Soil Moisture Using A Bias-Aware Kalman Filter: Validation Using Different Models
Jean-Michel Perraud (CSIRO)	A Software Ecosystem For End-To-End Hydrological Ensemble Modelling Workflows
David Robertson (CSIRO)	How Can Ensemble Streamflow Forecasts Inform Decisions On The Management Of Environmental Flows?
Seung Beom Seo (Seoul National University)	Improvement Of Drought Outlooks Using A Bayesian Inference Approach
Durga Lal Shrestha (CSIRO)	Schaake Shuffle: Does It Work For All Forecasts?
Adam Smith (Bureau of Meteorology)	Development Of A Pilot Forecast Service For Extended Lead Time Flood Forecasts For The Hawkesbury-Nepean Valley
Natthachet Tangdamrongsub (University of Newcastle)	Assimilation of GRACE water storage and SMOS/SMAP soil moisture retrievals into CABLE using particle smoother
Jeffrey Walker (Monash University)	Diagnostic Assessment of Localized Flood Flow Behaviour
Albrecht Weerts (Deltares)	genRE: A Method To Extend Gridded Precipitation Climatology Datasets In Near Real-Time For Hydrological Forecasting Purposes
Albrecht Weerts (Deltares)	RWsOS: Clustered Multi-Hazard Early Warning In The Netherlands
Andy Wood (NCAR)	Watershed-Oriented Climate Forecast Products For Hydrologic Forecasters And Water Managers
Xuejun Zhang (Chinese Academy of Sciences)	Operational drought forecasting and skill assessment over China

Poster Session 2 (Wed 6 Feb 16:00-17:30)

Presenter	Title
François Anctil (Université Laval)	A Data Assimilation Scheme To Foster Model Cooperation Within A Hydrological Multimodel Ensemble
Louise Crochemore (SMHI)	How Much Can Continental Hydrological Forecasting Services Be Benefited From High-Resolution NWP Systems?
Rebecca Emerton (University of Reading/ECMWF)	GloFAS-Seasonal: An Operational Seasonal Global Hydro-Meteorological Forecasting System
Andrew Frost (Bureau of Meteorology)	Evaluation Of Fine-Scale Ensemble Seasonal Soil Moisture And Evapotranspiration Forecasts For The Sydney Region
Trine Jahr Hegdahl (Norwegian Water Resources and Energy Directorate)	Can Improved Meteorological Forecasts Improve The Flood Forecasts? A Case Study Of Selected Floods In Norway, 2013 To 2015
Wentao Li (Beijing Normal University)	A Comparison Of Statistical Post-Processing Methods For Short- To Medium-Range Precipitation Forecasts
Lucy Marshall (SMHI)	Advancing Our Understanding Of Data Assimilation For Hydrologic Predictions In Changing Catchments
Samuel Monhart (ETH/WSL)	Hydrometeorological ensemble predictions in Switzerland: the influence of pre- and post-processing on the forecast performance in different alpine catchments
Daniela Peredo-Ramirez (IRSTEA)	Assessment of the 2016 Flood Event On the Seine And Loire River Basins Using Ensemble Forecasts
Maria-Helena Ramos (IRSTEA)	Does HEPEX need a new cutting edge?
Andrew Schepen (CSIRO)	The HEPEX Seasonal Streamflow Forecast Intercomparison Project
Yong Song (CSIRO)	A Gibbs Sampler Bayesian Joint Probability Model
Ioannis Tsanis (Technical University of Crete)	Assessment Of The Probabilistic Forecasting Of The European Flood Awareness System
Carlos Velasco-Forero (Bureau of Meteorology)	Seamless Rainfall: A Multi-Scale Ensemble Rainfall Forecast Generator
Albrecht Weerts (Deltares)	Inter-comparison experiment of data assimilation by neural networks and variational state estimation for different hydrological model structures
Albrecht Weerts (Deltares)	HEPEX Data Assimilation Inter-Comparison Experiment
Micha Werner (IHE-Delft)	Functionality And Relevance Of Hydrological Models In Multi-Model And Multi-Forcing Ensembles From A Bayesian Perspective – A Study On The Magdalena-Cauca Macro-Basin, Colombia
Andy Wood (NCAR)	Improving Ensemble Forecasts In Watersheds With Seasonal Snowpack Through Data Assimilation Of Streamflow
Aizhong Ye (Beijing Normal University)	The contribution of ensemble streamflow forecasts to water resources optimization scheduling
Ervin Zsoter (ECMWF)	The Impact Of Land Data Assimilation On Global River Discharge Simulations

Abstracts

ON THE INCIDENCE OF METEOROLOGICAL AND HYDROLOGICAL PROCESSORS: EFFECT OF RESOLUTION AND RELIABILITY OF HYDROLOGICAL ENSEMBLE FORECASTS

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Abstract

Meteorological and hydrological ensemble prediction systems are imperfect. Their outputs could often be improved through the usage of a statistical processor, opening up the question of the necessity of using both processors (meteorological and hydrological), only one of them, or none. This experiment compares the predictive distributions issued by four hydrological ensemble prediction systems (H-EPS) that make use of the Ensemble Kalman filter (EnKF) probabilistic sequential data assimilation scheme. They differ in the inclusion or not of the Distribution Based Scaling (DBS) method to post-process weather forecasts and of the ensemble Bayesian Model Averaging (ensemble BMA) method for hydrological forecasts post-processing. The experiment is implemented on three large watersheds and relies on the combination of two meteorological reforecast products: the 4-member Canadian reforecasts from CCMEP and the 10-member American reforecasts from NOAA, leading to 14 members at each time step. Results show that all four tested H-EPS lead to resolution values that are quite close to one another, with an advantage to DBS + EnKF. The ensemble BMA turns out to be unable to compensate for any bias left in the precipitation ensemble forecasts. On the other hand, it succeeds in calibrating ensemble members that are otherwise under-dispersed. If reliability is preferred over resolution, DBS + EnKF + ensemble BMA comes on top, making use of both processors in the H-EPS system. In the opposite case, DBS is preferred.

Keywords

Meteorological processor, hydrological processor, ensemble hydrological reforecasts, reliability, resolution.

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INTER-COMPARISON EXPERIMENT OF DATA ASSIMILATION BY NEURAL NETWORKS AND VARIATIONAL STATE ESTIMATION FOR DIFFERENT HYDROLOGICAL MODEL STRUCTURES

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Abstract

Data assimilation is an important part of operational forecasting systems. It allows for the estimation of initial model states based on uncertain observations and inexact model simulations. Compared to typical open loop simulations, data assimilation techniques reduce the uncertainty of the initial states by merging observations and simulations. While sequential techniques such as Ensemble Kalman Filter have been widely studied in hydrological applications, others are still at an early stage of research and development. This paper compares two emerging techniques for different hydrological model structures and analyses their advantages and drawbacks.

Extreme Learning Machines (ELM) are an emerging type of neural networks that do not require iterative optimization of weights and biases and are therefore much faster to calibrate than typical feed-forward backpropagation neural networks. Boucher et al. (2017) studied the use of ELM to update model states in the GR4J hydrological model coupled to the CemaNeige model to account for snow processes. On the other hand, the Moving Horizon Estimation (MHE) variational data assimilation introduces noise variables within a model and relies on numerical approaches to solve flexible formulations of objective functions to provide better initial estimates. Alvarado-Montero et al. (2017) have used this approach, in combination with multi-parametric modelling, to improve the states of the HBV model using long assimilation windows for a period of up to one year prior to the forecast time.

This research compares the improvement of the forecast performance using the ELM and MHE data assimilation techniques for identical sets of input data. The results are analysed using different forecast metrics. We compare the forecast performance of the two assimilation techniques using a hindcasting experiment of 5 years for the basin of the Mistassibi River located in the province of Quebec, Canada. Similarly, we compare results using a hindcasting experiment of 10 years for the basin of the Main River in Germany.

The work is part of the HEPEX-Data Assimilation Inter-comparison experiment (HEPEX-DA), which provides a common framework to compare data assimilation techniques within different research working groups. This is one of the first comparisons under the HEPEX-DA initiative and serves as a reference for future comparisons among this community.

Keywords

Data assimilation, extreme learning machines, multilayer perceptrons, variational assimilation.

References

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HYDROMETEOROLOGICAL ENSEMBLE PREDICTIONS IN SWITZERLAND: USING STREAMFLOW FORECASTS TO IMPROVE HYDROPOWER RESERVOIR OPERATIONS

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Abstract

Hydropower reservoir operation can be improved by considering streamflow forecasts when deciding how to operate the system, i.e., reservoir and power plant. Accurate and reliable streamflow forecasts are key to anticipate extreme events at different temporal scales, particularly on the short term (several hours ahead). Increased anticipation capability results into more flexible and adaptive hydropower operation over different time horizons from hourly operation, to weekly management, to monthly production planning.

The objective of this work is to develop a real-time hydropower operation system for Alpine snow and rain dominated system, which includes an ensemble streamflow forecasting system and a real-time control system scheme. The specific objectives are to analyze the quality of a set of streamflow forecasts on a retrospective dataset, to improve the hydropower system operations and to assess the utility of pre-processing meteorological forcing and post-processing streamflow forecasts in terms of hydropower performance.

The aim is to assess how much reservoir operations can benefit by the consideration of ensemble streamflow forecasts. We use a forecast-based adaptive management framework composed of a hydrometeorological ensemble prediction system and a real-time optimization system. The forecasting system used is the one developed and adopted in the HEPS4POWER project. This system is a further development of the one used by Jörg-Hess et al. (2015) for early detection of hydrological droughts in Switzerland. The new implementation has been setup for the Verzasca river basin. The hydrological model PREVAH is forced with the ECMWF extended-range forecasts providing 5 members for the hindcast period 1994-2014 and 51 members for the forecast period 2014-2015. In addition to the raw meteorological forecasts a quantile mapping technique is applied as a pre-processing. Furthermore, different post-processing techniques of varying complexity are used to refine the streamflow forecasts (Bogner et al., 2016).

We use a Model Predictive Control (MPC) scheme where the reservoir operations are periodically revised to include the most up-to-date streamflow forecasts. We use a deterministic optimization on a

rolling-horizon to define the operations for the following 30 days, we apply the reservoir release decision for the first day, and we re-optimize the operations for the following 30 days.

We repeat the optimization scheme for every forecast ensemble to estimate how the uncertainty in the forecasts translates into uncertainty in the reservoir operation performances. In so doing, we can assess how the buffering capacity of the reservoir can mitigate potential forecast inaccuracies. The assessment of the improvement in hydropower system performance will be based on the framework proposed in Anghileri et al., (2016).

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SKILFUL SEASONAL FORECASTS OF STREAMFLOW OVER EUROPE?

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Abstract

While climate-model-based seasonal streamflow forecasting experiments are abundant outside of Europe, they remain limited in Europe. This is because, although the quality of seasonal climate forecasts has increased over the past decades, there remains limited skill for the extra-tropics. Much effort is being made to increase the quality of seasonal streamflow forecasts worldwide. However, as their quality increases, their usability for decision-making lags behind. Translating the quality of a forecast into an added value for decision-making and incorporating new forecasting products into established decision-making chains are not easy tasks. While this has been explored for many applications of the water sector where decision-makers are already familiar with working on sub-seasonal to seasonal timescales (such as navigation, reservoir management, drought-risk management, etc), this is not the case for flood preparedness, where actions are currently taken on very short timescales (i.e. days in advance).

The European Flood Awareness System (EFAS) is at the forefront of seasonal streamflow forecasting, with one of the first operational pan-European seasonal hydrological forecasting system. Here, we present the skill of the EFAS seasonal streamflow hindcasts (Lisflood hydrological model forced with ECMWF's System 4 seasonal climate hindcasts) benchmarked against the Ensemble Streamflow Prediction (ESP; Lisflood forced with historical meteorological observations), using a variety of verification scores that cover several forecast attributes (i.e. accuracy, sharpness, overall performance and reliability) and for the upper and lower terciles of the distribution (Arnal et al., in review). Overall, the results show that the EFAS seasonal streamflow hindcasts are, on average, skilful for the first month of lead time only. However, parts of Europe display a longer predictability, up to seven months of lead time, for certain target months.

For decision-making, the ability of a seasonal forecasting system to predict the right category of an

event (e.g. above or below normal conditions) months ahead is of great importance. Our results demonstrate that, although the ESP is overall the most potentially useful forecasting approach for decision-making in Europe, the EFAS seasonal streamflow forecasts are more potentially useful than the ESP for certain seasons and regions, especially in winter for most of Europe.

Keywords

Seasonal, streamflow, climate-model-based forecasting, Europe, decision-making

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USING GLOBAL ENSEMBLE FORECASTS TO ISSUE FLASH FLOOD WARNINGS

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Abstract

Flash flood hazards have the highest mortality rates amongst flood types [Doocy *et al.*, 2013], yet currently there is no global flash flood forecasting system. The challenge is to develop such a system which has continuous global coverage, extends lead times beyond a few hours and contains meaningful information at relevant spatial and temporal scales.

Metrics from global Numerical Weather Prediction (NWP) ensemble forecasts can meet most of these requirements. For example the Extreme Forecast Index (EFI) approach developed at ECMWF [Lalaurette *et al.*, 2003] integrates the difference between the ensemble forecast and hindcast cumulative distribution functions, thus yielding an index of hazard extremity.

We applied the EFI approach to global, six-hourly, 51 ensemble member ECMWF forecasts of rainfall and surface runoff and use the results as a proxy for flash flood warnings up to 5 days ahead. For longer lead times, the warnings are spatially coarse, making it difficult to identify the localities most at risk. The warnings were refined by excluding those which lay outside of a predefined 'vulnerable areas' map, created by combining maps of 100 year return period flood extent, urban areas and strategic road networks.

The above method was tested on one year of surface runoff and rainfall EFI forecasts. Warnings were validated against global flash flood media reports using an area based methodology, where forecasted warning areas were weighted against reported flash flood locations buffered by their spatial uncertainty. Results found reasonable global predictability (hit ratio > 0.5) at lead times of 1-2 days. At greater lead times the false alarm ratio increased, possibly a result of increasing spread in the ensemble resulting in smaller EFI values. By restricting flash flood warnings only to the vulnerable areas it was possible to reduce the instance of false alarms.

This work demonstrates the ability of ensemble NWP forecasts to issue global flash flood warnings. Future work will aim to further refine the flash flood warnings, for example by the inclusion of hydraulic channel routing processes and more detailed vulnerability information.

Keywords

Flash floods, warnings, ensembles, global.

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LONG-RANGE STREAMFLOW FORECASTS IN DRYLANDS

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Abstract

Dryland rivers are vital sources of freshwater in many regions but have received little attention from the ensemble forecasting research and operations community. This may be in part due to the technical difficulty of producing ensemble predictions in ephemeral rivers. Ephemeral rivers can display strongly non-linear relationships between rainfall and runoff that are difficult to simulate while generating ensembles that can handle zero values is very challenging using conventional statistical techniques.

We generate long-range (12-month) forecasts at a monthly time step using the well-known Ensemble Streamflow Forecasting (ESP) method for 80 Australian catchments, of which 20 are ephemeral rivers. ESP forecasts show reasonably good performance in perennial rivers, but they perform poorly in ephemeral rivers, with low or negative skill at all lead-times, strong biases, and very poor reliability.

We then apply a new staged error model to the ESP forecasts. The error model has four stages: 1) data transformation, 2) bias-correction, 3) autoregressive updating and 4) uncertainty quantification and propagation. A crucial innovation is the use of data censoring to handle zero values when error model parameters are estimated: parameters are estimated using maximum likelihood, with zero values in both observations and simulations treated as censored data.

The error model can extract useful information from the ESP forecasts for ephemeral rivers, while correcting other deficiencies in the forecasts. Forecasts are generally skillful at short lead-times (1-2 months), and transit to climatology-like forecasts at longer lead times. Bias-correction of transformed data can handle the strongly non-linear biases in ephemeral rivers. The data censoring technique produces reliable predictions, correctly estimating the incidence of zero values. These techniques admit the possibility of producing useful, long-range streamflow forecasts in semi-arid and arid regions.

Keywords

Ephemeral rivers, data censoring, ESP, drylands, error modelling.

HYDROLOGIC MODELS TO SUPPORT DECISION MAKING IN THE MURRAY DARLING BASIN

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Abstract

The Murray-Darling Basin extends across a large area of south west Australia with a highly variable inflow. The Basin is comprised of twenty three major rivers flowing through four states and one territory. Low rainfall, high evaporation, large floodplains and diversions for town and agriculture characterise highly variable flows in these rivers and means that much of the surface water does not reach the ocean. For over 100 years, a range of agreements, policies and plans have been implemented in an attempt to manage the Basin water resources equitably.

The Water Act 2007 led to the establishment of the Murray Darling Basin Authority (MDBA), which is responsible for developing and implementing the Basin Plan. The Basin Plan aims to ensure the water resources are shared equitably between all water uses in a sustainable way. The MDBA is also responsible for directing the sharing of the River Murray System's water on behalf of the states. This involves managing assets, sharing the water between states and directing the operations to meet the needs of individual states from the River Murray System.

This presentation will overview how the MDBA uses models to inform planning, policy and operational decision making. Models have underpinned most key policy initiatives in the Basin, such as the Salinity and Drainage Strategy, the CAP and the Basin Plan. The application of models to support operational decision making will then be discussed, including the role of ensemble forecasts to support operational decisions. Finally, the presentation will present some of the challenges and emerging issues with modelling in the MDBA and how ensemble forecast may inform decision making into the future.

THE USE OF RADAR-BASED RAINFALL OBSERVATIONS AND FORECASTS TO PROVIDE ENHANCED FLOOD FORECASTS AND WARNINGS IN AUSTRALIA

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Abstract

The Australian Bureau of Meteorology has been investigating how quantitative radar rainfall estimations and ensemble nowcasting radar rainfall products can further improve its operational flood forecasting service. It is expected that the incorporation of high resolution (spatial and temporal) gridded rainfall data may increase flood warning lead times and greatly improve the robustness of flood warning services provided.

The current operational flood forecasting and warning service is primarily based on the national network of rain gauges and gridded deterministic forecast rainfall from a number of Numerical Weather Prediction (NWP) models and the Bureau's official forecasts (NexGen). In this study, the Bureau's Hydrological Forecasting System (HyFS) has been modified to import gridded rainfall products for both Quantitative Precipitation Estimation (RAINFIELDS) and Quantitative Precipitation Forecast (QPF) (STEPS - Short-term Ensemble Prediction System) products. STEPS produces probabilistic forecasts numbering up to 35 ensemble members that are updated every 6 to 10 minutes. The QPF from STEPS can be based on radar rainfall observations only to provide rainfall forecasts up to 110 minutes in the future (nowcast), or radar rainfall observations gradually blended with a downscaled NWP model rainfall forecast to extend the rainfall predictions up to 13 hours in the future.

Selected historical flood events were used as case studies to assess the performance of the ensemble hydrological forecasts to produce suitable and accurate flood estimations. Results were analysed qualitatively by comparing the hydrographs (e.g. Figure 1) simulated from different rainfall forecast guidance and then a basic methodology was introduced for the quantitative assessment of the simulation results. The case studies have shown that it is difficult to discriminate between errors from the data, the hydrological models and the users. However overall STEPS skill is comparable to the Bureau's official forecast NexGen, STEPS's main advantage lies in its frequent updates and providing a rainfall forecast with only a few minutes latency.

Identified areas for improvement include the HyFS configuration, other technical requirements, and operational flood forecaster training. In particular the STEPS data is discussed in detail with suggestions to alter its format to best suit the need of the flood forecasting and warning services. Further investigation is needed to fully address the efficient use of a very frequently updated rainfall forecast in

an operational environment, i.e. how will flood forecasters incorporate flow predictions based on the STEPS probabilistic forecasts that may change a number of times every hour when the current flood forecasting and warning processes and practices are typically based on rainfall predictions updated only a few times each day.

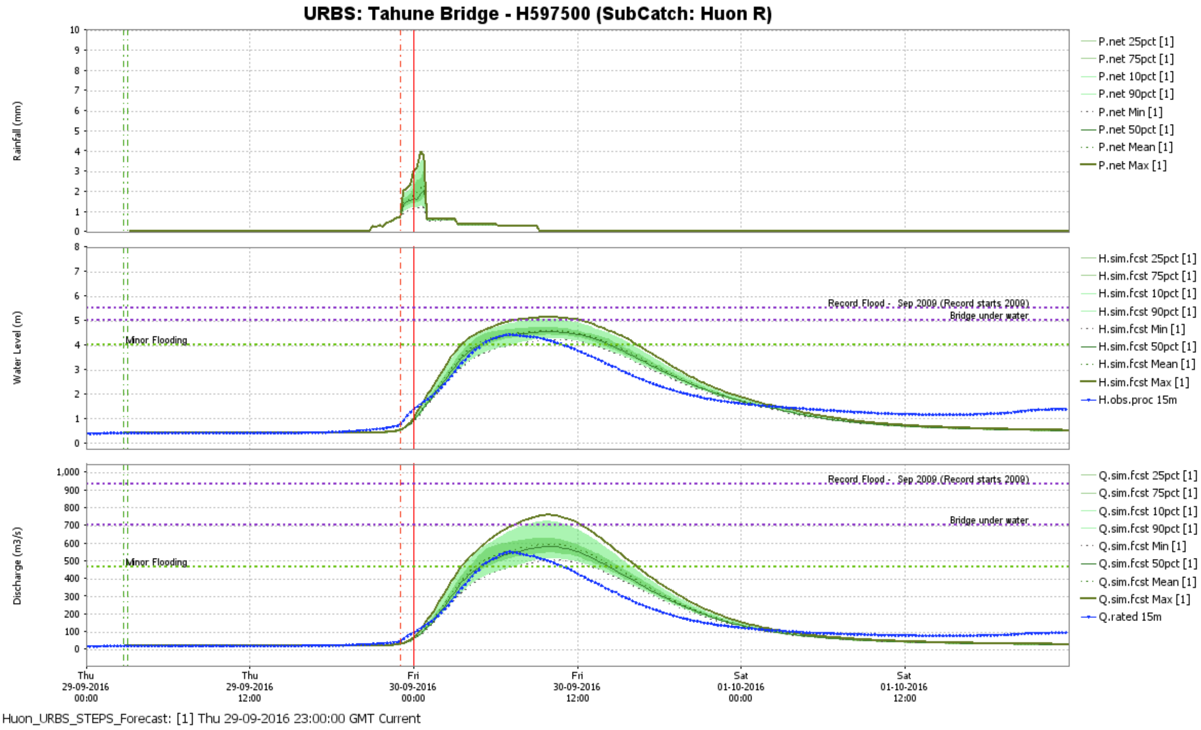

Figure 1: STEPS probabilistic forecast at Tahune Bridge (Huon River) in September 2016

Keywords

Radar rainfall, probabilistic forecast, flood forecasting.

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CONFIDENCE IN FLOOD WARNING SYSTEM AND THE VALUE OF ENSEMBLE FORECASTS

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Abstract

The value of streamflow forecasts is directly linked to their usefulness for the decision maker. For instance, in the context of flood mitigation, forecasts are used in the decision to alert (or not) the population. While early warnings provide more time for the population to adjust (e.g. by removing furniture from basements, sandbagging, etc), raising an alarm too early also increases the likelihood of false alarms. This, in turn, could lower the population's confidence toward the warning system. Similarly, last minute warnings would also hurt the population's confidence or induce unnecessary stress.

We study the optimal warning decision in this context, and under three ensemble streamflow forecasting systems: a statistically dressed deterministic forecasts, and two forecasting systems based on meteorological ensembles (with and without state variable uncertainty estimation). Forecasts for 2011-2014 are produced for the Montmorency watershed in Quebec (Canada) and compared with corresponding observations.

We consider a risk averse decision maker who sees the benefit of early warnings, but also of preserving the population's confidence in the warning system. Indeed, low confidence levels would reduce the probability that the population would take future alarms seriously and therefore increases the probability of individuals refusing to evacuate. The optimal solution is given by a dynamic optimization problem, solved using dynamic programming:

$$V(x,p) = max_{\sigma}\{U(x,\sigma,p) + \delta EV(x',p') \vee x\},$$

where the state variables are $x \in [0,1]$,the decision maker's belief regarding the flood, and $p \in [0,1]$,the population's confidence level. Every period, the decision maker chooses $\sigma \in \{0,1\}$,i.e. to raise an alarm or not. Future values, x' and p', are themselves a function of previous state variables and decisions. The function $U(x,\sigma,p)$ is the decision maker's von Newmann Morgenstern (von Newmann and Morgenstern, 1944) utility, which accounts for the probability of a flood (given the forecast) as well as the probability that the population disregards the alarm (given the confidence level).

We find that the decision to trigger an alarm is increasing with the probability of flood, as well as with the population's confidence level. This implies that, when the population's confidence level is low, the decision maker triggers an alarm more frequently, hoping to restore the population's confidence. When the population's confidence level is high, the decision maker is more cautious and triggers the alarm

only if the probability of flood is large enough.

We find that forecasts based on meteorological ensembles outperform the dressed deterministic forecasts. They lead to higher level of confidence among the population and higher utility for the decision maker. This implies that a decision maker equipped with such ensemble forecasts would be able to make better decisions, leading to: less false alarms, less missed events, and higher welfare.

Keywords

Economic value of forecasts, decision-making, risk-aversion, flood forecasting

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ASSIMILATING P-BAND MICROWAVE SOIL MOISTURE OBSERVATIONS TO IMPROVE ROOT ZONE SOIL MOISTURE ESTIMATION

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Abstract

Soil moisture (SM) forms an important part of the complex system that helps with understanding the water cycle and climate system. However, observations of SM are limited to indirect measurements, from either sparse meteorological network stations or near-surface remote sensing data. A fundamental limitation of existing satellite SM observations is that they only provide information on the top ~5 cm layer of soil. These satellites use passive microwave (MW) sensors operating at L-band (21 cm; 1.4 GHz) [1]. However, a new proposal to use P-band, which has a longer wavelength (41 cm; 750 MHz), is expected to provide information on the top 15-30 cm layer of soil.

This study used a synthetic twin experiment to assess how assimilating P-band (30 cm) derived SM improves root zone SM prediction as compared to that from L-band (5 cm). The synthetic observational data used in this experiment is derived from in-situ SM measurements by adding a 10% error to account for the retrieval algorithm. The SM observations were taken from the University of Newcastle's (UON) Scaling and Assimilation of Soil Moisture And Streamflow (SASMAS) experimental catchment SM network, located in the Hunter region of Eastern Australia [2]. The near-surface SM observations from this dataset were assimilated into the CSIRO's Community Atmosphere Biosphere Land Exchange (CABLE) land surface model via an Ensemble Kalman Filter (EnKF) for the S2 monitoring site between 2010 and 2015. The SASMAS in-situ SM measured at 0-5 cm, 0-30 cm, 30-60 cm and 60-90 cm depths were subsequently used to calibrate and validate results, with and without observational constraint. Nash-Sutcliffe Efficiencies (NSE) and Root Mean Square Errors (RMSE) were computed to evaluate the results.

Preliminary results show an overall improvement in root zone SM while assimilating P-band MW data; model evaluation methods resulting in NSE>0 and RMSE<0.1 m^3/m^3. The top soil (0-30 cm) NSE and RMSE showed slight improvements while the 60-90 cm soil moisture showed significant improvements. The root zone improvement suggests that CABLE's soil hydrology is redistributing the updated moisture through the layers successfully. The results are particularly sensitive to how much the meteorological forcing variables are perturbed. An L-band assimilation experiment will be performed and compared against this synthetic P-band experiment. The soil in CABLE is defined as homogeneous leading to unusual results as soil properties change in the profile.

This study will demonstrate the potential for P-band MW to be used to improve SM estimations compared to estimations based on L-band MW. This improvement could be applied in fields such as weather prediction, agricultural water management and water planning. This study is the framework for future work to develop an irrigation scheduling scheme to demonstrate a potential application of P-band MW.

Keywords

CABLE, EnKF, Soil Moisture, Data Assimilation, P-band

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POST-PROCESSING PRECIPITATION FORECASTS FROM A HIGH RESOLUTION CONVECTIVE-PERMITTING WEATHER MODEL FOR NATIONAL SCALE SHORT-TERM FLOW FORECASTING IN NEW ZEALAND

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Abstract

Flooding is the most frequent natural disaster in New Zealand, and hydropower makes up most of the renewable energy. A National Flow Forecasting System capable of providing forecast information, at both gauged and ungauged river reaches, will be a great asset for assessing risk of floods and downstream impacts, and supporting hydropower operations as well as recreational, environmental and cultural uses of water.

This work will present key aspects and challenges of the development of a national short-term flow forecasting system for New Zealand rivers. An approach aiming to generate ensemble precipitation forecasts for a national scale flow forecasting system by post-processing raw numerical weather precipitation predictions will be introduced.

The country's vast river network is forecast by coupling the hydrological model TopNet with a high resolution convective-permitting weather model, the New Zealand Convective Scale Model (NZCSM).

TopNet is a distributed hydrological model, based on TOPMODEL concepts of runoff generation controlled by sub-surface water storage. Within each subcatchment, a water balance model is solved with an implementation of a kinematic wave channel routing algorithm (Beven et al., 1995). The NZCSM numerical weather prediction model is a local implementation of the UK Met Office Unified Model System (UM) for New Zealand, with a grid resolution of 1.5km. The combination of TopNet over the country, or the National Hydrological Model (NHM), and NZCSM is applied to the highly diverse environment of the New Zealand catchments to provide water information required nationally.

Although high resolution weather models simulate precipitation more realistically than large scale models, they can also exhibit bias with a tendency for persistent over-estimation of light drizzle and under-estimation of heavier precipitation particularly during flood events in high elevation regions (Cattoën et al., 2016). We investigate a precipitation post-processing and ensemble generation method based on a Bayesian joint probability model (Robertson et al., 2013), Schaake shuffle (Clark et al., 2004) and lagged ensemble forecasts. To apply the rainfall post-processor at national scales, we need to rely

on a gridded product (Virtual Climate Station Network (Tait et al., 2006)) as the "truth" of observed precipitation. The VCSN interpolates observed meteorological values onto a grid covering New Zealand at a 5km spatial resolution and daily timescale, larger than the 1.5km and hourly weather model resolution. This brings challenges including hourly disaggregation of forecasts calibrated at daily lead times, and the choice of historical template data used for the Schaake shuffle.

We will discuss the implementation of the post-processing method and present some initial results from the Hutt river catchment in the Wellington region in New Zealand.

Keywords

Ensembles, post-processing, national model

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USE OF ARTIFICIAL NEURAL NETWORKS IN SHORT-TERM STREAMFLOW FORECASTING FOR THE SNOWY MOUNTAINS SCHEME

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Abstract

Accurate and timely inflow forecasts are essential to optimizing the day-to-day operations of the Snowy Mountains Scheme, but the nature of alpine catchments presents challenges to simple rainfall-runoff models. The spatial variability of rainfall is typically much higher in complex terrain, which increases the variability of the runoff response. In addition, snowpack can partially or completely cover some sub-catchments over winter, modulating the runoff response in a highly non-linear manner.

An in-house streamflow forecasting model has been developed to aid inflow predictions. The model is based on an artificial neural network (ANN) trained using historical streamflow and meteorological drivers. The ANN is capable of predicting short-term changes to streamflow with a high degree of accuracy. Longer-term predictions are made by feeding the short-term streamflow prediction back as an input, while using numerical weather prediction (NWP) model data for future values of the meteorological inputs. To characterise potential forecast uncertainty, an ensemble of ANNs is used, with each one trained on a slightly different subset of the available historical data. Small perturbations are also applied to the input precipitation to simulate uncertainties in the meteorological inputs.

This study presents an evaluation of the streamflow model to determine the relative contributions of ANN internal variability and NWP prediction errors to overall streamflow forecast uncertainty. A cross-validation over five years using observed (as opposed to NWP-derived) meteorological drivers will be performed using a number of slightly different ANN configurations to evaluate the sensitivity to model inputs. A shorter period of re-forecasts using NWP-derived inputs will be compared to these results to evaluate the decline in forecast skill with lead time up to four days. Metrics considered for the evaluation include: mean error and bias of total and peak daily streamflow; accuracy of probabilistic streamflow forecasts; and event-based metrics for high-inflow events.

Keywords

Streamflow forecasting, artificial neural networks, ensemble forecasting

IMPROVING ENSEMBLE FORECASTS IN WATERSHEDS WITH SEASONAL SNOWPACK THROUGH DATA ASSIMILATION OF STREAMFLOW

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Abstract

Data assimilation has been demonstrated to improve streamflow forecasts; however, few studies [Abaza et al., 2015; Clark et al., 2017] have investigated the effects of the assimilation based solely on streamflow observations in basins where seasonal snowpack plays an important role in runoff generation. We apply a Sequential Importance Resampling (SIR) particle filter (PF) based solely on streamflow observations at the outlets of two basins with seasonal snowpack—the North Fork Flathead River at Hungry Horse Reservoir and the Green River at Howard Hanson Dam in the Pacific Northwest U.S.—to improve estimates of initial hydrologic conditions (IHCs) for 0- to 6-day lead time streamflow forecasts. We examine four dimensions: 1) combined model-observation uncertainty, 2) hydroclimate, 3) season, and 4) the minimum number of IHC ensemble members needed for forecast initialization. Streamflow forecasts are evaluated in terms of mean absolute error, correlation, percent bias, continuous rank probability score, and the alpha reliability index. Based on these metrics, the PF that assumed uncertainty in the likelihood function of only 10% (near maximum of uncertainty in gauged streamflow) did not perform as well as the PF that assumed 25% uncertainty, suggesting the need to incorporate model errors in the likelihood function. Larger improvements in forecast performance were attributed to the PF at Hungry Horse (where winter snow is the primary form of precipitation) than at Howard Hanson (where fall rain and winter snow are both important sources of precipitation). In both basins, the PF improved streamflow forecasts most strongly in spring, which is also when synthetic truth experiments show the most improvement in initial snow water equivalent. Finally, we found that similar forecast performance was possible if only the 20 highest weighted particles—out of 100 IHC ensemble members—were used to initialize streamflow forecasts.

Keywords

Particle filter, data assimilation, streamflow, seasonal snow

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FLY ME TO THE MOON: A REVIEW OF ENSEMBLE FLOOD FORECASTING 10 YEARS ON

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Abstract

10 years ago we wrote a review on Ensemble Flood Forecasting considering how operational flood forecasting systems were adopting weather ensemble prediction systems (EPS), to drive their predictions. This talk will reexamine the scientific drivers of this shift to ensemble flood forecasting to illustrate just how far we've come and the many advances made in both the science and practice of ensemble flood forecasting. Drawing on examples from the European and Global Flood Awareness Systems (EFAS and GloFAS) some recent successes and remaining challenges in providing operational and useful forecasts will be considered. I will also encourage us to be bold in our HEPEX endeavours and to fly to the moon and play among the stars!

SKILL SENSITIVITY IN EUROPE AND SITE-SPECIFIC DIAGNOSTICS BASED ON CATCHMENT CHARACTERISTICS

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Abstract

Advances in understanding of climate continuously lead to improved seasonal meteorological forecasts, which can consequently increase the confidence of hydrological prognosis. In line with these advances, there is a necessity to develop operational seasonal forecasting services at the pan-European scale, capable of providing users with climatological and hydrological information at the continent scale and addressing user needs for different water-related sectors. The skill of such forecasting services is subject to different sources of uncertainty, i.e. model structure, parameters, initial conditions and meteorological forcing input.

Here, we investigate the relative contributions of initial hydrologic conditions (IHCs) and meteorological forcing (MF) to the skill of a pan-European seasonal hydrological forecasting system. The Ensemble Streamflow Prediction (ESP) and reverse ESP (revESP) procedures are used as proxy of hydrological forecasting uncertainty due to MF and IHC uncertainties, respectively. ESP is built from perfect initial conditions and historical precipitation and temperature forcings, whereas revESP is built based on historical initial conditions and perfect precipitation and temperature forcings. We further calculate the critical lead time (CLT), i.e. the lead time after which the importance of MFs surpasses the importance of IHCs, as a proxy of the river memory. The end point blending (EPB, Arnal et al., 2017), a computationally-light derived version of the variational ensemble streamflow prediction assessment (VESPA, Wood et al., 2016), is also conducted to provide diagnostics of skill sensitivity to IHC and MF over forecast months and forecast aggregations in a set of chosen catchments that are representative of the European hydro-climatic gradient. In all analyses, both model state initialisation (level in surface water, i.e. reservoirs, lakes and wetlands, soil moisture, snow depth) and provision of climatology are based on forcing input derived from the WFDEI product, a combination of the ERA-Interim reanalysis and of satellite products (Weedon et al., 2014), for the period 1981-2010. The European version of the HYPE hydrological model (E-HYPE) was used throughout this investigation.

We firstly analyze these results in the context of prevailing hydro-climatic conditions for about 35400 European basins. The contribution of ICs and MFs to the hydrological forecasting skill is shown to vary considerably according to location, season and lead time. These analyses further allow a clustering of: (a) basins in which hydrological forecasting skill may be improved by better estimation of IHCs, e.g. via data assimilation of in-situ and/or satellite observations; and (b) basins in which skill improvement is more sensitive to improved MFs. These clusters can be associated with categories of hydro-climatic characteristics, which are finally illustrated through skill elasticity graphs in a set of European catchments.

Keywords

Hydrological modelling, E-HYPE, initial hydrological conditions, pan-European scale, EPB

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HOW MUCH CAN CONTINENTAL HYDROLOGICAL FORECASTING SERVICES BE BENEFITED FROM HIGH-RESOLUTION NWP SYSTEMS?

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Abstract

Operational hydrological forecasting services provide important information for water resources management and preparedness against extreme events. Despite the generally adequate performance of these services, there is still a need for diagnosing limitations and providing continuous improvements. Some important efforts on predicting extreme hydrological events are targeted towards improving the skill of weather forecasts via assimilation of earth observations and/or application of high-resolution numerical weather prediction (NWP) models. State of the art pan-European hydrological services (SMHI's WaterInfo) are based on ECMWF weather deterministic forecasts, which are provided at 16 km horizontal resolution. Nevertheless it is expected in principle that NWPs with higher spatial resolution will provide the weather signal to predict better the hydrological events, particularly the spatially localized extremes events. As a result, SMHI has been exploring the high resolution (2.5 km horizontal grid-distance) NWP HARMONIE-AROME (Hirlam Aladin Regional/Meso-scale Operational NWP In Europe) configuration for short-range predictions. In the HARMONIE-AROME configuration, extreme precipitation events are addressed by assimilating surface remote sensing data regarding snow and soil moisture.

Despite the various developments on NWPs, in natural river systems the dependency between precipitation and hydrological extremes is not linear but rather varies as a function of catchment scale and type and antecedent conditions. However, when reality is represented numerically, the streamflow response at the catchment scale also depends on the way precipitation is represented in the hydrological models. Here, we aim to assess the improvements on the performance of the pan-European hydrological forecasting services from using high-resolution NWPs in comparison to the benchmark ECWMF deterministic forecasts. We investigate a number of precipitation events over Europe using the E-HYPE hydrological model, and hence its spatial discretization, and analyze the peak streamflows from ECMWF deterministic and HARMONIE-AROME forecasts. The analysis is focused on 5 and 2 precipitation events over the Southern and Northern European domain respectively, which resulted into flashfloods. We further analyze improvements as a function of catchment type and

scale, antecedent conditions and precipitation properties.

Keywords

Hydrological forecasting, E-HYPE, extreme events, high resolution NWP

DIAGNOSTIC ASSESSMENT OF LOCALIZED FLOOD FLOW BEHAVIOUR

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Abstract

Floods are the most commonly occurring natural disasters and cause severe economic damage, in addition to having far reaching social consequences. Hydrodynamic models, traditionally used for flood forecasting, are affected by multiple sources of uncertainty, which can be reflected through ensemble forecasting. Model structure, inputs, forcings, parameterization, and spatiotemporal domain discretization, all contribute to the total uncertainty in the final flood forecasts. Therefore, flood extent and depth observations are required, to constrain or improve the ensemble of model predictions, through calibration or assimilation. Recent years have witnessed a lot of research, on the global impact of assimilating remotely sensed flood information on flows. However, there is still limited understanding on where Earth Observation data can add value to model forecasting skill and why. As flow behaviour in different portions of the channel are often governed by different hydraulic controls, it is expected that the impact of assimilation will vary spatially. In this study, a diagnostic assessment of flow behaviour is carried out, to identify the regions where remote sensing observations can offer maximum improvement. This is achieved by quantifying the deviation from kinematic flow behaviour and characterising regions of uniform hydraulic complexity. The proposed approach is tested for the Clarence catchment in Australia, using the LISFLOOD-FP hydraulic model, to simulate 2D flood inundation using observed inflows for a flood event which occurred from 25th Jan to 08th Feb, 2013. The “roughly” calibrated model will be used to simulate flood flows in the study catchment, using the kinematic wave and inertial approximation of the shallow water equations, available as solvers in LISFLOOD-FP. The differences in modelled water depth using the two aforementioned approaches, will be used to characterise flow behaviour for different parts of the channel. Isolating sub-reaches where flood flow patterns are primarily linear or hydrodynamic, can also provide insightful information to inform the implementation of hydraulic assimilation. Furthermore, such an analysis can facilitate targeted satellite acquisitions, to subsequently improve the impact of assimilation on flood predictions, which can be critical for operational forecasting applications.

Keywords

Uncertainty, hydrodynamic modelling, flow behavior, assimilation, remote sensing.

COMPLEX PICTURE FOR LIKELIHOOD OF ENSO-DRIVEN FLOOD HAZARD

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Abstract

El Niño Southern Oscillation (ENSO), a mode of variability which sees fluctuations between anomalously high or low sea surface temperatures in the Pacific, is known to influence river flow and flooding at the global scale. The anticipation and forecasting of floods is crucial for flood preparedness, and this link, alongside the predictive skill of ENSO up to seasons ahead, may provide an early indication of upcoming severe flood events.

Historical probabilities provide key information regarding the likely impacts of El Niño and La Niña; for the impact on precipitation, these are readily available, and are often used as a proxy for flood hazard. However, the nonlinearity between precipitation and flood magnitude and frequency means that it is important to assess the impact of ENSO events not only on precipitation, but also on river flow and flooding.

We estimate, for the first time, the historical probability of increased flood hazard during El Niño and La Niña through a global hydrological analysis, using a new 20th Century ensemble river flow reanalysis for the global river network. We further evaluate the added benefit of the hydrological analysis over the use of precipitation as a proxy for flood hazard.

Our results map, at the global scale, the probability of abnormally high (or low) river flow during any given month during an El Niño or La Niña, and show that the likelihood of increased or decreased flood hazard during ENSO events is much more complex than is often perceived and reported.

Keywords

ENSO, El Niño, Early Warning, Flood Forecasting

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Emerton et al., 2017: Complex Picture for Likelihood of ENSO-Driven Flood Hazard, Nature Communications, 8:14796

GLOFAS-SEASONAL: AN OPERATIONAL SEASONAL GLOBAL HYDRO-METEOROLOGICAL FORECASTING SYSTEM

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Abstract

Seasonal hydrological forecasting has potential benefits for many sectors, including agriculture, water resources management and humanitarian aid. At present, operational seasonal hydrological forecasts for large or global scales are few and far between. While smaller scale systems have begun to emerge around the globe over the past decade, a system providing consistent global scale seasonal forecasts would be of great benefit in regions where no other forecasting system exists, and to organisations operating at the global scale, such as disaster relief.

We present here a new operational global ensemble seasonal hydrological forecast, currently under development at ECMWF as part of the Global Flood Awareness System (GloFAS [Alfieri et al., 2013]). The new seasonal outlook builds upon the flood forecasts available through GloFAS, in order to extend the forecast horizon from the30-day flood forecast to a 4-month flow outlook, providing early indication of both high and low flows. This system takes the long-range runoff forecasts from the new ECMWF SEAS5ensemble seasonal forecast system (which incorporates the HTESSEL land surface scheme [Balsamo et al., 2011]) and uses this runoff as input to the Lisflood [van der Knijff et al., 2010] routing model, producing a seasonal river flow forecast out to 4 months lead timefor the global river network.

The first version of the seasonal outlook will be available as new layers in the GloFAS interface from late autumn 2017, providing a global overview of whether flow is likely to be anomalously high, or low, in the coming 4 months, with more detailed information and forecast products provided throughout the global river network.

We introduce the new operational GloFAS seasonal outlook, outlining the modelling platform, forecast products and initial results of the forecast evaluation.

Keywords

Seasonal forecasting, global scale forecasting.

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MEDIUM RANGE ENSEMBLE FLOOD FORECASTING IN WAIKATO RIVER BASIN, NEW ZEALAND

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Abstract

It has long been recognized that if communities could be provided with advance flood warnings, the adverse effects associated with it could be minimized. This paper discusses medium-range (7-10 days) flood forecasting using ECMWF-51 ensemble rainfall forecasts. A hydrological model was established for the Waikato River Basin to provide medium-range forecasts for agricultural and electricity authorities' water supply and demand management decision-making. The study compared observed average rainfall with forecast rainfall issued by ECMWF for a complete calendar year. The results indicated that the ECMWF ensemble forecasts provided significantly reliable and accurate rainfall forecasts for the study area. This methodology could be used to generate medium range flood forecasts for decision-making by various organizations. The study revealed that the probabilistic nature of the ensemble weather forecast has unique benefits and can assist in effective decision-making around optimal allocation of available water resources, when accounting for forecast rainfall.

Keywords

Ensemble forecasts, flood, water resources management, decision support

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EVALUATION OF FINE-SCALE ENSEMBLE SEASONAL SOIL MOISTURE AND EVAPOTRANSPIRATION FORECASTS FOR THE SYDNEY REGION

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Abstract

This work describes the testing of dynamic seasonal forecasts in the Sydney region based on the Bureau of Meteorology's Australian Community Climate and Earth-System Simulator Seasonal (ACCESS-S) climate hindcast outputs downscaled to ~5km and used as daily forcing into the landscape water balance model AWRA-L. This fine-scaled seasonal soil moisture and evapotranspiration forecasting service is potentially useful for a range of applications including water demand estimation and maintenance of pipes for urban water utilities amongst other uses.

The Bureau of Meteorology is currently implementing a new seasonal prediction system, ACCESS-S. ACCESS-S has considerable improvements compared to the current system (Hudson et al., 2013), including parameterisation schemes and resolution (over Australia the horizontal resolution is increased from 250 km to 60 km). An empirical CDF downscaling approach (Griffiths et al., 2017) has been applied to the ACCESS-S system to produce climate outputs at the ~5km grids aligned with the Bureau's daily AWAP historical climate grids (Jones, Wang and Fawcett, 2009).

The Bureau's operational AWRA-L model (Frost et al., 2016; Viney et al., 2015; see www.bom.gov.au/water/landscape), provides estimates of gridded daily soil moisture, evapotranspiration, runoff and deep drainage covering 1911 until yesterday; with AWAP historical climate data used as forcing. This trial seasonal forecast application uses hindcast downscaled ACCESS-S ensemble climate data as input to AWRA-L (covering 1990-2012), rather than retrospective historical climate data.

Initial evaluation (Fig 1) shows the correlation of forecasts with what occurred according to historical forcing data; indicating the strong influence of initial conditions and differing skill of climate forcing outputs for different starting months and lead times.

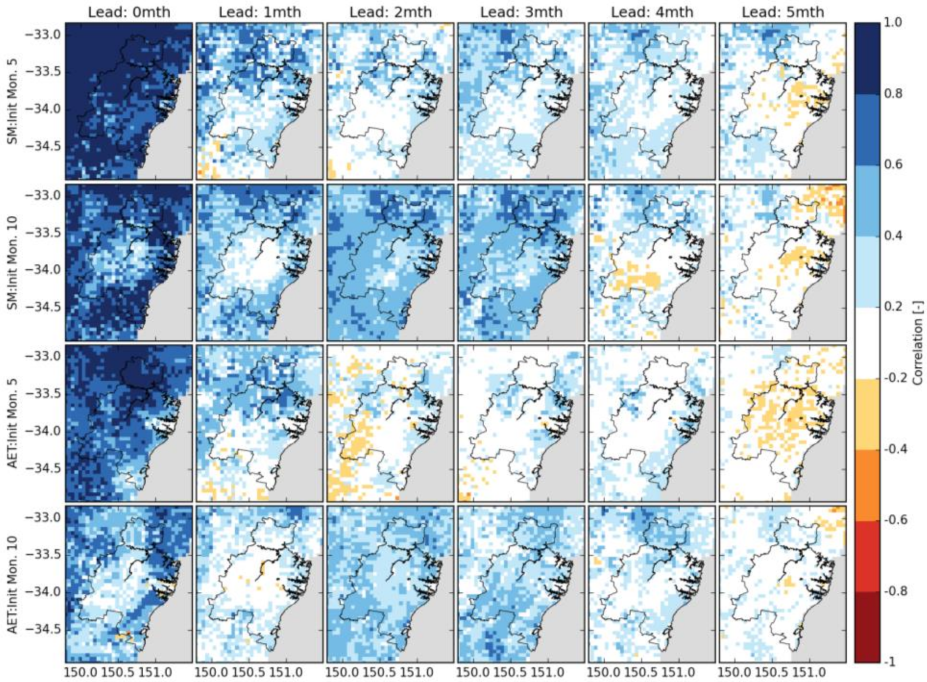

Figure 1. Sydney May (Init 5) and October (Init 10) correlations for Soil moisture (SM) and AET for 0-5 month lead times covering 2000 to 2011 against modelled AWRA-L outputs using historical AWAP forcing.

Keywords

Seasonal forecast, soil moisture, evapotranspiration.

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ASSESSMENT OF THE PROBABILISTIC FORECASTING OF THE EUROPEAN FLOOD AWARENESS SYSTEM

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Abstract

The skill of the improved version of the European Precipitation Index based on Climatology (EPIC, Alfieri et al., 2012), the European Runoff Index based on Climatology (ERIC, Raynaud et al., 2015), developed to provide a flash flood early warning up to 5 days in advance, is evaluated. ERIC gridded data of 1 km resolution on river level for the European domain between 1990 and 2010, obtained for a set of dates where floods were recorded and for a forecast range of 92 hours, is considered. Flash flood events were used within the framework of two projects, HYDRATE FP6 at European level and REINFORCE in the island of Crete. For each recorded flood event, the ERIC index within a radius of 75 km was examined for values exceeding 1. The results showed that: (a) there are flood cases where the ERIC index did not exceed the threshold of 1 within the search radius; (b) there are cases where the ERIC index exceeded the threshold within the radius when we consider any time within the forecast range, and (c) there are cases where the threshold value was exceeded with simultaneous prediction of the timing of the event. The analysis of the recorded flood events in the HYDRATE database have shown that ERIC exhibits skill to provide flood warning. The results show a 63% success rate to warn about the flood event within the 92 hours of the forecast, while in 46% of the cases it also warned about the timing of the event.

In contrast to these results, for the flood events in the island of Crete, it was found that the ERIC index exhibits very limited skill to produce warnings for floods. The reason for this is that, in the European Flood Awareness System (EFAS), the ERIC index is based on the LISFLOOD discharge simulations, which deal with large riverine floods. Furthermore, ECMWF forecasts do not have an adequate resolution to resolve the orographic effects on precipitation, which leads to precipitation maxima that are heavily biased. Finally, the sizes of the watersheds in the island are, on average, quite small. Therefore, the capacity of the ECMWF – LISFLOOD – ERIC modeling sequence to capture an increase in flows and, simultaneously, the location of the flood is limited. High-resolution ensemble early warning systems are needed to improve flood forecasting in the island of Crete and reduce the uncertainty on the location and timing of flash floods.

Keywords

Flash floods, probabilistic forecasting, HYDRATE database, ERIC.

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DEVELOPING AN ENSEMBLE 7-DAY STREAMFLOW FORECAST SERVICE FOR AUSTRALIA

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Abstract

The Bureau of Meteorology provides a deterministic 7-day streamflow forecast (SDF) service as part of its water information role and responsibilities under the *Water Act 2007*. The service is currently available to the public for 88 catchments across Australia, and forecasts indicate likely daily river flow volumes in the coming week. There has been a growing demand for an ensemble streamflow forecast service that brings greater confidence and reliability to the existing service. The Bureau is planning to release its first national ensemble 7-day streamflow forecast service by July 2019. Thirty catchments in the current service were selected based on their hydrological characteristics, hydro-climatic location and strategic importance, for evaluation of the short range probabilistic streamflow forecast system. Research using rainfall forecasts from alternative numerical weather prediction models for Australian catchments has demonstrated plausibility of the probabilistic short range streamflow forecasts by CSIRO and the Bureau of Meteorology. Performance of the multi model ensemble rainfall forecasts from the Australian Community Climate and Earth-System Simulator – Global Ensembles (ACCESS-GE, 24 ensembles), Poor Man's Ensemble (PME, ensemble mean), and European Centre for Medium-Range Weather Forecasts (ECMWF, 50 ensembles) of the atmospheric model for streamflow forecasting will be presented and discussed. ACCESS-GE and ECMWF rainfall forecasts are post-processed using a Bayesian joint probability model (Robertson *et al.,* 2013) to correct biases and quantify uncertainty. Ensemble streamflow forecasts for catchment outlets are generated by forcing the forecast rainfall to a hydrological model. Streamflow forecasts are post processed using the Error Representation and Reduction In Stages (ERRIS, Li *et al.,* 2015) model. The accuracy and reliability of rainfall forecasts are evaluated at the sub-catchment scale, and the also evaluated for streamflow forecasts at catchment outlets. Raw and post-processed rainfall and streamflow forecasts are assessed separately to identify the value of post processing. Evaluation results of the quality of forecast rainfall and streamflow are presented with uncertainty estimates.

Keywords

Ensemble, 7-day streamflow forecast, ACCESS-GE, PME, ECMWF

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IMPROVING SEASONAL PREDICTION OF UK WINTER STREAMFLOW

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Abstract

Winter (December-January-February, DJF) in the UK is a key season for water management. Drier than normal conditions can suppress recharge of reservoirs and groundwater levels that can be critical for the provision of water supplies through the following summer, but above normal soil moisture and river flows enhance flood risk. Skilful hydrological forecasts of season-ahead prospects for above or below normal streamflow volumes would be extremely beneficial for decision-making in operational water management and is an active area of research.

Recent work by Harrigan et al. (2017) has shown that traditional Ensemble Streamflow Prediction (ESP) forecasts for DJF, with predictability from Initial Hydrologic Conditions (IHCs) alone, are skilful against climatology in many catchments in the south and east of the UK (higher catchment storage), but not for catchments in the north and west (lower catchment storage) (see Figure 1). However, there are several avenues that might improve upon the performance of traditional ESP that exploit the known influence of the North Atlantic Oscillation (NAO) on the hydroclimate of the north and west in winter: 1.) *ESP_NAO* – sub-sampling ESP members based on NAO+/NAO- years, and 2.) *Dynamic_P* – using a derived precipitation product from the UK Met Office's dynamical seasonal climate forecast system (GloSea5) by Baker et al. (in review) based on atmospheric circulation downscaling, which has shown to give improved winter seasonal prediction skill over the direct precipitation forecast by GloSea5.

The *ESP_NAO* approach uses IHCs initialised on the 1st of December from the GR4J hydrological model forced with sub-sampled historic climate sequences based on NAO+/NAO- years. The *Dynamic_P* approach also uses the same IHCs generated on the 1st of December, but is instead forced forward in time with downscaled DJF average precipitation from Baker et al. The DJF averaged precipitation forecast values were temporally disaggregated to daily values for running though the hydrological model using a historic-sequence-correction method advocated by Tanguy et al. (in prep). Potential improvements of these two more complex forecasting approaches in overall performance, sharpness, and reliability is benchmarked against traditional ESP over a 20-year hindcast period (winters 1992/93 to 2011/12). This work is part of the Improving Predictions of Drought for User Decision Making (IMPETUS) project and provides insight to when and where scientific advancements in

seasonal forecasting can be beneficial to water management.

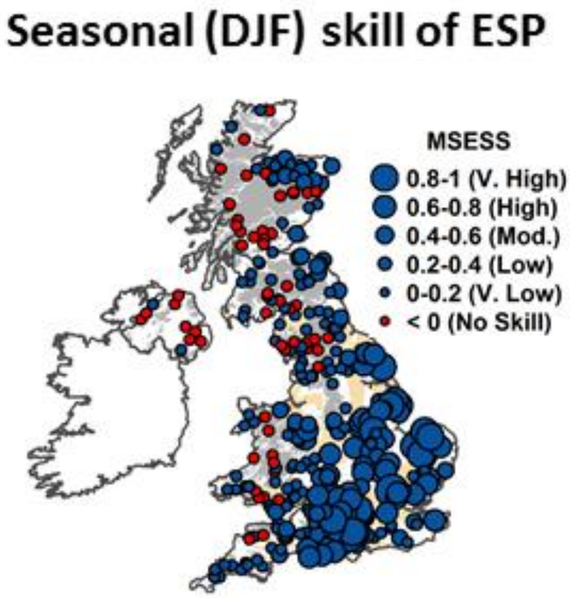

Figure 1: ESP skill against climatology for December-January-February (DJF) averaged streamflow based on a 51-member ensemble mean using the Mean Squared Error Skill Score (MSESS); adapted from Harrigan et al. (2017).

Keywords

ESP, dynamical precipitation, Seasonal forecasting, NAO, UK.

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CAN IMPROVED METEOROLOGICAL FORECASTS IMPROVE THE FLOOD FORECASTS? A CASE STUDY OF SELECTED FLOODS IN NORWAY, 2013 TO 2015

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Abstract

The quality of hydrological flood forecasts is important so that flood warnings can be issued in due time. By enabling operational flood forecasters to issue warnings based on probabilities for exceeding critical warning threshold, different recipients can make appropriate action based upon own risk/loss assessments. The Norwegian flood forecasting service is based on a single prediction of temperature and precipitation from Applications of Research to Operations at Mesoscale (AROME) (first two days) and European Center of Medium-range Weather Forecast (ECMWF HRes) (from day 3 to 9) that are used for forcing the hydrological models. Subsequently an auto-regressive statistical model is used to achieve probabilistic forecasts. An alternative to this approach for assessing the uncertainty in flood forecasts is to use ensemble forecasts of precipitation and temperature to create a hydrological ensemble.

The meteorological ensemble forecasts are created by small perturbations in the initial conditions of numerical weather predication (NWP) models. The spread of meteorological ensemble reflects the atmospheric stability, and hence large spread indicates large uncertainty. The flood forecast depends on the quality of precipitation forecast. For seasons with temperatures around zero, temperature forecast quality is also important. For example, if the temperature forecast provides sub-zero temperatures during an event with high precipitation, the flood forecast might miss an actual flood. Alternatively, too high forecasted temperature in snow-covered areas might result in a false alarm. The largest floods in Norway (1789 and 1995) are typical combinations of rainfall and snowmelt induced floods.

The main aim of this study is asses and improve the flood forecasts skill by using different forcing data. For selected flood events, we investigate the following:

- Will ensemble forecast provide added value to the Norwegian flood forecasting service?
- Are we able to improve the skill of hydrological ensemble forecasts, by calibrating the temperature and precipitation ensembles?

To achieve these aims, we study several flood events in Norway in the period 2013 to 2015. Some floods are generated by rain and other are generated by both snowmelt and rain. For all catchments

we use the operational HBV model, forced with both AROME, ECMWF HRes and ENS. For the ECMWF ENS we apply both gridded (quantile mapping with transformation parameters from Met Norway) and catchments specific (in progress temperature and precipitation calibration methods).

The results so far show that the hydrological ensemble forecasts are improved by using the gridded calibration method for around 30-60% of the catchments, depending on season. The gridded calibration reduces the cold bias in temperature ENS, and increases the reliability of precipitation ENS. A work in progress is to establish a catchment specific calibration of the meteorological forecasts. The working hypothesis is that better adapted approaches for calibration of the meteorological input will improve both meteorological and hydrological forecasts, and hence improve the quality of flood warnings in Norway.

Keywords

Flood forecasting, ensemble calibration.

POTENTIAL FOR ENHANCED FLOW FORECASTING THROUGH SATELLITE-BASED RIVER GAUGING

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Abstract

Over the past century, a large number of gauging stations has been established globally to monitor river discharge. Measured river discharge data have proven invaluable to monitor the global water cycle, assess flood risk, and guide water resource management. However, more recently there is a decline in the number of active stations and stations are highly unevenly distributed globally (Vörösmarty et al., 2001). While not a substitute for station measurements, remote sensing is a cost-effective technology to acquire information on river dynamics at the global scale (Bjerklie et al., 2003). The general approach has been to develop rating curves relating satellite observations to river discharge measured in situ, which inherently prevents its use for ungauged rivers (Van Dijk et al., 2016). Alternatively, hydrological models can estimate river discharge globally. While subject to errors and biases, these estimates do create potential opportunities to develop satellite-based discharge monitoring in ungauged rivers. Our aim is to develop a continuous, consistent, and up-to-date river discharge product at a global scale. To do that, we use gridded surface water extent information from two satellite data sources: (1) the Global Flood Detection System (GFDS) passive microwave data with 0.09°×0.1° daily flood signal from merged 4-day average, and (2) MODIS optical data with 8-day NBAR composites of imagery resampled to 0.05°×0.05° (MCD43C4.005). Both data were available for the period of 2000-2014. The hydrological model used here is the World-Wide Water Resource Assessment (W3 version 2) model (Van Dijk et al., 2013), which estimates river discharge at a spatial resolution of 0.05°×0.05° with global coverage from 1980 to 2014. The in situ measurements used here for validation are monthly discharge data for all available end-of-catchment stations in the world's largest 925 rivers (Dai, 2016). Comparison between W3 model simulated river discharge and in situ discharge was possible for 719 stations. The results show that 86% of rivers have a correlation coefficient (R) exceeding 0.6, and 46% of rivers R>0.8. This suggest that that the W3 model generally provided reasonable estimates of river discharge dynamics globally. When comparing the remote sensing (MODIS or GFDS) observations with the W3-simulated river storage, strong correlations are found for many larger rivers in South America, Africa, South Asia, and northern high latitude regions. This suggests that it is possible to develop rating curves based on remote sensing (MODIS or GFDS) and the W3 model. This also creates potential opportunities to assimilate the remote sensing (MODIS and GFDS) observations, or derived discharge estimates, into the model to improve river discharge estimation, and based on these, streamflow forecasts.

Keywords

River Discharge; W3 Model; GFDS; MODIS

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VIEWING ENSEMBLES THROUGH THE EYES OF THE END-USER

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The Australian Business Roundtable recently reported that the total economic cost of natural disasters in Australia was $18.2Billion per year averaged over the last 10 years. The cost is expected to grow at 3.4% per annum reaching a massive $40B per annum by 2050. Death and destruction caused by natural disasters disrupt and adversely affect societal wellbeing across the time continuum short, medium and long term. Impacts from natural disasters are exacerbated in developing and less developed countries. In addition, out of 17 UN Sustainable Development Goals which came into effect in 2016, three are directly related to availability of a secure supply of water.

Water forecasts and the provision of hazard warnings directly impact public safety, economic prosperity and in general, societal wellbeing. In the sphere of Public Safety, a paradigm change is taking place shifting focus from response and recovery to analysing risks and building resilience. In managing water resources, the effort has shifted in many countries to optimising current resources rather than exploiting or searching for new sources.

The development and practical use of ensembles face a number of challenges including those related to the advancements in science as well as end-user adoption. Whilst a significant amount of choreographed effort has gone to scientific advancement, more work is required to assist end-users with the application of hydrological ensembles to drive decision support systems.

The author will present three case studies to justify the end user's call for ensembles. From a public safety view point, evacuations are carried out well in advance of areas going under water, especially if floods are expected to cut-off arterial roads compromising orderly evacuation. The Hawksbury–Nepean Pilot demonstrates the need for probabilistic flood forecasts to improve the understanding of risks associated with planning evacuations. The second case study involves managing competing demands placed on reservoir operators where maximising water harvesting to supply consumptive users directly compete with the need to have sufficient air space in the reservoir to minimise flood risks. A case study from a reservoir operating in the upper Murray catchment will be used to highlight the need for ensemble based forecasts. The third example relates to optimising releases from reservoirs to meet agricultural demand. The use of Bureau's probabilistic seasonal forecasts in the Lachlan Valley in NSW to provide irrigators with advanced notice of probable water allocations demonstrate the efficacy of leveraging hydrological ensembles to drive economic prosperity.

Through the case studies, the author will demonstrate the benefits of early involvement of end-users in the development of ensembles, especially in applications involving decision support systems.

IMPACT OF HYDROLOGICAL MODEL UNCERTAINTY ON PREDICTABILITY OF SEASONAL STREAMFLOW FORECASTING IN THE RIVER RHINE BASIN

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Abstract

In recent studies on the predictability of seasonal streamflow forecasting the focus is usually on predictability resulting from initial conditions and boundary conditions. The hydrological model uncertainty itself is often neglected. Here we apply three different types of models for seasonal streamflow forecasting of large tributaries of the River Rhine to analyze the impact of hydrological model uncertainty: the lumped model GR6J-CemaNeige, the semi-distributed model HBV and the distributed model LARSIM. To be consistent among the models the parameters of all models have been automatically calibrated with the Shuffled Complex Evolution (SCE-UA) using the same observed meteorological input data aggregated to the model elements. The goodness-of-fit of the individual models at the different gauges differs due to the different model structure and spatial resolution.

As meteorological forcing the ECMWF System4 reforecast data set from 1981-2016 downscaled to the respective model elements is used. The performance of the seasonal forecasts is verified against observed flow and simulated flow with downscaled ERA-Interim reanalysis as meteorological forcing. As the meteorological model of ERA-Interim and ECMWF System4 is identical and as ECMWF System4 reforecasts are initialized by ERA-Interim the simulation using ERA-Interim as “observed” meteorological forcing could be interpreted as the upper limit of predictability using ECMWF System4. Common performance indicators (correlation coefficient, mean error (bias), mean absolute error (skill score), mean squared error (skill score), continuous ranked probability (skill) score) are applied. Additionally, to evaluate the value of the forecast, the concept of the relative economic value is applied, too.

By comparing the skill of the individual models the impact of hydrological model uncertainty (model structure and spatial resolution) on predictability and value of seasonal streamflow forecasting is evaluated for the Rhine basin. Furthermore ways of combining the different forecasts are presented in order to examine whether a hydrological multi-model combination could improve the skill of seasonal streamflow forecasting.

Keywords

seasonal forecasting, model uncertainty, multi-model, predictability

A COMPARISON OF STATISTICAL POST-PROCESSING METHODS FOR SHORT- TO MEDIUM-RANGE PRECIPITATION FORECASTS

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Abstract

Precipitation forecasts from numerical weather prediction (NWP) models are used as inputs to hydrology models to generate hydrological forecasts. However, raw precipitation forecasts suffer from uncertainty due to errors in model structure, parameters and initial/boundary conditions. The uncertainty leads to various biases in raw forecasts, specifically in ensemble mean and spread. Statistical post-processing methods can be applied to correct those biases and quantify the uncertainty in the forecasts. For precipitation forecasts, several properties of precipitation variable need to be considered including its non-normality and the heteroscedasticity of predictive residual. Different types of post-processing methods have been developed over the years, including ensemble pre-processor (EPP), Heteroscedastic censored logistic regression (HCLR), censored, shifted gamma distributions (CSGD)-based EMOS, ensemble dressing etc.

In this study, we compared several popular post-processing methods for short- to medium-range precipitation forecasts. The experiments are conducted using multiyear precipitation reforecasts from the Global Ensemble Forecast System (GEFS) in several river basins in China. Verification metrics such as CRPSS, BSS, reliability and resolution are applied to assess the effectiveness of the post-processing methods.

Preliminary results show that EPP, CSGD-based EMOS and HCLR all improve the forecast skill in terms of CRPSS and BSS, using a 20-year reforecasts as training datasets. The results show that the performance of these three post-processing methods is generally similar. EPP, HCLR, and CSGD-based EMOS can deal with the problem of non-normality and heteroscedasticity of precipitation variable. Moreover, we also tested the influence of the length of training data on post-processing results. We fitted post-processing models using 3, 5, 10 and 20 years of reforecasts with a 60-day window centered on each forecast date. The results show that longer training years are specifically useful to improve forecast skill for heavy precipitation events.

Keywords

Post-processing, precipitation, hydrology ensemble forecasting.

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SOIL MOISTURE ASSIMILATION FOR ENSEMBLE STREAMFLOW PREDICTION

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Abstract

Continuous streamflow forecasting has been widely used as a tool to provide important information for flood warning, drought prediction, and water resources management. A typical streamflow forecasting system incorporates catchment hydrologic models to simulate runoff generation, concentration and propagation processes. Nevertheless, those models are usually conceptualized and are prone to various sources of uncertainties due to errors and uncertainties in the meteorological forcing, initial wetness conditions, model structure and parameters. Therefore, they require calibration and/or real-time constraint using observations.

Soil moisture is a control variable in catchment hydrologic process. It governs the runoff-infiltration partitioning so as to impact the streamflow prediction. Recent advances in remote sensing techniques provide a new capability for large scale near-surface soil moisture monitoring. Consequently, assimilation of soil moisture for hydrologic forecasting is an attractive proposition for operational forecasters. However, there is no demonstrable consensus on the benefit of assimilation of soil moisture in streamflow prediction, and how to optimally integrate the remotely sensed products to improve the forecasts remains a big challenge.

This study investigates the potential benefit of “smoothing” surface soil moisture information back in time using streamflow prediction. A two-soil-layer hydrologic model, GRKAL, was used to incorporate the near-surface soil moisture information. A synthetic soil moisture assimilation study was conducted for a set of lumped catchment systems with different concentration times. A fixed-window ensemble Kalman smoother was used to propagate soil moisture information back in time so as to maximize the benefits of soil moisture information. The results indicate that the smoother can address errors in antecedent state variables more thoroughly, compared with the traditional ensemble Kalman filter. The improvement in antecedent state variable analysis can be further propagated to the streamflow forecasts through the routing process. The superiority of the smoother is more significant for catchments with longer concentration times. The strength of the smoothing approach exhibited in this synthetic study indicates a potential to improve streamflow forecasting in real world applications.

Keywords

Streamflow forecasting; soil moisture; remote sensing; ensemble Kalman smoother.

THE ROLE OF HYDROLOGICAL ENSEMBLE PREDICTION IN FORECASTS OF FLOOD AND ITS COMPONENTS OVER THE UPPER BRAHMAPUTRA BASIN, CHINA

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Abstract

Many studies have shown that ensemble flood forecasting based on numerical weather predictions can provide early warning with extended lead time. However, the role of hydrological ensemble prediction in forecasts of flood volume and its components over the upper Brahmaputra Basin has not been systematically investigated. This study adopted the Variable Infiltration Capacity (VIC) model to forecast annual maximum flood events and annual first flood events in the upper Brahmaputra Basin based on the precipitation, maximum and minimum temperature data from European Centre for Medium-Range Weather Forecasts (ECMWF). N-Pareto-Optimal simulations are proposed to account for more scenarios of model parameters in VIC. The results show that the method of N-Pareto-Optimal simulations can significantly improve the accuracy of forecasts in flood volumes. The accumulative precipitation from ECMWF over a flood event exhibits evident overestimation in the annual first flood events and obvious underestimation in the annual maximum flood events. It is shown that ensemble flood forecasting system can skillfully predict the volume of annual maximum flood with a lead time of 10 days, and has skill in forecasting the snowmelt-induced flood volume about 7 days in advance. The accuracy of forecasts for the annual first flood is inferior, and the flood volume can be predicted in only 5 days ahead. The performance in 7-day accumulated volumes is better than the peak volumes. In terms of streamflow components, the snowmelt-induced component in baseflow during the annual first flood is irrelevant to lead time, whilst during the annual flood events, an obvious deterioration with lead time increasing can be perceived. From this study, it is concluded that the snowmelt-induced flood volume plays an important role in the upper Brahmaputra Basin especially in the annual first flood. Increased research efforts should be expended to improve the forecasts skill in this area.

Keywords

HEPEX, N-Pareto-Optimal simulations, flood volume, streamflow components

WIND AND WAVE CLIMATE: DESIGN SEA STATE FROM ENSEMBLE FORECASTS

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Abstract

Uncertainties in the prediction of Atmosphere and Ocean extremes challenge the design and operation of marine systems. Construction and maintenance of these systems rely on accurate statistical analyses of historical datasets that provide the practitioner with return period estimates. In non-polar regions wind and wave loads define the main stresses for structures and ships, thus an accurate estimation of their return period is crucial for a cost effective design of structures and ship operations both offshore and in coastal areas. In the past 20 years the European Center for Medium Range Forecasts (ECMWF) have been constantly producing, upgrading and storing a large amount of data from forecasts and reanalysis models.

The Ensemble Prediction System consists of a series of forecast ensemble members propagated from the best estimate of the atmosphere-ocean initial state, with slightly perturbed initial conditions. The propagation of these perturbations defines the forecast confidence level over the medium range. The advantages of an Ensemble probabilistic approach become clear in the evaluation of long-term ocean extremes for the estimation of the uncertainties connected to model representation of reality, and for the possibility to evaluate the dataset over an extended time period.

Breivik et al. (2013, 2014) demonstrated that ensemble members show low correlation at advanced forecast lead times (9-10 days) guaranteeing the independence needed to perform common inference statistics. The aim of the present research is to estimate wind and wave return periods from a 6 years (2010-2016) Operational Ensemble Forecast dataset. The short time series will guarantee stationarity for long term extremes estimation. The results will then be compared with Extreme Value Analyses performed with commonly used reanalysis model datasets over the same time window. However, as some of the literature contributions show, stationarity is not always the case for ocean extremes (*Young et al.*, 2011). Hence the research will further develop and investigate different time series datasets. The results for long term wind and wave extremes will then be examined to justify the existence of possible trends over the world oceans.

Keywords

Ensemble Forecasts, Wind, Waves, Extreme Value Analysis

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CURRENT STATUS OF THE OPERATIONAL MULTI-MODEL ENSEMBLE PREDICTION SYSTEM AND CLIMATE SERVICE ACTIVITIES AT APEC CLIMATE CENTRE

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Abstract

Since its inception in 2005, the Asia-Pacific Economic Cooperation (APEC) Climate Center (APCC) has devoted considerable efforts to developing a multi-model ensemble (MME) prediction system for producing improved and well-validated seasonal forecasts in both probabilistic and deterministic framework for research and operational purposes. Currently, the APCC has issued MME 3-month mean (seasonal) predictions for upcoming 6 months in the form of tercile-based categorical probabilities, with one-month lead time, and disseminated it to APEC member economies. The probabilistic MME forecasts (PMME), as an official seasonal outlook at APCC, is based on an uncalibrated multi-model ensemble, with model weights being inversely proportional to the random errors in the forecast probability (Min et al., 2009) and a parametric Gaussian fitting method is applied to estimate tercile-based categorical probabilities. Along with PMME, several deterministic MME methods are operationally exploited for seasonal forecasts; a simple averaged MME, empirically-weighted MME (Yun et al. 2003, 2005), and calibrated MME schemes (Kug et al. 2008). The presentation will give a detailed description and comprehensive assessment of the APCC operational MME methods, as well as an overview of recent development and plan for further activities to enhance climate services at APCC.

Keywords

Multi-Model Ensemble, Model Calibration, Probabilistic Forecast, Forecast Verification

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HYDROMETEOROLOGICAL ENSEMBLE PREDICTIONS IN SWITZERLAND: THE INFLUENCE OF PRE- AND POST-PROCESSING ON THE FORECAST PERFORMANCE IN DIFFERENT ALPINE CATCHMENTS

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Abstract

In recent years meteorological ensemble prediction systems have increasingly been used to feed hydrological models in order to provide probabilistic streamflow forecasts. Such hydrological ensemble prediction systems (HEPS) have been analyzed for different lead times from short-term to seasonal predictions and are used for different applications. Especially at longer lead times such forecasts exhibit systematic biases which can be removed by applying bias correction techniques to both the meteorological and/or the hydrological output. However, it is still an open question if pre- or post-processing or both should be applied.

We present first results of an analysis of pre- and post-processed extended-range hydrometeorological forecasts. In a first step the performance of bias corrected and downscaled (using quantile mapping) extended-range meteorological forecasts provided by the European Centre for Medium Range Weather Forecasts (ECMWF) is assessed for 1637 ground observation sites across Europe. Generally, bias corrected meteorological forecasts show positive skill in terms of the Continuous Ranked Probability Skill Score (CRPSS) up to three (two) weeks for weekly mean temperature (precipitation) compared to climatological forecasts. For the topographically complex Alpine region, skill is generally lower but the relative gain in skill resulting from the bias correction is larger.

The pre-processed meteorological input of one year of ECMWF extended-range forecasts and corresponding 20 years of hindcasts is used to feed a hydrological model for three selected catchments in the Alpine area in Switzerland. Different post-processing techniques are applied to correct the resulting streamflow forecasts. Our result indicates a positive effect of pre-processing on the skill of streamflow forecasts for all lead times. However, seasonal differences are evident with a stronger positive effect on the skill in the transition seasons (spring and autumn) when the effect of temperature and corresponding snowmelt plays an important role. Newly developed statistical methods based on quantile regression and neural networks are applied to test the effect of post-processing hydrological predictions. We show that depending on the catchment and its hydro-morphological characteristics, the

skill can be enhanced significantly, but for the first two weeks only. Future work will include the combination of these corrected streamflow forecasts with electricity price forecasts to optimize the operations and revenues of hydropower systems in the Alps.

RECENT DEVELOPMENTS IN EVOLUTIONARY DATA ASSIMILATION AND MODEL UNCERTAINTY ESTIMATION FOR HYDROLOGIC FORECASTING

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Abstract

Data assimilation by means of Particle Filters (PFs) have received increasing attention in hydro-geosciences, as an effective tool to improve model predictions in nonlinear and non-Gaussian dynamical systems. The implication of dual state and parameter estimation using the PFs in hydrology has evolved since 2005 to the most effective and robust framework through evolutionary PF approach based on Genetic Algorithm (GA) and MCMC, the so-called EPFM. In this framework, the prior distribution undergoes an evolutionary process based on the designed mutation and crossover operators. The merit of this approach is that the particles move to an appropriate position and then the ensemble spread is improved by means of MCMC. We report the usefulness and effectiveness of the proposed EPFM on conceptual and highly nonlinear hydrologic models over several river basins located in different climate and geographical regions in the US. In addition, we elaborate on our recent development in model uncertainty characterization within data assimilation which has been the most challenging issue in hydrologic modelling and forecasting. Traditional methods rely on subjective, ad-hoc tuning factors or parametric distribution assumptions that may not always be applicable. We present a data-driven approach to model uncertainty characterization that makes no assumption about the form of the distribution. In the experiments, it is shown that the proposed method leads to substantial improvements in estimation of both the latent states and observed system outputs over a standard method involving perturbation with Gaussian noise. Also, the application of this method is shown on nonstationary catchments which have been under the influence of climatic and land use change.

Keywords

Data Assimilation, Particle Filter, Model Uncertainty, Genetic Algorithm, MCMC.

THE 2013/14 THAMES BASIN FLOODS: DO IMPROVED METEOROLOGICAL FORECASTS LEAD TO MORE SKILFUL HYDROLOGICAL FORECASTS AT SEASONAL TIMESCALES?

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Abstract

The Thames basin (UK) experienced 12 major Atlantic depressions in winter 2013/14 which led to extensive and prolonged fluvial and groundwater flooding. This exceptional weather coincided with highly anomalous meteorological conditions across the globe. Atmospheric relaxation experiments, whereby conditions within specified regions are relaxed towards ERA-Interim reanalysis, have been used to investigate teleconnection patterns [Knight et al. 2017, Watson et al. 2016]. However, no studies have examined whether improvements to seasonal meteorological forecasts actually translate into more skilful seasonal hydrological forecasts.

This study applied relaxation experiments to reforecast the 2013/14 floods for three Thames basin catchments with different hydrogeological characteristics. Atmospheric relaxation experiments were conducted by the European Centre for Medium Range Weather Forecasts (ECMWF) [Rodwell et al. 2015] with seasonal hydrological ensemble reforecasts produced using the European Flood Awareness System (EFAS). All reforecasts were initiated on 1st November 2013 and ran for 4 months with a daily time-step.

The tropics played an important role in the development of extreme conditions over the Thames basin. Greatest hydrological forecasting skill was associated with the tropical Atlantic and less with the tropical Pacific, although both captured the seasonal meteorological flow anomalies. Relaxation applied over the north-eastern Atlantic produced confident ensemble forecasts, but hydrological extremes were under-predicted; this was unexpected with relaxation applied so close to the UK. Streamflow was most skilfully forecast for the catchment that represented a large drainage area with high peak flow, while permeable lithology and antecedent conditions were important for skilfully forecasting groundwater levels. As primary stakeholders, the Environment Agency are responsible for managing flood risk in the UK. Based on the improved hydrological forecasts forced by relaxation applied in the tropical Atlantic, an operational flood alert would have been triggered 6 weeks in advance of the first floods occurring in the Thames basin.

Atmospheric relaxation experiments can improve our understanding of extratropical anomalies and the potential predictability of extreme events such as the Thames 2013/14 floods. However, the seasonal hydrological forecasts differed to what was expected from the meteorology alone, thus there is

knowledge to be gained by considering both components. In the densely populated Thames basin, the use of seasonal forecasts that consider local hydrogeological context can provide an effective early alert of potential high-impact events, allowing for better preparedness.

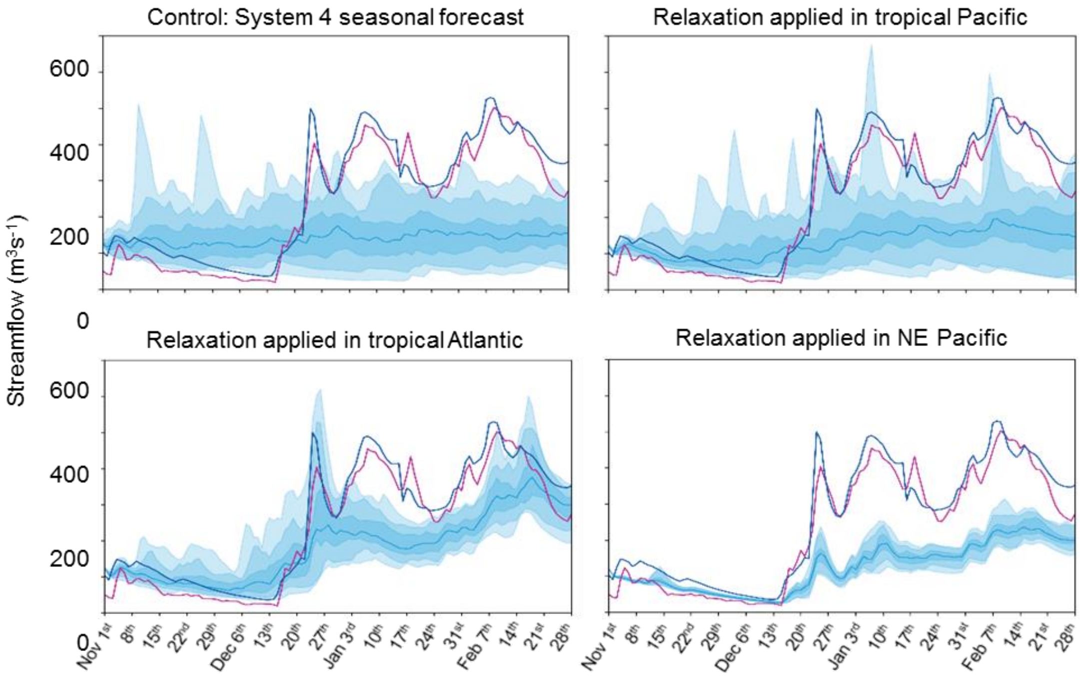

Figure 1: Improvements to ensemble streamflow (m^3s^{-1}) forecasts for one Thames basin catchment; a comparison between the control forecast and with relaxation applied in the tropical Pacific, tropical Atlantic and NE Atlantic. Shows daily forecast median with shading for min., 5th, 25th, 75th, 95th and max. of the ensemble. Pink line = observations from local river gauging station, dark blue line = EFAS simulated water balance.

Keywords

Seasonal forecasting, hydrometerology, flooding, Europe, early-warning, IMPREX.

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OPERATIONAL WEATHER VERIFICATION AT THE AUSTRALIAN BUREAU OF METEOROLOGY

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Abstract

The Australian Bureau of Meteorology produces, among other variables, probabilistic forecasts of precipitation amount and deterministic forecasts of temperature, humidity, wind speed and direction and significant ocean wave height. Existing verification systems have evaluated the forecasts for many years and cover timeframes of recent days to weeks, and the current month/season/year in the context of the longer-term past.

The verification system has administrative benefits, in that it supports automated reporting of Key Performance Indicators that describe overall accuracy of the Bureau's forecast products. The system also provides scientific benefits by identifying strengths and weaknesses of the existing products. It allows forecasters to receive rapid feedback so as to identify and correct persistent biases in the products but also identify exceptional recent forecast errors, as part of situational awareness.

Throughout 2017, the Bureau is implementing a new realtime operational verification system with intuitive interactive graphics that evaluate forecasts on multiple timescales (e.g. "how good were the forecasts yesterday?", "How good are they generally?"). The system also compares the expert official forecasts to the objective input guidance.

The new system is built in a Python framework that supports the retrieval of forecast and observations, calculation of a range of verification metrics, saving and querying a range of verification results and visualisation and dissemination of results. The framework has been extended using Rshiny for web-based interactive visualisation.

Keywords

Forecast verification, Operational, Python, Precipitation, Meteorology

EARTH SYSTEM MODELLING @ECMWF – IMPLICATIONS FOR HEPEX AND HYDROLOGY

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Abstract

In order to make further advances in numerical weather prediction (NWP), many weather forecasting centres including ECMWF, have recognised that they need to take better account of the interactions between different components of the Earth system. The challenge is to identify dominating processes and strike a balance between necessary complexity, simplicity and operational restrictions. The atmosphere, the continental land surface, the oceans and sea ice are all Earth system components which interact. Improving these interactions will not only advance weather forecasts but can also increase the skill of other environmental forecasts including oceans and hydrology as part of one holistic earth system.

In this talk, the current and the potential future developments of hydrological components at ECMWF will be explored. We demonstrate how a simple set-up of the ECMWF land surface scheme, HTESSEL, linked to a runoff routing algorithm compares favourably to other models. We also highlight that a multi-model multi-forcing system outperforms individual set-ups. This demonstrates the potential of improvements through the inclusion of land surface uncertainty (a traditionally strong area in hydrology). Future data such as those provided by Sentinel will allow us to constrain the parameter space and advance to higher resolutions. Land surface schemes such as HTESSEL should also begin to include more processes related to human-based activities, providing additional capabilities in predictability. The ECMWF modelling system can also be used for longer range forecasts including decadal forecasts and climate projections. Inclusion of an interactive carbon cycle in these has the potential to directly alter these future climate risk assessments.

In summary, in order to produce better forecasts on a range of time and space scales, hydrological and meteorological science have to continue to move closer together so that there can be a full handshake of ideas, techniques and future progress.

Keywords

Land surface modelling, uncertainty, meteorology.

ADVANCING OUR UNDERSTANDING OF DATA ASSIMILATION FOR HYDROLOGIC PREDICTIONS IN CHANGING CATCHMENTS

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Abstract

Hydrologic modelling methodologies capable of handling non-stationarity are becoming ever more important, particularly given the global prevalence of rapid and extensive land use change. This is particularly true in the context of Hydrologic Forecasting using Data Assimilation. Data Assimilation (DA) has been shown to dramatically improve forecast skill in hydrologic and meteorological applications, although such improvements are conditional on using bias-free observations and model simulations. A hydrologic model calibrated to a particular set of land cover conditions has the potential to produce biased simulations when the catchment is disturbed. This means that bias correction methods should in theory be incorporated along with state-estimation DA in order to avoid degradation in forecast quality.

We provide new insights on this issue, namely the impacts of systematic errors or biases in hydrologic data assimilation in the context of forecasting in catchments with changing land surface conditions. It is shown that when doing state-estimation DA in such cases, the impact of systematic model errors on assimilation or forecast quality is dependent on the inherent prediction uncertainty that persists even in pre-change conditions. Streamflow forecasting with perfect meteorological inputs is undertaken using state estimation DA for a range of deforested catchments in Australia and Vietnam. Results demonstrate that systematic model errors as a result of changing catchment conditions do not always necessitate adjustments to the modelling or assimilation methodology, for instance through re-calibration of the hydrologic model, time varying model parameters or revised offline/online bias estimation. This occurs whenever the model biases are within the range of the pre-change prediction uncertainty, allowing the latent states to be adjusted during assimilation to reflect changed conditions.

Keywords

Data Assimilation, Land-use Change, Model Error

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ESTIMATION OF THE OBSERVATION BIAS FOR REMOTELY SENSED SOIL MOISTURE USING A BIAS-AWARE KALMAN FILTER: VALIDATION USING DIFFERENT MODELS

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Abstract

In the assimilation of remotely sensed soil moisture values into hydrologic models, the estimation of the observation and forecast biases, in addition to the state variables, is receiving increasing attention. This study focuses on the evaluation of a methodology to estimate all these variables. Two conceptual rainfall-runoff models are used for this purpose. Soil Moisture Ocean Salinity (SMOS) soil moisture data are assimilated into these models for 169 unregulated sub-basins of the Murray-Darling basin in Australia. It has been found that a bias-unaware filter, either with or without prior rescaling of the soil moisture observations, does not lead to good results. In addition to estimating the state variables, estimating the observation bias has been found to be more important than the forecast bias, but the best results are obtained when both biases are estimated. A comparison of the soil moisture simulations, either biased or unbiased, to the unbiased observations leads to a poor agreement. However, both the biased and unbiased simulations compare very well to the unbiased observations. This again shows the importance of a good estimation of the observation bias. The observation biases obtained using both rainfall-runoff models are in very good agreement. The overall conclusion from this paper is that bias-unaware assimilation of remotely sensed soil moisture values into conceptual rainfall-runoff models is not recommended. Furthermore, it is important to not only estimate the forecast bias, but the observation bias as well.

Keywords

Kalman filter, observation bias, soil moisture, rainfall-runoff model.

AN OPERATIONAL PAN-EUROPEAN SEASONAL HYDRO-CLIMATIC FORECASTING SERVICE

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Abstract

Seasonal forecasts have great potential for user groups that are affected by climatic variations and that could manage such variations to their advantage through better predictions. Due to insufficient skill over the European domain for dynamic forecasts, seasonal forecasts have traditionally been based on historical climatology in this region. Now when meteorological forecasts have improved in skill, there is a necessity to develop operational services capable of making the seasonal information available to users and of addressing their needs. The Copernicus Climate Change Service (C3S) at ECMWF will soon provide seasonal forecasts as open data and to explore its usefulness in Europe, SMHI developed a demonstrator interface as a proof-of-concept (SWICCA). The demonstrator communicates the ensemble of pan-European seasonal hydro-climatic indicators at the catchment scale.

Here, we present the pan-European seasonal forecasts visualized in the demonstrator interface (http://swicca.climate.copernicus.eu/indicator-interface/seasonal-forecasts-maps/). The seasonal hydro-climatic indicators made available are post-processed from different variables (precipitation, temperature and river flow). They are based on the ECMWF System 4 seasonal climate forecasts and the E-HYPE hydrological model (Donnelly et al., 2016; Hundecha et al., 2016), and are updated on a monthly basis when the new seasonal forecasts become available.

The ECMWF System 4 forecasts are firstly bias adjusted using a modified version of the Distribution Based Scaling method (Yang et al., 2010). The reference dataset used both in the bias adjustment and in the initialisation of the E-HYPE model is the Global Forcing Dataset (GFD; Berg et al., 2017); an SMHI operational system that generates bias-adjusted fields of precipitation and temperature, by combining re-analysis and forecast products from ECMWF with observations from GPCC and GHCN-CAMS. These adjusted seasonal forecasts are used to force the E-HYPE hydrological model and produce forecasts initialised on the 1st of each month and with 7 months lead time.

Seasonal information is presented as maps and graphs, including the option to download the data. The map shows the anomaly for each catchment and lead month using as reference either the normal values (based on terciles) or the extreme values (10th and 90th percentiles) for the month of interest and the catchment conditions. The user has further the option to mask the catchments in which seasonal forecasts have no skill (based on re-forecast analysis); meaning that climatology is more predictive than ECMWF System 4. The graphs display the median and different percentiles of the ensemble of forecasts, and the high and low thresholds of the normal and extreme conditions for the month of interest.

The demonstrator also provides the users with metadata information, and forecast skill information at the European scale. A forum enables a continuous dialogue between providers and users on the platform, allowing user feedback and further improvement of the interface to fit user needs. In the SWICCA contract, five appointed users across Europe are currently evaluating the usefulness and added value of these forecasts for their business with irrigation, drinking water supply, water-allocation planning, hydropower production and flood warnings.

Keywords

Hydrological modelling, pan-European scale, forecast communication, end-user needs, skill assessment

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ASSESSMENT OF THE 2016 FLOOD EVENT ON THE SEINE AND LOIRE RIVER BASINS USING ENSEMBLE FORECASTS

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Abstract

From 28 to 31 May 2016, a heavy rainfall event reached the northern part of France. The episode was persistent and followed by additional rainfall that lasted until 3 June. The high amounts of rainfall led to severe flooding in northern France, mainly over the Upper and Middle Seine river basin and in several tributaries of the Middle Loire river basin. The peak flow at the Seine River in Paris (6.10 m) was reached in the early hours of 4 June. It was estimated to be the highest level in nearly 35 years (it is estimated that the 1982 flood reached 6.18 m). It caused flooded banks and forced landmarks located close to the river (such as the Louvre and the Orsay museums) to shut down. According to Météo-France, May 2016 was the rainiest month of May in northeast France since 1959. In Paris, a total point rainfall accumulation was observed at 178.6 mm, which is a record for this month since 1873, when measurements started. June was also an active month with several record breaking events. Rainfall accumulations over June-May were 1.5 above normal in the Central and Val de Loire region, as well as on the northern and eastern country borders. In Île-de-France (Paris and its surrounding area), these totals were even up to 3 times the average at some rain gauge locations. This study aims at evaluating the performance of ensemble forecasts when precipitation ensembles are used as input to the operational hydrological model GRP for flood alert. We provide a brief overview of the 2016 flood event in France and present the re-forecasts of the flood event using the PEARP rainfall ensembles from Météo-France as input to the hydrological model. The results show that the scenarios of the ensemble forecasts allow to better capture the peak discharges, although they do not compensate for uncertainties in the hydrological modelling. We also discuss the role of uncertainties from precipitation forcing and initial conditions, as well as the influence of data assimilation on the results.

Keywords

Ensemble forecasting, May-June 2016 floods, Seine and Loire river basins

A SOFTWARE ECOSYSTEM FOR END-TO-END HYDROLOGICAL ENSEMBLE MODELLING WORKFLOWS

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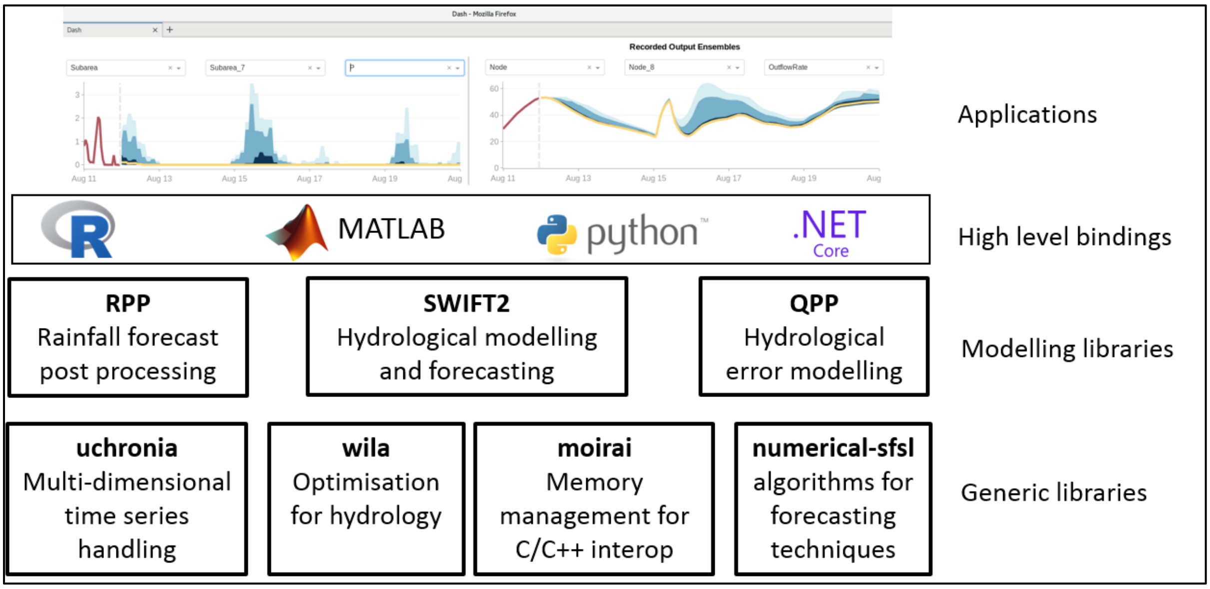
Abstract

At the HEPEX 2016 workshop we presented a software stack for ensemble short-term streamflow forecasting for research and operational purposes (Perraud et al., 2016). While the features available to users in the original product SWIFT2 remain available with improved access arrangements for a broader spectrum of users, the underpinning software stack has significantly evolved to achieve broader goals such as enhanced software interoperability, maintainability and reuse.



A key driver and a testbed in this endeavour is porting the Rainfall Post Processor RPP (Robertson *et al.*, 2013) from an implementation in MATLAB for research purposes to a version in C++ for research and operational purposes. To achieve seamless interoperability between RPP and the catchment streamflow modelling, several subsystems are now fully componentized, some of them open source. A small but key memory management module, *moirai*, can handle proper data referencing and memory allocation across distinct R and Python packages. The centrepiece library for interoperability is, however, the software library *uchronia* for multi-dimensional time series such as ensemble forecast (Perraud *et al.*, 2017). Multi-dimensional time series can be passed between RPP and the hydrologic model without using transient NetCDF files. We envisage *uchronia* will also play a key role in meshing with dedicated data and metadata provenance management systems.

Keywords

Software, Ensemble streamflow forecasts, modelling framework, interoperability.

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IMPROVING OPERATIONAL DECISION MAKING AND SERVICES: COLLABORATION IN SCIENCE, SYSTEMS AND COMMUNICATION

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Abstract

This presentation will describe examples of where collaboration across disciplines and between organisations has overcome some of the challenges in operational flood forecasting and warning. The important role of ensemble forecasting in our journey will be highlighted.

The Environment Agency in England and the UK Met Office have a long history of working closely together to provide the best possible guidance and flood warning services to Government, emergency responders and communities. However, following severe flooding during summer 2007 and the subsequent Pitt Review (Pitt, 2008), there have been significant changes to organisational arrangements in flood forecasting. These include much closer collaboration between meteorologists and hydrologists, and developing probabilistic forecasts and risk based warnings (Pilling et al., 2016). Following a number of severe flood events during winters 2013-14 and 2015-16, coupled with a drive from the changing landscape in national incident response, there became a desire to identify flood events at even longer lead time. This earlier assessment and mobilization is becoming increasingly important and high profile within Government. For example, following the exceptional flooding across the north of England in December 2015 the Environment Agency have invested in 40 km of temporary barriers that will be moved around the country to help mitigate against the impacts of large flood events.

High resolution deterministic and ensemble Numerical Weather Prediction models are used to drive hydrological models in the UK (e.g. Price et al., 2012). A recent development includes using downscaled hydrometeorological data to generate probabilistic river flows at 6 days lead time using the Delft-FEWS / Grid-to-Grid modelling system. Furthermore, major project is underway in the Environment Agency to transform the current hydrological forecasting system to provide more detail and flexibility to display and intervene with the forecast when necessary.

An example of collaborative research to enhance an operational service is the Surface Water Hazard Impact Model being developed within the Natural Hazards Partnership (NHP, 2017). This partnership which includes the Met Office and Environment Agency, as well as others, has developed an impact model that draws on receptor datasets in a pre-calculated impact library, relating these with real-time probabilistic rainfall and surface runoff forecasts.

Another recent and collaborative initiative is between the Environment Agency in England and the Australian Bureau of Meteorology with a Memorandum of Understanding formalising co-operation

between the two organisations. This includes: (i) technology, innovation and development of warning systems; (ii) developing our people; (iii) service development (iv) customer and partner engagement and embedding effective actions. The journey together has recently started, but we are convinced that it will reap rewards for both organisations.

Keywords

Collaboration, Operations, England, Ensembles, Improvements.

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IMPACT OF DATA ASSIMILATION ON THE USAGE OF MULTIPLE MODELS

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Abstract

The value of hydrological forecasts largely relies on the correct estimation of uncertainties (Thiboult et al. 2017). The three main sources of uncertainties (Thiboult et al. 2016) are: (i) the meteorological forecasts, (ii) the initial conditions and (iii) the hydrological model structure. The first source of uncertainty can be estimated by using ensemble meteorological forecasts, the second by including a probabilistic data assimilation procedure, and the third one by using several dissimilar hydrological models. The data assimilation step is found to be quite important, strongly modifying model behaviours to improve both accuracy and reliability of the forecast. However, it is still unknown to what extent the initial properties of the hydrological multimodel impact the overall quality of the forecast system.

The recently developed Empirical Multistructure Framework (Seiller et al. 2017) provides a tool to create a large quantity of diverse lumped hydrological models. It consists in identifying functional components in existing ("parent") models and combining them to produce new ("child") models. Applying the EMF to twelve parent models, Seiller et al. (2017) produced around 108 800 new hydrological models, some of them having the ability to build accurate, sharp, and reliable hydrological ensembles for streamflow simulations.

The EMF opens the door to the building and testing of many multimodels of various sizes and properties. In this study, we aim at transposing the EMF to an ensemble prediction system. In particular, we aim at understanding how probabilistic data assimilation techniques modify the properties of hydrological ensembles. Are the initial properties of the hydrological ensemble important for high-quality streamflow forecasting or is data assimilation sufficient to compensate discrepancies in the hydrological component of the ensemble prediction system?

Keywords

Hydrological multimodel, probabilistic data assimilation, ensemble prediction system.

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CONTRIBUTION OF ENSEMBLE FORECASTING APPROACHES TO FLASH FLOOD NOWCASTING AT GAUGED AND UNGAUGED CATCHMENTS

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Abstract

Among the different types of floods, flash floods can be particularly dangerous, notably due to specific challenges people at risk, forecasters and risk managers face when dealing with this type of event: rapid rising of river water levels, short lead time to activate flood alerts and social response, difficulties in forecasting localised and intense precipitation events, as well as the lack of quantitative data to improve the understanding and modelling of flash floods. The setup of flood alert systems for nowcasting usually focuses on capturing in advance a signal of an upcoming extreme event to generate short-range (0–6h ahead) forecasts and produce flash flood guidance and flood alert maps. This is usually based on the extrapolation in time of observed weather radar images. This can be complemented by the use of high resolution numerical weather model outputs, alone or combined with radar imagery propagation, to short-range forecasting. In this study, we discuss the use of ensemble approaches to quantify uncertainties in flash flood nowcasting systems and provide probabilistic information for flood alert at very short lead times. We present a review of existing approaches and recent developments, highlighting the potential ways the HEPEX community can contribute to tackle challenges specifically related to flash flood nowcasting. The presentation is illustrated with recent work carried out in France for the ensemble nowcasting of flash floods at gauged and ungauged catchments.

Keywords

Ensemble nowcasting, flash floods, ungauged catchments.

DOES HEPEX NEED A NEW CUTTING EDGE?

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Abstract

Since 2004, HEPEX (Hydrologic Ensemble Prediction Experiment; www.hepex.org) has fostered a community of researchers and practitioners around the world. During this time, it has contributed to establish a more integrative view of hydrological forecasting and to operationalize several techniques that contribute to enhance the accuracy and reliability of operational forecasting systems. Here, we present a summary of the main activities and achievements undertaken since the initiative started, but we also engage a discussion on how the community should continue its efforts: nearly fifteen years later, what else can HEPEX do to contribute to advance hydrologic ensemble prediction? What should HEPEX be in 10 years' time? The aim is to move forward with updated goals in order to better tackle the main challenges the community face today, almost fifteen years after the first meeting that launched HEPEX as a novel experiment in the international hydrological sciences community.

Keywords

Ensemble prediction, challenges, opportunities.

HOW CAN ENSEMBLE STREAMFLOW FORECASTS INFORM DECISIONS ON THE MANAGEMENT OF ENVIRONMENTAL FLOWS?

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Abstract

The health of many of Australia's riparian and aquatic ecosystems requires regular inundation of environmental features such as floodplains and wetlands. Over many decades, Australia's water resources have been developed to support urban and agricultural water use. This has resulted in changes in the frequency of wetlands and floodplains being inundated and a decline in ecosystem health. Recent government initiatives have supported the delivery of environmental flows that seek to improve the health of riverine ecosystems. These environmental flows involve releasing water from upstream storages to coincide with flow events in unregulated tributaries in order to increase the downstream event peak or duration and inundate floodplains and wetlands. However, inundation of floodplains to achieve environmental objectives may also result in unintended impacts, such as the inundation of infrastructure and other assets, if unregulated tributary flows are different to what is expected.

This poster describes an initial investigation into how ensemble streamflow forecasts can be used to understand expected tributary flows and what management strategies can be adopted to reduce the likelihood of unintended inundation. Models to produce hourly streamflow forecasts for lead times of up to 10 days were established for four tributaries in the Murray-Darling Basin, and six years of retrospective ensemble streamflow forecasts generated and evaluated. A workshop with river operators was held to illustrate the forecast process, demonstrate the accuracy of the ensemble streamflow forecasts changes with forecast lead time, and analyze a series of case-studies on how the forecasts could be used to achieve a predetermined flow target. Analysis was performed to understand how ensemble forecasts can be used to assess operational risks and illustrate how infrastructure could be designed to mitigate this risk.

Key findings from this investigation are:

- River operators believe the ensemble streamflow forecasts are sufficiently accurate at the lead times necessary to make decisions on the environmental flow releases.
- The ensemble streamflow forecasts are less uncertain on the falling limb of the hydrograph and therefore making releases after the forecast hydrograph has peaked has lower risk.
- The risk of unintended inundation was found to be reduced if the unregulated component of the environmental flow was smaller than the regulated release.
- River operators use many sources of information, including their experience, in making operational

decisions and will therefore require time to become familiar forecast information. An off-line simulation environment where they can experiment with forecasts and decisions would expedite their quantitative use of ensemble forecasts.

- Infrastructure can reduce the risk of unintended inundation and its design would require detailed understanding of the relative costs of inundation and mitigation infrastructure.

Keywords

Ensemble streamflow forecasts, forecast applications, environmental flows.

LESSONS LEARNT FROM THE EDGE SEASONAL HINDCAST EXPERIMENT

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Abstract

Worldwide, extreme hydrometeorological events caused serious damage to society and infrastructures. Developing a seamless and skilful prediction systems from the short- to the medium-range including seasonal forecasts is a key tool for short-term decision making at local and regional scales. The EDgE project commissioned by the Copernicus Climate Change Service [1] and implemented by the ECMWF provides a unique opportunity to investigate the skill of a large multi-model ensemble for predicting extreme hydrometereological events over the Pan-EU domain at a high spatial resolution of 5x5 km^2.

Daily meteorological forecasts (P, Ta, Tmin, Tmax) for the Pan-EU domain at 1° spatial resolution are available from the North America Multi-Model ensemble (NMME) and ECMWF. The used ensemble comprises four models with 52 realizations in total. These forecasts are downscaled to 5 km resolution with the external drift Kriging to induce orographic effects. Additional forcing variables are obtained using the MTCLIM algorithm [2]. High-resolution seasonal hydrologic forecasts (SeFo)[4,5,6] are then obtained for the hindcast period of 1993-2012 using four hydrologic/land-surface models: mHM [3], Noah-MP, VIC and PCR-GLOBWB. The Ensemble Streamflow Prediction (ESP) method is used as a benchmark, and initial conditions are created using the observational based E-OBS datasets.

Metrics such as the Brier Skill Score (BSS), the False Alarm Rate (FAR), and the Probability of detection (POD) are estimated for hydrologic indicators like the occurrence of high and low streamflow percentiles (floods, and hydrological drought) and lower percentiles of soil moisture (agricultural drought) for lead times of 1 to 6 months. These indicators are co-designed with stakeholders in Norway (hydro-power), UK (water supply), and Spain (river basin authority) to provide improved information for decision making.

The results of the EDgE (SeFo) chain shows that the ECMWF-S4 and CanCM4 models have larger skill than the other two seasonal forecast models over Europe (GFDL-FLOR and LFPW). The uncertainty of the initial conditions of the HMs is crucial for the skill of the SeFo chain. In particular, the ECMWF-S4 with all HMs leads to the best skill scores (Fig 1). The skill scores of both of driving seasonal forecast models and ESP are regionally differentiated. For example, Northern Europe exhibits higher predictability due to the persistence induced by cold processes (e.g., snow). In general, the major

source of poor forecasting skill is the little skill in precipitation forecast. Extreme events such as the 2003 European drought are consistently forecasted by all models at short lead times of 1-2 months. At 6-month lead-time, models show little skill to forecast extreme events.

The experience gained in the EDgE SeFo experiment will be tested in four regions across the globe (Brazil, Ecuador-Peru, Iran, Sudan) in the project SaWaM [7].

Keywords

Seasonal Forecast, seamless parameterization, EDgE, soil moisture drought, floods

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IS IT BETTER TO POST-PROCESS SEASONAL RAINFALL AND TEMPERATURE FORECASTS AT DAILY OR MONTHLY TIME STEPS?

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Abstract

Hydrological models used in seasonal streamflow forecasting often require skilful and reliable forecasts of meteorological inputs at a daily time step. Nowadays, it is common to calibrate forecast ensembles from seasonal climate models using statistical methods to reduce biases and make forecast probabilities reliable. Much progress has been made in calibrating forecasts of monthly and seasonal totals where climate signals are strong (e.g. Schepen et al. 2014); however, the successful generation of properly calibrated daily time-series is much more challenging because it requires getting the temporal correlation structure right in order to get the daily, monthly and seasonal forecast aggregates to be reliable. When models require multivariate inputs, e.g. rainfall and temperature, it is vital to get physically coherent forecasts with correct inter-variable relationships, and multivariate statistical methods are required to do the post-processing (e.g. Schefzik 2016).

In this study we aim to post-process rainfall and temperature forecasts simultaneously and to provide physically coherent ensembles of daily time-series for input to hydrological models. Because we are targeting seasonal forecasts, an important question is raised: is it better to post-process the forecasts at daily or monthly time steps? We therefore develop two new modelling approaches: (1) monthly-to-daily post-processing whereby forecasts are calibrated at the monthly time step and disaggregated to daily; and (2) daily-to-daily post-processing whereby forecasts are calibrated at the daily time step directly.

Calibration models for individual forecast time periods and lead times are established using the Bayesian joint probability (BJP) modelling approach, which yields forecasts with correct inter-variable relationships. The Schaake Shuffle is applied to connect up ensemble members across lead times and to instil correct temporal correlation characteristics in the forecasts. We demonstrate that both approaches yield skilful and reliable forecasts with correct inter-variable relationships and temporal correlation structure. Examples are provided that elicit the strengths and weakness of the competing post-processing approaches. The new forecasts will be used to force hydrological models and produce ensemble streamflow forecasts.

Keywords

Calibration, ensembles, disaggregation, time-series, BJP

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THE HEPEX SEASONAL STREAMFLOW FORECAST INTERCOMPARISON PROJECT

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Abstract

The Hydrologic Ensemble Prediction Experiment (HEPEX; www.hepex.org) is establishing a seasonal streamflow forecasting intercomparison project (SSFIP), or test bed, with the goal of understanding the strengths and weaknesses of the various ensemble forecasting approaches being developed in forecasting centers around the globe. While some centers have produced forecasts for decades (e.g. Ensemble Streamflow Prediction - ESP - in the United States and elsewhere), recent years have seen the proliferation of new operational and experimental streamflow forecasting approaches. Forecasting centers invariably develop their own modelling approaches and, consequently, model validation and forecast verification strategies vary greatly. Thus it is difficult to assess whether the approaches employed in some centers offer more promise for development than others. This motivates us to establish a forecasting test bed to facilitate a diagnostic evaluation of a range of different streamflow forecasting approaches, and their components, over a common set of catchments, using a common set of forecast verification methods. Rather than prescribing a set of scientific questions from the outset, experiments are dictated by the basin "host" and notable differences in methods applied to each basin. The initial pilot of the testbed involved testing CSIRO and NCAR forecasts for the Murray River, Australia, and the Hungry Horse reservoir drainage area, USA. To support this CSIRO and NCAR have developed data and analysis tools, data standards and protocols to formalize the experiment. These include requirements for cross-validation, verification, reference climatologies, and common predictands. Additional catchments/approaches are in the process of being added to the test bed through the inclusion of new forecasting centers. This presentation describes the SSFIP experiments, pilot basin results and scientific findings to date.

Keywords

Ensemble, forecasts, streamflow, intercomparison, verification

HEPEX DATA ASSIMILATION INTER-COMPARISON EXPERIMENT

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Abstract

There is a rapidly increasing number of remote sensing products with a potential application in operational hydrology. In combination with ground observations, these products may improve the identification of hydrological systems at forecast time as a basis for more accurate forecasts including the quantification of uncertainty. Although many data assimilation techniques exist for operational hydrology (Liu et al., 2012), there is a lack of inter-comparison between these approaches. We present a contribution to fill this gap by the implementation of the HEPEX Data Assimilation Inter-comparison Experiment (HEPEX-DA).

The main purposes of HEPEX-DA are i) to learn from each other, share, test, compare and improve techniques and expertise related to data assimilation (DA) for hydrological models, ii) to implement and employ an easy-to-use and modular test bed for data assimilation experiments with freely available or open source data, models and DA techniques, iii) to assess the performance of data products from ground observation or remote sensing and their added value in DA, iv) to address the added value of DA in forecasting applications, v) to encourage reproducibility of results and vi) to disseminate results in the scientific community and to supply enhanced tools for operational forecasting systems.

We present the current status of the HEPEX-DA test bed and on-going experiments (see for example Alvarado Montero et al., 2016), invite researcher to join this effort and outline future scientific work.

Keywords

Data assimilation, flood forecasting, inter-comparison experiment.

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IMPROVEMENT OF DROUGHT OUTLOOKS USING A BAYESIAN INFERENCE APPROACH

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Abstract

Reliable drought outlooks rely on accurate seasonal/sub-seasonal streamflow. To improve streamflow forecast skill, this study develops a new streamflow forecasting model based on a Bayesian inference method. The ensemble members are driven by the Ensemble Streamflow Prediction (ESP) approach with a rainfall-runoff model to define prior information. The relationship between the observed streamflow and two predictors, the mean value of the streamflow ensemble members and the antecedent streamflow is used for the estimation of a likelihood function. The role of the estimated likelihood is the correction of errors that arise from a rainfall-runoff model. The forecast model applies a simple Bayesian inference model based on the normal distribution function. Kolmogorov-Smirnov goodness-of-fit test was used to see if the data follow a normal distribution. Though the assumption of normal distribution was not suitable in a few months of several basins, it is accepted in most cases. The posterior information is then obtained by combining prior information and data information (likelihood function). To avoid getting negative values from posterior distribution, mean of likelihood is limited to a number greater than zero. The main advantage of the proposed forecast model (hereinafter, Bayesian-ESP) is that it improves the streamflow prediction accuracy by correcting model errors that arise in ESP. Besides, the Bayesian-ESP provides probabilistic features in the drought outlooks. The conditional probability given antecedent streamflow and the ensemble members driven by the ESP returns the most probable forecast and the uncertainty around that value. To validate the proposed model, parameters of Bayesian-ESP were calibrated by the data from 1971 to 2010 and validated with the data from 2011 to 2016.

The Bayesian-ESP, when compared to ESP, reduces the error of streamflow forecast and improves the predictive detection of drought occurrence. The inclusion of antecedent streamflow in a likelihood function increases the forecast skill especially during the dry season. Though prediction skill diminishes as forecast lead-time increases, the overall results demonstrate that the Bayesian-ESP is a viable option for producing reliable and unbiased time-series of weekly to seasonal streamflow forecasts.

Keywords

Ensemble Streamflow Prediction, Bayesian inference, drought outlook

THE OPERATIONAL SEASONAL STREAMFLOW FORECASTING SERVICE FOR AUSTRALIA: ASSESSMENT AND COMMUNICATION OF FORECAST QUALITY AT THE NATIONAL SCALE

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Abstract

Ever since the Bureau of Meteorology launched the seasonal streamflow forecasting service (http://www.bom.gov.au/water/ssf/) for Australia in 2010, it has investigated and developed rigorous verification methods, systems and products to measure and communicate the quality of ensemble forecasts. Forecast verification is important to monitor, compare and improve forecast quality over time, but also to convey that quality in a manner that is scientifically robust, and easily understandable. The Bureau places a strong emphasis on the assessment of forecast skill to remain transparent on forecast performance and to support continued improvement of forecast quality.

We have developed a comprehensive and automated cross-validation system that tests forecast model performance through iterative re-calibration and retrospective forecasting. From these results, we calculate a range of measures and produce graphic products for internal inspection, as well as those for public release. These include products to show forecast quality at a single location over time, to summary charts that are now accepted as an effective visual tool to show spatial and temporal variation of forecast skills across sites and seasons in a single plot.

In recent years, as the service expanded across the country, new challenges in forecast verification have emerged. These challenges relate to the diverse range in hydro-climatic conditions and catchment characteristics that occur across the nation. Locations with intermittent or ephemeral flows tend to have very high uncertainty in their estimated skill scores, which make it difficult to provide a synoptic view of forecast quality at the national scale. In addition, limited length of the hindcast period of an operational climate model hinders the objective assessment of overall performance of rainfall-runoff modelling.

Thus far, we have provided deterministic skill scores, each of which was derived from probabilistic forecasts over the entire cross-validation period. The skill scores can be sensitive to a few outlier events such as a major flood and may be subject to a high level of uncertainty. To assess the uncertainty, we have recently applied a bootstrapping method to skill score estimation. In parallel, for more effective communication with users, we have developed new ways to present and summarise different forecast quality metrics with a single numeric or graphic representation.

Keywords

Seasonal, streamflow, forecast, verification, Australia.

SCHAAKE SHUFFLE: DOES IT WORK FOR ALL FORECASTS?

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Abstract

Ensemble precipitation forecasts from numerical weather prediction (NWP) models have a wide range of applications, and are used routinely by experts and the general public to prepare for weather conditions in coming days. Statistical post-processing methods have been used to generate ensemble precipitation forecasts that are unbiased and reliable (Shrestha et al., 2015). The response of streamflows to a rainstorm is highly dependent on the spatial distribution of precipitation in a catchment as well as on the timing and duration of a rainstorm. This requires that each ensemble member of the post-processed forecasts must be a field that extends across space and time in a realistic way. The Schaake shuffle (Clark et al., 2004) is a very popular method for generating ensemble members with appropriate space-time correlations.

In this study, we evaluated the performance of a post-processing method and the Schaake shuffle for two NWP forecast products: 1) The deterministic ACCESS-G NWP, operated by the Bureau of Meteorology and 2) the mean of the 'Poor Man's Ensemble' (PME), an ensemble of 8 deterministic NWP models. Forecasts are evaluated first at individual subareas and at individual lead times to assess the efficacy of the post-processing. Forecasts are then evaluated at the catchment scale (aggregated from subareas) and for cumulative precipitation (accumulated over lead time) to assess the efficacy of the Schaake shuffle to instill realistic space–time correlations in the forecast ensembles.

Post-processed forecasts have low bias and have lower errors than raw forecasts. The post-processed forecast from ACCESS-G and PME are equally reliable at individual lead times and subareas. However, for accumulated forecasts, the reliability of calibrated PME is worse than calibrated ACCESS-G (Fig 1 top right panel). This suggests that the Schaake shuffle method is not so effective for PME rainfall forecast. This is likely because raw PME forecasts are more autocorrelated than observations (Fig 1, bottom panel), a consequence of taking the average of several forecasts. This is not compatible with the Schaake shuffle used to instil temporal and spatial correlations in the forecasts. Other issues with the Schaake shuffle and alternative approaches will be discussed in the presentation.

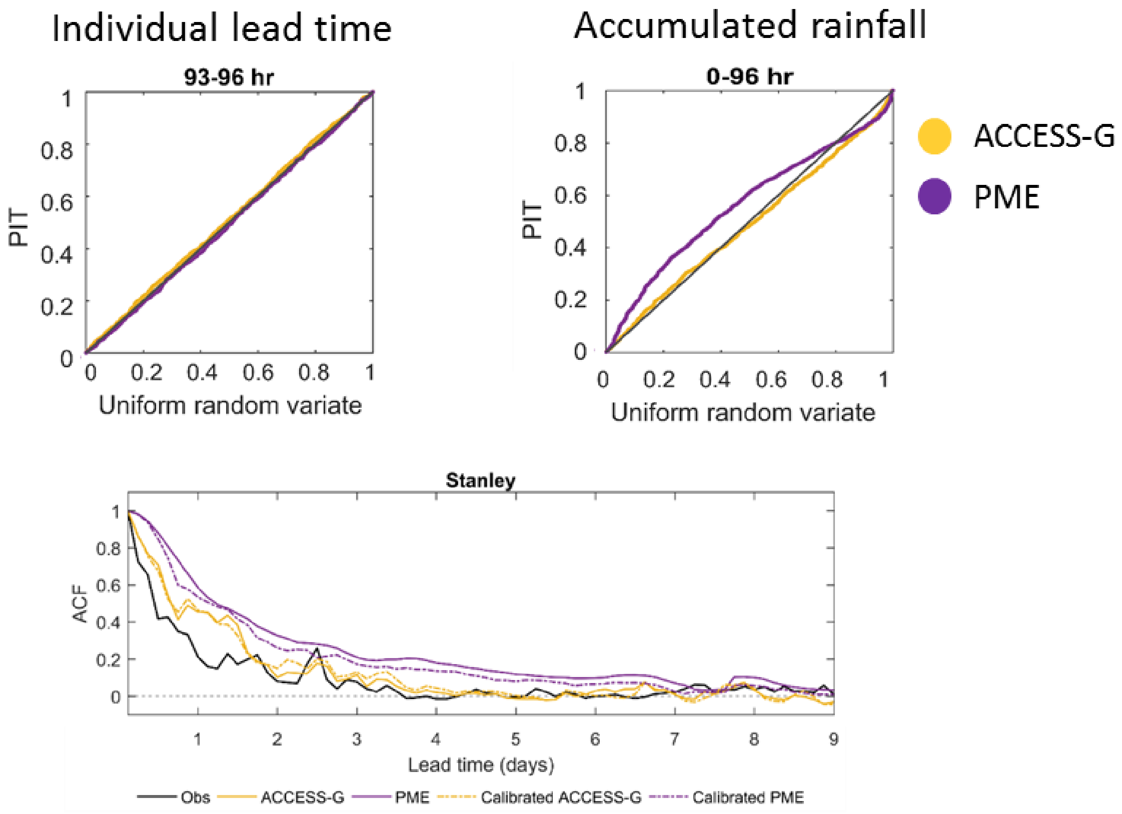

Figure 1. Top panels: Probability Integral Transform - uniform probability plots (PIT). In PIT plots, reliable forecasts follow the 1:1 diagonal. Bottom panel: auto-correlation function of observations and rainfall forecasts.

Keywords

Rainfall Post-processing, Numerical Weather Prediction, Schaake shuffle, ensemble forecasting

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DEVELOPMENT OF A PILOT FORECAST SERVICE FOR EXTENDED LEAD TIME FLOOD FORECASTS FOR THE HAWKESBURY-NEPEAN VALLEY

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Abstract

The 425 km^2 Hawkesbury-Nepean Valley is located in Western Sydney (Figure 1) and is part of the 22,000 km^2 Hawkesbury-Nepean Catchment that drains to the Pacific Ocean. It is now more than 150 years since the record Hawkesbury-Nepean flood of 1867. At this time the Hawkesbury River at Windsor reached almost 20m, and 13 lives were lost. In contrast the tidally influenced level typically varies from around 0 m to 1 m, however the probable maximum flood (PMF) has been estimated to be around 26 m at Windsor. Currently there are as many as 134,000 people living and working on the Hawkesbury-Nepean floodplain. It is estimated that if a flood similar to the 1867 flood occurred now it would require the evacuation of 90,000 people, with 12,000 residential properties being affected, and $5bn in damages. In response to this flood risk the Australian Bureau of Meteorology is developing a pilot service to provide extended lead time flood forecasts for the Hawkesbury-Nepean Valley. The Bureau is utilising ensemble rainfall forecasts, and ensemble flood forecasts to increase the lead time of flood forecasts.

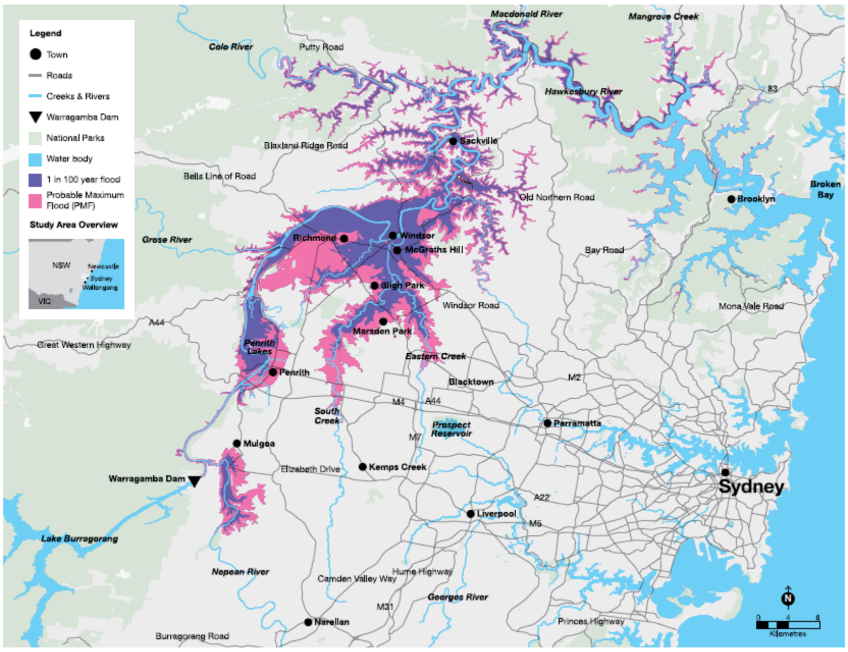

Figure 1: The Hawkesbury-Nepean Valley Floodplain (Source: Infrastructure NSW, 2017)

Keywords

Flood forecast, Pilot service, Ensemble

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A GIBBS SAMPLER BAYESIAN JOINT PROBABILITY MODEL

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Abstract

The Bayesian joint probability modelling approach (BJP) has been used for many applications, including statistical streamflow and climate forecasting, and post-processing of weather, climate and hydrological predictions. The BJP modelling approach uses a multivariate normal probability distributions at its core. When variables subject to a lower bound, such as streamflow and rainfall, are included in the model, they are treated as censored data where values equal to the lower bound are assumed to have a unknown precise value less than or equal to the lower bound. The use of a multivariate normal distribution also permits the data to have missing value. When data have missing or censored values, the existing implementation of the BJP requires complex matrix manipulations and multi-dimension integration which can impose a substantial computational burden.

This presentation introduces a new formulation of the BJP that adopts a Gibbs Sampling approach. The Bayesian Gibbs sampler differs from the existing in two important ways: (a) conditional distributions of the model parameters are explicitly formulated and sampled directly, and (b) missing and censored data are treated as unknown parameters of interest. Missing and censored values for a variable are drawn sequentially from conditional distributions, which replaces a multi-dimension integration problem into series of one-dimension sampling problems. We apply this Bayesian model to forecast streamflow with frequent and continuous zero flow occurrences. We show that the model inference and prediction become much simpler, when dealing with the censored data. This model can be used for many other applications involving missing and censored data.

Keywords

Gibbs Sampler, Bayesian, streamflow, censoring, missing, forecasting.

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A HYDROLOGICAL MONITORING AND SEASONAL FORECAST SYSTEM USING SATELLITE AND CLIMATE MODEL DATA OVER CHINA

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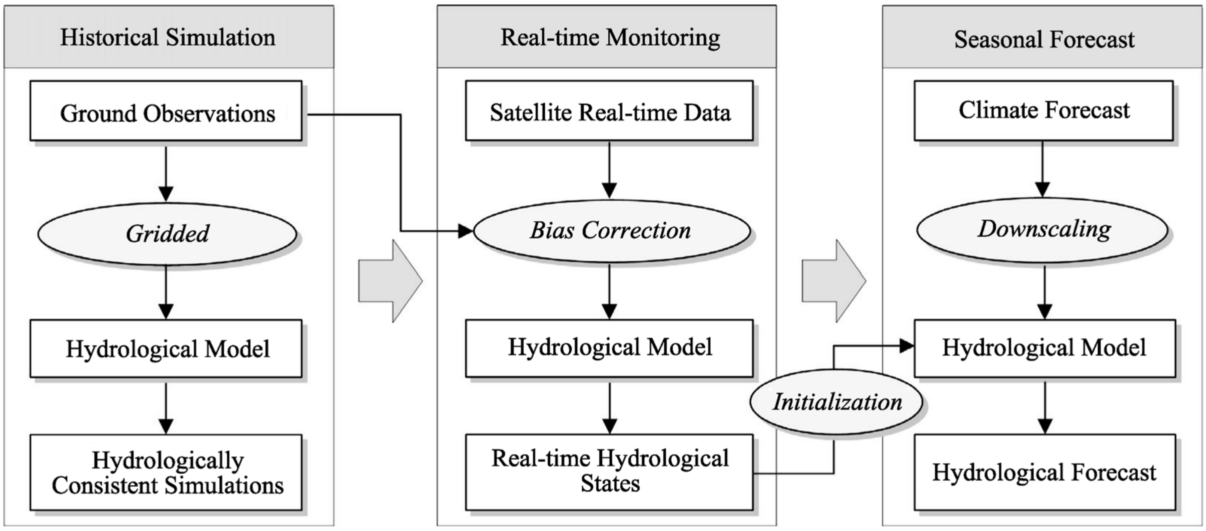
Abstract

Hydrological monitoring and forecast are critical for disaster mitigation and water resources management. Although large investments have been made in climate forecasting and in related monitoring of land surface conditions, the experimental streamflow monitoring and forecast system is yet to be developed for China. We propose a frame to collect near-real-time meteorological forcings from various sources, to apply land surface hydrological model to simulate hydrological states and fluxes, and to generate ensemble seasonal forecasts of river discharge and soil moisture over China. A retrospective land surface hydrologic fluxes and states dataset with a 0.25° spatial resolution and a 3-hourly time step was developed using the Variable Infiltration Capacity (VIC) model as driven by gridded observation-based meteorological forcings from the 1950s. The VIC simulations were carefully calibrated against the available streamflow observations and the simulated river discharge matched well with the observed monthly streamflow at the large river basins in China. The near-real-time satellite precipitation product was adjusted at each grid to match the daily precipitation distribution with the ground observations during the period of 2000-2010. The adjusted satellite precipitation was used to simulate hydrological states and fluxes in a near-real-time manner and to provide initial hydrological conditions for seasonal forecast. The climate model (CFSv2)-based forecast and ensemble streamflow prediction (ESP)-based forecast are both retrospectively performed to predict drought at one dry season and one wet season over southwestern China. The results show that the satellite-aided monitoring is able to provide a reasonable estimate of forecast initial conditions in real-time mode. The CFSv2-based forecast exhibits comparable performance against the observation-based estimates for the first month, whereas the predictive skill largely drops beyond 1 month. Compared to ESP-based forecast, CFSv2-based forecast ensembles give more skillful soil moisture drought forecast during the dry season, as indicated by a smaller ensemble range, while the added value of CFSv2-based forecast is marginal during the wet season. A quantitative attribution analysis of soil moisture forecast uncertainty demonstrates that forecast skill is mostly controlled by initial conditions at the first month and that uncertainties in climate forecasts have the largest contribution to soil moisture forecast errors at longer lead times.



The configuration of hydrological monitoring and seasonal forecast framework for China (Tang et al., 2016)

Keywords

Hydrological monitoring, Seasonal forecasting, Ensemble forecasting, China.

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ASSIMILATION OF GRACE WATER STORAGE AND SMOS/SMAP SOIL MOISTURE RETRIEVALS INTO CABLE USING PARTICLE SMOOTHER

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Abstract

This study aims to improve the estimates of soil moisture (SM) and groundwater storage (GWS) by assimilating soil moisture retrievals from the Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP), and terrestrial water storage (TWS) from the Gravity Recovery And Climate Experiment (GRACE) satellite missions into the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model using the particle smoother framework (PS). The PS is developed for joint data assimilation (DA) in order to accommodate different types of posterior error distribution and thus allow realistic system representation where the distribution of model and observation errors are usually unknown. This study utilizes the ensemble Gaussian particle smoother, a variant of PS, to reduce the particle degeneracy and impoverishment problems caused by an insufficient number of particles (Plaza Guingla et al., 2013). The uncertainty of GRACE observations is obtained directly from the full error variance-covariance matrix provided as a part of the GRACE data product. This method demonstrates that the use of a realistic representation of GRACE uncertainty, which is spatially correlated, leads to an accurate water storage computation (Tangdamrongsub et al., 2017). Three different DA scenarios are considered in which all observations are used (joint DA) or only one observation is used (GRACE-only, SMOS&SMAP-only), to investigate the benefit of the joint DA over the GRACE DA and SMOS&SMAP DA cases. The developed joint DA scheme is demonstrated over the Goulburn catchment (Rüdiger et al., 2007) located in the Upper Hunter region, NSW, where the ground observations (surface SM and groundwater level) are available for evaluation of our results.

Preliminary results show that our developed joint DA successfully integrate SMOS&SMAP soil moisture retrievals and GRACE-derived TWS information into a fine vertical and spatial scale (~25 km), leading to a noticeable improvement in the surface soil moisture (~5 cm) and groundwater layers. On average, the joint DA improves the surface SM and GWS computation in terms of temporal correlation coefficient (ρ) by ~11% (from 0.69 to 0.76), and ~89% (from 0.31 to 0.58), respectively. The GRACE DA leads to a significant improvement of ~128% (from 0.31 to 0.7) in GWS estimates but degrades the surface SM estimates by ~27% (from 0.69 to 0.51). In contrast, the SMOS/SMAP DA improves the surface SM estimate by ~9% (from 0.69 to 0.75) but degrades the GWS estimate by ~29% (from 0.31 to 0.22).

In conclusion, the joint DA provides a crucial benefit to both surface SM and GWS computation, compared to a single observation DA cases. The different temporal and spatial characteristics of GRACE data likely make GRACE DA less responsive to surface SM. Similar explanation can be applied for the insensitivity of the GWS update in SMOS&SMAP DA case. Apparently, the problems can be

resolved by the joint DA, which improves the overall performance of the model simulated water storage.

Keywords

GRACE, SMOS, SMAP, Data assimilation, water storage

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A DATA ASSIMILATION SCHEME TO FOSTER MODEL COOPERATION WITHIN A HYDROLOGICAL MULTIMODEL ENSEMBLE

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Abstract

Hydrological forecasting is subject to various sources of uncertainty. Among the main sources that deteriorate forecasting quality, hydrological model initial condition and structure play a major role. An array of methods has been developed to quantify and reduce them. In particular, data assimilation proved to be efficient to reduce error related to the initial conditions. Furthermore, a multimodel approach that combines dissimilar hydrological models conveniently deciphers the uncertainty related to the hydrological model structure. These two techniques are compatible and improve forecasting further when adequately combined (Thiboult et al., 2016). However, within such framework, hydrological models are updated individually, regardless of the multimodel ensemble behavior, i.e. model states are reinitialized only to improve a single model performance, not the ensemble performance.

We suggest here a novel data assimilation approach to update simultaneously all models composing the multimodel pool. The aim is no longer to improve individual model performance, but the multimodel ensemble itself by making the models cooperating during the data assimilation. The algorithm is based on the traditional Sequential Importance Resampling algorithm (SIR) but differs in the nature of the particle and the way particle likelihood is computed.

In the suggested method, traditional particles are replaced by meta-particles, which are defined as a collection of individual models' particle. Therefore, the meta-particles carry a probabilistic information. Subsequently, the likelihood is derived from a measure of similarity between the observation and a meta-particle probability density function.

The methodology is applied to several catchments in the Province of Québec. Preliminary simulation results indicate that the multimodel data assimilation scheme improves upon the traditional particle filter applied individually to each model.

Keywords

Data Assimilation, Particle Filter, Multimodel, Uncertainty.

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Thiboult, A., Anctil, F., Boucher, M.-A. 2016. Accounting for three sources of uncertainty in ensemble hydrological forecasting. Hydrological and Earth Sciences System, 20, pp.1809-1825.

OPPORTUNITIES AND CHALLENGES IN DELIVERING WATER AVAILABILITY FORECASTS – SHARING THE AUSTRALIAN EXPERIENCE

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Abstract

The Australian Bureau of Meteorology has national responsibilities for delivering water forecasting services through a legislative mandate under the *Water Act 2007*. These water availability forecasting services add value to existing services including weather, climate and oceans. Prolonged droughts, and demand for water for domestic, agricultural and industrial uses, have increased significantly over the past few decades. These factors have made high quality water availability forecasts across a range of time-scales more important for effective water resources planning and operations.

Water availability forecast services range from hours to days to seasons (Tuteja, 2015). The hourly forecasting service includes those for floods that provide real time operational forecasts of river heights to enable the public to take protective actions. The 7-day streamflow forecast service is designed to assist with water resource management and to provide additional guidance for flood forecasting. The service is currently available for 168 locations across 88 catchments (Hapuarachchi *et.al.*, 2016). It provides advanced notice of high flow events, and assists with emergency storage management and environmental water releases. The current service provides daily updates of the deterministic 7-day forecasts. Work is current underway to transition the current deterministic service to include ensembles. The Bureau is currently undertaking research to extend this forecast service to 30 days ahead. The seasonal forecasting service currently delivers ensemble forecasts of 3-months total streamflow volume for 318 key water supply locations across Australia (Feikema *et. al.*, 2015). Many water agencies currently benefit from this service, including those making decisions about water allocations, agriculture, water markets planning, reservoir operations, setting restrictions and environmental releases. The Hydrologic Reference Stations (HRS) includes a set of 222 well-maintained river gauges of long, high quality streamflow records managed by Australian and State water agencies (Zhang *et. al.*, 2016). The stations included in the HRS provide suitable target locations for delivering ensemble water forecasts at short, seasonal and decadal time scales. Capability to deliver water, sediment and nutrient forecasts for the Great Barrier Reef for improved management of the reef has also been developed by the Bureau of Meteorology.

Important elements of development of these operational services include strong partnership and cooperative engagement with users, researchers and stakeholders. The Bureau has developed these services through enduring research and development collaboration – in particular with CSIRO through the Water Information Research and Development Alliance (WIRADA), the Bureau's own research and development group, and several academic institutions. Research, operational, technology and

communication challenges associated with delivering national water forecasting service for Australia will be discussed.

Keywords

Water Act 2007, 7-day, seasonal, streamflow forecasting, Bureau of Meteorology, Australia.

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COMPARISON OF ENSEMBLE FLOOD FORECASTS FROM TWO REGIONAL ENSEMBLE PREDICTION SYSTEMS: SIMPLE DOWNSCALING OF GLOBAL EPS AND REGIONAL DATA ASSIMILATION

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Abstract

We developed an ensemble flood forecasting system composed of a regional ensemble prediction system (EPS) and a distributed hydrological model, the rainfall-runoff-inundation (RRI) model (Sayama et al. 2012). The regional EPS was made up by the weather research and forecasting model (WRF) and local ensemble transform Kalman filter (LETKF) (Hunt et al. 2007, Miyoshi and Kunii 2012). The WRF-LETKF assimilated conventional observation data archived in National Centers for Environmental Prediction (named PREPBUFR: prepared binary universal form for the representation of meteorological data) on high resolution model grids (3 km interval) relative to the forecast error covariances from the EPS itself, and created initial conditions and ensemble perturbations. Then, the forecast accuracy could be improved rather than a simple downscaling of global EPS, where the initial conditions and ensemble perturbations depended on the global EPS. We examined its validity by ensemble flood forecasting experiments in Japan and the Philippines.

In a flood event in Japan (Kinugawa River flood event in 2015), WRF-LETKF outperformed the simple downscaling of global EPS. WRF-LETKF predicted the possibility of flood occurrence with forecast lead time of 18 to 54 hours, while the simple downscaling could predict it at 18 hours lead time only (figure (a), (b)). Ensemble spread of the simple downscaling was smaller than those of WRF-LETKF, resulting in less possibility of extreme flood occurrence. On the other hand, for flood events in the Philippines (Pampanga River, Luzon Island in 2009 to 2011), the simple downscaling of global EPS outperformed the WRF-LETKF (figure (c), (d)). In these cases, ensemble spread in WRF-LETKF was smaller than that of simple downscaling. We speculate that WRF-LETKF, which had assimilated abundant observation data around Japan, worked better in Japan case. On the other hand, in the Philippines case the number of observation was less, which resulted in reduced performance of WRF-LETKF. We concluded that suitable methods of EPS may differ with respect to the region.

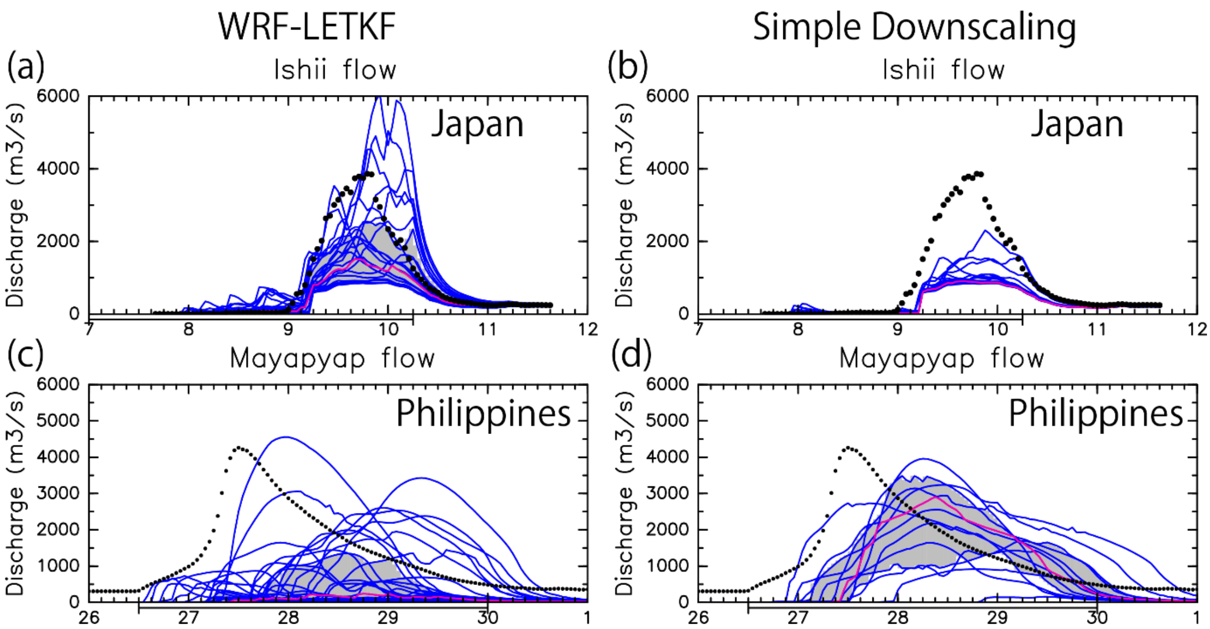

Figure. Examples of ensemble flood forecasts by the WRF-LETKF (a, c) and by simple downscaling (b, d). Blue lines show ensemble forecasts, with 25 to 75 quantiles by grey shade. A pink line in each panel shows ensemble median. Black dots are observed discharge. A bar under the horizontal axis shows the period of numerical weather prediction. Numbers on the horizontal axis indicate days.

Keywords

Regional EPS, WRF, LETKF, Japan, Philippines

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DOES EVENT-BASED VERIFICATION LEAD TO DIFFERENT RESULTS FROM EQUAL-INTERVAL VERIFICATION?

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Abstract

Performance of hydrometeorological ensemble forecasts is often evaluated to measure improvement of ensemble prediction methods and the forcing data used. For such evaluation, verification metrics based on daily (or other equal interval) time steps serve their purpose. The other purpose of verification of ensemble forecasts, is to inform (potential) users of the effectiveness of the forecasts when used in operational decision making, e.g. for flood early warning. Also for this application, verification on the basis of daily or other equal interval time steps is frequently used.

This presentation discusses whether for operational decision making in some applications, such verification results may be misleading. In the case of flood early warning, for example, when applying daily verification, events of multiple-days will be scored as multiple hits (or misses), while in reality it is only one event that is forecasted (or not).

In such cases event-based verification may be preferred. This type of verification, however, needs further discussion, e.g. on how to deal with correct rejections, and how to automatically discretise time series in events.

These issues will be addressed in a comparative study to analyse whether event-based verification leads to significantly different results from daily verification.

Keywords

Ensemble forecasts, verification methods, event-based, equal interval.

GENRE: A METHOD TO EXTEND GRIDDED PRECIPITATION CLIMATOLOGY DATASETS IN NEAR REAL-TIME FOR HYDROLOGICAL FORECASTING PURPOSES

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Abstract

To enable operational flood forecasting and drought monitoring, reliable and consistent methods for precipitation interpolation are needed. Such methods need to deal with the deficiencies of sparse operational real-time data compared to quality-controlled offline data sources used in historical analyses. In particular, often a fraction of the measurement network reports in near real-time. For this purpose we present an interpolation method, generalized REGNIE (genRE), which makes use of climatological monthly background grids derived from existing gridded precipitation climatology datasets. We show how genRE can be used to mimic and extend climatological precipitation datasets in near real-time using (sparse) real-time measurement networks in the Rhine basin upstream of the Netherlands (approx. 160.000km^2). In the process, we create a 1.2x1.2 km transnational gridded hourly precipitation dataset for the Rhine basin (van Osnabrugge et al., 2017). Precipitation gauge data is collected, spatially interpolated for the period 1996–2015 with genRE and inverse-distance squared weighting (IDW), and then evaluated on the yearly and daily timescale against the HYRAS and EOBS climatological datasets. Hourly fields are compared qualitatively with RADOLAN radar based precipitation estimates. Two sources of uncertainty are evaluated: station density and the impact of different background grids (HYRAS vs EOBS). The results show that the genRE method successfully mimics climatological precipitation datasets (HYRAS/EOBS) over daily, monthly and yearly time frames. We conclude that genRE is a good interpolation method of choice for real-time operational use. genRE has the largest added value over IDW for cases with a low real-time station density and a high resolution background grid.

Keywords

genRE, real-time, Interpolation, Hourly precipitation rate, forcing

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A FIRST USE CASE OF OPERATIONAL ENSEMBLE DISCHARGE FORECASTS FOR HYDROPOWER PRODUCTION ON THE RHONE RIVER: EVALUATION OF SEVERAL POST-PROCESSING METHODS

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Abstract

The Compagnie Nationale du Rhône (CNR), France's leading producer of energy exclusively generated from renewable sources, runs 3035 MW of hydroelectric installed capacity, mainly located along the Rhône River. Since 2001, CNR has developed a wide experience in operational forecasting for hydropower production purpose, developing an integrated forecasting chain running from meteorological predictions to energy trading. More recently, CNR started to lay the foundations of a future probabilistic forecasting chain, through the works of Bellier *et al.* (2016; 2017).

Recent evolutions in European mechanisms used for ensuring electricity networks balance, including weekly tenders of control reserve availability, as well as growing needs for maintenance planning have encouraged CNR to design a medium range ensemble-based operational tool for predicting the Rhône River discharge. This first use case of ensemble hydrological forecasts can be seen as a preliminary design of the future CNR probabilistic operational forecasting chain. The model provides quantiles of daily discharge forecasts at seven hydrometric stations located along the Rhône River, up to 14 days ahead. It takes as input precipitation and temperature forecasts from the Ensemble Prediction System (EPS) of ECMWF. Daily rainfall-runoff models adapted from GRP (Perrin *et al.*, 2003), including a snow melting component, compute streamflow on 24 sub-catchments of the Rhône River. Finally, discharge is routed along the river to produce forecasts at the seven target locations.

For operational use, having accurate and reliable forecasts is essential. In this study, we focus on the comparison of several post-processing algorithms used to correct forecasting biases. Post-processing methods are here directly applied to discharge predictions. Several post-processing methods are compared, including Quantile Mapping, Ensemble Model Output Statistics (EMOS, Gneiting *et al*., 2005) and Quantile Regression Forests (QRF, Meinshausen, 2006) (see figure as example). Results highlight the superiority of EMOS and QRF over Quantile Mapping, mainly due to a better ability to correct reliability biases. Both EMOS and QRF provide satisfying performance, showing clear improvements of CRPSS as compared to raw predictions, despite specific drawbacks inherent to each method. In particular, EMOS main drawback appears to be the absence of dependence of the calibrated variance on raw ensemble mean, which results in frequent over-dispersed predictions for low discharge values. QRF post-processing proved to be effective when calibrated over a sufficiently long historical period, with performance significantly decreasing otherwise.

Results obtained in this first use case, and lessons learned from the comparisons of post-processing methods will further feed the design of a future, more complex, probabilistic forecasting tool, aiming at being efficient over a large range of lead-times and able to account for multiple NWP as input.

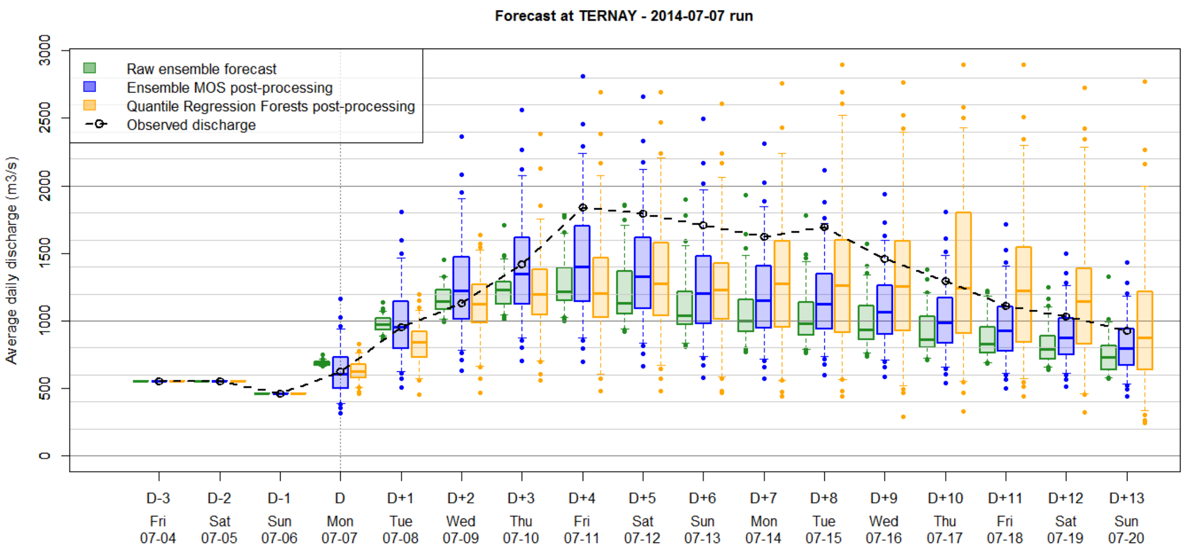

Figure 1: Illustration of a 14 days-ahead discharge forecast at Ternay (Rhône River). Comparison of raw ensemble predictions, Ensemble MOS post-processed predictions, Quantile Regression Forests post-processed predictions and observed discharge.

Keywords

Ensemble discharge prediction, Hydropower, Post-processing, Ensemble MOS, Quantile Regression Forests

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SEAMLESS RAINFALL: A MULTI-SCALE ENSEMBLE RAINFALL FORECAST GENERATOR

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Abstract

Forecast rainfall maps with temporal and spatial characteristics that match those ones in observed rainfall data are required to achieve high quality and robust hydrological simulations. In catchments where changes in the spatial location of rain patterns are important, such as small area basins, high temporal and spatial resolution rainfall maps, both observed and forecast, are critical to facilitate quick and frequent diagnoses of possible flooding. In bigger catchments, uncertainties in the forecast rainfall for longer lead times (next day to one week ahead) may also drive to different possible outcomes in the likely hydrological response of the basin. The Bureau of Meteorology is developing “Seamless Rainfall” as a methodology to generate large ensembles of high spatial and temporal resolution quantitative rainfall forecasts for both short and long lead times. A multi-scale methodology (STEPS, Bowler et al, 2006) is used to blend deterministic rainfall forecasts from Numerical Weather Prediction (NWP) models with a stochastic model of forecast error, which has the space-time properties of observed rainfall. By blending the rainfall predictions from NWP models scale by scale, it is possible to recognise the increased skill of the models at short lead times and larger spatial scales, and the reduced skills especially at long forecast lead times and small spatial scales. The stochastic model of forecast error is applied at each scale, adding increasingly more variability at small spatial scales and longer forecast lead times, while preserving the space-time structure of rainfall.

In its initial version, Seamless Rainfall can generate ensembles of hourly, downscaled precipitation forecasts out to 7 days with a resolution of 2 km × 2 km over 1000 km x 1000 km domains across Australia, blending rainfall forecasts from Bureau of Meteorology’s Australian Parallel Suite (APS) Australian Community Climate and Earth-System Simulator (ACCESS) Global model (ACCESS G) (~ 40 km ×~ 40 km, 3 hourly out to 10 days) and ACCESS-R (Regional) (~12 km × ~12 km, hourly out to 3 days) models. In future versions Seamless Rainfall may be able to blend additional deterministic NWP models such as ACCESS-C or ECMWF and probabilistic rainfall forecasts from ACCESS-GE or ECMWF Ensemble.

Keywords

Quantitative Rainfall Forecast Ensembles.

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SENSITIVITY OF POWER SYSTEM OPERATIONS TO WATER AVAILABILITY: INSIGHT FOR DESIGNING ENSEMBLE HYDRO-METEOROLOGICAL FORECASTS

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Abstract

Interannual variability in water availability across the Western U.S. can result in a variation in electricity production cost of over +/- 10%, i.e. a $4M annual difference (Voisin et al. 2017). The production cost is sensitive to water availability because hydropower, like other renewable energy sources, have low production cost which implies that they are first dispatched by the economic optimization of power operations. Hydropower is providing multiple services to power operations: hydropower generation in a load-following mode, or for coordination with thermo-electric plants, but also for reserve and frequency regulation. My hypothesis is that the processing (and type of information), and value, of flow forecasts for each hydropower plant should vary based on reservoir operations constraints (reservoir storage capacity, downstream flooding thresholds, etc) and also on hydropower services to be provided by the plant. In this presentation, I will provide an economic evaluation of a range of monthly flow forecast errors (mean biases) and relate them to the representation of hydropower in power system operations planning. I hope to open a discussion on others' experience on the design (calibration for skill and value) and use of flow forecasts for power system operations.

Keywords

Hydropower; economic optimization; forecast errors; reservoir operations.

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A SEASONALLY COHERENT CALIBRATION (SCC) MODEL FOR POST-PROCESSING NUMERICAL WEATHER PREDICTIONS

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Abstract

Calibration models are often employed to post-process forecasts from numerical weather prediction (NWP) models to reduce bias, produce reliable ensemble spread, and ensure coherence - forecasts are not worse than climatology forecasts. Calibrated forecasts should reflect seasonal variation in climatology and performance of the NWP forecasts. This may be achieved by establishing calibration models separately for individual months. However, in practice establishing separate models for individual months is often not feasible because archives of NWP forecasts are too short (1-4 years). A common practice is to use just one calibration model for all year round. This can lead to calibrated forecasts that lack seasonal variation in climatology, especially when the underlying skill of the raw NWP forecasts is low, such as at long forecast lead times. Such calibrated forecasts are clearly unacceptable for locations where there is strong seasonality in climate. When used for hydrological forecasting, they could lead to poor hydrological forecasts.

In this study, we introduce a seasonally coherent calibration (SCC) model that can work with short NWP forecast data and yield calibrated forecasts that have observed seasonal climatology, regardless of the underlying skill of the raw NWP forecasts. We present the theory of the SCC model and demonstrate its efficacy using a case study of post-processing precipitation forecasts at a rain gauge in northern Australia.

IMPROVING HYDROLOGICAL MODELLING/PREDICTIONS FOR THE RHINE RIVER IN THE FRAMEWORK OF THE IMPREX PROJECT

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Abstract

About 60% of the Netherlands is flood prone caused by both riverine flooding and storms surge or a combination of the two in the delta. Riverine flood hazard is caused by floods on the two major Rivers Rhine and Meuse. Flood risk assessment is anchored in Dutch law/policy. Flood forecasting is well developed, starting after the great floods of 1993 and 1995. During the late 1990's hydrological models were built for both rivers and subsequently used in both policy studies and operational flow forecasting. While small improvements in hydrological modelling were introduced, implementing more drastic changes to the hydrological modelling approach (e.g. different model concepts, data assimilation, and different input data sources) is difficult because of the use of the models in policy studies. Small changes in estimated flood risk can results in major costs to improve flood protection (e.g. levees).

Within the H2020 IMPREX project we follow a stepwise approach to move from a single proprietary hydrological legacy code to an open source distributed hydrological modelling framework (wflow, Schellekens, 2016) which allows for testing of hydrological modelling choices, numerical solution, etc. (see Clark et al., 2015; Kraft et al. 2011) and taking advantage of as much available observational and spatial data sources as possible to improve forecast accuracy and skill. A method to extend gridded precipitation climatology data sets in Near Real-Time for Hydrological Forecasting Purposes was already developed and tested (van Osnabrugge et al., 2017). Results of this still ongoing work will be shown (1) focusing on changing potential evaporation from a monthly mean profile to hourly varying satellite/NWP based potential evaporation estimates, (2) introducing asynchronous data assimilation and its effect on hydrological forecast performance and (3) we will also highlight effects of the change from lumped to distributed modelling.

Keywords

Rhine, distributed modelling, open source, hydrologic predictability, potential evaporation.

RWSOS: CLUSTERED MULTI-HAZARD EARLY WARNING IN THE NETHERLANDS

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Presented by: Albrecht Weerts

Abstract

For the Netherlands, being a low-lying county in a river delta, the potential impact of flood events can be devastating. Such flood events can be caused by severe storm events on the North Sea or Dutch lakes, or by high flow conditions from the Rhine or Meuse rivers. In addition, extended periods or drought combined with low flow conditions increasingly cause issues with navigability, water shortage and salinity intrusion. To adequately manage these hazards, the Dutch government provides a number of early warning services, and to do so effectively, strong cooperation on regional, governmental and intergovernmental level is a necessity.

To improve this cooperation, the Dutch government recently clustered the separate flood and drought forecasting services into one common centre (the Water Management Centre for the Netherlands) and one common software environment (the Rijkswaterstaat clustered operational systems, RWsOS) to provide multi-hazard early warning. From the RWsOS, forecasting services are provided for the Dutch North Sea and coastline, the Rhine and Meuse rivers, IJsselmeer and Markermeer, and for a number of canals and flood protection barriers. Additionally, drought forecasting services are provided for the whole of the Netherlands.

The RWsOS applies a number of common building blocks for data management and exchange. This allows for an efficient exchange of data and information with international partners (other forecasting agencies along the North Sea and in the catchment areas of the Rhine and Meuse rivers) and regional partners (Waterboards and regional crisis managers). Also, by clustering these services and providing a common user interface, interaction and collaboration between the various governmental departments involved has increased. The resulting forecasts and alerts are disseminated to the general public in a standardized and uniform manner, partially as open data, stimulating usage and uptake by the public and into downstream services.

Keywords

multi-hazard ews, forecasting & warning service, alerting, decision support

ARE GLOBAL MODELS SKILLFUL IN FORECASTING FLOODS, DROUGHT, AND THEIR IMPACTS IN DATA SCARCE AREAS?

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Abstract

Recent years has seen the emergence of global monitoring and forecasting systems, both for floods and droughts. In many cases hydrological models at the heart of these are not calibrated; the complexity of that task, as well as the lack of consistent calibration datasets at the global level make that an intractable problem. As a result forecasts made with these models are typically not as absolute values, but rather as anomalies with respect to a reference model climatology. While this provides consistent forecasts, the increasing attention to forecasting impacts rather than hazard raises the question on whether these impacts can indeed reliably be predicted. In this paper we explore this question using a recently developed water resources re-analysis. This global water resources re-analysis dataset contains an ensemble of models, including both global hydrological models as well as global land-surface schemes, run for the 1979-2014 period using a meteorological re-analysis data. Models are available at a 0.5 degrees and 0.25 degrees and were developed within the EU-FP7 Earth2Observe research initiative (Schellekens et al., 2017). These results do not constitute forecasts, but can provide insight in how flood and drought events that have impacts can be predicted.

Indicators derived from model results are used to identify flood and droughts, with threshold levels selected to determine the timing and severity of events. Flood events are determined as events exceeding defined return period thresholds, derived using the Gumbel extreme value distribution. A timeline of flood events is developed using model outputs, and is benchmarked against an equivalent timeline developed using observed data. A second benchmark is developed based on reported events collated from disaster impact databases. These benchmarks are developed for a set of hydrological gauges in the Limpopo basin in Southern Africa, a data scarce region. For drought events several drought and water scarcity indicators are derived. The consistency with which drought events are identified across the model ensemble is compared, and where available against benchmarks developed based on observed datasets.

Results show that while the spread between the results of the models in the ensemble is appreciable, indicators for both floods and drought are generally consistent, both across models and compared to indicators developed based on observed data. The example in Figure 1 shows that model biases, particularly in the small catchment, lead to over-prediction when using an observed climatology, though the higher resolution model showing an improvement over the low resolution model. Observed events,

as well as events leading to reported impacts are, however, reasonably predicted when the model climatology is used as reference.

Overall results show that global scale hydrological models do provide valuable information in predicting extreme events that lead to impacts in data sparse areas, though care must be taken in interpreting absolute values of model results.

Keywords

Floods, Droughts, Global models, Impacts

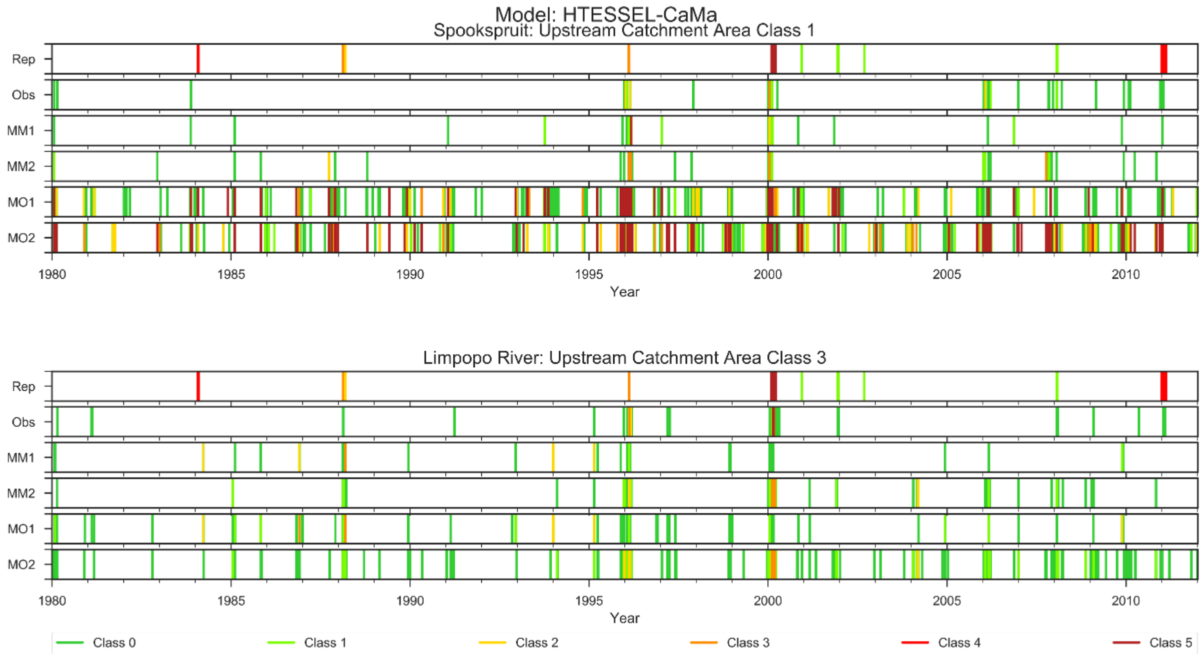

Figure 1: Occurrence of flood events of increasing magnitude class at the Spookspruit gauge (252 km^2; upper panel) and in the main Limpopo River (98240 km^2; lower panel). Model flood events identified using model climatology at (MM1 & MM2) or observed climatology (MO1 & MO2), and compared to benchmarks based on observed data (Obs) and derived from disaster impact databases (Rep). Index value indicate models with resolution 0.5^0 (1) and 0.25^0 (2).

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MERGING OF EXTENDED- AND SEASONAL-RANGE FORECASTS TO IMPROVE SUBSEASONAL TO SEASONAL HYDROLOGICAL FORECASTS

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Abstract
The forecast lead-time from sub-seasonal to seasonal (S2S; here defined as the time span beyond two weeks and up to two months) has the potential to be very useful for decision makers. It has up until recently not received much attention. The most obvious reason for this lack of interest is the inherent difficulty to provide skilful predictions on sub-seasonal or monthly timescales. The skill of S2S depends on the initial conditions of the model system, as for the short- to medium-range forecast, but also on the slowly evolving boundary conditions provided by sea surface temperatures, storage of water in the hydrosphere (snow, soil and ground water, reservoirs etc.) stratosphere/troposphere interaction etc. However, the steady increase in spatial resolution in global models, the availability of good quality observations to constrain the model initial state and the recent effort to couple processes from day 1 (for example ocean, land, sea-ice interaction, troposphere/stratosphere feedbacks) has increased skills beyond 10 days and opened the way to explore the predictive skills at longer lead times.

The European Centre for Medium-Range Weather Forecasts (ECMWF) has been particularly active in promoting the S2S timescale with the recent extension up to 46 days of its operational ensemble prediction system (ENS). These forecasts are available twice a week (on Mondays and Thursdays) and complement the seasonal forecast outlook from ECMWF's seasonal forecast System-4 (SYS4), which has monthly updates and a 7-month horizon. In a preparatory study, we have already shown how the concatenation of the ENS and SYS4 in a seamless system can provide the most accurate weather forcing for applications to be run across all time scales more than the single use of SYS4. This is mostly due to the better hydrological initial conditions, but also because of the more updated model version in the first six weeks and more frequent meteorological forecasts, which are available twice a week rather than monthly. Building on the availability of the seamless system that, while covering the seven months horizon has all the benefits of the ENS, the S2S prediction skills for hydrological forecasts over Europe were tested using the European Flood Awareness system (EFAS).

The main aim is to define the limits of hydrological predictability at the S2S time scale. Specifically to answer the questions of how far the S2S extend, if there are regimes (high/low flow) and regional variations that affect the predictability and what is the role played by seasonality. Finally, given that the benefits from the point of view of the final users is that forecasts in the S2S range might also provide "actionable" information we will investigate the added benefit for the final user of information at this lead time. The results point to an increase in predictability of around 30 days against climatology when looking at the entire spectrum of discharges (Figure 1). Stratifying the discharge into low- and high-flows shows an even longer limit of predictability for low-flows, whereas the predictability of high-flows

is lower in terms of CRPSS. This is expected since the timing of precipitation is very important for high-flows. The results are potentially very useful for sectors where low-flow forecasts are important, for example for shipping, waterpower production and water resources. The future steps will be to test the forecast to some operational test cases, and investigate how the forecast bias can be reduced.

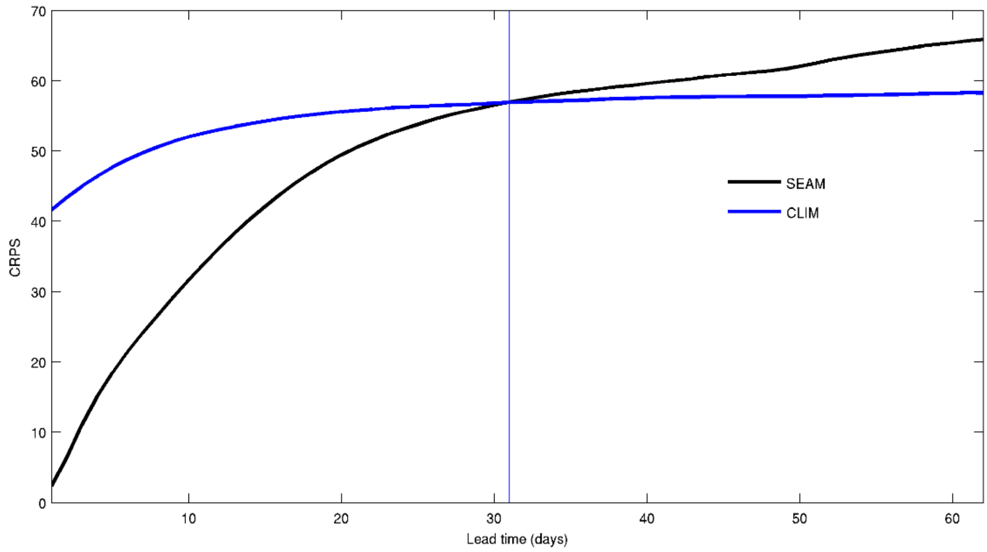

Figure 1. Potential range of predictability for the seamless forecasting system in comparison with a climatological forecast. The figure shows mean CRPS (continuous ranked probability score) over Europe as a function of lead-time. The blue vertical line denotes the limit of predictability for the seamless forecast.

Keywords

Seamless, sub-seasonal, seasonal, hydrological, forecasts

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WATERSHED-ORIENTED CLIMATE FORECAST PRODUCTS FOR HYDROLOGIC FORECASTERS AND WATER MANAGERS

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Abstract

Operational sub-seasonal to seasonal (S2S) climate predictions have advanced in skill in recent years but are yet to be broadly utilitized by stakeholders in the water management sector. While some of the challenges that relate to fundamental predictability are difficult or impossible to surmount, other hurdles related to forecast product formulation, translation, relevance, and accessibility can be directly addressed. These include, e.g., products being misaligned with users' space-time needs, products disseminated in formats users cannot easily process, and products based on raw model outputs that are biased relative to user climatologies. In each of these areas, more can be done to bridge the gap by enhancing the usability, quality and relevance of water-oriented predictions. In addition, water stakeholder impacts can benefit from short-range extremes predictions (such as 2-3 day storms or 1-week heat waves) at S2S time-scales, for which few products exist. Although the climate forecasts are not for hydrologic variables, products of this type complement hydrologic predictions in providing situational awareness for streamflow forecast operations and water management decision making.

We present interim results from an R2O effort sponsored by NOAA MAPP to (1) formulate climate prediction products to support water stakeholder adoption, and to (2) explore opportunities for extremes prediction at S2S time scales. The project is currently using NCEP CFSv2 and National MultiModel Ensemble (NMME) reforecasts to develop real-time watershed-based climate forecast products, and to train post-processing approaches to enhance the skill and reliability of raw real-time predictions. Prototype S2S climate data products (forecasts and associated skill analyses) are operationally staged at NCAR (http://hydro.rap.ucar.edu/s2s/) to facilitate further product development through interactions with water managers. Initial demonstration products include CFSv2-based bi-weekly climate forecasts for sub-regional scale hydrologic units, and NMME-based monthly and seasonal prediction products. Raw model mean skill at these time-space resolutions for some periods (e.g., weeks 3-4) is unusably low, but for other periods, and for multi-month leads with NMME, precipitation and particularly temperature forecasts exhibit useful skill.

Keywords

Sub-seasonal, seasonal, climate forecast, watershed, water management

EXPLORING THE APPLICATION OF ENSEMBLE PREDICTION METHODS ACROSS REGIONAL FORECASTING DOMAINS

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Abstract

HEPEX has long emphasized the importance of advancing capabilities in key areas such as hydrologic data assimilation, meteorological forecast downscaling and calibration, and streamflow forecast post-processing. Many methodological studies in last decade have been oriented toward operational flow prediction (versus large-domain land surface modeling) have focused on the performance of new methods in individual watersheds. Yet increasingly, streamflow prediction is being performed in a large-domain context, where the applicability and efficacy of watershed-specific methods are less well understood. The move toward large-domain, higher resolution forecasting systems in a number of nations compels a new focus on applicability of ensemble methods in such regional or national systems, which may lack the agility and/or observational density of watershed-specific systems. In this presentation, we discuss practical challenges in this area and present findings from an effort to develop a real-time regional-scale system for medium-range ensemble streamflow prediction. The forecast workflow includes the downscaling of GEFS meteorological forecast ensembles, land surface modeling with an HRU-based implementation of the SUMMA modeling framework, data assimilation via a sequential particle filter, ensemble initialization of forecasts using probabilistic forcings, and streamflow forecast post-processing. Key challenges inherent in the forecast approach include model calibration across ungauged watersheds, and the propagation of ensemble data assimilation updates from gaged watersheds toward poorly monitored watersheds within the forecast region. We report on the performance of ensemble flow forecasts produced within western US implementations of the NCAR System for Hydromet Analysis, Research and Prediction (SHARP), in comparison with real-time operational forecasts from other official sources.

Keywords

Ensemble streamflow forecasting, data assimilation, downscaling, real-time, parameter estimation, verification

THE CONTRIBUTION OF ENSEMBLE STREAMFLOW FORECASTS TO WATER RESOURCES OPTIMIZATION SCHEDULING

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Abstract

With the development of social economy, the demand for water is increasing, while water resources can be scarce in some areas because their evenly distribution in space and time. Besides, the rapid growth of population makes it increasingly more difficult for people to survive in areas of water shortage. The optimization of water resources scheduling can alleviate the unbalance between supply and demand of water resources. It is however difficult to get the optimal water resources scheduling if the streamflow forecast is not accurate. In this study, we try to improve the water resources scheduling based on ensemble streamflow forecast. We developed a distributed hydrological model and a water resources optimization scheduling model in the Ming River basin. The Climate Forecast System Version 2 (CFSv2) ensemble precipitation forecast was used to drive the hydrological model and get ensemble streamflow forecasts. The historical observed mean streamflow, the ensemble mean streamflow and the ensemble streamflow forecasts were used as input to the water resources optimization scheduling model. This allowed us to compare the results of three water resources optimization scheduling and assess the contribution of ensemble streamflow forecasts to water resources optimization scheduling.

Keywords

Ensemble streamflow forecast; water resources; optimization scheduling

A THEORETICAL STUDY ON ADJUSTMENT OF RESERVOIR OPERATING RULES USING ENSEMBLE STREAMFLOW FORECASTS

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Abstract

New hydrologic information motivates reservoir operators to update their operating policy. In Korea, forecasted meteorological ensembles have been recently issued to public which can help improving reservoir operations. In tradition, reservoir operations in Korea are highly dependent on historical data. During the drawdown period in Korea (October to June), the current reservoirs are operated to comply with an annual guideline that was designed based on low flow statistics. However, as the distribution of inflow water could change due to climate change, using current statistics for future planning can lead to water supply failures. Therefore, it is necessary to adjust the annual guideline with additional information for the future. In Korea, K-Water, the government agency which is in charge of operation of all the multi-purpose dams, has started to utilize GloSea5, a forecasted meteorological ensemble, for future decision-making. K-Water generated inflow forecasts driven by K-DRUM rainfall-runoff model with GloSea5 meteorological ensemble. Initially, some low flow statistics, such as the 5% quantile of inflow ($q_t^{5\%} = F_{Q_t}^{-1}(0.05)$), can be adjusted based on the Bayesian concept. The distribution of inflow estimated from past data is considered as prior information. Then, the likelihood function is estimated using the predicted inflow data from GloSea5. The 5% quantile of inflow is then updated from the posterior distribution obtained from combining prior information and the likelihood function, using the following equations. The annual guidelines are also edited from these adjusted 5% quantiles of inflow.

$$q_{g,t}^{5\%} = F_{Q_t|G}^{-1}(0.05)$$

$$F_{Q_t|G} = P(X_t \le x_t \mid G_t \le g_t) = \frac{P(G_t \le g_t \mid X_t \le x_t)P(X_t \le x_t)}{P(G_t \le g_t)}$$

$P(G_t \le g_t \mid X_t \le x_t)$: Cumulative probability of Glosea5 conditioned by observed inflow
$P(X_t \le x_t)$: Cumulative probability of observed inflow
$P(G_t \le g_t)$: Cumulative probability of Glosea5

Finally, this method is hypothetically applied to Yongdam Dam, Korea, and compared with the current rule to prove its theoretical feasibility.

Keywords

Ensemble Streamflow Forecast, Reservoir Operation, Bayesian Inference, GloSea5

FUNCTIONALITY AND RELEVANCE OF HYDROLOGICAL MODELS IN MULTI-MODEL AND MULTI-FORCING ENSEMBLES FROM A BAYESIAN PERSPECTIVE – A STUDY ON THE MAGDALENA-CAUCA MACRO-BASIN, COLOMBIA

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Abstract

Nature diversity seems to be the best example from which humankind may learn to understand and solve several current issues. The role species play within ecosystems is analogous to the role different hydrological models have within an ensemble, regarding functionality and relevance. Since hydrological models are imperfect, they are not able to represent all the processes occurring in a hydrosystem.

Multi-model and multi-analysis procedures have shown that predictions made using ensembles that take into account different model structures and different meteorological forcing datasets are more skillful and reliable (Davolio *et al*., 2013). In spite of this, in the literature, it has not been reported about the power different members of an ensemble have through time, i.e., if the structure of the models and forcing data have either the same behavior in wet or dry seasons or an average response through time and also through space.

The research here reported has applied a Bayesian analysis, on a monthly scale, of the value that each member has in an ensemble developed to represent observed discharge in 88 streamflow gauges in the Magdalena-Cauca macrobasin in Colombia (257,000 km^2), in the period 1981-2011. The best ensembles (BE) for each gauge were selected from a set of possible combinations that comprised the hydrological and land surface models: VIC, WFLOW, MESH and DWB; forced with four different meteorological datasets: quasi-observed, ERA-Interim, WFDEI and MSWEP, and a set of global hydrological models forced with the MSWEP (LISFLOOD, WaterGAP3 y HTESSEL), and the EartH2Observe Tier-1 ensemble (Schellekens *et al*., 2017). The performance statistic used to select the members of the ensemble was the Kling-Gupta Efficiency (KGE). The BE were evaluated with the Bayesian Model Averaging (BMA) technic so that the weights of the ensemble could be determined. Also, monthly ensembles were built with BMA, obtaining the weighted values and the performance of each member, in each month.

The results indicate that in general, the BE improve the values of the KGE in 83% of the streamflow gauges considered in the analysis, in comparison with the best model forced with different meteorological datasets, or different models forced with only one meteorological dataset. A high diversity in the members of the ensembles was observed, yet for streamflow gauges nearby, and also from month to month, making it not clear a relationship between dry/wet season and members of the

ensembles. Finally, the research evidenced that all the individual models and the ensembles analyzed have a poor performance in subbasins in the upper part of the Magdalena-Cauca watershed.

Keywords

Magdalena-Cauca macrobasin, Bayesian approach, Multidiversity, EartH2Observe.

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OPERATIONAL DROUGHT FORECASTING AND SKILL ASSESSMENT OVER CHINA

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Abstract

Accurately tracking and predicting the evolution of land surface conditions in a real-time manner is critical for drought diagnosis, assessment, and early-warning. In this study, we aim to develop an experimental real-time drought monitoring and seasonal forecasting framework based on the Variable Infiltration Capacity model (VIC) over China. Within this framework, the VIC model is forced with satellite data for the real-time monitoring of land surface conditions. Initialized with the satellite-aided monitoring, three types of forecasts were designed and implemented, wherein the VIC model is separately driven with: 1) a global atmospheric model forecast (ECMWF seasonal forecast system - S4); 2) the traditional ensemble streamflow prediction approach (ESP) resampled from historical data, and 3) a conditional ESP approach (conESP) that is conditional on the ENSO (El Niño-Southern Oscillation) signal. Using the deterministic and probabilistic metrics, we determined and compared the skill of these three drought forecast types, which are derived from both real-time initial hydrologic conditions and seasonal climate forecasts, in predicting commonly used drought indices. This operational framework and the relevant skill assessment will provide operational guidance for risk mitigation and water management.

Keywords

Drought monitoring and forecasting, satellite data, climate model, skill assessment

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THE IMPACT OF LAND DATA ASSIMILATION ON GLOBAL RIVER DISCHARGE SIMULATIONS

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Abstract

The Global Flood Awareness System (GloFAS; Alfieri et al. 2013) is one of the few global scale applications that currently exist. In GloFAS the real time discharge forecasts are compared with climatological simulations to detect the severity of high flow situations. In the current setup, the real-time discharge is based on operational ensemble runoff outputs of ECMWF which are produced by the coupled atmosphere-land-ocean system, including the HTESSEL (Balsamo et al. 2011) land surface model and land data assimilation for soil moisture and snow cover. The GloFAS discharge climatology is derived from ERA Interim Land data (ERAI-Land; Balsamo et al., 2015) which was produced by HTESSEL in the stand-alone ("offline") mode uncoupled from the atmosphere and forced with ERA Interim input.

In the offline HTESSEL simulations, such as ERAI-Land, there is no data assimilation component, thus no soil moisture or snow increments are present. The atmosphere is fixed, not allowing any positive feedback mechanism, making the surface water budget closed. In the real time GloFAS component where the forecasts are produced using coupling and data assimilation, however, the analysis of soil moisture and snow can add or subtract water leaving the water budget unclosed. The atmosphere-land coupling with the data assimilation system, as used in the operational IFS, provides an improved realism of the surface conditions, in particular better soil moisture and snow cover. However, as it leaves the water budget unclosed, it does not necessarily bring the same benefits in the representation of the hydrological cycle.

In this study we have analysed the impact of the land-atmosphere coupling and data assimilation on the global flood predictions. Discharge simulations were compared in the climatological context, one derived directly from operational ERA5 data, the new ECMWF climate reanalysis succeeding ERA Interim (Hershbach and Dee 2016), which includes atmosphere-land coupling and land data assimilation leading to an unclosed water budget, and also an offline HTESSEL version, forced with ERA5 data, which provides a closed water budget. ERA5 is still in production, so the analysis could be based on a 15-year sample with roughly 600 global stations providing discharge observations.

The two simulations were analysed for how they handled the mean, the variability and the peaks in the discharge time series, and also different verification scores, such as the Nash-Suttcliffe Index, were used to compare their skills. Results generally highlight significant differences between the two

simulations. The analysis of these differences can help diagnose the beneficial and the yet suboptimal aspects of the land surface processes in the operational set up. We believe it is important in helping the future earth system model developments with land data assimilation and through this in supporting the global flood forecasting activities.

Keywords

Global flood forecasting, land surface modelling, land data assimilation, water budget, discharge simulations

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