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SONICS: A NOVEL IN-HOUSE DEVELOPMENT SYSTEM FOR DETECTION AND FORECASTING POTENTIAL RIVER FLOODS IN PERU

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Abstract: The increasing frequency and intensity of weather extreme events in the Tropical Andes and hydrological hazards in Peru highlight the importance to develop hydrological prediction tools for supporting Early Warning Systems at national and local scales, even when real-time and ground data are limited (Llauca et al., 2021b, 2021a). This work introduces a novel system for detection and forecasting potential river floods across 12 thousand river reaches in the Peruvian domain. The SONICS system (https://www.senamhi.gob.pe/?p=observacion-de-inundaciones) is an operational framework and product for monitoring and forecasting daily flow increases that could potentially generate river floods (Figure 1). It was developed by the SENAMHI's Hydrology Department based on three sources: a) The meteorological gridded dataset called PISCO (Aybar et al., 2020; Huerta et al., 2022), b) the PISCO_HyD_ARNOVIC dataset for simulated daily water discharges (Llauca et al., 2023), and c) numerical daily precipitation forecast models (ETA, GFS, and WRF). SONICS can anticipate daily flow increases upper than percentile 70 until with 7-day lead time and categorize them as low (green flag), moderate (yellow flag), high (orange flag), and very high hazard (red flag) levels across the whole country. Also, users can visualize and download forecast information for a particular river reach of interest through the SONICS app (available online at https://harold-llauca.shinyapps.io/sonics/).

This novel system represents an important contribution to SENAMHI's climate services and hydrological risk management in Peru, even in often poorly gauged catchments. For instance, the SONICS system was useful in providing short-term discharge scenarios and supporting decision-making during the weather extreme events in March-April 2023, when the Peruvian coast was strongly affected by the unusual non-organized tropical cyclone "Yaku" and the anomalous sea surface temperature warming of the region Niño 1+2 called "El Niño Costero". Future work will incorporate a new multitemporal (hourly, daily, weekly and monthly time steps) and high-scale (32 thousand of river reaches) hydrological simulation for Peru, using parsimonious GR models (Perrin et al., 2003) and a finer hydrographic network taken from MERIT-Hydro product (Yamazaki et al., 2019).

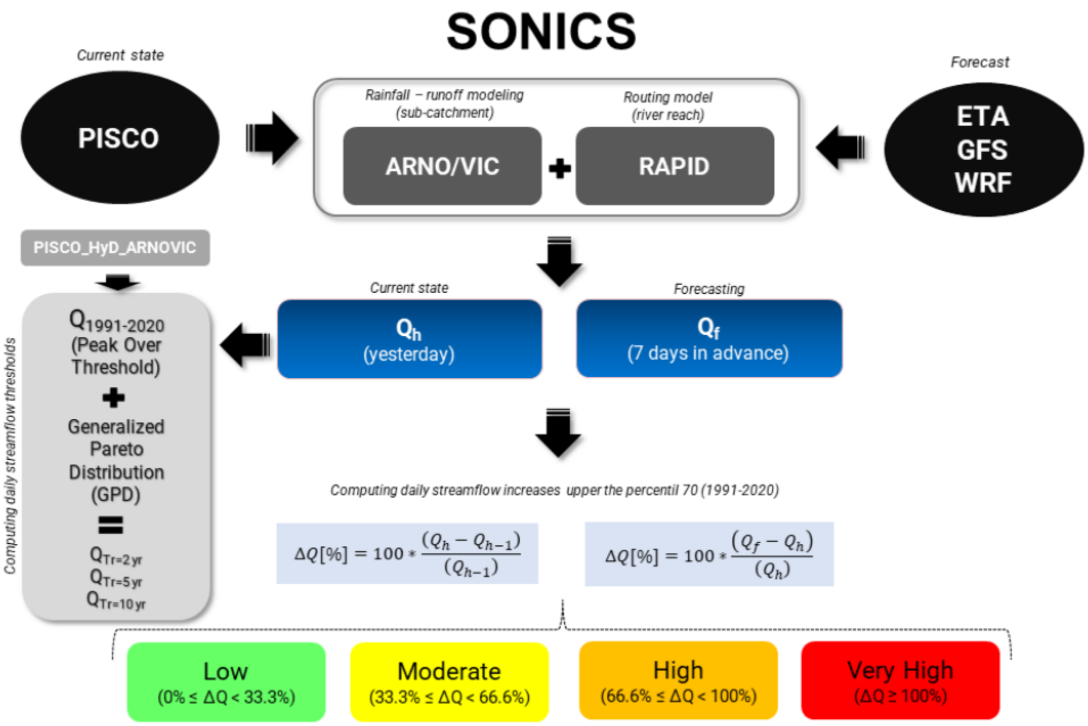

Figure 1. *Workflow of the operational SONICS system in Peru.*

Keywords: *Peru; climate services; river floods; tropical Andes; Niño Costero; cyclone Yaku.*

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A HYBRID MULTI-BASIN ML FLOOD MODEL DRIVEN WITH SEASONAL CLIMATE FORECASTS FROM C3S

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Abstract: Reliable streamflow forecasts are essential for managing flood risk, but are challenging to produce at seasonal timescales. One approach that is currently underexplored is the use of hybrid methods that predict floods using machine learning (ML) models driven by subseasonal-to-seasonal climate model predictions. Here we develop and test a novel hybrid system to predict seasonal flooding. We train a machine learning model to predict the highest daily streamflow in each season using climate inputs drawn from the C3S multimodel ensemble. We address the following research questions: (i) To what extent can a multi-site machine learning model that spans multiple river gauges enhance the skill of seasonal flood predictions compared to single-site models? (ii) What is the best way to structure the ML model to extract the maximum information from the multi-model climate ensemble? (iii) Does the length of the training period limit the skill of the hybrid seasonal forecasts? (iv) To what extent can the ML model generate skillful forecasts in ungauged catchments? (v) How does the skill of flood forecasts obtained from this hybrid approach compare with that of existing forecasting systems?

Keywords: *Seasonal-to-subseasonal forecasting, machine learning, floods*

CHALLENGES OF OPERATIONAL WEATHER FORECAST VERIFICATION

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Abstract: Operational weather forecast agencies encounter significant challenges in the verification and evaluation of forecasts. To address these issues, a series of online workshops were organized, engaging operational personnel from six countries, including model developers, observations managers, operational meteorologists, and verification system developers. Through discussions and polls, five prominent themes emerged: inadequate verification approaches, incomplete and uncertain observations, challenges in assessing performance aligned with users' real-world experiences, miscommunication and misinterpretation of forecasts and complex verification information, and various institutional factors. Additionally, nearly fifty urgent scientific questions relevant to operational practices were identified, accompanied by calls to action. These include the design of forecast systems with verification in mind, better availability of observations, creation and adoption of community software systems and the fostering of an interdisciplinary community inclusive of operational agencies, users, and researchers.

Keywords: *Weather forecasting, verification, evaluation, performance assessment, communication, accountability.*

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Pagano, T.C. and 19 others 2023. Challenges of Operational Weather Forecast Verification. Bulletin of the American Meteorological Society (submitted).

TESTING A BAYESIAN JOINT PROBABILITY MODELING APPROACH TO BIAS CORRECT SUB-SEASONAL AND SEASONAL FORECASTS FOR DROUGHT RISK MANAGEMENT IN SPAIN

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Abstract: The potential of user-driven climate services to facilitate proactive drought management approaches is leading intensifying efforts to develop and test climate services that include hydro-meteorological forecast products. In Spain, there is an interest to incorporate forecast knowledge into drought risk management, partially by integrating climate information into the currently operational drought indices. In the process of climate service information uptake, the first and most relevant aspect that fosters credibility of the forecasts is the quality of the climate information, usually expressed in terms of uncertainty, reliability, and accuracy. Post-processing techniques play a crucial role in the enhancement of forecast quality. In this study, we post-process daily rainfall and temperature sub-seasonal (European Centre for Medium-Range Weather Forecasts (ECMWF) Extended Range) and seasonal (ECMWF System 5) forecasts for a region within the Douro River Basin in Spain. We use a Bayesian Joint Probability (BJP) modeling approach for bias correction and the Schaake Shuffle method for conserving temporal correlation across lead times (Schepen et al., 2018). We also assess the forecast quality by means of a set of scores and metrics that incorporate the local definition and understanding of drought in the region, thus being relevant for stakeholders in the context of drought management. Expected results aim at improving benchmark forecast products by reducing bias, improving reliability, and enhancing forecast skill when compared to climatology. Additionally, we assess the performance of the bias-corrected forecast for a variety of historical drought events and deepen the comprehension of drought prediction in the region. This study is framed within broader research that intends to demonstrate the forecast value for proactive and sustainable drought risk management in the Douro River Basin. We foresee three main contributions. First, we expect to contribute to the experience in the implementation of the BJP modeling approach for calibrating forecasts in Europe, where this method has been little used. Second, we explicitly consider insights of user perceptions of climate information quality in the specific context of drought decision-making, thus contributing to the literature on climate services co-production. Third, we aspire to contribute to the state-of-the-art knowledge on seasonal forecasting in Spain, thereby advancing the usability of climate information for proactive and sustainable drought risk management by river basin authorities.

Keywords: Forecast calibration and evaluation, Forecast skill, Bayesian Joint Probability, Schaake Shuffle, Drought risk management.

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ENHANCING SEASONAL HYDROLOGICAL FORECASTING VIA LOCAL DATA INTEGRATION AND MACHINE LEARNING

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Abstract: *Seasonal hydrological forecasts are often plagued by two challenges: model imperfections in reference simulations and skill deterioration in forecasts, both of which can be mitigated through the integration of local knowledge and data. This study presents a post-processing framework that leverages machine learning to better integrate local data, thus improving the quality of seasonal forecasts. We apply this framework for streamflow forecasting over Europe using the E-HYPE hydrological model driven by bias-adjusted ECMWF SEAS5 seasonal meteorological forecasts, and specifically addressing the issue of model imperfections within hydrological model simulations. Four post-processing methods - generalized linear model, random forest, quantile mapping, and long short-term memory (LSTM) model - are deployed to refine the output from the hydrological model to align more closely with local observations, covering ~1100 stations across the European domain. Variations in improvement across the post-processing methods are evaluated concerning spatial distributions and hydrological characteristics. Our results indicate that the performance of the four methods varies spatially and according to hydrological characteristics, with LSTM consistently outperforming the best at most stations. The added value of post-processing methods correlates with specific hydrological characteristics; notably, drier river systems receive higher skill improvement. This hybrid approach to seasonal streamflow forecasting effectively captures local conditions and meets user expectations more accurately, which underscores the potential of machine-learning enhanced services in customizing large-scale hydro-climate services using local data.*

Keywords: *Seasonal forecasting, Post-processing, Machine learning, LSTM, Hydrological predictions*

SHORT TERM DROUGHT PREDICTION BASED ON STABLE STATES BETWEEN THE LAND AND THE ATMOSPHERE

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Abstract: Prolonged drought has devastating societal impacts ranging from recreation to water and food supply and can ultimately result in significant financial losses. In a warming world, the frequency of seasonal- and multi-year drought episodes is likely to increase. Those in the poorest countries who rely on domestic ecosystem services (including food production) are the most vulnerable. Accurate drought prediction has the potential to reduce negative impacts and support societal resiliency by informing sustainable water-management and planning practices. Such predictions require a thorough understanding of the physical mechanisms that lead to the onset, persistence, and recovery of drought and the ability to replicate these processes in forecast models at appropriate time scales (weeks to months). While synoptic drivers play a key role in drought development, there is increasing evidence that the land surface plays an important role in the skill of sub-seasonal to seasonal forecasts. However, there is still a lot unknown about the direct impact of local processes, such Land-Atmosphere (L-A) interactions, on drought evolution due to low signals relative to the noise of natural variability and insufficient observational data sets. Here we present our work on using a statistical based prediction of drought evolution based on the stable states between the land and the atmosphere. This will be done by producing short-term (30 day) predictions of the Coupling Drought Index (CDI) and precipitation and comparing them with observations from reanalysis over a period of 2015-2022 in order to make use of global measurements of soil moisture from SMAP. The statistical model is based on the Coupling Stochastic Model (CSM; Roundy et al. 2014), which is a Markov-Chain model based on the persistence in L-A coupling regime but was recently updated to include a simple soil moisture model. The strengths and limitation of this prediction method will be discussed as well as future directions for improving global drought forecasting through remotely sensed observations.

Keywords: *Statistical Prediction, Drought, Land-atmosphere interactions, SMAP*

References:

Roundy, J. K., and E. F. Wood, 2014: The Attribution of Land–Atmosphere Interactions on the Seasonal Predictability of Drought. Journal of Hydrometeorology, 16, 793–810, https://doi.org/10.1175/JHM-D-14-0121.1

THE IOWA FLOOD CENTER REAL-TIME STREAMFLOW FORECASTING SYSTEM

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Abstract: A real-time streamflow forecasting system is presented that produces predictions for about 1000 locations in the state of Iowa, United States, including communities and stream sensors. The core of the system is a distributed hydrologic model that represents the landscape using hillslopes and channels. MRMS radar rainfall and MODIS based evapotranspiration are forced into the model to estimate the most current state of the system. These are used as initial conditions to produce 5-day ahead forecasts, after forcing the model with HRRR 18-hour precipitation forecasts. The system cycle loop repeats every one hour. The skill of the model to simulate discharge with observed rainfall has been evaluated in previous studies (Quintero et al., 2020), but less is known about the performance of the system in forecasting mode. Here is presented a preliminary evaluation of the forecast performance, conducted at about 150 basins with available streamflow measurements, ranging from 10 to 35,000 km^2. The evaluation provides some insights about what is the value for the predicted river stages from: the spatial scale of the basins, the lead time horizon, the quality of the precipitation forecasts, the hydrologic model structure, the assimilation of streamflow data in the model, and the severity of the flood events.

Keywords: *Streamflow forecast, forecast evaluation, data assimilation, lead time*

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DEVELOPING THE POST-PROCESSING OF THE EUROPEAN FLOOD AWARENESS SYSTEM'S FORECASTS

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Abstract: *Flood forecasts can help mitigate the human, infrastructure, economic, and environmental impacts of floods by improving preparedness. However, to be useful in the event of a flood the products from these early warning systems must be useful and useable. This requires continuous development accounting for the changing requirements of users and developments in both science and technology. The European Flood Awareness System (EFAS), part of the European Commission's Copernicus Emergency Management Service (CEMS), provides complementary flood forecasts to EFAS partners across the whole of Europe. The EFAS 'post-processed forecast product' is generated for the location of approximately 1600 river gauge stations where sufficient historic and near-real time river discharge observations are available. The aim of this product is to provide an error-adjusted forecast up to a maximum lead-time of 15 days. Following a workshop with the EFAS partners and a forecast skill assessment a roadmap for future developments of the EFAS post-processed forecast product was designed to ensure the user's changing requirements are satisfied (Matthews et al., 2023, Matthews et al., 2022). Here, we present the progress made in implementing this roadmap including improvements to the post-processing methodology to better account for the different hydroclimatic regimes and data availability across Europe, and changes to the post-processed forecast product to make it more locally relevant and useful to the EFAS Partners.*

Keywords: *EFAS, post-processing, flood forecast product, co-production, continental-scale, uncertainty*

References:

Matthews, G., H. L. Cloke, S. L. Dance, E. Hansford, C. Mazzetti, and C. Prudhomme, 2023: Co-Design and Co-Production of Flood Forecast Products: Summary of a Hybrid Workshop. Bull. Amer. Meteor. Soc., 104, E1058–E1066, https://doi.org/10.1175/BAMS-D-23-0061.1.

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ADVANCING DRINKING WATER MANAGEMENT WITH HYDRO-CLIMATE SERVICES: THE CO-GENERATION SUCCESS STORY OF SMHI AQUA

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Abstract: Hydro-climate services have emerged as a promising solution for addressing the needs of the drinking water supply sector. In this study, we showcase the potential of co-generation in promoting the adoption of a service that supports decision-making and ensures sustainable water resource utilization. Our insights are based on the SMHI Aqua service co-generation storyline. The core of this study is based on the implementation of a comprehensive framework based on four pillars: co-design, co-development, co-delivery, and co-evaluation. This framework relied on active engagement and close collaboration among service purveyors, data providers, and users. Region Gotland and three more drinking water producers across Sweden participated in the process. The result of co-generation was the SMHI Aqua hydro-climate service, which consists of three main components: data assimilation, forecast production, and a decision support system.

To simulate freshwater availability in surface and groundwater reservoirs, two hydrological models were customized to local conditions. These models generate short- and long-range forecasts, which are updated twice a day. Real-time hydro-meteorological measurements are integrated to update the model and initialize the forecasts. Additionally, the service allows for the simulation of various freshwater availability scenarios for the upcoming months through the implementation of different water extraction strategies provided by the users. The hydro-meteorological data, both measured and modelled, are accessible through a user-friendly web-based platform. The platform presents the information in an informative and easily understandable manner. Efficient communication of the hydro-meteorological information, including the propagated uncertainty, is crucial for water managers to make informed decisions.

The study emphasizes the importance of knowledge co-evolution in ensuring the successful uptake of hydro-climate services. Furthermore, the benefits of adopting such services extend beyond water-related users. By guaranteeing access to freshwater and improving awareness and preparedness for extreme conditions, the impact reaches policy makers and the broader public. Overall, feedbacks from the users highlight that the implementation of the co-generated SMHI Aqua hydro-climate service remarkably improved their operational routines for drinking water management. By actively involving all stakeholders and implementing a comprehensive framework, the co-generation approach facilitates informed decision-making, sustainable water resource utilization, and improved resilience to extreme conditions.

Keywords: *Hydro-meteorological forecasting; Co-generation; Drinking water supply; SMHI Aqua; Decision support system.*

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Cantone, C., Ivars Grape, H., El Habash, S., Pechlivanidis, I. G. 2023. A co-generation success story: improving drinking water management through hydro-climate services. Climate Services (Accepted).

EVALUATION OF MULTI-BASIN HYDROLOGICAL MODELS IN TERMS OF QUANTILE EXTREMES

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Abstract: Hydrological models are generally calibrated and validated using a suite of well-known statistical metrics, which sometimes lack clear connection and tailoring to the user needs and therefore limits the evaluation, e.g. in the case of global climate services. Flood (or drought) forecasting is a main task in operational application, where a model is required to predict whether the streamflow will be above (below) some high (low) quantile sometime in the future. Examples include threshold exceedance in the European Flood Awareness System (EFAS) and quantile-based drought advisories in Sweden. We propose that evaluation based on quantile extremes should be introduced to better address the model performance from the users' perspective. Meanwhile, communications with users can be enhanced by outlining both recommendations and constraints based on their application. Therefore, a pair of quantile-based evaluation metrics based on quantiles is introduced, addressing the accuracy in amplitude as well as temporal matching of quantile extremes, to complement commonly used model performance assessment metrics. The introduced metrics are compared to conventional statistical metrics, at seven case study areas across the world, with three model settings representing different forcing datasets and calibrations, generated from the global hydrological model World-Wide HYPE (WW HYPE). The results suggest that the performance quantified by quantile-based metrics may differ from that based on conventional ones. This implies that different evaluation metrics reveal different aspects of the models' capability, supporting their application under the corresponding circumstances. This enables us to propose three model application scenarios: generally applicable models, conditionally applicable models, and exceptionally applicable models. For instance, the WW HYPE with global dataset and local calibration can yield optimal estimates concerning the timing of quantile extremes, despite its suboptimal performance in conventional evaluation metrics. Therefore, it may be considered as a conditionally applicable model which can be used in regions with limited local datasets, supplying dependable information for decision-makers in formulating strategic plans for water resources management.

Keywords: *Quantile extreme, temporal matching, application-based evaluation, global hydrological model.*

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IMPROVING THE PERFORMANCE OF HYDROLOGICAL MODEL FORECAST USING A TIME-VARYING MULTIVARIATE ENKF ASSIMILATION

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Abstract: Conceptual hydrological models are widely utilized for estimating and forecasting streamflow for various applications. However, the presence of uncertainties within these models necessitates the improvement of current modeling strategies. Previous research has demonstrated significant enhancements in the predictive performance of hydrological models when both soil moisture (SM) observations and streamflow (Q) observations from interior catchment locations are assimilated using multivariate assimilation (MVDA). However, due to the transient nature of catchments influenced by climatic and human factors during the assimilation period, dynamic updating of model parameters is especially valuable for longer assimilation periods (Xiong et al., 2019). Accordingly, in this study, Level 2 Advanced Scatterometer (ASCAT) soil moisture and in-situ streamflow observations from Central Water Commission, India, are utilized together to update the model states and parameters simultaneously. The popularly utilised Ensemble Kalman filter was used for the sequential assimilation of SM and Q to improve the streamflow forecast at the Bharathapuzha river basin (BRB) using a simple conceptual Two Parameter Model (TPM). Results indicate that the assimilation strategy considering time-varying multivariate assimilation (TV-MVDA) and time-invariant MVDA, both outperformed the case without any assimilation. TV-MVDA performed slightly better than the MVDA case, yielding improvements of 1.56% in RMSE, 4.38% in PBIAS, 1.16% in KGE, and 1.2% in R^2 values. Similarly, streamflow forecasts indicated that TV-MVDA exhibited superior performance compared to the time-invariant case. For instance, the KGE value rose to 0.78 from 0.72. These results highlight the importance of simultaneously updating model parameters during assimilation. Nevertheless, further analysis is required across a range of catchments with diverse climatic and topographic characteristics to verify the robustness of the proposed assimilation procedure. Such investigations will provide a comprehensive understanding of the assimilation strategy's effectiveness and applicability in different hydrological settings.

Keywords: *Data assimilation, Streamflow forecast, Satellite Soil moisture*

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SPATIAL MODE-BASED CALIBRATION (SMOC) OF FORECAST PRECIPITATION FIELDS FROM NWP MODELS

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Abstract: Statistical calibration of precipitation forecasts from numerical weather prediction (NWP) models is routinely performed grid-cell by grid-cell, aiming to produce accurate and reliable ensemble forecasts for precipitation fields. Calibrated ensemble members from different grid-cells are then connected using ensemble reordering to form spatially structured ensemble forecasts. However, ensemble reordering approaches are often found to be problematic in practice. For example, the well-known Schaake shuffle is generally criticized for not considering real physical atmospheric states of precipitation events.

To overcome limitations with ensemble reordering, this study proposes a spatial mode-based calibration (SMoC) model for post-processing forecast precipitation fields and producing ensemble forecasts with inbuilt spatial structures, so that ensemble reordering is not required. The SMoC model is developed based on spatial modes derived from empirical orthogonal function (EOF) analyses of precipitation fields and linear regressions of derived EOF expansion coefficients of the first few dominant modes. Distributions of regression residuals are used to quantify associated forecast uncertainty. Unlike calibration models that are applied to forecast grid-cells individually, SMoC is applied to the whole forecast fields, and the spatial structure is therefore inherently present in calibrated ensemble forecasts.

The performance of SMoC is evaluated by applying it to NWP precipitation forecasts over the Brisbane drainage basin in eastern Australia and comparing it with post-processing through calibrations grid-cell by grid-cell using the seasonally coherent calibration model followed by ensemble reordering using the Schaake shuffle. Results show that SMoC calibrated forecasts are of high quality at both grid-cell and basin scales and the spatial structure is well embedded in calibrated ensemble members. Compared with the conventional grid-cell by grid-cell post-processing, SMoC avoids drawbacks of ensemble reordering, is computationally far more efficient, and most importantly leads to better forecast performance. As a significant advance in forecast post-processing, SMoC can effectively improve users' capability in acquiring high-quality ensemble forecasts of precipitation fields.

Keywords: *Forecast precipitation fields, Statistical calibration, Spatial structure, Empirical orthogonal function, Spatial modes, grid-cell by grid-cell post-processing*

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CONNECTIONS BETWEEN ELECTRICITY PRODUCTION AND CLIMATE VARIABILITY IN EUROPE: A SPATIAL AND TEMPORAL ANALYSIS

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Abstract: This study investigates the correlation between electricity production potentials (hydro power, wind power, and solar power) in Europe and 12 climate indices representing climate variability. Monthly data for electricity production potentials and climate indices were obtained, and the seasonal cycle was extracted to capture inter-annual variability. Spearman correlation and bootstrap methods were employed for correlation analysis and significance testing, respectively. The spatial patterns of correlation maps revealed that the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Scandinavian Pattern (SCAND) exhibited the strongest correlations with electricity production data among the studied indices.

For hydro power potential, positive correlations were observed in the western part of Scandinavia and the northern region of the UK with AO and NAO, while negative correlations were found in southern and eastern Europe. In contrast, SCAND exhibited an opposite spatial pattern of correlations. Wind power potential displayed significant positive correlations with AO and NAO throughout Scandinavia and the UK, but showed significant negative correlations with SCAND in all areas north of 50°N. Solar power potential demonstrated significant negative correlations with AO and NAO in the western part of Scandinavia and the western region of the UK, while in the southern part of Europe (south of 50°N) with SCAND. Significant positive correlations for solar power potential were observed in central and southern Europe with AO, southern Scandinavia, central-western Europe, and the Iberian Peninsula with NAO, and northern UK, western Scandinavia and northeastern Europe with SCAND.

Temporal persistence of the correlations between power data potentials and climate indices was examined using cross-correlation analysis with lagging months ranging from 0 to 5. The persistence of the correlation varied across regions and climate indices. Additionally, composite analysis was conducted to quantify the relative differences in power data potentials during positive/negative phases of AO, NAO, and SCAND compared to neutral phases. The results indicated a general pattern of positive anomalies in the north of Europe and negative anomalies in the south for AO and NAO (opposite pattern for SCAND). Furthermore, solar power potential exhibited the least amplitude in the anomaly, with values remaining within +/-20%.

This research provides valuable insights into the relationship between energy production and climate indices in Europe, highlighting the regional variations and temporal persistence of the correlations. The findings contribute to a better understanding of the influence of climate variability on electricity production potentials, which can aid in forecasting, decision-making processes and future energy planning.

Keywords: *Electricity production potentials; Climate indices; Climate variability; Europe; Spatial patterns; Temporal patterns.*

THE ROLE OF EARTH OBSERVATIONS AND IN SITU DATA ASSIMILATION IN SEASONAL HYDROLOGICAL FORECASTING

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Abstract: Earth Observation (EO) data are a valuable complement to in situ measurements in hydrology because they provide information in locations where direct measurements are unavailable or prohibitively expensive to make. Recent advances have enabled the assimilation of different datasets into hydrological models to better estimate states and fluxes, which leads to improved hydrometeorological forecasts. The assimilated data exert additional controls on the quality of forecasts; it is therefore important to apportion the contributions from the hydrometeorological forcing and assimilated data. Model outputs are commonly used to benchmark forecast systems during the assessment of their performance. We propose a diagnostic framework that uses observation as benchmark to assess the sources of skill and infer the seasonal importance of assimilated and forcing datasets. The framework is tested using two forcing datasets derived from historical observations and a downscaled Global Circulation Model (GCM) to assimilate four EO and two in situ observations to generate the initial states for generating the forecasts. In addition, we use the Swedish snowmelt-dominated Umeälven catchment and the HYPE model over the period 2001-2015. The results show that all assimilations improve the forecast skill but the improvement depends on the season and assimilated data. The lead times during which data assimilation influences forecast skill also differ between datasets and seasons and the assimilated datasets generally exert more control on the streamflow forecasting skill than meteorological forcing data.

Keywords: *Hydrological modeling, data assimilation, earth observations, seasonal forecasting, skill apportionment, forecasting skill performance*.

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Musuuza, J. L., L. Crochemore, and I. G. Pechlivanidis. Evaluation of earth observations and in situ data assimilation for seasonal hydrological forecasting. Water Resources Research, 59(4):e2022WR033655, 2023. doi: https://doi.org/10.1029/2022WR033655.

IMPROVING GLOFAS RAPID INUNDATION MAPPING PRODUCTS THROUGH SATELLITE DATA ASSIMILATION

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Abstract:

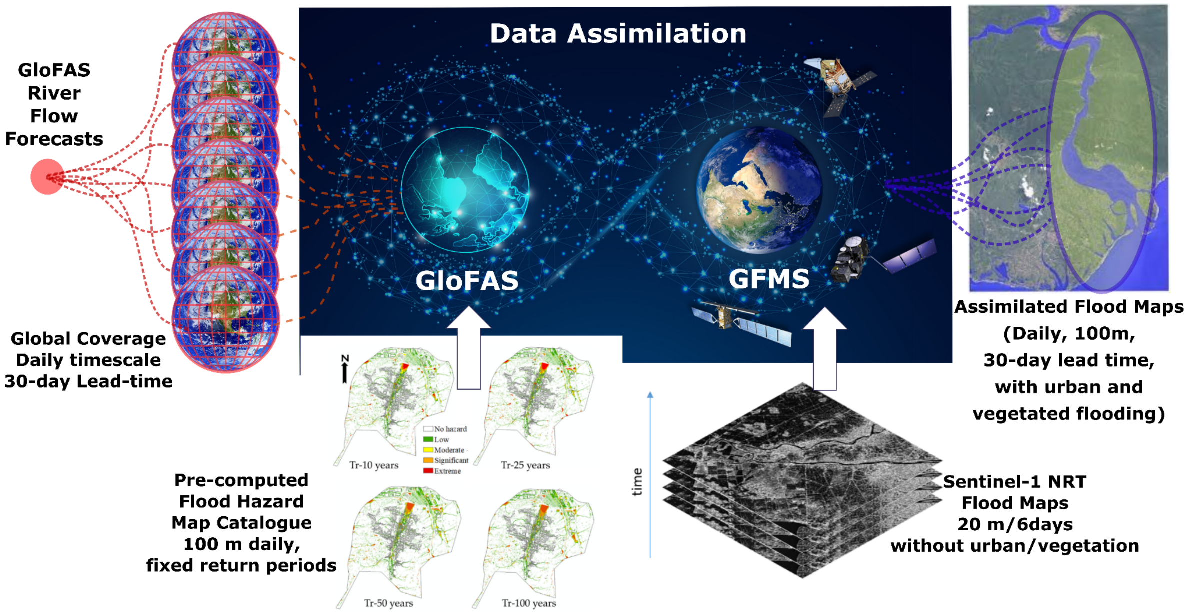

Figure 1. *Graphical abstract of the proposed extension to the GloFAS Rapid Inundation Mapping Product using the Global Flood Monitoring Product.*

Concurrent developments in the fields of Earth Observation yielding big data for a variety of applications and compute capacities to process such data at large scales, has enabled the development of Digital Twins of the Earth which can help anticipate extreme events and test policy intervention impacts. Here we propose a Digital Twin focused on flood disasters through early warning and improved preparedness, to produce globally consistent flood inundation products. Aligned with user-centric design principles, a multi-tier user requirement collection strategy was implemented with varying levels of engagement, to identify key product features desired by the stakeholder community.

Accordingly, in this pilot study in the frequently flooded Severn Catchment, UK, existing global near-real-time flood products offered by the Copernicus Emergency Management Services will be combined to enable moderate resolution inundation predictions with lead times over 72 hours at daily scales globally. Specifically, we propose to combine the Global Flood Mapping (GFM) and Global Flood Awareness System (GloFAS) Rapid Mapping products through data assimilation to enable medium-range forecasting of inundation maps and mitigate the problems in each data source. For the GLoFAS Rapid mapping product, GloFAS simulated streamflow is used to identify the inundation extent from a precomputed library of flood hazard maps at 100m resolution daily, using predefined thresholds for design flood events at a given gauge (Dottori et al., 2017). On the other hand, the GFM product provides 20m flood inundation maps based on Copernicus Sentinel-1 with <8 hours latency every 6 days along with classification uncertainties, but excluding challenging areas for radar sensors such as urban, vegetated, and arid regions (Matgen et al., 2020).

The proposed data assimilation strategy (See Figure 1), would not only enable more accurate flood maps daily by allowing weighted combinations of the design flood maps to better represent real-world conditions, but also help increase coverage to include areas excluded by the GFM product. Moreover,

the assimilation algorithm offers maximum flexibility, by being model agnostic (i.e. any model, even local ones can be used), resolution agnostic (i.e. technically any spatiotemporal configuration for satellite observations can be integrated), and transferable (i.e. can be reapplied to a new test site without extensive retraining or reconfiguration). Furthermore, assimilating different types of observational data is also possible in future as structured in situ or citizen science measurements become available. Outcomes from this proof-of-concept study will inform future research and development in the context of digital twins of the Earth focused on increasing flood risk resilience and bridging the global flood protection gap.

Keywords: *Flood Inundation Simulation, Data Assimilation, Digital Twins, GloFAS, GFM, CEMS, Earth Observation*

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EVALUATION OF CONTINENTAL-SCALE ENSEMBLE HYDROLOGICAL FORECASTS FROM ENVIRONMENT AND CLIMATE CHANGE CANADA: A COMPARISON WITH FORECASTS FROM THE GLOBAL FLOOD AWARENESS SYSTEM (GLOFAS)

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Abstract: Environment and Climate Change Canada (ECCC) is in the process of deploying a continental-scale hydrological prediction system known as the National Surface and River Prediction System (NSRPS). Operating at a resolution of 30 arc seconds, NSRPS currently generates Ensemble Streamflow Predictions (ESPs) for over 6.2 million km^2 (~ 6.2 million grid points). Issued once per day, the ensemble is composed of twenty-one members and provides 16-day forecasts. NSRPS differs from other hydrological forecasting systems in operational use in Canada by being continental in scope and by relying on an Earth System Modelling (ESM) approach for prediction.

In order to assess the value of forecasts issued by NSRPS, a comparison is performed with a similar ESP system available over all of Canada: the Global Flood Awareness System (GloFAS) from the European Centre for Medium-Range Weather Forecasts (ECMWF). In addition, NSRPS ESPs are compared against two main references: an ensemble climatological reference, and a deterministic persistence reference.

The comparison of NSRPS ESPs against these three references is focused on the Great Lakes and St. Lawrence watershed as well as on the Nelson and Churchill watersheds (total area of about 2.5 million km^2), but altogether they cover a wide variety of different geomorphological conditions that can be encountered in Canada. Moreover, the evaluation is limited to the Spring, Summer and Fall of 2022. These spatial extent and temporal period limitations are due to NSRPS ESPs' availability at the time of the evaluation. The evaluation graphics shown here consist of the recent evaluation standards defined for the NSRPS ESPs, which will be used to assess the benefit of future system upgrades.

For most stations, NSRPS performs better than GloFAS in terms of Continuous Ranked Probability Score (CRPS), but the median of the potential CRPS across the 393 common stations selected is very similar for days 3-16. Both systems suffer from a lack of spread, particularly for short lead times.
NSRPS is generally better than the climatological reference roughly up to the 6-day horizon, but this threshold shows a high variability depending on the domain, season, or score considered. When comparing against persistence, we found that the ensemble mean of NSRPS was generally better than it in terms of dynamics starting from the 6-day horizon, but this threshold is actually directly related to the size of the basin considered. Finally, looking at score maps allowed to highlight some of the most problematic areas/periods for NSRPS (mainly in terms of bias). A link has been established between these NSRPS problematic areas/periods and a lack of different physical processes' representation, or with issues related to data assimilation. Some of the major upcoming NSRPS improvements that will help overcome some of the main issues identified during this evaluation will be mentioned as well.

Keywords: *Continental-scale hydrologic forecasts, ensemble streamflow predictions, earth-system modelling, ensemble verification, probabilistic evaluation, system comparison.*

EFFICIENT AND PRECISE FLOOD INUNDATION PREDICTIONS USING THE LSG MODEL

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Abstract: Floods are one of the most frequent and devastating natural disasters for human communities. Traditionally, hydrodynamic models are used to predict flood inundation. However, the computational demand of running these models scales with their resolution and complexity. This means accurate high-resolution (i.e. high-fidelity) models cannot easily be deployed usefully for real-time flood inundation forecasting over large domains or for situations where models need to be run repeatedly (e.g. statistical analysis in design and planning).

We introduce a new modelling approach that supercharges hydrodynamic models for speed while maintaining high accuracy. We found that spatial-temporal patterns of flood inundation simulated using an extremely simplified (and hence super-fast) hydrodynamic (i.e. low-fidelity) model can be mathematically transformed to reproduce similar results as a high-fidelity model. The mathematical transformation consists of first using Empirical Orthogonal Function (EOF) analysis to reduce the dimensionality of the low-fidelity data to just a few key features, and secondly, using pre-trained Sparse Gaussian Process models to convert the low-fidelity feature to high-fidelity features. We call this new modelling approach the hybrid Low-fidelity, Spatial analysis, and Gaussian Process Learning (LSG) model (Fraehr et al., 2022, 2023). By basing the predictions on a low-fidelity model, the LSG model can incorporate spatial-temporal correlations and simulate the entire dynamic evolution of the flood inundation.

The LSG model demonstrates a significant reduction in computational demand, predicting flood inundation more than three orders of magnitude faster than a conventional high-fidelity model while maintaining high accuracy. The LSG model can evaluate flood risk accurately, rapidly, and repeatedly as events unfold, a capability that has the potential to greatly assist active decision-making during flood emergencies to save lives and protect assets.

Keywords: *Flood inundation; hydrodynamic models; surface water; hydraulics; modelling*

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AN EVALUATION OF SUBSEASONAL HYDROMETEOROLOGICAL ENSEMBLE FORECASTS AT DIFFERENT TIME SCALES

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Abstract: Due to the chaotic nature of the atmosphere, it is challenging to obtain skilful daily precipitation forecast at lead times beyond 14 days. However, cumulative precipitation forecasts over a period (such as cumulative precipitation of lead 1-30 days) can still be skilful. Therefore, we evaluated cumulative subseasonal precipitation forecasts over different temporal scales (including scales of 1-1 day, 1-2 days, …, 1-7 days, …,1-30 days) over China. The results show that the correlation coefficients between 1-7 day cumulative precipitation forecasts and corresponding observations reach a peak of 0.7~0.8. The correlation coefficients between 1-30 day cumulative precipitation forecasts and corresponding observations can still be larger than 0.4 in several hydroclimatic regions in China, which indicates skilful cumulative precipitation forecasts in those regions.

Moreover, we also investigated if the skill in cumulative precipitation forecasts can transfer to skilful cumulative streamflow forecasts. We post-processed ECMWF subseasonal precipitation forecasts by Bayesian joint probability model, and used post-processed precipitation forecasts as inputs to hydrological model and generated hydrological ensemble forecasts in several basins in China. Preliminary results show that although daily streamflow forecasts are not skilful after about 10 days, cumulative streamflow forecasts over 1-21 day can still be skilful in terms of CRPSS relative to climatology.

Keywords: *Subseasonal forecast, streamflow forecast, precipitation forecasts*

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ENHANCING SUB-SEASONAL HYDROLOGICAL DROUGHT PREDICTIONS IN THE EUROPEAN ALPINE SPACE USING EFAS FORECASTS

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Abstract: In recent years, the European Alpine space has witnessed unprecedented low-flow conditions and drought events. Given the heavy reliance of various economic sectors on sufficient water availability, including hydropower production, navigation and transportation, agriculture, and tourism, early warnings tailored to local low-flow conditions are crucial for decision-makers.

The European Flood Awareness System (EFAS) has been instrumental in providing flood risk assessments across Europe with up to 15 days of lead time since 2012. Expanding its capabilities, EFAS started generating long-range hydrological outlooks for sub-seasonal to seasonal horizons. Despite its original design for floods, previous investigations have revealed EFAS's potential for simulating low-flow events. Building upon this finding, this study aims to leverage EFAS's enhanced anticipation capability to improve the predictability of drought events, specifically in Alpine catchments, while providing support to trans-national operational services.

This research investigates the integration of the 46-day sub-seasonal EFAS forecasts into a hybrid forecasting system. Our case study encompasses 139 catchments in the European Alpine space. To improve the accuracy of low-flow predictions and understand their spatio-temporal evolution, we employ the Temporal Fusion Transformer (TFT), a machine learning algorithm. Additionally, we incorporate various features such as European weather regime forecasts, streamflow climatology, hydropower proxies, and spatial relationships among forecast stations.

Our evaluation focuses on assessing the onset and magnitude of the predicted drought events. We also measure the reliability of ensemble forecasts using metrics like the Continuous Ranked Probability Skill Score (CRPSS). Our first results from evaluating EFAS simulations for low flow conditions show that EFAS tends to simulate streamflows with shorter durations for continuous time steps below low flow thresholds. As a result, there are indications of lower drought severity compared to the results obtained from local model simulations, particularly during dry years such as 2003 and 2018. Further results on sub-seasonal forecasts will be shown and discussed. Through this study, we aim to shed light on the application of EFAS forecasts in sub-seasonal hydrological drought predictions and in particularly challenging geographical locations such as the Alpine region. Our findings will contribute to evaluating the potential of these forecasts for providing valuable information for skilful early warnings. Furthermore, this research will aid to inform regional and local water resource management efforts in their decision-making.

Keywords: *EFAS, sub-seasonal, hybrid forecasting, drought prediction, European Alpine space, Temporal Fusion Transformer, early warnings*

MAKING BETTER FORECASTS: DEVELOPING AND APPLYING ADVANCES IN STATISTICAL STREAMFLOW FORECASTING TECHNIQUES ACROSS SCALES

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Abstract: This presentation brings together recent and ongoing work to develop and apply novel statistical techniques in sub-seasonal to seasonal, and seasonal to decadal, forecasting both in the UK and internationally. Data assimilation techniques, namely Particle and Ensemble Kalman filtering, have been appraised for streamflow forecasting in the UK showing improvements over short lead times, whilst bias correction improves forecast skill over longer lead times (Tanguy *et al.,* in prep). Work is underway applying the JEDI (Joint Effort for Data assimilation Integration, Trémolet and Aulighé, 2020) framework to explore the benefits of data assimilation further, for both soil moisture and streamflow forecasting both with the GR6J model (Pushpalatha *et al.,* 2011), and the UniFHy modelling framework (Hallouin *et al.,* 2022) to unite streamflow, soil moisture and groundwater forecasts as part of the HydroJULES project. Bias correction and model blending techniques have also been explored globally within the UK NC-International programme using the ULYSSES multi-model global seasonal forecasts (Copernicus Climate Change Services). Weighting each model according to its Kling-Gupta Efficiency (KGE) score improves the forecast over a basic ensemble average, including over ungauged basins, and bias correction further improves the results (Chevuturi *et al.,* 2023). These data assimilation, bias correction and model blending techniques are now being considered for implementation in the operational UK Hydrological Outlooks and are likely to form the basis of international recommendations for the integration and improvement of individual forecasting systems contributing to the global Hydrological Status and Outlooks System (HydroSOS).

UK hydro-climatology is heavily influenced by atmospheric circulation patterns, the principal of which is the North Atlantic Oscillation (NAO). Both the UKSCaPE and CANARI projects are exploring the potential improvements in hydrological forecasting that can be achieved through the better understanding and statistical quantification of the NAO and other key atmospheric and oceanic drivers in the Arctic-North Atlantic region. The relative importance of including climatic processes in UK hydrological forecasts over the skill provided from hydrological memory is being assessed. For example, ensembles of historical weather analogues corresponding to the distribution of seasonal NAO forecast conditions (Stringer, *et al.,* 2020) have been applied to the UK Hydrological Outlooks system and have been tested in winter, with further work underway to assess the skill over other seasons. This wealth of statistical and technical advances used in isolation or combination, depending on the known benefits in space and time, have the potential to greatly improve skill in sub-seasonal to decadal hydrological forecasting.

Keywords: *Data assimilation, model blending, bias correction, North Atlantic Oscillation*

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DELIVERING BETTER FORECASTS: CO-DEVELOPING HYDROLOGICAL STATUS AND OUTLOOKS SYSTEMS FOR INCREASED WATER SECURITY

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Abstract: This presentation brings together recent and ongoing work to co-develop and deliver hydrological status information and sub-seasonal to seasonal hydrological forecasts both in the UK and globally. Successful stakeholder engagement and collaboration is critical in translating data for decision making and ensuring the uptake of services in operational practice. The Hydro-JULES programme is implementing a wider UK National Capability engagement strategy (UKRI, 2022), investing in co-development and multi-stakeholder engagement to ensure the maximum uptake of the scientific and technical innovations it produces. A dedicated "applications" task, with a sub-task focussed on forecasting, is collating scientific tools and advances, and testing them in the UK Hydrological Outlooks operational forecasting system. Continual engagement work across the Hydro-JULES programme will enable access to appropriate, and useful outputs for water resources managers, tailored to their needs.

The global scale WMO Hydrological Status and Outlook System (HydroSOS) initiative (Jenkins *et al.,* 2020) is being co-developed with National Hydrometeorological Services and river basin authorities, among others, to unite hydrological status and outlooks systems coherently across scales. Existing local, regional and global hydrological status and outlooks systems have all been developed independently and use different metrics and modes of conveying the information. HydroSOS is co-creating standards and guidelines for the consistent quantification and presentation of hydrological information across scales, thus enabling a locally informed, global picture of hydrological risk and water resource availability. Furthermore, HydroSOS is working with stakeholders to co-develop status and outlooks systems where they are not currently available, thus increasing local capacities and resilience to water-related hazards.

Here we highlight some of the successful engagement activities that have been conducted as part of the HydroJULES and HydroSOS initiatives and showcase the progress in the co-development of online Hydrological Status and Outlooks tools under these national and international programmes.

Keywords: *Hydroclimate services, status and outlooks systems, decision-making, stakeholder engagement, international collaboration*

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ENHANCING TROPICAL CYCLONE RAINFALL FORECASTS FOR ANTICIPATORY HUMANITARIAN ACTION USING MACHINE LEARNING

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Abstract: Tropical Cyclones (TCs) pose a significant threat to vulnerable livelihoods and economies especially in coastal areas, due to multiple hazards including extreme rainfall and storm surge, which in turn lead to devastating riverine and coastal flooding. Currently, the effectiveness of sub-seasonal forecasts of TC precipitation to support decision-making and anticipatory actions is limited due to the lack of skill of numerical weather prediction models, particularly in predicting the severity and location of extreme rainfall with a sufficiently long lead time. To enhance the current levels of forecast skill, we introduce a post-processing methodology for precipitation forecasts that leverages a popular deep-learning algorithm (U-Net). Our Machine Learning (ML) model aims to reduce biases in TC precipitation forecasts and refine their spatial accuracy. To achieve this, we use a composite loss function, combining the Mean Absolute Error (MAE) and the Fractions Skill Score (FSS), to train the ML model. We demonstrate the potential of our ML-based approach by applying it initially to reanalysis data (ERA5) and subsequently to ensemble forecasts from ECMWF, with a lead time of up to 15 days. We evaluate the post-processing adjustments by considering action-relevant scores, such as False Alarm Ratios (FAR) and Hit Rates (HR). We further tailor the verification scores to the needs of humanitarians by incorporating in their definition an acceptable margin of spatial error based on target action scales. Our ML model's training and validation rely on a historical dataset of global TC precipitation events, using ECMWF re-forecasts over 20 years and a multi-source observational dataset (MSWEP) as reference. Our results show that the proposed approach can significantly improve the spatial accuracy of TC precipitation forecasts, leading to reduced false alarms and increased hit rates. Finally, we discuss the potential of our action-oriented forecast verification and post-processing approach to be applied operationally to improve real-time forecasts and better support anticipatory actions.

Keywords: *Tropical Cyclones, Rainfall Forecasts, Post-processing, Machine Learning, Action-oriented Verification*

EVALUATION OF A REAL-TIME REGIONAL ENSEMBLE FLOW FORECASTING SYSTEM IN CATALONIA OF A 2-YEAR TERM

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Abstract: Extreme floods are one of the most harmful and frequent natural hazards, especially in Mediterranean areas. To minimize the impact of flood events, a well-designed Flood Early Warning System (EWS) should be able to effectively provide timely and accurate forecasted flood information in specific river sections, which can be used to issue warnings to manage emergencies and support the response (Corral et al., 2019). The accuracy of the flow forecasts depends on the source of rainfall input (observed and forecasted), the rainfall-runoff model, the quality of the routing component, and lead time. The probabilistic forecast is an effective way to consider the inherent uncertainty in forecasts (Boelee et al., 2019; Palmer, 2017). Ensembles provide a general estimate of the uncertainty of forecasts and, in particular, the probability of the occurrence of extreme events (Merz et al., 2020). The assessment of the system's performance after a long-term application is fundamental.

This study presents an approach to evaluate the flow forecasts based on the multiple step-ahead method (WMO, 1992), where the quality of the forecasts is analyzed as a function of the lead time. For this purpose, the quality of the forecasts has been analysed on the most significant rainfall events for a period of 2 years. The forecasted flow has been compared with both (i) the observed flow information, and (ii) the simulated result (0-h lead time forecast).

This approach has been implemented within the real-time probabilistic flow forecasting system, running since June 2020 at regional level in Catalonia (NE Spain) and generating flow forecasts in all the gauging stations of the Catalan Water Agency. The precipitation forecasts used in the system are produced by the European Centre for Medium-range Weather Forecasts (ECMWF), which is composed of 52 members. The modified rainfall-runoff HBV model works in continuous mode using rainfall observations and precipitation forecasts to generate probabilistic flow forecasts.

The main objective of this work has been the long-term evaluation of the real-time probabilistic flow forecasts obtained between June 2020 and June 2023. During this period, 49 significant events have been identified, and the flow forecasts have been analysed in 41 gauging stations in 8 main catchments. The performance of the system has been evaluated using both deterministic and probabilistic scores presented as a function of lead time.

Keywords: *Ensemble Flow Forecasting, Performance Evaluation, Deterministic and Probabilistic Scores*

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JOINTLY VERIFYING AND EVALUATING SEASONAL FORECASTS FROM CLIMATE SERVICES: EXPERIENCE FROM THE H2020 CLARA PROJECT

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Abstract: Assessing the information provided by co-produced hydro-climate services is a timely challenge given the continuously evolving scientific knowledge and its increasing translation to address societal needs. We propose a cross-sectoral evaluation and verification framework to assess jointly service forecast quality and value, and lessons learnt from its implementation. This framework stems from the work carried out within the H2020 CLARA project whose aim was to produce hydro-climate services for a variety of sectors, based on the seasonal forecasts available through the Copernicus Climate Data Store, and that would be financially sustainable.

In this framework, the quality of the service forecasts is firstly assessed and their skill deduced from a comparison with various business-as-usual techniques. In parallel, an assessment of the value of the information embedded in the services for decision-making is performed against business-as-usual knowledge and a hypothetically perfect service. The framework follows a transdisciplinary (from data purveyors to service users) and interdisciplinary chain (climate, hydrology, economics, decision analysis). It is illustrated on six hydro-climate services responding to knowledge needs from the water resources management, agriculture, and energy production sectors.

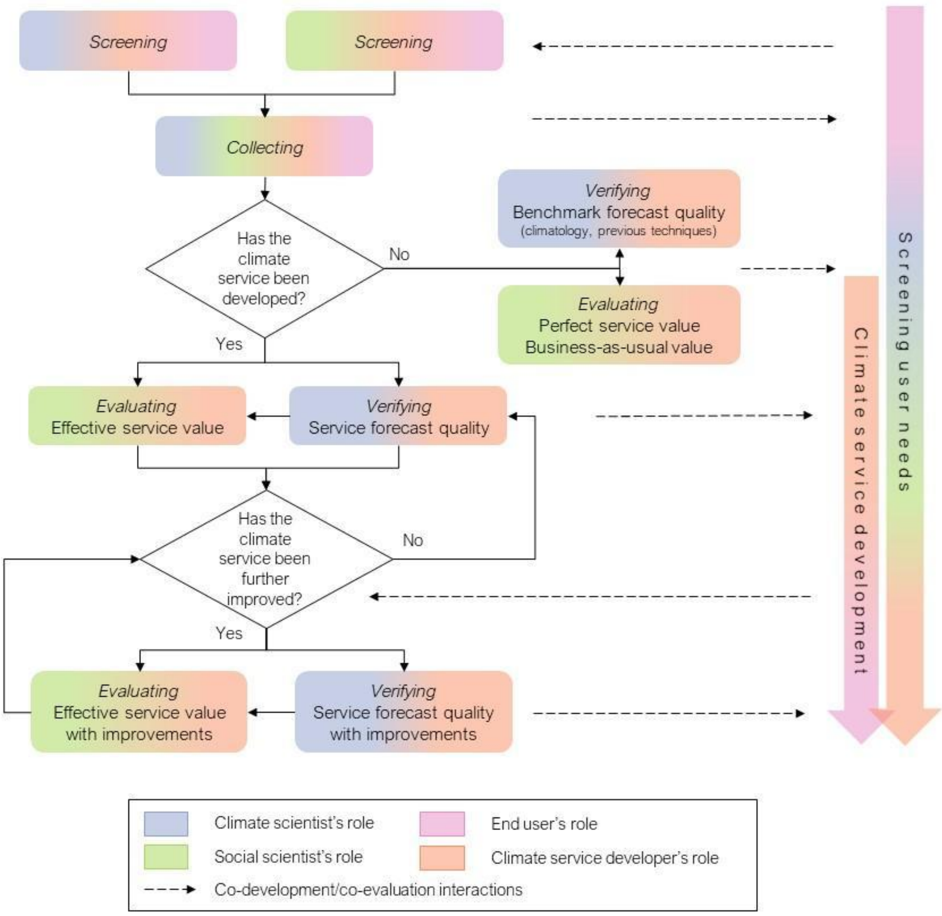

Figure 1. *Joint and continuous verification and evaluation framework for hydro-climate services*

This joint forecast verification and service evaluation exercise highlights various qualities, skills and values across physical variables, services and sectors. The diagnostics provided by the joint assessment improve on individual quality and skill assessment by bringing forth more dimensions and an in-depth analysis of the sources of service value. Service co-production should thus consider simultaneously and iteratively the quality of the hydro-climate information provided and its value for decision-making to inform robust enhancement strategies. Such effort, however, requires prolonged collaborations between social and climate scientists, service developers and service users, beyond the lifespan of common research projects and for building communities that allow such long-term collaborations (as HEPEX could very well be).

Keywords: *Climate services, verification, evaluation, co-development, co-evaluation*

SUB-SEASONAL FORECASTING OF SHALLOW GROUNDWATER LEVELS IN SWITZERLAND

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Abstract: Groundwater level monitoring is vital for water resource managers to obtain information about the current state of the groundwater system and to make informed decisions. Particularly during and after periods of drought, groundwater abstractions can further amplify groundwater level declines. This can affect drinking water supplies and reduce base-flow rates to rivers maintaining aquatic ecosystems. As climate change is expected to increase the frequency and intensity of hydrological extremes, severe drought events become more likely, potentially increasing the gap between groundwater demand and supply. Recent severe and prolonged drought events over Europe have shown that even relatively water rich countries like Switzerland are prone to drought events. An early warning system of a potential groundwater drought could help water managers make informed decisions in advance to counteract the effects of drought or prepare for its potential consequences.

In this ongoing study we investigate the use of sub-seasonal range meteorological forecasts to predict groundwater levels in alluvial shallow aquifers across Switzerland. Groundwater levels at ten monitoring wells covering the country with varying groundwater dynamics are modelled using lumped parameter groundwater models from the Pastas software (Collenteur et al., 2019). Because the residual errors are strongly correlated, these are modelled using an AR1 noise model. Daily precipitation, potential evaporation, and temperature obtained from MeteoSwiss are used as model inputs. We demonstrate that the groundwater levels at these locations could be predicted with high accuracy using this combination of models and historical data. These calibrated models are subsequently used in forecasting mode using ensembles of meteorological forecasts obtained from MeteoSwiss with a 31-day lead time. The forecast skill is evaluated using weekly re-forecasts over the period 2012-2022.

Preliminary results indicate that the forecast skill for small lead times primarily depends on the memory of the groundwater system. For larger lead times the skill is more determined by the meteorological forecasts. This result is expected because there is a lag of a few days to weeks between infiltration events and groundwater level responses, depending on the characteristic memory time of the groundwater system. Because groundwater systems are typically long memory systems and errors persist through time, there is a need to model the residual errors and correct the forecasts using this information. We present the setup for the groundwater level forecasting system and the results of the forecast evaluation. The relationship between groundwater system memory time and forecast skill is discussed as well. In a later stage of the project, we plan to make groundwater level forecasts available to the public through the Swiss drought information platform (drought.ch, Zappa et al, 2014).

Keywords: *Groundwater, forecasting, pastas, malefix*

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A REPRODUCIBLE DATA-DRIVEN WORKFLOW FOR PROBABILISTIC SEASONAL STREAMFLOW FORECASTING OVER NORTH AMERICA

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Abstract: Seasonal streamflow forecasts are critical for many different sectors - e.g., water supply management, hydropower generation, and irrigation scheduling. Initial hydrological conditions (e.g., snow water content and soil moisture) are an important source of hydrological predictability on seasonal timescales. Snowmelt is the main source of runoff generation in high-latitude and/or high-altitude headwaters basins across North America, and the basins downstream. As a result, data-driven forecasting that is based primarily on snow observations is a well-established approach for operational seasonal streamflow forecasting in these basins.

The aim of this work is to establish a benchmark of the predictability of streamflow based on snow information over seasonal timescales across North America. To this end, we developed a reproducible data-driven workflow and implemented it for a large sample of basins with a nival (i.e., snowmelt-driven) regime across North America. The workflow uses snow water equivalent (SWE) measurements as predictor data and streamflow observations as predictand data for the period 1979-2021. SWE measurements are from the Canadian historical Snow Water Equivalent dataset (CanSWE; Vionnet et al., 2021), the Natural Resources Conservation Service (NRCS) manual snow surveys, and the SNOTEL automatic snow pillows in the USA. Streamflow observations are from the National Water Data Archive, HYDAT, in Canada and from the United States Geological Survey (USGS) in the USA. The SWE datasets are gap filled using quantile mapping based on neighboring SWE and precipitation stations (from the Serially Complete precipitation and temperature Dataset for North America, SCDNA; Tang et al., 2020). Principal Component Analysis is then used to define a small set of independent predictor components. These principal components are used as predictors in a regression model to generate ensemble hindcasts of streamflow volumes for basins across North America.

We employ a user-oriented evaluation approach to examine the performance of probabilistic hindcasts generated for 75 nival basins with limited regulation across North America (the basin areas span a wide range, varying from 9 to 273,500 km^2). Our analysis yields valuable insights aimed at streamflow forecasters, snow surveyors, decision-makers, and workflow developers. The forecasting workflow comprises a collection of Jupyter Notebooks that are shared on GitHub alongside the publication of the research outcomes to facilitate applications in other cold regions and/or the advancement of methods. We will do a live demonstration of the workflow to showcase its practical implementation.

This work is a contribution of the Global Water Futures (GWF) and the Cooperative Institute for Research to Operations in Hydrology (CIROH) programs.

Keywords: *Reproducible workflow, data-driven, ensemble streamflow forecasting, seasonal, North America, snowmelt-driven regime*

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AVAILABILITY OF SOLAR, WIND AND HYDROPOWER ACROSS EUROPE

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Abstract: One approach for forecasting the availability of renewable energy sources focuses on their long-term statistical behaviour as part of the hydro-climatic system. While such statistical information neglects the nearest future, it provides a basis for both management and design of renewable energy production, including appropriate shares of renewable energy sources as well as spatial distribution of power plant locations. This study has used a 35-year historical record of daily climatic data covering the European continent to reveal the spatio-temporal characteristics in renewable energy sources, in particular their covariation distributed on the spectrum periods from days to decades. We find that one of the best options provided a minimum of variation in the energy availability is based on 2:4:1 shares of solar, wind and hydropower and that spatio-temporal management should consider coordination distances longer than 1,200 km to gain from the continental climate conditions. Spatiotemporal management of the electricity production under such conditions induces a Virtual Energy Storage Gain that is several times larger than the energy storage capacity available in European hydropower reservoirs.

Keywords: *Solar, wind and hydropower, renewable electricity production, renewable energy complementarity, spatio-temporal management of renewable energies*

References:

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REGIONAL SCALE FORECASTING FOR SURFACE WATER FLOODS

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Abstract: Forecasting the location, timing and severity of surface water flooding is notoriously difficult. The provision of national level guidance for surface water flooding is well established in the UK, the Flood Guidance Statement provides information for first responders with up to four days lead time alongside public facing National Severe Weather Warnings. At nowcasting lead times (less than 6 hours) some responsible organisations are starting to develop bespoke solutions based on radar and are increasingly turning to street level information. Between these scales there remains an operational need for enhanced regional forecasts to support proactive response to flood events. Such provision needs to balance the uncertainty in rainfall forecasts with information at the spatial scale and lead time required by responders.

In response to this need the iCASP project developed FOREWARNS (**F**lood f**ORE**casts for Surface **WA**ter at a **R**egio**N**al **S**cale). FOREWARNS compares reasonable worst-case rainfall from a neighbourhood-processed, convection-permitting ensemble forecast system against pre-simulated flood scenarios, issuing a categorical forecast of surface water flooding severity at the scale of UK river catchments. The skill and usefulness of the forecasts was evidenced through objective verification comparing FOREWARNS to rainfall and impact records over the period 2013-2022, and in a workshop with users exploring past case studies (an example is shown in Figure 1). Results indicate that FOREWARNS provides useful information to complement the existing national scale guidance, but there remain questions for future development. Particular challenges are consistency between forecast runs and different forecast products, and determining the most appropriate lead time for communicating regional scale information.

During summer 2023 FOREWARNS will be further evaluated alongside the Met Office and Flood Forecasting Centre current operational models as part of a Met Office testbed. Initial results will be presented from the testbed and reflections offered on the potential for regional scale surface water flood forecasts to improve the current forecast provision.

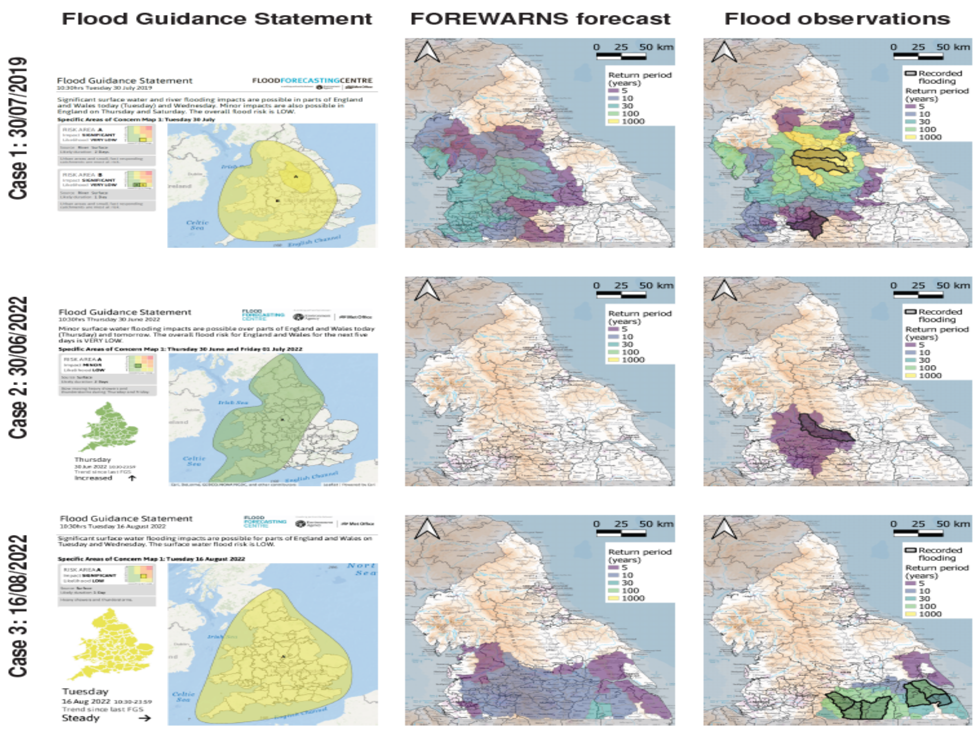

Figure 1. *Comparison of National Flood Guidance Statement issued by the Flood Forecasting Centre*

(yellow shading represents areas at LOW risk of surface water flooding), FOREWARNS forecast (shading represents expected return period of surface water flooding) and radar SWF proxy observations (shading) and catchment-level locations of recorded floods (bold borders and stippling) for one case study event on 16th August 2022 (Source: Maybe et al., 2023)

Keywords: *surface water flooding, regional scale, forecast skill, users*

References:

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TRENDS AND UNCERTAINTY IN LONG INFLOW PREDICTIONS FOR HYDROPOWER MANAGEMENT

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Abstract: Hydro Tasmania, Australia's largest hydropower generator and water manager, relies on 20+ year inflows scenarios to assess the long-range sustainability of their power generation system. Many methods are available for stochastic data generation, but they often assume a stationary climate. In locations where inflow data have long-term trends, assuming a stationary climate in stochastic data is likely to underestimate future wet or dry extremes, in particular for sequences of dry or wet months or years. Assuming a non-stationary climate moves the generation of stochastic scenarios closer to the realm of forecasting: using initial conditions (in this case trend) to predict the future.

To address these issues, we have developed the Trend and Uncertainty in Long Inflow Predictions (TULIP) model. TULIP is a Bayesian model that generates long-range predictions of inflows at the monthly time step. TULIP accounts for:

1. Heteroscedasticity and skew in inflow data by using data transformation with the sinh-arcsinh transformation, and zero values with censoring
2. Spatial correlation between inflow sites
3. Autocorrelation using a first-order autoregressive model
4. Linear trend in inflow, by inducing trends into the Fourier coefficients
5. Seasonal variation in properties (1)-(4), using Fourier series to control the parameters

TULIP is being implemented operationally by Hydro Tasmania to replace its existing method of generating stochastic scenarios, which assumes a stationary climate. At sites with long-term trends in historical inflow, we show that TULIP produces more reliable long-range predictions than is possible if a stationary climate is assumed (Fig 1). This allows TULIP to produce more realistic projections of future drought, allowing Hydro Tasmania to better plan for the long-range sustainability of its system. In this presentation we describe the TULIP model and its performance.

A crucial assumption of predictions of TULIP is that current trends – defined by a fixed period of inflow – are indicative of future trends. We discuss how this assumption may be problematic and describe plans to incorporate projections from climate models into TULIP. This will bridge the gap between historical trends and long-range future trends.

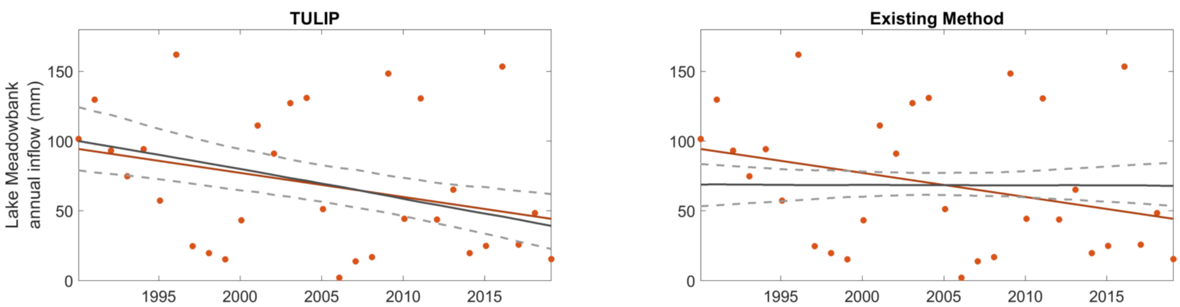

Figure 1. *Representation of trends in inflows to Lake Meadowbank by TULIP (left) and the existing Hydro Tasmania method for generating stochastic series (right). Red points and trend lines show observations; black trends and confidence intervals show modelled trends.*

Keywords: *Bayesian inference, uncertainty, long-range prediction, hydropower*

TRENDED CLIMATOLOGY FOR SEASONAL STREAMFLOW FORECASTS

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Abstract: The influence of predictor variables diminishes over time, and thus, *climatology forecasts* emerge as reasonable predictions of future events based on historical observations alone. Climatology forecasts assume historical observations are random samples from a *stationary probability distribution*, and future events will likewise be samples from that distribution. Production of climatology forecasts is well established, and they are often sufficient to reproduce primary temporal patterns (such as daily or seasonal fluctuations) along with uncertainty estimates for those forecasts. Climatology forecasts are integral to many decision-making processes, especially for relatively long-term planning beyond the horizon of forecast skill, and as a baseline in forecast evaluation (Fortin et al., 2014).

Seasonal streamflow forecasts are important for waterway and reservoir management, predicting water availability, and understanding drought and flood risks. Lead times for seasonal streamflow forecasts are typically 1 to 6 months. Seasonal streamflow forecast skill typically drops off rapidly with lead time as predictor variables such as antecedent catchment conditions, climate indices, or climate forecasts have less influence, or carry greater uncertainty (Schepen et al., 2016).

Long-term (decades) trends have been observed in streamflow records across the globe (e.g., Marhaento et al., 2021; Yeh et al., 2015). These trends have often been attributed to climate change, correlating to observed changes in precipitation and evaporation (Amirthanathan et al., 2023). The presence of trends in predictor variables (e.g., precipitation) may allow the observed trends to be appropriately reproduced in short-lead forecasts. However, for long lead times, climatology forecasts, which assume a stationary probability distribution, may lead to predictable forecast bias (positive in the case of a declining trend) and excessive spread.

Here, we forecast a non-stationary probabilistic climatology using a long and high-quality streamflow dataset with stations across Australia. Our selected method considers the uncertainty in the trend as well as the spread in de-trended space. We use a sliding window strategy to ensure suitability of the method for real-world application and evaluate forecasts against standard stationary probabilistic climatology.

The non-stationary probabilistic climatology can provide similar accuracy to traditional forecasts, with a CRPS skill score of over 20% obtained for 10% of site-months. Caution is required in application, however, as positive skill was only achieved for approximately half the site-months, and the average skill was just 3%. Clear spatial clustering of positive skill was observed in inland Victoria, where significant observed trends have been observed. Results similarly varied by month. In May positive skill was observed in over 75% of sites with an overall average of 14% skill, and skill scores exceeded 25% at 23% of sites.

Keywords: *Seasonal streamflow, long-lead, trend, HRS*

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LONG RANGE IMPACT-BASED FORECASTS FOR AGRICULTURAL DROUGHT EARLY WARNING IN AUSTRALIA

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Abstract: Early warning of drought is critical for national water security, farm business outcomes and government planning. The Drought Early Warning System (DEWS) project is developing indicators to measure and forecast the extent and severity of drought impacts in the Australian agricultural sector with a focus on accessing economic risks. Through a multi-disciplinary approach, long-range climate forecasts are combined with biophysical and agro-economic models to generate impact-based drought indicators, translating climate data into specific impacts such as crop yields, pasture growth and farm profits.

In this work, we develop a high-resolution spatial forecasting system to generate forecasts of rainfall, temperature, solar radiation, vapour pressure and evaporation on a 5km grid across Australia, at a daily time step out to 18 months ahead. Forecasts are derived from the Bureau of Meteorology's ACCESS-S2 climate model. Forecast calibration and downscaling are implemented using Bayesian joint probability modelling and an empirical disaggregation approach, which seamlessly extends forecasts beyond the 7-month range of the climate model. The ensemble forecasts are targeted at multiple observational datasets to drive a suite of models including APSIM, Grassgro, AussieGRASS and farmpredict.

The climate inputs are fed into the suite of DEWS models, the outputs of which become indicators that will be presented as percentiles for a defined historical reference period. The definition of an appropriate reference period is a challenging problem given significant changes in both temperature and rainfall patterns across Australia over the last century and decadal scale climate variability. Assuming recent farm practices are adapting to climate trends, the recent 30-40 year period is adopted as the baseline, a period which also corresponds to historical ABARES farm survey data. To maximise the interpretability of the products, key users have been engaged in a co-design process.

The DEWS software platform has been developed as a real-time forecasting system hosted within Senaps, a cloud-based scientific workflow orchestration platform and secure data service. The drought indicator products are being prototyped and will be published online via the Climate Services for Agriculture (CSA) platform, which is currently under development. We discuss the potential impacts of the forecasting system and the ongoing work to rigorously validate the forecasts.

Keywords: *Early Warning, Drought, Impacts, Hydro-climate, Post-Processing, Downscaling, Verification, Risk*

COMMUNICATING PROBABILISTIC FLOOD FORECASTS MAPS TO DIFFERENT USER GROUPS

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Abstract: Following exceptional flood events in spring 2017 and 2019, the provincial government of Quebec (Canada) launched a long-term program called INFO-Crue. This program aimed at 1) improving the delineation of flood risk zones and 2) improving several components of their operational flood forecasting system. Among the desired improvements was the addition of probabilistic flood forecast maps to complement the already existing ensemble streamflow forecasts, covering 28 000 river reaches. Probabilistic flood forecasts maps are an emerging product. They provide citizens and decision-makers with water depth and extent, which might convey more tangible flood information for some people compared to streamflow values. Water depths and extent can also be used more directly than streamflow as part of an impact-based forecasting set-up. While the notion of forecast uncertainty is well accepted by most decision-makers, it also has the potential to be overwhelming and confusing. Therefore, visualising probabilistic flood forecast maps and communicating the information to the general public and to decision-makers poses multiple challenges. In this presentation we will synthesise the results from a large-scale qualitative study aiming at understanding end-users needs and preferences concerning flood forecasts in general, and probabilistic flood forecast maps in particular. This study involved long interviews with participants, which included 28 government representatives, 52 municipalities, 9 organisations, as well as 37 citizens and farmers. The participants were asked a variety of open questions regarding their needs and preferences as well as their decision-making mechanisms. One key element of the interviews was the presentation of four alternative visualisation prototypes for probabilistic forecasts of flood depth and extent. The participants were asked to compare those prototypes, to express their preferences in terms of colour maps, wording and the representation of uncertainty. They also provided useful comments on potential modifications to those prototypes and sometimes suggested ideas for entirely new prototypes. Most participants, regardless of their role or background, had the same overall preference in terms of the proposed prototypes, with prototype number 2 the overall favorite (see Figure 1 below). Nevertheless, we also found several specificities among the respective preferences of different user groups. Our results also highlight issues related to the understanding of probabilities in the context of flood forecast maps. The results of this research are currently being used to inform the design of the new forecast communication and visualisation platform in the province of Quebec, Canada.

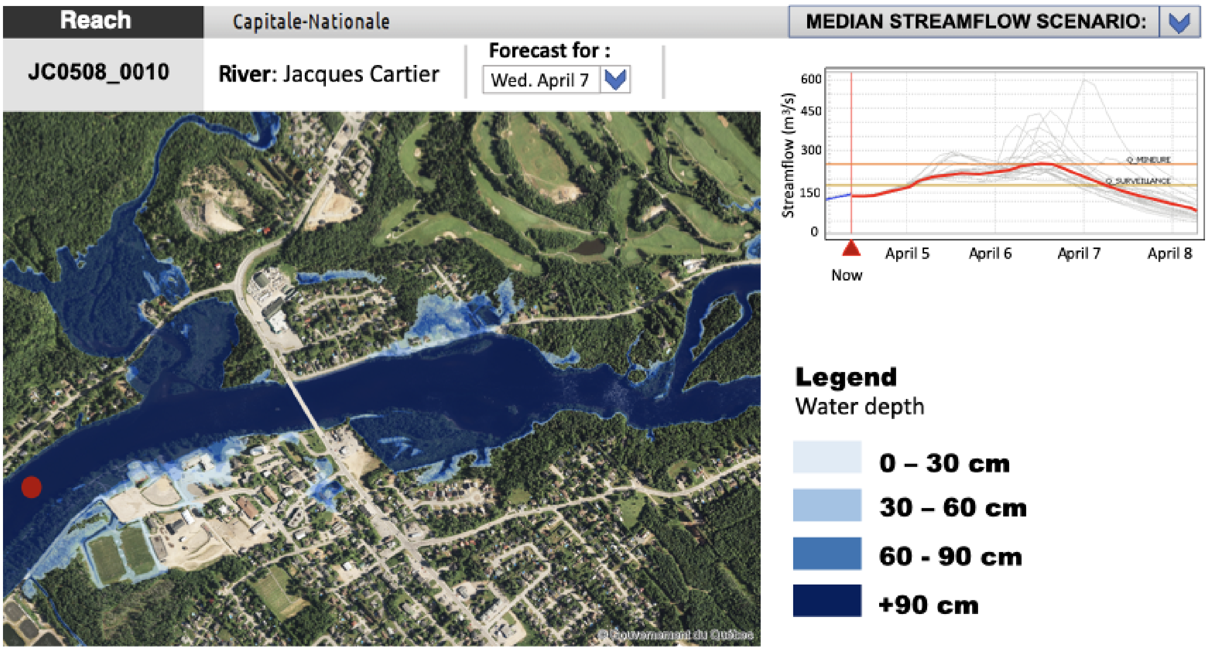

Figure 1. Prototype number 2 for the visualisation of probabilistic flood maps

Keywords: *Forecast communication, forecast visualisation, flood forecast maps, decision-making under uncertainty*

HYDRO TASMANIA'S SHORT- TO LONG-RANGE ENSEMBLE INFLOWS PREDICTION (SLEIP) SYSTEM

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Abstract: Despite the potential benefits of hybrid statistical-dynamical ensemble forecasting systems, they are rarely used to inform hydropower operations. Here we describe a new operational system run by Australia's largest hydropower generator, Hydro Tasmania, to inform hydropower operations and manage flood risk. The system produces forecasts at two timescales: 1) forecasts at the hourly time step to lead times of 10 days (short-range); 2) forecasts at the daily time step to lead times of 3 months (outlooks). Forecasts are generated by calibrating ensemble precipitation forecasts from Numerical Weather Prediction (NWP) or Coupled Climate Prediction (CCP) models with Bayesian joint probability models. Calibrated precipitation forecasts are then used to force initialised semi-distributed hydrological models. Uncertainty in hydrological modelling is quantified with staged error models. In some catchments, forecasts are used to force infrastructure models.

The performance of the system is assessed with retrospective forecasts. We show that ensemble predictions at the hourly time step outperformed Hydro Tasmania's existing deterministic forecasting system to lead times of 7 days (the maximum lead time of the deterministic forecasts). Hydro Tasmania has not previously produced longer range outlooks, and accordingly we benchmark these against climatology forecasts. We show that the outlooks can be skillful for the first month in spring and revert to climatology forecasts at other times of year. The operational forecasts are generated through a combination of Deltares' Flood Early Warning System (FEWS) software and custom software that encodes the statistical and hydrological models.

Keywords: *Hybrid prediction systems, hydropower, operational forecasting*

BASIS FOR A FLOOD WARNING SYSTEM IN A FAST-FLOW MEDITERRANEAN CATCHMENT

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Abstract: The operation of hydropower systems relies on the hydraulic conditions of the water system. Their management is usually carried out based on certain operation rules (e.g., turbine minimum and maximum discharge) and environmental flows requirements. This complex process is even more complex in multipurpose dams, which must guarantee an equilibrium between an optimum storage for production and the capacity needed for flood abatement, among others. In addition to this complexity, in semiarid areas the high recurrence of torrential precipitation-runoff events mean quick decisions need to be taken to prevent the associated damages. All these facts are translated into a huge range of possibilities that makes the optimization of decision-making processes difficult. On the one hand, several meteorological forecasting systems at different spatiotemporal scales are currently available, however, the high uncertainty linked to the rapid response time of these catchments limits their use. On the other hand, the insufficient number of real time monitoring networks (e.g. precipitation gauges and water level controls) challenges the creation of early warning systems with appropriate uncertainty quantification.

This study proposes the basis for the definition of an early warning system based on a limited number of real time in situ measurements in a Mediterranean catchment. The Cala dam (59 hm^3), located in the Rivera de Cala River, was chosen as pilot area. The Cala dam is mainly used for hydroelectric production, but also for irrigation and leisure activities. Their upstream catchment (535 km^2) is characterized by agroforestry uses and a quick response to intense precipitation due to steep slopes, shallow soils and groundwater redistribution. In situ historical information from stations with available real time data in the watershed is used to: (a) define driver indicators of key streamflow states (e.g., a threshold in the cumulative precipitation since the beginning of the hydrological year or precipitation intensity over certain months); and (b) characterize and cluster precipitation-runoff events over the catchment.

Two indicators were chosen: the water volume stored in the reservoir and the estimated probability of occurrence of a discharge event in the next hour based on antecedents' precipitation. This information was translated into a decision tree using a conditional structure that constitutes the basis of the designed early warning system. This simple scheme, which follows the operational rules of the reservoir, allows to identify the potential occurrence of a warning situation. The approach was validated based on historical information within a hindcast process during an evaluation period. This methodological approach could be easily transferable into other Mediterranean catchments with similar characteristics.

Keywords: *Mediterranean catchments, early warning, decision tree*

ENHANCING NMME PRECIPITATION FORECAST ACCURACY USING SM2RAIN-CLIMATE: A CASE STUDY OVER EUROPE

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Abstract: Precipitation forecasting plays a crucial role in various applications, such as water resource management and agricultural planning. Accurate predictions of precipitation forecasts enable decision-makers to implement effective strategies for water allocation and conservation. The North American multi-model ensemble (NMME) [1] provides valuable ensemble forecasts for precipitation, aiding in improved decision-making processes. However, the NMME forecasts often suffer from systematic biases, which can hinder their reliability and practical utility. Therefore, bias correction techniques are necessary to enhance the accuracy and usability of the NMME forecasts.

This study focuses on the application of the Random Forest method to bias correction of NMME precipitation forecasts using a newly developed precipitation product called SM2RAIN-Climate as a reference baseline. SM2RAIN-Climate stands out as a unique global dataset that estimates rainfall based on satellite soil moisture observations. For this purpose, seven individual NMME models, including CanCM4i, COLA-RSMAS-CCSM4, NCEP-CFSv2, GFDL-CM2p1-aer04, GFDL-CM2p5-FLOR-A06, GFDL-CM2p5-FLOR-B01, and NASA-GEOSS2S, were employed across all months and at 0.5–3.5 months lead times over Europe, covering the period from 1998 to 2020. The assessment analysis results indicate an enhancement in the overall average Pearson's correlation coefficient, with an improvement of 0.15. Additionally, a considerable reduction in the root mean square error (RMSE) of 8.1 mm (25.8%) was observed. This study demonstrates the potential of using SM2RAIN-Climate as a valuable tool for bias correction of NMME precipitation forecasts.

Keywords: *Precipitation, NMME, SM2RAIN*

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IMPACT-BASED FLOOD WARNINGS IN SWEDEN USING A FLOOD INUNDATION MAP LIBRARY APPROACH

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Abstract: The Swedish Meteorological and Hydrological Institute SMHI has in October 2021 introduced impact-based flood warnings in addition to the existing warnings for high flows. The flood warnings can capture fluvial flooding along rivers and lakes where the upstream area is larger than 50 km^2. Pluvial flooding cannot be simulated within this setup, but it is taken account of in a meteorological warning instead ("cloud burst"). Floods are simulated for 13,500 sub-catchments of the national hydrological model S-HYPE[1,2]. Only sub-catchments with an upstream area larger than 50 km^2 are included. Approximately 10,000 river catchments are modelled with the coupled 1D-2D hydraulic model LISFLOOD-FP[3] and around 3,500 lake catchments are modelled with a simplified GIS-interpolation model in GRASS-GIS[4], where inundation is a function of water level from S-HYPE. The simulated catchments have an average size of 8 km^2. The spatial resolution is generally 5 m for the river models, but was locally increased to 1 m where, e.g., dam structures were not properly reflected otherwise. A flood inundation map library was generated that includes water depth maps for 6 return periods (2, 5, 10, 25, 50, 100 years) for each of the simulated catchments.

The only calculation that is done operationally is the interpolation of the water depth map to the forecasted flow return period (Fig. 1). The associated impacts are automatically calculated through intersection of the interpolated water depth map with different impact data maps, e.g. roads and railway network or buildings[5,6]. The impacted objects are automatically summarised for minor warning areas (around 5 km of a river stretch or lake shore) and visualised in a hydrological forecasting system that the officer on duty analyses twice daily.

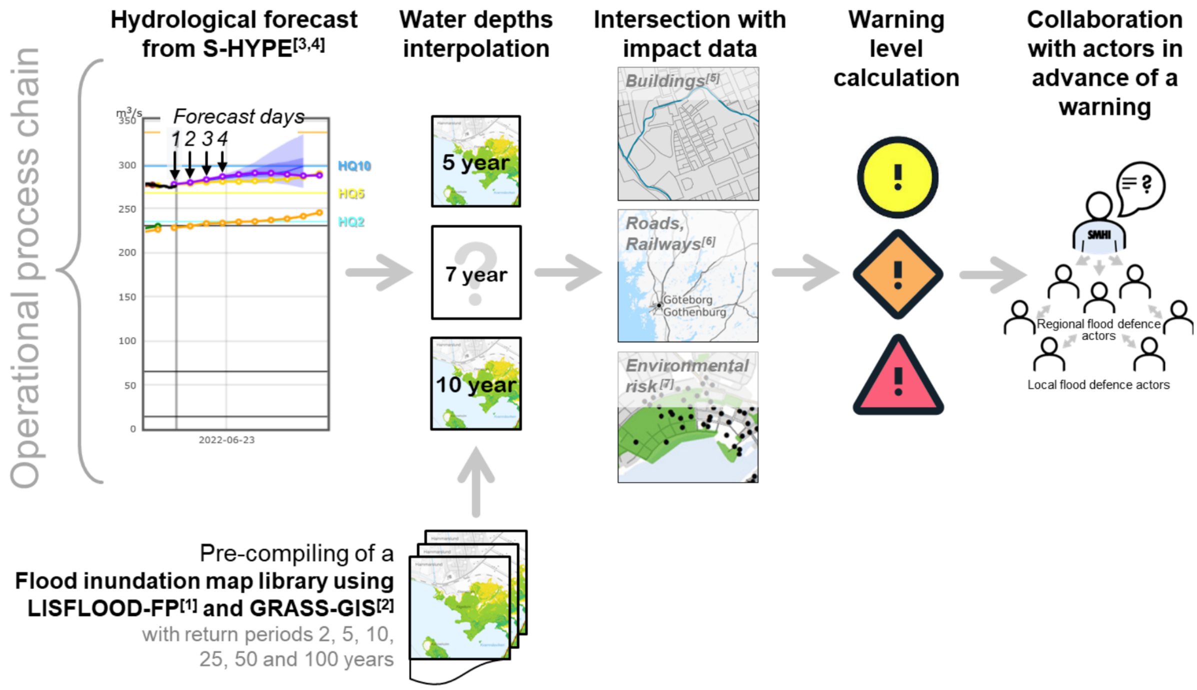

Figure 1. *Schematic of the modelling strategy used for the impact-based flood warnings in Sweden. A flood inundation map library is created in advance in offline simulations and applied in the operational process chain run twice daily.*

The warning level is automatically assessed according to predefined criteria. A unique feature of the impact-based warnings in Sweden is the mandatory collaboration with regional flood defence actors in advance of a warning, allowing to incorporate local knowledge into the warning. Detailed information on affected objects and inundated area is shared with the regional authorities, but on the warning homepage for the public, flood warnings are aggregated and summarised in a more general way. No detailed water depth maps are shared with the public.

A validation for case studies in southwestern Sweden in 2020 shows promising results for higher flow return periods, but the system tends to send too many alarms for the lower return periods. In addition, after 1,5 years of operational service and 2 events with flood warnings, the warnings are perceived as too extreme, which means that the criteria need to be adjusted. This work in progress, i.e. the evaluation of the system and its flaws as well as possible ways to cope with it will be the main focus of the contribution, though a general overview will be included as well, of course.

Keywords: *Impact-based flood warnings, flood inundation map library, LISFLOOD-FP, fluvial flooding*

References:

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[5] *Lantmäteriet. https://www.lantmateriet.se/en/geodata/geodata-portal/ (several data layers, e.g. buildings, water courses, DEM).*

[6] *Trafikverket. https://bransch.trafikverket.se/ (several data layers: roads, railways, bridges).*

[7] *Swedish county administrative boards. EBH-kartan, https://ext-geoportal.lansstyrelsen.se/standard/?appid=ed0d3fde3cc9479f 9688c2b2969fd38c (open source, in Swedish).*

FLOODGAN 2.0: DYNAMIC PLUVIAL FLOOD FORECASTING USING DEEP LEARNING

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Abstract: Recent flash flood events revealed how severe and fast the impacts of heavy rainfall can be. Still, pluvial flood warnings are limited to meteorological forecasts, water level monitoring, or hydrological forecasts which are insufficient to warn people against the local and terrain-specific flood risks. The core problem lies within the calculation time of hydrodynamic (HD) models as the required computation times are too high for real-time applications.

To overcome the computation time bottleneck of HD models, the deep learning model floodGAN has been developed (Hofmann & Schüttrumpf, 2021). FloodGAN combines two adversarial Convolutional Neural Networks (CNN) that are trained on high-resolution rainfall-flood data generated from rainfall generators and HD models. The model translates the flood forecasting problem into an image-to-image translation task whereby the model learns the non-linear spatial relationships of rainfall and hydraulic data. Thus, it directly translates spatially distributed rainfall forecasts into detailed and accurate hazard maps within seconds, as evaluated in a case study in the city of Aachen.

Building upon FloodGAN, we introduce FloodGAN2, which enhances the original model by incorporating time series forecasting, additional hydraulic parameter prediction, and the capability to process larger areas (e.g. entire cities) due to efficient RAM usage. These capabilities were unlocked through the incorporation of recent Deep Learning advances such as residual- and upscaling layers, refining the resolution of predicted flood extents. These advances allow FloodGAN2 to provide time-varying flood hazard maps enabling better predictions of the dynamics of flood processes. Moreover, by extending its applicability to larger areas, FloodGAN2 offers a scalable solution tailored to address the challenges faced by various urban environments. The model has been trained and evaluated in a case study in the city of Aachen and was able to consistently reach R^2 scores greater than 0.9 on testing data. This enhanced flood forecasting model represents a step forward in the development of real-time early warning systems for pluvial flooding, contributing to more effective and information-rich risk mitigation and resilience.

Keywords: *Deep Learning, Generative Adversarial Networks, Hydrodynamic Models, Real-Time Pluvial Flood Forecasting*

References:

Hofmann, Julian; Schüttrumpf, Holger (2021): floodGAN: Using Deep Adversarial Learning to Predict Pluvial Flooding in Real Time. In: Water 13 (16), S. 2255. DOI: 10.3390/w13162255.

A USER CENTRED DESIGN APPROACH TO CO-DEVELOP A DECISION SUPPORT SYSTEM FOR IMPACT-BASED FLOOD WARNINGS TO IMPROVE LOCAL FLOOD PREPAREDNESS

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Abstract: The Norwegian Water Resources and Energy Directorate (NVE) has the national responsibility to manage floods, landslides, and avalanches by way of planning, protection, warning, emergency management and R&D. Since 1995 NVE has assessed the national risk for floods, with daily updates on the webpage varsom.no – and on yr.no in collaboration with the Norwegian Meteorological Institute and the Norwegian Broadcasting Corporation.

As a country with 1748 kilometres from north to south and 400 river basins NVE is limited to assess flood risk on a regional level, which means that our main target groups – local governments and emergency preparedness sector – must translate the regional warnings into potential local impacts.

In line with requests by the local government and recommendations by the World Meteorological Organisation NVE started up a 4-year pilot project in 2022 with the aim to develop an impact-based flood warning system. This includes developing a tool enabling local governments and emergency preparedness sector to execute actions at the right level based on the regional warnings. In doing so we have taken a user centred design approach, inviting the local governments in our five pilot municipalities into the process of identifying and developing the solution. The pilots each represent different flood challenges and systems and skillset of responding to flooding.

In collaboration with our five pilot municipalities and the consultant agency Comte Bureau we have embarked on a service design journey. During approximately 6 months, we will investigate, reveal, and understand the user needs, both the visible and underlying needs. We are using different methods (including, but not limited to interviews, workshops, observations, and simulations) to learn from our pilot municipalities and personnel involved in emergency preparedness. We will continue to co-create with our pilot municipalities and iterate until we have a solution that is based on and developed together with the end-users.

Service design as methodology and a co-creating approach is not only pivotal to innovative processes, but emergency responses are also a unique psychological context where decisions need to be taken at a split second and the potential outcome of a decision or non-decision may have huge consequences. It is crucial that the right person get the right information at the right time, and in the right way. Thus, to truly understand such situations and what the users need, we must put ourselves in their shoes and invite the users to be a part of the entire process.

Keywords: *Flood warnings; natural hazards; flooding; avalanches; communication; impact-based warning; service design; user centered approach*

MEDITERRANEAN AND PAN-EUROPEAN FORECAST AND EARLY WARNING SYSTEMS AGAINST NATURAL HAZARDS: A CONTRIBUTION TO THE EARLY WARNINGS FOR ALL (EW4ALL) INITIATIVE

Jürg Luterbacher[*] and the MedEWSa consortium partners

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Abstract: The Mediterranean and pan-European forecast and Early Warning System against natural hazards (MedEWSa) is a recently funded Horizon Europe. MedEWSa's vision is to provide novel solutions to ensure timely, precise, and actionable natural hazard and extreme weather event impact and finance forecasting, and to deliver EWS that supports the rapid deployment of first responders to vulnerable areas. It is a sophisticated, comprehensive and innovative solution that innovates through the enhancement of existing, established tools, addresses multi-hazards and cascading effects in order to prepare an output that is tailored to the exact needs of stakeholders, which ranges from enhanced preparedness to rapid and accurate deployment of first responders. MedEWSa will be based on 8 pilot sites, using areas, regions and countries from Europe, the southern Mediterranean and Africa being impacted by natural hazards and extreme events with cascading effects (Figure 1).

The MedEWSa consortium is coordinated by WMO and includes partners from NMHS (Egypt, Sweden, Israel, Greece, Slovakia, Austria, Italiameteo), ECMWF, Red Cross, African Union, SMEs, academia, research institutions, first responders, civil protections, NGOs, local & regional governments, private sector SMEs, crisis planners.

MedEWSa have also foreseen Lighthouse stakeholders who facilitate scalability considerations at a national level, include cross-boundary aspects as well as the response chain in multi-country events, capitalise on and develop/exploit further alternative risk transfer solutions, as well as fully consider needs, requirements and inputs from last mile practitioners and stakeholders.

The project directly addresses the challenge of the UN SG's EW4all initiative:
- Offers hazard information/risk analysis for meaningful EW allowing governments, communities and individuals to understand risks related to impending events and to act to minimise impacts
- Contribute to impact-based forecasting, service delivery related to natural hazards for countries
- Develops a fully integrated impact-based multi-hazard EWS in Europe/N Africa
- AI-based decision-support solutions for improved impact prediction of multiple hazard dynamics and their interdependencies
- Demonstrates how WMO research is leading efforts to extend EWS to vulnerable and underserved regions, and communities

The talk will present the vision of MedEWSa and links to the EW4all initiative.

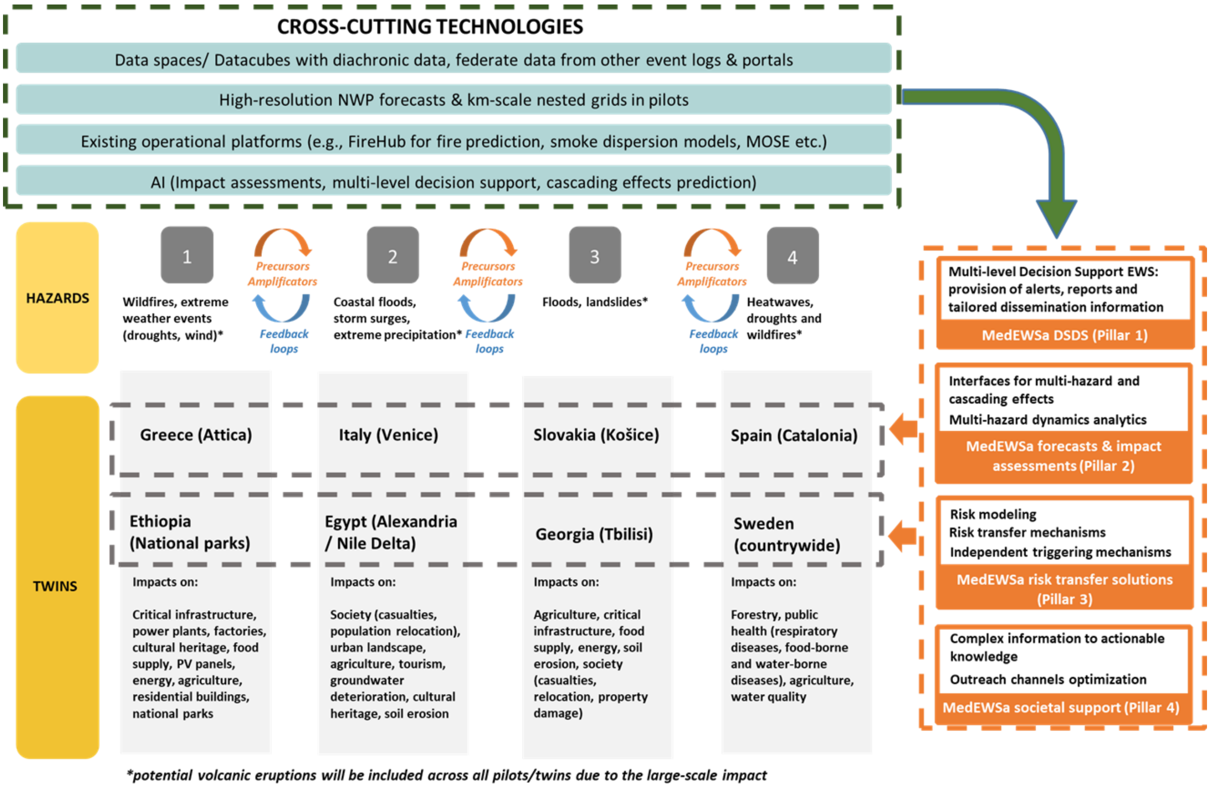

Figure 1. *MedEWSa twins bridge areas with different climatic and physiographic conditions, yet facing similar hazardous events, in order to deliver meaningful and long-term knowledge transfer and exchange of best practices:*
- *Twin #1: Greece – Ethiopia: wildfires and extreme weather events*
- *Twin #2: Italy – Egypt: coastal floods and storm surges*
- *Twin #3: Slovakia – Georgia: floods and landslides*
- *Twin #4: Spain – Sweden: heatwaves, droughts and wildfires*

Potential volcanic eruptions will be included across all pilots/twins due to their large-scale impact

Keywords: *Early Warning Systems, natural hazards, impact-based forecasting, MedEWSa, EW4all initiative, AI-based decision-support solutions*

A BRIEF HISTORY OF CO-CREATING AND THE INTEGRATION OF LOCAL KNOWLEDGES, DATA AND NEEDS IN CLIMATE SERVICES

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Abstract: Climate services aim to provide tailored climate information to users and decision makers that is useful and of added value to the climate relevant decisions they make. Recent decades have seen significant advances in the science that underpins information provided through climate services, not least due to the combined efforts of science groups such as HEPEX. These include advances in weather forecasting, sub-seasonal to seasonal forecast and climate prediction, and how uncertainty in climate data can be understood, visualised and communicated. Despite these advances, barriers remain to the uptake of climate services, and though their usefulness is well established, their actual use remains elusive. Further improving accuracy, such as through more reliable seasonal forecasts through improved bias correction methods, contributes to increased credibility and consequent usage, but additional dimensions include the salience and legitimacy of services provided, and recognition that users and decision makers consider multiple knowledges, including their own local knowledges; contexts, perceptions and preferences, as well as the knowledges obtained through scientific data.

Here we present some of the progress made in the EU-H2020 I-CISK research and innovation project. Through trans-disciplinary research, this project aims to develop a co-creation framework through which social and behaviourally informed, human centred climate services are co-created with their intended users. The framework recognises the relevance of local data and knowledge in fostering the usage of climate services, and considers the different dimensions of local knowledge, as well as how local and scientific knowledge can be integrated. The research developed within the project is largely developed within the context of seven Living-Labs, situated across Europe and Africa. In each of these, multi-actor platforms have been established, each representing a range of stakeholders and spanning several sectors. The project is working closely with stakeholders in these Living Labs in co-creating pre-operational climate services tailored to their co-identified needs. In this contribution we provide a brief reflection on the collaboration and interaction in these Living Labs, and share experiences of how the co-creation process and exploration of local knowledge contributes to the co-design of climate services relevant to the intended users. We explore some of the do's and don'ts we have uncovered thus far, and reflect on how developing research in a team that spans across physical and social sciences changes our own perspectives on climate services.

Keywords: *Climate Services, Co-creation, Local knowledge, Seasonal Forecasting.*

A CONTINENTAL US TESTBED FOR BASIN-SCALE S2S CLIMATE PREDICTIONS SUPPORTING WATER MANAGEMENT

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Abstract: Sub-seasonal (from 2 weeks to 2 months) to seasonal climate predictability and prediction are becoming a growing focus of operational climate prediction centers as well as stakeholders, who seek outlook information in the gap between weather and traditional seasonal climate time scales. Although some mechanisms of predictability on sub-seasonal to seasonal (S2S) scales are known and to some extent understood – e.g., persistent ocean or land surface anomalies, synoptic circulation features such as the Madden-Julian Oscillation – their predictability and prediction skill for S2S climate at resource management scales still remains near the threshold of usability for decision-making. Improving our understanding both of S2S predictability as well as how best to harness it using available observational and modeled datasets (including reanalyses and climate forecasts) and methods (including multi-model combination strategies, empirical and hybrid prediction approaches, climate forecast conditioning and post-processing) will have wide-ranging benefits. Recognizing this value, US agencies have steadily invested in improving S2S climate prediction capabilities. Modest advances have come in the US through coordinated activities such as the National Multi-Model Ensemble (NMME; Kirtman et al, 2014) and the NOAA-led SubX S2S prediction effort (Pegion et al, 2019). Additionally, recent federal competitions (e.g., S2S climate prediction 'rodeos') have highlighted potential improvements from the use of machine learning.

From the stakeholder perspective, however, advances in S2S prediction from the research community have been difficult to discern, interpret, and leverage. Numerous studies exist, but are typically isolated efforts and are impossible to relate to current practice. There is a pressing need to create a common, structured, coherent testbed effort -- and one that engages both developers and stakeholders -- for evaluation, benchmarking and communication of potential advances in S2S climate prediction for predictands that are relevant to stakeholders and applications. This presentation describes a new basin-focused US testbed for evaluation and benchmarking of numerous possible strategies for S2S prediction targeting specific applications, including creating conditional weather inputs for real-time hydrology and water management prediction systems. The testbed is being developed to support several western US water forecasting projects. To solicit both feedback, advice and collaboration, we present the testbed, its protocols, and results to date, focusing on weeks 2-4 and months 2-3 precipitation at the basin scale from climate forecast models, empirical predictions, hybrids, with and without post-processing.

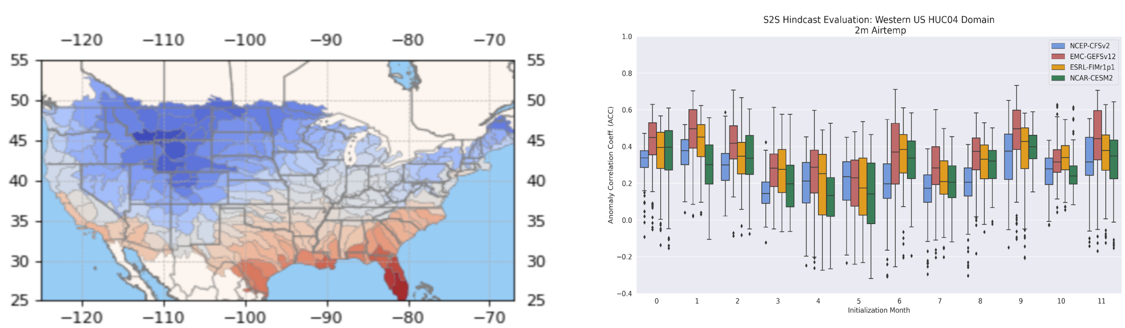

Figure 1. *US testbed 'basin' domain (left) and intercomparison of S2S model forecasts for temperature (right) over the western US.*

Keywords: *S2S forecast, precipitation, temperature, testbed, climate, water management, hydrology, dynamical, empirical, hybrid, machine learning*

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Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction, Bulletin of the544 American Meteorological Society, 95(4), 585–601. *https://doi.org/10.1175/BAMS-D-12-00050.1*

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A SKILL ANALYSIS OF THE EUROPEAN FLOOD AWARENESS SYSTEM

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Abstract: The European Flood Awareness System (EFAS) of the Copernicus Emergency Management Service is an operational forecasting system whose aim is to raise awareness about floods in European transnational rivers. It produces probabilistic, medium-range discharge forecasts twice a day by running the open-source hydrological model LISFLOOD with four different meteorological forcings, two deterministic forecasts from the DWD (German Weather Service) and the ECMWF (European Centre for Medium Range Weather Forecasts), respectively, and two probabilistic forecasts from ECMWF and the Cosmo Consortium (COSMO-LEPS). Based on these forecasts, flood notifications are issued to the EFAS partners if a set of criteria is met: contributing area larger than 2000 km², lead time from 48 to 240 h, at least one deterministic model exceeds the discharge threshold (5-year return period), and at least one probabilistic model predicts 30% exceedance probability of that discharge threshold for three or more consecutive forecasts.

However, the operational EFAS is being regularly updated, so the configuration of EFAS has changed since the time these notification criteria were defined. For instance, the temporal resolution has increased from daily to 6-hourly, and the spatial resolution is planned to improve from 5km to approximately 1.5 km (1 arcminute).

This study aims at assessing the skill of the notification criteria above presented with the current system setup, and to derive a new set of criteria that optimizes the notification skill. We will focus on three research questions: (i) how can we combine the different models (deterministic and probabilistic) into a grand ensemble and what probability threshold optimizes skill? (ii) Is the persistence criterion (i.e. 3 consecutive forecasts need to provide persistent predictions of high flood risk) adding to the skill both at shorter and larger lead times? (iii) Can we reduce the contributing area threshold without compromising skill?

The study will make use of reanalysis, driven by meteorological observations, and forecast data at over 1200 points across Europe. By comparing the reanalysis data with the simulated discharge threshold, a total of 678 “observed” flood events have been identified in the years 2021 and 2022. We have tested 4 approaches in which to combine the 4 meteorological forcings and several combinations of the probability and persistence criteria. For each of the runs we computed binary classification skill metrics such as recall, precision and the f-beta score, and we have searched for the combination of criteria that maximizes this latter metric. We have also looked into how the skill of the system evolves with lead-time and catchment area.

The outcome of this study will be applied to the EFAS operational system, directly impacting the preparedness of the relevant authorities in future flood events.

Keywords: *EFAS; floods; notification*

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ADVANCES AND GAPS IN THE SCIENCE AND PRACTICE OF IMPACT-BASED FORECASTING OF DROUGHTS

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Abstract: Advances in impact modelling and numerical weather forecasting have allowed accurate drought monitoring and skilful forecasts that can drive decisions at the regional scale. State-of-the-art drought early warning systems are currently based on statistical drought indicators, which do not account for regional vulnerabilities, and hence neglect the socio-economic impact for initiating actions. The transition from conventional physical forecasts of droughts towards impact-based forecasting (IbF) is a recent paradigm shift in early warning services, to ultimately bridge the gap between science and action. The demand to generate predictions of "what the weather will do" underpins the rising interest in drought IbF across all weather-sensitive sectors. Despite the socio-economic benefits being expected to be high, migrating to this new paradigm presents myriad challenges. In this paper, we provide a comprehensive overview of IbF of droughts, outlining the progress made in the field. Additionally, we present a road map highlighting current challenges and limitations in the science and practice of IbF of droughts and corresponding needs for advancing this emerging field. More specifically, we identify seven scientific and practical challenges/limitations: the contextual (inadequate accounting for the spatio-sectoral dynamics of vulnerability and exposure), human-water feedbacks (neglecting how human activities influence the propagation of drought), typology (oversimplifying drought typology to meteorological drought), model (mostly reliant on machine learning models), data (mainly textual and lacking collection protocols for all sectors) with the linked sectoral limitation (mainly agriculture in the science) and geographical limitation (mainly Europe for the science, and economically developing regions in the practice). Our vision is to facilitate the IbF progress and its use in making informed and timely decisions on mitigation measures, thus minimizing the impacts of droughts globally.

Keywords: *Drought, impacts of drought, drought impact-based forecasting, early warning systems, early action*

ALLOWING HUMAN EXPERTISE ON METEOROLOGICAL ENSEMBLE FORECASTS

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Abstract: To optimize the operation of its run-of-the-river hydropower plants, CNR forecasters use daily a deterministic operational hydrometeorological forecasting chain to deliver hourly inflows up to 4 days ahead. A probabilistic version of this short-term forecasting chain has been recently developed, based on the work of Bellier [2017, 2018, 2021]. This new chain is designed to consider the uncertainties associated with the various modelling processes, focusing on the reliability and consistency of the issued probabilistic forecasts.

Although automated meteorological and hydrological modelling tools provide very useful hydrological forecasts, these forecasts can still be improved thanks to human expertise. Thus, the CNR deterministic forecasting chain considers a human-in-the-loop approach, allowing forecasters to add their experience on meteorological and hydrological processes (Célié *et al.*, 2019). The probabilistic framework makes this expertise more difficult, as the forecaster has too many data to consider, with multiple scenarios on multiple lead times and basins. Some of the challenges for the use of ensemble forecasts is to provide 1) a summary of the ensemble forecasts for a rapid analysis and use by the forecasters, and 2) a possibility to manually correct these forecasts while maintaining the ensemble reliability and the spatial and temporal consistency.

Clustering techniques are already used by forecasting centres to sum up meteorological ensembles in coherent groups (e.g., Straus *et al.*, 2007). Usually, supervised clustering is set up on geopotential heights for mid-term lead times. Yet, at shorter lead times, (Day to Day+3), geopotential fields from ensemble forecasts follow similar temporal evolutions, making such clustering techniques less pertinent.

Our work focuses on short term lead times, testing spatio-temporal coherent unsupervised clustering applied directly on precipitation fields, as local effects uncertainty results in different precipitation pattern evolutions even if geopotential fields remain similar.

Once the clusters obtained, impacts of the modification of these clusters by forecasters are assessed, considering two kinds of modification:

- Removing a cluster (this cluster is considered as very unlikely),
- Changing precipitation values of the cluster on specific basins and lead times (accounting for local effects or known model bias).

These modifications can endanger the statistical properties of the forecasts and make them become unreliable or inconsistent, despite the statistical corrections applied before expertise. The evaluation of statistical properties of pseudo modified forecasts on a 2008-2022 period shows that precautions must be taken to limit manual modifications. For example, a minimum number of members should be kept to ensure reliability. Nevertheless, the first results show that expertise is possible, and can be done on cluster representative members and then applied to each member inside the cluster.

Keywords: *Expertise; clustering; forecasts reliability*

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ENERGIFORSK - COORDINATING THE HYDROPOWER INDUSTRY'S HYDROLOGICAL RESEARCH NEEDS

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Abstract: Energifork's research programme Hydrological development in the hydropower industry, HUVA, strives to contribute with new hydrological knowledge to ensure that the hydropower industry can remain a successful part of the energy transition. Improvement of inflow forecasts for hydropower application is not driven by any other forum in Sweden and HUVA constitutes an important and unique network in the field.

Streamflow forecasting is a prerequisite for optimised water management and efficient hydropower production. As the energy system changes, and intermittent energy production increases, the regulating capacity of hydropower becomes increasingly important. This change also affects the pattern of hydropower production and water management over time. In addition, fluctuations in inflow patterns will be further exacerbated by a changing climate. Together this will lead to even greater demands for accurate inflow forecasts and further development of the models and planning tools used for efficient water resource management. Through HUVA researchers can secure funding for research and development projects that can support the industry in strengthening their tools to meet these challenges.

Keywords: *Hydropower, Research needs, Forecasting*

CONTINUOUS VERIFICATION TO IMPROVE FORECASTERS FORECASTING SKILL

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Abstract: Forecasters may learn much from quality assessment of historical forecasts. Forecast verification can be used for this quality assessment but this is typically done with analyses that involve long records of forecasts, thereby providing information of average forecast skill. We believe that in operation forecasting practice, forecasters should also learn from quality assessment on single events. It would hereby help if the forecasters can learn from this quality assessment shortly after the event, since this keeps the learning cycle (action, feedback, formulate improvements, trial) as short as possible. Furthermore, we argue that careful assessment of recent forecasts in a multi-model forecasting setup (i.e., multiple NPW or multiple hydro models), may help forecasters to determine which models are most reliable in the current situation.

To facilitate forecasters with quality assessment of recent forecasts, we have developed a framework for continuously verifying model quality and total forecast quality, and disseminating the resulting quality assessments in various formats in a web portal. We here report on the following procedures, how they work with the Delft-FEWS forecasting software, and highlight how continuous verification may actually help forecasters to make better forecasts. Finally, we also present an outlook of how this framework is to be improved further, including ensemble verification and verification of decision optimization models.

Keywords: *Forecast verification, forecaster training, continuous evaluation, decision optimization*