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IMPROVING PREDICTIONS AND MANAGEMENT OF HYDROLOGICAL EXTREMES

Deliverable 4.5: The White Paper on Hydrological Prediction

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Abstract	This White Paper provides: (1) a synopsis of the current state-of-the-art of atmospheric and hydrological forecasting, with a focus on medium-range to seasonal scales of prediction for increased preparedness, (2) the lessons learnt from IMPREX including the current forecast weaknesses identified and the need for the local tailoring of forecast output, and (3) a vision for how to improve these forecast systems/products in future research and operations.

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1 Summary

The aim of the European Union Horizon 2020 project IMproving PRedictions and management of hydrological EXtremes (IMPREX) is to improve society's ability to anticipate and respond to future extreme hydrological events in Europe across a variety of uses in the water-related sectors (flood forecasting, drought risk assessment, agriculture, navigation, hydropower, utilities). Following the research undertaken within IMPREX, this White Paper provides: (1) a synopsis of the current state-of-the-art of atmospheric and hydrological forecasting, with a focus on medium-range to seasonal scales of prediction for increased preparedness, (2) the lessons learnt from IMPREX including the current forecast weaknesses identified and the need for the local tailoring of forecast output, and (3) a vision for how to improve these forecast systems/products in future research and operations.

2 State-of-the-art atmospheric and hydrological forecast systems

Hydrological forecasts are employed for many purposes. They are used, for instance, by civil protection authorities to prepare society for upcoming extreme hydrological events, such as floods and droughts; by reservoir managers to decide on releasing or storing water for a variety of uses (e.g. agriculture, hydropower); by watershed managers to anticipate drought risks; and for navigation and aquatic ecosystems needs. A typical forecast system uses hydrometeorological observations to determine the initial hydrological conditions in (near-) real time; weather forecasts of precipitation and other atmospheric variables to drive a reliable hydrological and/or hydrodynamic model over a particular area; forecasters (experts) to evaluate risks and when necessary, issue warnings; a mechanism to communicate the hydrological forecasts and warnings to users (including visualisation practices, dissemination channels and metadata); a server to archive past and current forecasts; and evaluation protocols to assess the forecast quality and conduct post-event analyses. The hydrological model (representing physical processes and occasionally human impacts within the catchment, for example, river catchment relief, soil types, and storages) transforms precipitation into runoff and propagates it through the river network to predict the river discharge evolution in time and is a main part of this forecast chain.

A key component of hydrological forecasting is the driving meteorological forecast. Weather forecasting is achieved through a process known as Numerical Weather Prediction (NWP), whereby numerical models that describe atmospheric and oceanic motion are integrated from an initial atmospheric state to determine future weather conditions (e.g. Bauer et al., 2015). For skilful NWP forecasts, it is essential to have a global observation network including, for example, low Earth orbit and geostationary satellites, aircraft, radiosondes, and ocean buoys. These observations are blended into NWP models in a step called data assimilation to generate the initial atmospheric conditions from which the weather forecasts are run for a given forecast time horizon. As there are uncertainties in the initial atmospheric conditions and because of errors in the numerical model formulations that represent physical processes, an ensemble of forecasts (or possible future scenarios) is often created, and these probabilistic forecasts allow for the quantification of predicted uncertainty. There are multiple time horizons that can be targeted by the forecasts: from the short-range (0–3 days), to the medium-range (3–14 days), to the sub-seasonal scale (15–45 days), up to seasonal time scales (3–12 months). Centres, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and the UK Met Office, provide forecasts over these time horizons.

Several systems run on a pan-European scale to deliver probabilistic flood forecasts and related information for European national flood forecasting agencies and the European Civil Protection and Humanitarian Aid Operations. One such system, the operational Early Warning System for floods of the Copernicus Emergency Management Service, is the European Flood Awareness System (EFAS; Thielen et al., 2009; Smith et al., 2016). EFAS has run operationally since 2012 and uses multi-model weather forecasts. Given its proven usefulness for flood forecasting out to two weeks, the EFAS forecast horizon was recently extended from 15 days to seven months. It can now operate together with other months-ahead forecasting systems, such as the pan-European hydro-climatic seasonal forecasting service from the Swedish Meteorological and Hydrological Institute (SMHI), that has been developed under the Copernicus Climate Change Service (C3S) to support society and European authorities with consistent past, present, and future climate data and enhanced information on impacts, including those concerning the water sector.

3 Lessons and weaknesses identified

Although hydrometeorological forecast skill is improving gradually, these forecast systems still have issues in terms of reliability and sharpness. This means that users not only need to develop procedures to ingest forecast information into their decision support system, but they also need to employ techniques to consider these imperfections and the probabilistic nature of the results. In this section, forecast issues that have been highlighted within IMPREX are discussed.

3.1 Gaps in global observed data

The global hydrological cycle describes the circulation of water through the atmosphere, land, rivers, lakes, and oceans in its different phases (liquid,

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solid, and vapour). In coupled hydrometeorological NWP models, its two main branches are represented by the atmospheric branch, which mostly consists of evapotranspiration, water vapour fluxes, condensation, and precipitation; and the terrestrial branch, which focuses on the movement and storage of water in continents and oceans. For both branches, modelling efforts rely on global observations, which consists of a complex system of surface- and space-based sensors (e.g. in-situ stations, radar, rain and river discharge gauges, satellite, radiosondes) owned and operated by national and international agencies.

Research has highlighted many gaps in global observation coverage, which in turn affects hydrometeorological forecasting and its quality. For example, there are many incomplete and not up-to-date hydrological records stored in the Global Runoff Data Centre (GRDC); this is partly due to the voluntary nature of the data upload process. In terms of the atmosphere, many data sparse regions exist, especially over the global oceans. In 2018, a diagnostics study by Lavers et al. (2018) identified errors in the atmospheric branch of the global hydrological cycle. Using ECMWF medium-range forecasts and unique flexible dropsonde observations (measuring atmospheric pressure, temperature, wind, and humidity) deployed from research aircraft, the assessment showed that the source of the largest uncertainties in the flux of water vapour over the northeast Pacific Ocean was due to the winds above the planetary boundary layer, i.e., at about 1-1.5 km of altitude. As such, accurate wind observations made regularly would benefit the modelling of the global hydrological cycle.

The paucity of global surface observations of the terrestrial branch of precipitation and river discharge (and the unknown anthropogenic influences, such as irrigation and reservoir regulation) hamper the undertaking of many verification studies at the global scale. Currently there is sparsity in spatiotemporal coverage (e.g., fewer precipitation gauges or radar imagery in mountainous regions) and an inadequate data sharing between countries (e.g., lack of standardisation protocols, and legal and financial mechanisms to support shareable databases). In turn, it is currently not possible in many regions to accurately evaluate the skill of predictions from coupled large-scale hydrometeorological models. In particular, the performance of large-scale hydrological predictions for local (catchment-based) applications in the water sector varies widely, according to a location’s physiographic characteristics, water resources variability in time, and users’ needs for information in their decision-making process. Therefore, within IMPREX a high-resolution (both temporally and spatially) dataset of areal average precipitation, temperature and potential evapotranspiration (e.g. based on satellite downwelling shortwave radiation) for the Rhine river was developed using a method that can be used in operational hydrological forecasting for the Rhine (Osnabrugge et al., 2017;

2019). Subsequently this dataset was used to verify the ECMWF ensemble forecasts of aforementioned variables for the Rhine River (Osnabrugge et al., 2019). These high-resolution datasets have the advantage of better representing the heterogeneities that are not captured by the relatively coarse grid scale of the atmospheric model.

3.2 Hydrological model assessments

The application of medium-range NWP ensemble forecasts for navigation-related forecasting on the River Rhine showed several shortcomings in the hydrometeorological forecasting chain. First, NWP ensemble forecasts are biased and they have too narrow prediction intervals for surface variables like precipitation. Typically, these issues propagate through to the hydrological forecasts.

Second, especially in low flow conditions, forecast errors are dominated by (systematic and statistical) uncertainty in the hydrological model and the initial conditions (soil moisture, reservoir water level, and snowpack). To improve the estimation of the initial conditions of the hydrological model and thus improve the hydrological forecasts, data assimilation methods (commonly Ensemble Kalman Filter) have been applied with some success. Another obvious way to improve hydrological forecasting skill is to improve hydrological modelling (supported by better historical forcing datasets) and the fidelity of hydrological process descriptions which was researched for the Rhine (Imhoff et al., 2019). Statistical post-processing methods, whose main goal is to increase reliability of probabilistic predictions (e.g. Bayesian Model Averaging, BMA; Ensemble Model Output Statistics, EMOS), have been applied to the hydrological ensemble forecasts. It is only when a well-calibrated predictive uncertainty is provided to the end-user that rational decision making based on a cost-benefit analysis is possible.

Third, in an attempt to assess seasonal forecasting skill, different hydrological model configurations in terms of set-up and model structure, complexity, and spatial resolutions (lumped, semi-distributed and distributed) have been further combined. Different post-processing methods (i.e. BMA, EMOS, equal weighting) have been applied to weight the individual model outputs resulting in added value from multi-model averaging. In the case of the post-processing of continentally and regionally calibrated models, no model had superior performance (IMPREX Deliverable 4.3). Further investigations are needed on how the interplay between uncertainties in the hydrological model (structural and parameter), land surface initial conditions which affect system memory and predictability, and NWP output affect hydrological forecasting skill.

3.3 Origin of seasonal hydrological forecast skill across Europe

The seasonal forecasting skill for two pan-European hydrological systems (i.e. from the EFAS and SMHI services) has been evaluated (Arnal et al.,

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2018; Pechlivanidis et al., submitted). Results showed these forecasts can have skilful seasonal predictions of anomalously high or low river flows (i.e., flows above or below average) in winter in Europe. However, a comparison with traditional seasonal river flow forecasting methods (i.e., methods based on historical observations of local meteorological conditions) shows that the use of NWP-based seasonal meteorological forecasts can only outperform these traditional methods in the first forecast month. This result reflects the limited skill of seasonal meteorological forecasts over Europe and suggests that knowledge of the initial hydrological conditions of the river basins (i.e., snowpack, soil moisture, streamflow, and reservoir levels) and the predictable early forecast horizon in the atmosphere are an important source of predictability for seasonal streamflow forecasting over Europe. The evaluation also highlighted that improving seasonal meteorological forecasts would yield a larger improvement of the seasonal streamflow forecasts (compared to improving the initial hydrological conditions) beyond the first forecast lead month.

The findings contributed to better understanding of the sources of skill in seasonal predictions, in turn identifying potential obstacles to improved seasonal hydrological predictions. The regions in Europe where users could benefit from improved seasonal meteorological forecast systems for hydrological forecasting were located. These are areas with a generally wet hydroclimate, such as western Norway, Ireland, United Kingdom, northern Spain, the Alps, Italy, and the eastern shore of the Black Sea. Interestingly, research found that the areas with skilful seasonal streamflow forecasts are not collocated with regions of the highest seasonal precipitation and temperature forecast skill. This is related to the process of cascading forecast skill from meteorological to hydrological predictions on seasonal time scales across Europe.

3.4 User requirements for hydrometeorological forecasts

A mismatch between the low skill currently available in (calibrated) seasonal meteorological forecasts and the high expectation from the user community for hydrometeorological forecasts at such lead times has become clear. The communication of forecast uncertainty proved to be an essential step and still a challenging one because decision making in many sectors is not fully developed to consider probabilistic (or ensemble) scenarios; and it is only when water managers and stakeholders have confidence in forecast quality and uncertainty that they will use them in their decision-making. The interactions between forecast providers and users during IMPREX sectoral applications also provided evidence that, with the growing number of climate services issuing forecasts and outlooks on future climate and water resources, a new challenge for modellers and users is the joint evaluation of the strengths and weaknesses of the ensemble of hydrometeorological forecasts issued by different systems and sources. Such evaluation comprises skill (quality) and value (economical or societal) of forecasts when these are effectively used to make decisions that might impact activities at short- or long-term horizons, and these types of evaluation have been undertaken in IMPREX sectorial case studies. This is an important step towards assessing which forecast system best aligns with a user's requirement for informed decision-making on future hazardous conditions. It is important to recognise that skill is in the eye of the beholder and a forecast which may be judged as unskilful for a certain user group may have utility (or value) to another.

4 Vision for the future

4.1 Numerical model advancements

The Earth's climate system is a complex coupled system composed of the atmosphere, the oceans, and the land surface (including rivers, lakes, glaciers, and aquifers) and they all interact and affect hydrometeorological predictability. An open question remains on the strength of coupling required between these components in a forecast system. It has been hypothesised that the improved representation of the interactions between earth system components, made possible via an efficient earth system data assimilation approach, a more adequate representation of physical process, NWP and hydrological models with higher resolution, and an increasing computing power, will lengthen the skilful forecast horizon and will ultimately contribute to hydrometeorological prediction developments and improved forecast skill of high-impact extreme events. Furthermore, we argue that data assimilation and modelling improvements should advance the concept of 'seamless prediction', providing more system-coherent forecasts across different temporal and spatial scales. All these efforts could improve hydrometeorological models, which would lead to advances in closing the water balance and better simulation of the whole spectrum of hydrological events (floods and droughts).

4.2 Improved earth monitoring

A fundamental requirement for forecast system development is the broadening of the Global Observing System through European and International collaboration. Increasing the number of observations is essential for all parts of earth system modelling, from initialising NWP and hydrological models, to calibrating forecast outputs for user applications and evaluating forecasts. For example, satellite observations tailored towards low altitude moisture and winds would yield improvements in forecasting the atmospheric branch of the global hydrological cycle. The development of remote sensing methods for the subsurface compartment of the terrestrial branch of the hydrological cycle would be particularly welcome for

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understanding and modelling hydrological processes at the global scale for local applications. Furthermore, more precipitation and river discharge gauges and snow water observations are needed, based on both traditional in-situ monitoring and innovative sensor networks (e.g., crowdsourced hydrologic data, mobile sensors), to enhance our capacity for better characterizing local hydrological behaviour. Note that wider access to existing observations, data that are present but not currently shared in real-time, may also improve hydrometeorological forecast skill. It is thought that the World Meteorological Organisation (WMO) Hydrological Observing System (WHOS) for hydrological observations could be the dissemination platform for this effort.

Information on anthropogenic influences, such as dams, is essential to represent large and potentially predictable impacts on hydrological discharge and associated extremes. These current gaps are particularly hindering the development and evaluation of global hydrological forecast systems and preventing local applications from fully benefiting from the spatially and temporally coherent predictions these systems can provide to inform decision-making. In regional water resources and risk management, the large-scale perspective tailored to interact with local applications and concerns could be a facilitator in the (sometimes conflictual) management of water use and water-related risks across sectors.

4.3 Interaction between forecasters and users to improve forecasts

The approach needed for improved forecast skill requires information exchange and engagement between forecast providers and users. Provision of observations affords the opportunity to enhance process modelling and to objectively evaluate hydrological forecast systems, thus identifying and addressing model weaknesses, which, in turn, can lead to model improvements and better hydrological forecasts. Improved forecasts will be used more often by stakeholders, with increased feedback provided to the modelling systems completing the loop in the 'system-user' interface. Users in the water sector have different needs and expectations towards NWP-based seasonal hydrological forecasts. In many situations in Europe, these forecasts do not yet have the skill necessary for their immediate and routine use by water managers and stakeholders. Seasonal forecasts often need to be post-processed, downscaled and bias adjusted to the local climate and hydrological characteristics. Some sectors have in-house human and financial resources to conduct experiments in practice, but others need additional guidance, training, and tools — all which have a financial cost — from forecast and service providers. Despite the variety of situations, it is, however, largely recognized that forecast skill can be potentially improved. Supporting the dialogue between service providers and users is a step forward to adding value to large-scale predictions and contributing to informed local decision-making.

4.4 From early warning to early action

Extending forecast lead time is an overall goal to gain preparedness for extreme hydrological situations. Given the limited skill of seasonal predictions in Europe beyond two months lead time, it is strongly suggested that forecast providers and users be encouraged to explore together the use of sub-seasonal forecasts. These forecasts are targeted at lead times of 2–6 weeks, and have shown some skill over Europe, originating from large-scale atmospheric teleconnections (Ferranti et al., 2018). The use of sub-seasonal forecasts can be fostered by supporting showcase applications, where forecast providers and users interact through an operational platform and in person-to-person settings to build multi-modelling approaches, visualise outlooks and impacts at different scales, and co-evaluate the performance of sub-seasonal forecast systems in a dynamical and cooperative way. This gives the opportunity for collaborative projects in which knowledge is exchanged between model developers and users, and opportunities will emerge to extract useful information at sub-seasonal scales that eventually will be useful for improving the skill of seasonal forecast systems. Cooperation is key to build confidence, promote sharing data and resources, and foster transparency, comparison and openness in forecast-targeted experiments. Further benefits would include the provision of better understanding of hydrometeorological forecast skill limitations, user's familiarisation with forecast quality, and the capability of users to make decisions conditional on the level of forecast accuracy. This may then lead to improvements in all parts of the earth system modelling chain and empower human response to predictions and management of hydrometeorological extreme events.

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