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Perspective

Improving predictions and management of hydrological extremes through climate services

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ABSTRACT

The EU Roadmap on climate services can be seen as a result of a convergence between the society's call for "actionable research", and the ability of the climate research community to provide tailored data, information and knowledge. However, although weather and climate have clearly distinct definitions, a strong link between weather and climate services exists that is not explored extensively. Stakeholders being interviewed in the context of the Roadmap consider climate as a far distant long term feature that is difficult to incorporate in present-day decision taking, which is dominated by daily experience with handling extreme events. In this paper we argue that this experience is a rich source of inspiration to increase society's resilience to an unknown future.

A newly started European research project, IMPREX, is built on the notion that "experience in managing current day weather extremes is the best learning school to anticipate consequences of future climate". This paper illustrates possible ways to increase the link between information and services for the water sector, by addressing weather and climate time scales and discussing the underlying concepts of IMPREX and its expected outcome.

The climate services paradigm

An agenda for climate change research has been with us already for a couple of decades, clearly triggered by the early climate assessments (e.g. Charney et al., 1979) and first IPCC reports completed in 1990. A significant volume of research has been funded by national and international public entities. Since the debut of the

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[7] http://climatemodeling.science.energy.gov/f/Water_Cycle_Workshop/Day2_Topic1_WhitePaper.pdf.

[8] https://www.wmo.int/pages/prog/wcp/ccl/meetings/ICT-CSIS/documents/presentations/EHP_ICT_Slides.pdf.

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European research Framework Programmes in 1984,[1] climate research has had a prominent position in the calls for proposals. Together with research funding through many national public programmes, this has led to an impressive increase in our understanding of climate, its drivers, and consequences of climate change on our environment, society and economic sectors, as documented in the IPCC assessment report series (e.g. Kovats et al., 2014 for Europe).

Over the years, a shift in the type of climate research has become noticeable, guided by a shift in funding requirements and public requests. Research has moved towards more "actionable climate research" (Asrar et al., 2012), which means that it has placed focus on providing climate information to guide business and policy decisions. Climate change has become a widely recognised topic. Although many aspects of the functioning of our climate system and its predictability remain unresolved, the request for actionable climate research is heard louder and clearer in the recent decade. We do not only want to know what's going on with our climate, we also need to know how to respond and act.

A modern term that appeared alongside with this research shift is "Climate Services". The European Commission has guided the development of a Roadmap (Street et al., 2015), where a definition of climate services is given: "We attribute to the term 'climate services' a broad meaning, which covers the transformation of climate-related data into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large. As such, these services include data, information and knowledge that support adaptation, mitigation and disaster risk management (DRM)". Our understanding of the climate system is thus intended to be packed as products that help society anticipate and mitigate climate change, adapt to the new situation and manage the potential disasters and new opportunities that are a consequence of it.

The Roadmap also recognises that in order to make climate services an effective means to cope with climate change and its effects, a change of the supply–demand structure of knowledge and information is necessary. We are moving from a situation where a scientific programme is no longer providing information solely to a public or private organisation, but instead to a network where creation and exploitation of knowledge and tools is realised: "We wish, making use of both supply- & demand-side actions, to help creating a European market for climate services in which public bodies and businesses provide cutting-edge customised information services and adaptation solutions to a range of end-users, both in the business to business domain, in the public decision-making domain, to consumers, making Europe a leading actor in this domain" (Street et al., 2015). Co-design, co-production, inter- and transdisciplinarity, relevance and authority are keywords illustrating the current day practice of climate research, innovation and implementation.

Although in meteorology and climate sciences "weather" and "climate" have clear definitions regarding their scope and time scale, the framing of weather and climate tends to distinguish weather and climate as features influence decisions within several water sectors in a quite different way. "Climate" tends to be framed as a future condition, relevant for planning, for which we should prepare or that we should try to avoid. On the other hand, "weather" is presented as a present-day condition that is very relevant for management and short-term decision making. Decision-making for (future) climate conditions is considered to be more difficult, due to the long time range at which climate change becomes decisive and is going to affect business, safety or wellbeing (Street et al., 2015).

"Weather is nearby and short-term, while climate is far away and long-term" is however a paradigm that can be questioned. Weather events in the (far) future will dominate the impacts of climate change in weather-sensitive activities. This notion is clearly addressed in many research projects that explore projections of weather extremes in future climate conditions (e.g. Hanson et al., 2006, 2007[2]). The climatology of weather patterns also in the present climate dictates their exceptionality, which will impact the way our structural and non-structural measures planned for climate change adaptation will respond. There is therefore a need to support decision making facing future weather that may be very different from today's reality. The use of long lasting experience gained with "weather services" (Mason, 1966) will likely significantly benefit the development of appropriate climate services for business and decision making.

Many of the climate change effects on society will affect the water sector. Water supply, wastewater, navigation, hydropower, agriculture, flood protection and drought risk, among others, are all sensitive to variable weather patterns at different space and time scales. Adequate "water services" can be informed by (and provide feedback to) climate services are thus essential to trigger innovation in the water sector and increase its capacity to adapt to climate change (see also the call from the European Innovation Platform EIP Water for water innovation services[3]).

In the first work programme of the European program Horizon 2020 for the Societal Challenge "Climate action, Environment, Resource efficiency and Raw Materials", a call for proposals was launched in the "Water" section: "Water cycle under Future Climate".[4] A striking feature of this call was that the expected impact was very broad and contained many elements that had all to be considered in each single candidate proposal: better precipitation and water cycle projections at various timescales; better forecasts of extreme hydrological events; impact assessment of weather extremes; and development of risk management strategies. Interestingly, (climate) projections and (weather) forecasting, (climate) risk and (weather) impacts were all mentioned in a single call for water research and innovation. Two consortia were selected and funded in response to this call, including the project entitled "Improvement of predictions and management of Hydrological Extremes (IMPREX)".[5] IMPREX is designed on the notion that "experience in managing current day weather extremes is the best learning school to anticipate consequences of future climate". In this paper we elaborate on the link between weather and climate in the context of providing climate services that will contribute to more efficient water services today, which, in their turn, will be better adapted to climate change impacts and conditions of tomorrow. We will illustrate this by discussing the conceptual view and expected outcome of IMPREX.

Link between weather and climate

For many sectors and applications it is difficult to design a robust decision context to anticipate necessary responses to extreme events in a far future. This future is uncertain, and thus is the return-on-investment of near-term decisions. A long history of coping with climatic extremes can help to build a robust framework of scenario assessment, adaptive risk management or cost-effective investment (Berkhout et al., 2013; Fernandez et al., 2014). Examples of this are the public flood protection measures in The Netherlands and the

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[1] http://horizon-magazine.eu/article/europe-s-framework-programmes-key-element-research-policy-europe_en.html.

[2] For instance, in the project "Modelling the Impact of Climate Extremes" (MICE) systematic attention is paid to the quality of the representation of extreme weather in state-of-the-art models, as well as to their projected changes and impacts of these future extremes.

[3] http://www.eip-water.eu.

[4] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/main/h2020-wp1415-climate_en.pdf.

[5] For the other funded project see http://www.projectbingo.eu.

drought management measures to assist agriculture in Australia. Extreme conditions are considered as an integral part of the system rather than as exceptional features. However, also in these decision contexts a trade-off between cost and protection level normally leads to a limitation of the level to which the system is protected. In addition, climate and weather is only one of the many drivers of decisions, which puts additional constraints on the robustness of the framework.

On the other hand, the number of sectors and entities dealing with activities that are socially and economically sensitive to climate and weather extremes is very large: insurance, (renewable) energy, agriculture, public health, water utilities, disaster management (e.g. Alfieri et al., 2012; Boucher et al., 2012). They have all more or less developed tools and/or practices to anticipate or respond to weather and climate, including extremes. Dutton (2002) has emphasised the emerging integration of weather information and models for risk, decision and finance. Today, the services provided by National Hydro-Meteorological Services (NHMSs) are widespread and generally well received by a large range of users (e.g. WMO, 2008). Their monetary value has been established for several socio-economic sectors (Doswell and Brooks, 1998) and assessed under current or future climate conditions for specific sectors (e.g. Hallegatte, 2012; Pappenberger et al., 2015). The development of closer relationships between weather and climate services and their users has also added motivation to push towards higher forecast skill, better data availability, higher resolution data and tailored weather indices. These are challenges that have been permanently present in the research community. In the community of professional users of weather and climate data it is generally well understood that there are scientific and computational limitations to the predictability of extreme events (Nobert et al., 2015). Also, there is an extensive expertise in the water sector on putting individual extremes in a climatic context, and expressing their magnitude in association with recurrence intervals or return periods (e.g. the 100-year flood). However, a number of recent high-impact events has raised the awareness that these statistical likelihoods may not be an appropriate reference in a non-stationary context (e.g. IPCC, 2012; Merz et al., 2014). The severity of extreme conditions may evolve in the future (e.g. Forzieri et al., 2014), raising also the question how well current day practices are fit to anticipate future conditions.

Before climate change is put central in any analysis of future extreme events, it may be worth to more closely evaluate how society is capable to anticipate current extreme conditions. It is far from obvious that we have exploited all scientific, governance, cultural and technical frontiers that play a role in the area of scientifically guided decision support. Understanding how society copes with extremes today may provide insights on how to utilise the link between weather and climate to improve the supply of “actionable information”.

A first notion of interest is that we don’t need a large change in the Earth’s climate to generate high-impact events that have no precedence. The current climate already shows a strong trend in relevant climatological (extreme) indices over a period as short as about 30 years (e.g. Westra et al., 2012). However, this climate is subject to natural climate variability at decadal time scales that allows statistical distributions of extreme events to be very different from what we experienced in the recent past (e.g. Roberts et al., 2015). The extensive research that followed on the famous temperature warming “hiatus” demonstrated clearly this large natural variability, which will also affect the regional statistics of extreme events (Cahill et al., 2015; Rodríguez-Fonseca et al., 2015). Thus, scenario building to evaluate response of society and environment to climate extremes does not necessarily require a long-term climatic context: also under present day conditions we can and will be surprised by extreme events.

Second, also in today’s practice of digesting hydrometeorological information into a decision support system, many improvements can still be realised. These improvements, for instance, concern a better climatology of current risk, a better observational record of extreme events and their impacts, a better decision-chain under stressful conditions, better availability of relevant data, better preparations to take measures when adverse effects occur, better adjustment between different stakeholders, and better understanding of compounding conditions that lead to adverse effects. Many of these topics refer to the practice of disaster risk reduction,[6] which is explicitly included in the Roadmap definition of Climate Services. Here also current challenges do not necessarily relate to improved understanding of the system operation under a future climate setting: also a present climate setting is a very solid ground to pursue improvements and increase resilience.

Third, a climatological shift in the statistical distributions of relevant events due to climate change is of high interest for many general resilience studies. However, in the end it is not a statistical distribution that will represent a particular extreme high-impact situation. It is the observed individual event within that distribution that will put to the test society’s capacity to cope with extremes. A better understanding of (unprecedented) weather patterns in a changing (or naturally varying) climate is of high interest (Hazeleger et al., 2015). This understanding can be improved by detailed surveys of unique historic or synthetic events, properly put in the context of a future condition, where a change in climate can be of much smaller importance than land use change, adjustment to earlier events, demography, economy etc. (Bouwer, 2013; Jongman et al., 2012).

Finally, anticipation of extreme events by a reliable and accurate forecasting system may prove to be a very effective adaptation measure. For example, Winsemius et al. (2014) demonstrated an adaptation and mitigation strategy in the agricultural sector by investigating how the frequency of extreme events (dry spells and heat stress conditions) may change in the future due to climate change over southern Africa and the predictability in seasonal forecasts. Wetterhall et al. (2015) find that seasonal forecasts have the potential to be used in a probabilistic forecast system for drought-sensitive crops, indicating that there is potential for a successful adaptation strategy. User surveys of present day meteorological services do point at the need for enhanced predictability of high-impact events. Yet, shifts in (potential) predictability at the short- to medium-range time scale is rarely analysed (DelSole et al., 2013), in spite of being a feature that is highly relevant for early warning and short-term anticipation to extreme events.

The IMPREX rationale

IMPREX is built on the idea that we can learn from today to anticipate tomorrow. Present prediction and projection systems, and present use of the information derived from these systems, are a starting point to understand, put in context and make progress on the impacts of a future climate on different climate-sensitive water sectors (Fig. 1). Pushing predictability of extreme weather events and their impacts to a longer lead time is already helpful for today’s activities of the public sector and private companies delivering weather, climate and water services.

Obviously, extended predictability and forecast lead times are dependent on spatial scales, and climate predictions beyond a certain time range are not feasible. However, there is still a wealth of information that can be deduced from realistic projections or scenarios cast in a future (climatic) setting. Detailed analyses of extreme events,

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[6] See for instance the Sendai Framework on Disaster Risk Reduction, http://www.unisdr.org/we/coordinate/sendai-framework.

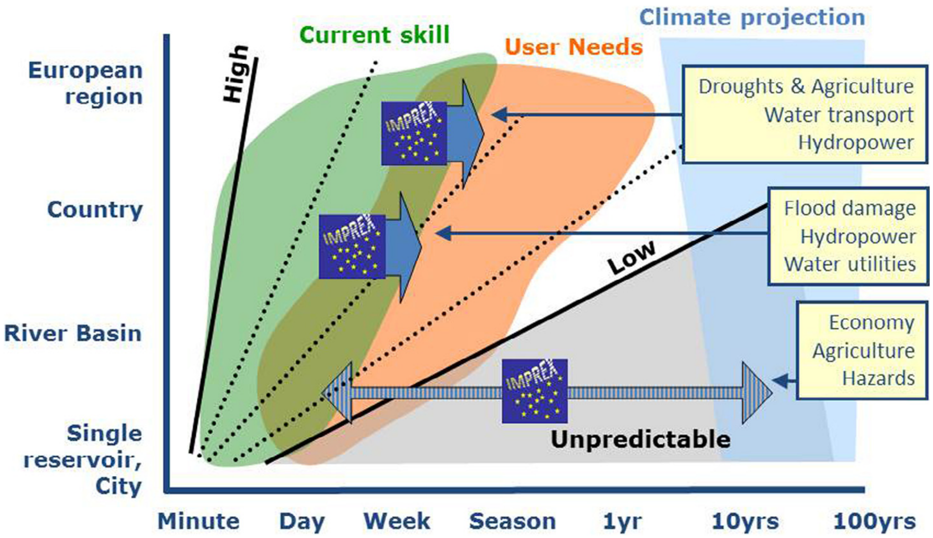

Fig. 1. Predictability of weather and climate models across spatial and temporal scales (ranging from "High" to "Low"): a mismatch between current forecast skill and user needs persists. IMPREX is designed to improve predictability at short-medium and seasonal time scales (upper two block arrows), and will develop new concepts to allow translation of the experience with present day events into the future (bottom arrow) (adapted with permission from Siegfried Schubert[7]).

supplied with a realistic description of the physical and non-physical elements that play a role in defining the impact of such events can enable a more realistic mapping of the potential consequences of extremes. Provided this information is tightly coupled to the current day practice of users and explicitly takes this current day practice into consideration in risk and impact assessments, climate projections can be informative to policy and decision-making. This is different from the "classical" strategy of scenario development, downscaling and impact assessment, such as traditionally followed in assessments by IPCC. Here, it is not only the climate projections that feed into sectorial applications, but also a realistic assessment of the non-climatic effects and potential responses is used to guide improvements in climate projections and in the predictability of (high-impact) extremes.

Apart from focusing on enhancing the realism of future climate projections by developing high resolution model capacity, a significant investment in improving and harvesting current forecasting systems will be applied in IMPREX. Currently, operational seasonal weather forecasting systems are coupled to hydrological applications. Novel data assimilation techniques and approaches for mapping current-day rare hydrological hazards and risks are put central in these new coupled systems. Recent evidence of enhanced predictability of hydrological anomalies at seasonal timescales in (wintertime) Europe (Scaife et al., 2014) can be explored further and be processed with other available information into a "hydrological risk outlook". This will give an indication of relative hydrological risks given forecasted or projected large scale features.

A portfolio of new concepts is being developed or tailor-made to several sectoral applications. To complement the "classical" downscaling chain (GCM-RCM-Impact model), realistic very high resolution images of weather events leading to extreme hydrological impacts (including the potentially large impact of several compounding low impact events) will be produced in the context of a changing climate. These "Future Weather" narratives cannot easily be expressed in terms of probabilities or recurrence intervals, as usually done in the analysis of stationary processes. However, they give a wealth of information on possible and yet unforeseen relevant processes and interactions (Hazeleger et al., 2015). In the water sector they can be used as input information for stress-testing current designs or systems, or for analysing whether current disaster-response structures are well designed. In addition, new statistical relationships between large scale climate indicators and hydro-meteorological impacts (beyond the traditional investigation of relationships with river discharges only) need to be explored (Ward et al., 2014). For instance, in IMPREX a water allocation scheme will be developed based on minimising risks over a given time frame (e.g. a season) rather than minimising damage at a relatively short time scale (e.g. a limited number of days).

Central to the project is a set of sectoral surveys, in which present day applications and practices are further analysed, upgraded and evaluated in a realistic setting. Examples include:

- Flood risk assessment procedures are developed for a number of river basins to enhance the reliability of the flood impact estimates. Forecasted discharge volumes will be translated to inundation area extent and probabilistic flood damage estimates (Merz et al., 2013) to improve decision taking.
- Several hydropower models operated by reservoir managers will be upgraded and fine-tuned to available and upgraded forecasts at medium-range to seasonal time scales. Focus will be placed on strategies to increase the system's understanding and modelling that is needed to optimise dam operation and water allocation under unprecedented or extreme conditions.
- Also for European Inland Waterway Transport (IWT) improved forecast skill at different lead times will be evaluated with considerations of a transportation cost structure model to quantify the potential economic benefit. A probabilistic IWT planning tool will be applied semi-operationally, and the added value of all information inputs throughout the forecasting chain will be quantified.
- Water utilities providing water to urban areas are supported by implementing a prototype water quality forecasting system driven by available forecasts and projections in a number of case study areas.
- Various operational drought monitoring products designed for agricultural planning (Beguería et al., 2014; Carrão et al., 2014), and analyses of the effect of climate change on European agricultural production (Supit et al., 2012; Trnka et al., 2014) are widely available. The poor utilisation of existing datasets and assessments (Acacio et al., 2013; Sivakumar et al., 2011) will be improved by a better connection between (changing) large scale

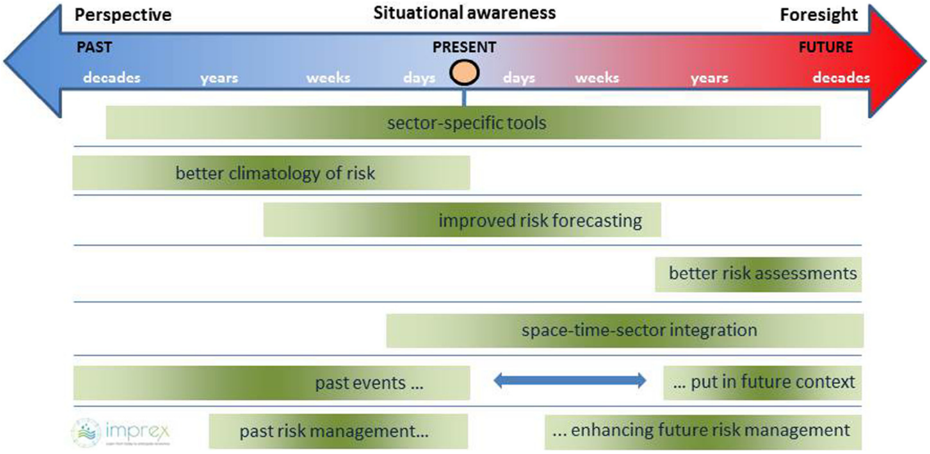

Fig. 2. IMPREX view on linking past and future time scales to improve services to water related sectors. Present-day practice is the starting point for developing and improving sector-specific tools supporting decisions related to coping with extreme hydrometeorological conditions. A better mapping of historical risk serves both the awareness of the sectors and the quality of forecasts. Enhanced detail and multi-disciplinary evaluation of future climate conditions improves the risk assessment for future conditions. Novel approaches to map cross-sectoral/spatial/temporal links, and map past extremes in a future context further enhance the understanding of the implications of changes in physical and non-physical drivers of hydrological risks. Adapted from Dasarath Jayasuriya (Bureau of Meteorology).[8]

climate characteristics and basin-specific (drought) characteristics that include local management effects. A decision support instrument for water resources management especially related to periods of water scarcity will be developed based on an integrated risk-based approach.

- Due to the strong global connectivity of trade and production, hydrological risks in a specific area are not limited to local climatic extremes but can be "imported" from remotely connected areas. Currently around 40% of Europe's water footprint originates from other countries and regions in the world (Hoekstra and Mekonnen, 2012). In IMPREX, the impact assessment model intercomparison ISIMIP (Warszawski et al., 2014) and the damage transfer model Acclimate (Bierkandt et al., 2014) will be used to make an in-depth analysis of these remote dependencies and vulnerabilities.

In all sectoral applications mentioned above, current day practice, embedded in dedicated forecasting and modelling tools, as well as strategic management structures and user involvement are explicitly taken into consideration. In addition, a cross-sectoral integration and risk trade-off analysis will be carried out for a few dedicated pilot study areas. In this analysis, multi-sectoral effects, such as the effects of droughts on hydropower operation, agricultural water and drinking water supply, will be considered in a comprehensive framework.

Learning from today to anticipate tomorrow means that links between past and future need to be clearly identified. Current day practice and future climate and risk assessments need to evolve together to improve hydrological risk forecasting, management and planning. The holistic view of these links is presented in Fig. 2, where a graphical display of various IMPREX approaches and anticipated results is provided.

Given the strong multi- and transdisciplinary nature of the field, it is essential to treat the interaction between forecasters, model developers, impact assessment experts and decision support advisors as a lively field of activity with near-continuous interaction. A typical sequential chain of information approach, which is generally implied by flow diagrams in which information is passing and updated while flowing through some kind of linear chain, is no longer appropriate. The real world is not sequential, and stakeholders do not wait until the "final" piece of information is available to improve their systems, but they update their strategies in a continuous way based on new lessons and insights. Similarly, scientific insights do not follow a sequential pathway. For a strong science-based development, continuous testing and adjustment of concepts is essential to guarantee progress and actionable results.

The IMPREX consortium was built to work in this arena of continuous science–practice interaction. It consists of a powerful combination of research institutions, operational hydro-meteorological services, SMEs with a strong risk assessment and communication portfolio, governmental stakeholders and users of hydro-meteorological forecasts and risk assessments in private and public entities.

Indicators for success

IMPREX is surely not unique in its ambition to bridge the gap between science and practice, between operations and planning, past and future, academic culture and a developing real world. However, it is unique in its ambition to respond actively to the current ambitions in which the call for "actionable science" and "co-creation" is clearer than ever. We do expect that the project can make a difference by ensuring tight interaction of experts with different background around practical problems with a fundamental nature. The bottom line is that we wish to enable decisions being taken in a rapidly developing and multi-faceted environment, yet making use of the best available knowledge and information at hand. We are well aware that decision-taking requires more than knowledge and information: it requires windows of opportunities, financial and political support, and often a certain amount of intuition and courage.

In our perspective IMPREX has succeeded if end-users in our selected pilots express that their understanding and the credibility of their decisions have increased; if a number of young scientists have spent time at the premises of a hydropower company, an agricultural resource planning organisation, or a shipping traffic centre; if the forecast quality of several extreme hydrological events has made even a small incremental improvement; if more people perceive climate related risks not only as something that is out of their range of vision, but actually as something that has to be dealt with in everyday practice, with risk perception shaping management and planning decisions; or if the project has generated a number of stories about realistic and complex chains of causes and effects acting as a guide for similar situations, and thus inspiring others to take better informed decisions.

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