HYDROMETEOROLOGICAL FORECASTING

Hydrometeorological forecasting: a long-term process

Less than half a century ago, skillful weather forecasting beyond a few days ahead was deemed fundamentally impossible. The atmospheric system was assumed to be too chaotic, the observations too few, the computing power insufficient, and the process understanding too limited. In contrast, we currently pick the fruits of high quality forecasts of hurricanes hitting coastal residents, timely warnings for elevated flood risks, and useful outlooks to manage agricultural practices or hydropower lake storage dynamics. This has become possible by acknowledging the need to join forces between observational experts, model developers and society-oriented forecast providers. And by accepting the need to take a long breath to build, upgrade, refine, couple, tune, tailor, test and adjust the complex forecasting systems. These systems produce today forecasts with high detail for a few days ahead to outlooks of climatic conditions at longer lead times.

The progress in the business of hydrometeorological forecasting and climate outlooks has been achieved by combining dedicated long-term resources resident in public dedicated hydrometeorological services, with focused project activities devoted to specialized components of the forecasting systems. IMPREX is happy to have made an incremental contribution to some of Europe's best hydrometeorological forecasting and climate projection systems. It has focused on crucial elements used in operational and policy-oriented decision support systems of institutions in the European water sector, while successfully embedding its findings in the development cycles of influential forecasting agencies.

IMPREX has contributed to global and limited area Numerical Weather Prediction (NWP) systems operated by ECMWF, the UK MetOffice and members of the Harmonie NWP consortium. It has worked on coupled hydrology/meteorology forecasting systems used for flood risk warnings, water allocation and seasonal outlooks operated by the European Copernicus Climate Change Service. It has also worked on creating enhanced detail in climate change projections by testing new experimental designs involving high resolution convection-permitting climate models operated by the Harmonie NWP consortium and the UK MetOffice.

How forecasts and climate outlooks are created

An atmospheric or hydrological prediction is designed to answer the question: what will the situation be at a certain point in the future, given the current situation? The forecast process starts by generating a picture of the current situation, the so-called "initial state" of a forecast. This is usually obtained by combining a previous forecast for the current time with observations of the current situation in a blending process called "data assimilation" which accounts for the uncertainties in both components. The initial state is progressed into the future by a sophisticated numerical model that contains the governing physical processes.

As the forecast lead time becomes longer, the forecast becomes more uncertain. Therefore, a number of simultaneous but slightly different forecasts will spread as lead time increases, due to imperfections in the observations and model formulation. This "ensemble forecast" reflects the uncertainty of the forecast, which is useful information in many decision contexts managing hydrological risks.

Global models are used to capture the entire planetary atmospheric system as a whole, while regional models are nested to provide spatial additional detail. Observations are used to initialize the forecasting systems, but also to carry out substantial verification guiding next-generation model improvements. Until systematic errors have been eliminated in the forecasting systems, observation-guided bias-adjustment remains an essential step in any hydrometeorological forecasting system.

Forecasts for the short- to medium-range (say, up to 2 weeks ahead) and for seasonal or longer time scales share this principle of dependence on a combination of initial states and model formulation, but have different keys to provide successful outlooks. Where at the short- to medium range the majority of information resides in an accurate high-resolution representation of the initial state and dynamics of primarily the atmosphere and land surface, the slow memory of oceans, vegetation and ice masses play an increasingly important role at the seasonal and longer time scales. Also the level of spatial and temporal detail at which meaningful information can be provided decreases with longer lead times.

Climate models are basically similar to models used for NWP. However, they are not designed to make a prediction based on the current situation, but on possible responses of the climate system to changing boundary conditions such as greenhouse gas concentrations and land use. Therefore initial conditions are not a key element, while model physics, ensemble projections, and verification of the quality of the projections are similarly important as for NWP systems.

The IMPREX contribution to the development of hydrometeorological forecasting and climate outlooks

Progress has been achieved on model systems addressing different time scales and environmental domains:

» Prediction of hydrology and meteorology at short-medium range (up to a couple of weeks)

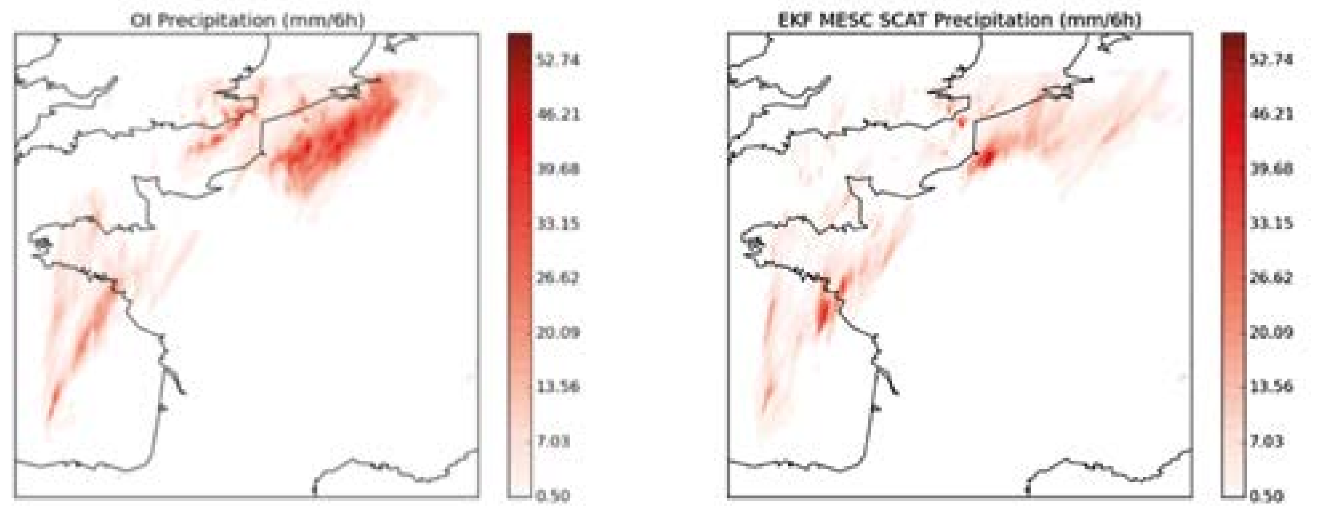
» Detection of benefits of better atmospheric observations to predict Atmospheric Rivers

Atmospheric rivers (ARs) are responsible for most of the horizontal transport of water vapor outside of the tropics and can cause extreme precipitation and affect the atmospheric circulation. The state-of-the-art weather forecasting systems used to forecast ARs and their impacts frequently have large errors in the water vapor transport. Research suggests that improved measurements of low-level winds, and to a lesser extent water vapor, would potentially enhance the prediction skill and reduce the uncertainty of these high-impact events significantly. This would yield benefits for hydrometeorological prediction.

Transect of an Atmospheric River. Shown is the Integrated Vapor Transport (IVT) as function of horizontal position within an atmospheric river. The light grey symbols denote the ECMWF forecast model first guess, the black symbols the in situ observations, and the dark grey symbols the ECMWF analysis that makes use of this observations, improving on the first guess[1].

Testing of an alternative land surface/soil moisture module in a Numerical Weather Prediction model for Europe

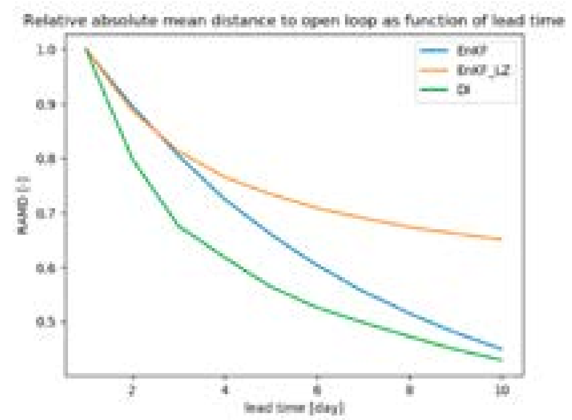
A state-of-the-art limited-area NWP system (Harmonie) was used to investigate the impact of enhanced surface data assimilation on the short-term prediction of extreme precipitation events. Improvements were applied to the background error statistics, application of a Kalman-filter, and utilization of satellite based soil moisture information. The effect on short-term prediction of extreme precipitation events was investigated in a number of case studies carried out over France, Italy and Sweden. Verification scores and subjective evaluation of one particular case showed that enhanced surface data assimilation did have an impact on short-term prediction of severe precipitation events and can lead to improved short-term forecast.



Rainfall forecast for a particular heavy-rainfall event with the original system (left) and the system incorporating the new land surface treatment (right).

Data assimilation of lake level and snow in hydrological river discharge and navigation models

Data assimilation methods have the potential to improve hydrological forecasts by reducing errors in the initial state of the model at the time of forecast. Popular variables that have been used to update the initial state are snow, soil moisture and discharge. The potential of using lake level measurements in state updating was explored. By means of a synthetic model experiment and a real world case applying the Ensemble Kalman Filter (EnKF) to a hydrological model of the Swiss Rhine, it was found that lake level measurements do contain information that could be related to upstream hydrological states and that there is therefore potential for improving the forecasts for longer than 10 days.



Relative absolute mean distance (RAMD) between forecasts from different initial conditions: 1) EnKF with Lake level, Upper Zone and Lower Zone states updated (EnKF), 2) EnKF with Lake level and Lower Zone Updated, 3) Direct insertion of lake levels. Updates with the EnKF were done based on lake level observations. RAMD expresses the convergence between the updated forecasts and the open loop as function of lead time, normalized by the error at lead time 1.

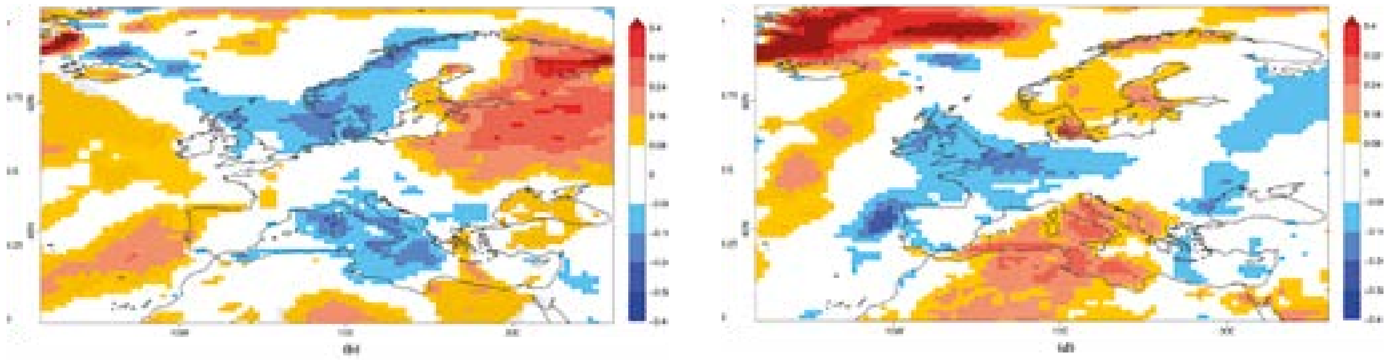
[1] Lavers, D. A., Rodwell, M. J., Richardson, D. S., Ralph, F. M., Doyle, J. D., Reynolds, C. A., Tallapragada, V., and Pappenberger, F. 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters. doi:10.1029/2018GL079019.

Prediction at seasonal time scales

Evaluation of the skill of seasonal forecasting systems

Seasonal forecasting is routinely carried out by a few meteorological services in Europe, including ECMWF and UKMO. They are intended to give probabilistic forecasts of generic climatological characteristics (including temperature, precipitation and solar radiation) one to 6 – 9 months ahead, allowing for anticipating anomalous climate conditions for agriculture, hydropower, river transport and other water-related sectors. The forecasting systems require extensive testing and calibration over long climatological periods, and system updates are implemented typically once every ~5 years. A new ECMWF version System 5 became operational in 2017, and in IMPREX verification and benchmarking against alternative seasonal forecasting systems has been carried out.

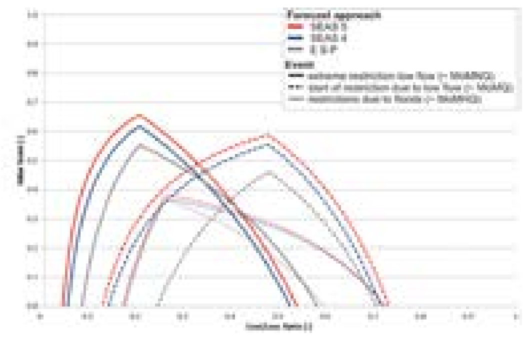
The temperature and precipitation forecasts from four climate models have been assessed using both deterministic and probabilistic approaches[2]. A number of Weighted Multi-Models (WMMs) ensembles were constructed from the individual models, and their respective forecasts were assessed. Consistent with existing literature, seasonal climate prediction skill over Europe was found to be fairly limited. A simple WMM system performs better than more complex combination systems, but does not always outperform the single best model within the multi-model ensemble.



A comparison between the skill of ECMWF System 5 and the earlier version System 4 gives a mixed picture. Orange and red areas show places where seasonal mean temperature in System 5 outperforms results from System 4 in Summer (top panel) and Winter (bottom). Blue areas show the opposite.

Also for a number of sectoral applications the usefulness of different (sub)seasonal forecasting systems was assessed and compared. For instance, seasonal forecasts are used to guide shipping transportation management of inland rivers[3]. A forecast can create economic value when it assists in optimizing the load and timing of transportation subject to river conditions. A comparison of the economic value of ECMWF Systems 4 and 5 was carried out, benchmarked against a statistical forecasting method. The maximum relative economic value one for perfect forecasts, while for a zero value no added value of the forecast compared to the (optimal use of a) climatology-based forecast can be demonstrated. The decision strategy behind the relative economic value assumes that i) the user aims at a long-term economic optimum (minimizations of expenses resulting from the preventive actions as well as the losses), ii) the user acts risk-neutral, and iii) the decision to take preventive actions solely depends on the financial costs and losses (economic gain is the only aspect the user bases the decisions on).

It was shown that particularly in the first forecast month the potential economic value of System 5 slightly outperformed the previous System 4 and statistical methods. In the second forecast month no significant difference between System 4 and 5 was shown.



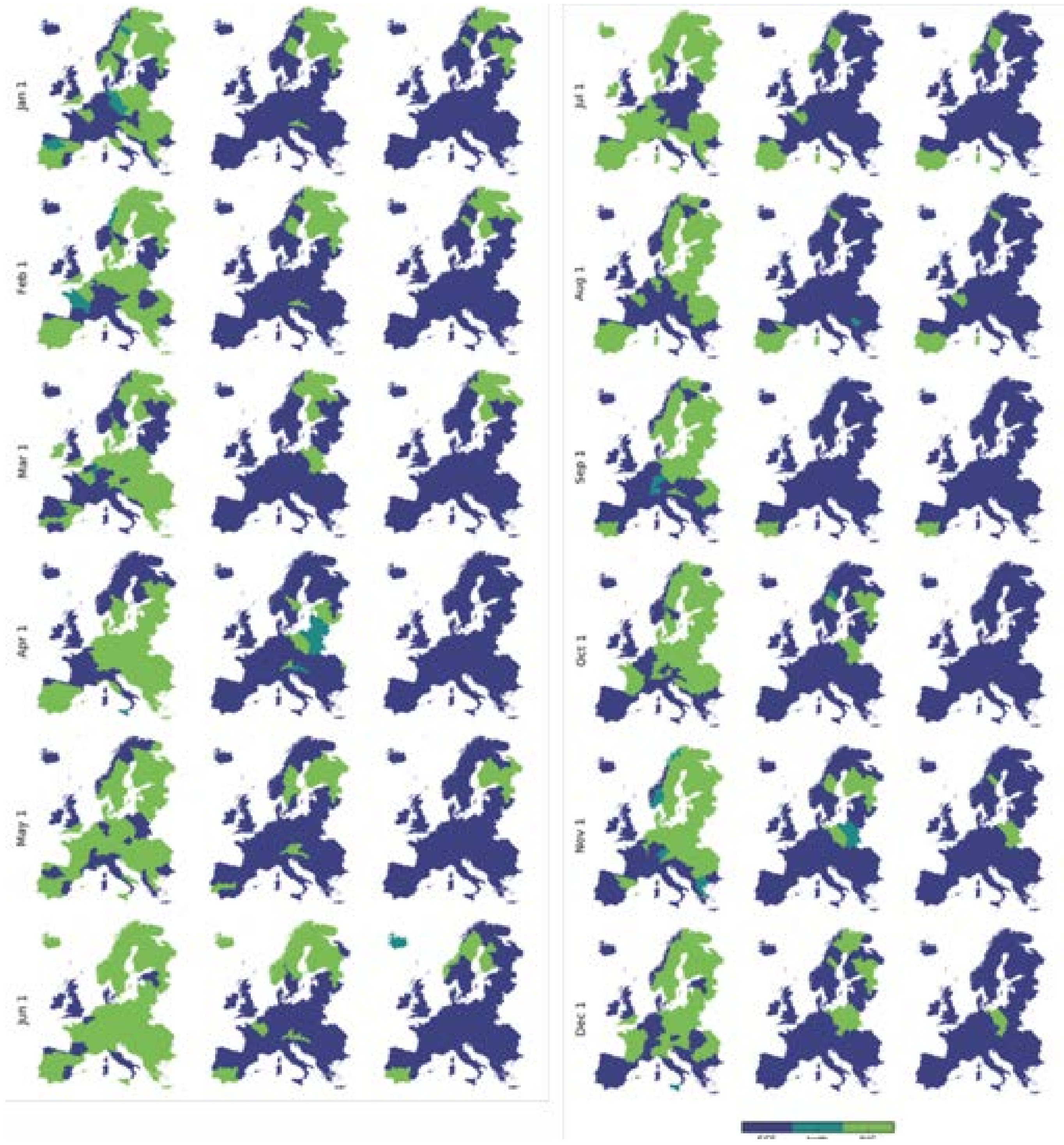
Index of economic value as function of cost/loss ratio for different types of events (restricting low flows, start of low flows, restriction due to floods) for shipping transport over the Rhine river for the first forecast month produced by System 5 (red curves), System 4 (blue) and the statistical model (grey). The System 5 curves are (slightly) higher in all domains

[2] Mishra, N., Prodhomme, C. & Guemas, V. Clim Dyn (2019): Multi-model skill assessment of seasonal temperature and precipitation forecasts over Europe; doi.org/10.1007/s00382-018-4404-z

[3] Meißner, D., B. Klein & M. Ionita, 2017. Development of a monthly to seasonal forecast framework tailored to inland waterway transport in central Europe. Hydrol. Earth Syst. Sci. 21(12), 6401-6423. https://doi.org/10.5194/hess-21-6401-2017

Improving seasonal forecasts of river discharge: do we need better initialization or better models?

Seasonal forecasts of river discharge are routinely produced using meteorological seasonal forecasting systems driving hydrological models. The European Flood Awareness System (EFAS) operated for the major European river systems by the Copernicus Climate Change Service and SMHI's European seasonal forecasting service are examples of such a forecasting system. The quality of any forecast depends on a combination of the quality of the initial conditions used to start the forecast, and the quality of the meteorological forcing for the prediction. For streamflow forecasting a potentially significant fraction of the skill can originate from information about the initial state of the system: anomalies in soil moisture or ground water, snow pack and water present in lakes and river network can give a persistent signature to the streamflow amount from a few weeks up to several years ahead.



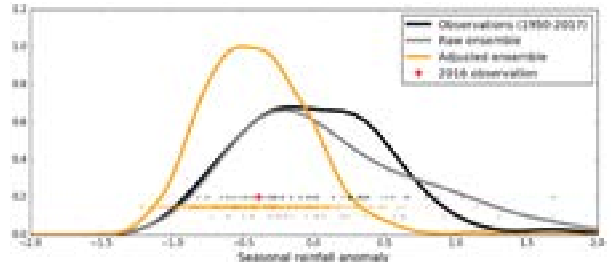
Dominant source of predictability over Europe for EFAS forecasts issues each calendar month. Results of up to 3 months lead time are shown. Green areas denote predominance of the role of initial hydrologic conditions, and in dark blue areas the atmospheric forcing is more important.

A systematic analysis of the factor that drives streamflow predictability has been carried out for 74 EFAS regions[4]. Forecast skill against the model's climatology was calculated for up to 3-months forecasts starting each calendar month. On average, to forecast the coming month, in most areas improving the initial state would lead to a higher discharge forecasting skill than improving atmospheric forecasts. As the lead time increases, the relative importance of improvement of the atmospheric forcing increases. In most areas, river flow forecasts three months ahead are more sensitive to improved atmospheric forecasts than to improved initial states. However, temporal and spatial variabilities are shown. For instance, in Scandinavia initial states also play a dominant role also for longer lead times, showing the importance of good initial snow and lake information. Over the Iberian Peninsula, the initial state dominates the uncertainty for forecast issued from June to September, a signal which persists until three months of lead time. The very dry climate highlights the importance of accurate initial ground water information, which has a long memory. Conversely, in rain-driven regions such as the UK or Norway, the quality of atmospheric forecasts drives discharge forecast skill the most, even for the month ahead. These results are used to benchmark seasonal forecasting systems and guide their further development to enhance performance and usefulness. A European sensitivity assessment tool is now available online for SMHI's European seasonal forecasting service[5].

An enhanced precipitation forecast signal in the MetOffice seasonal forecasting system

Limited skill of seasonal forecasting systems is caused by inherent limitations of the predictability of weather at a longer lead time, and by limited quality of the models and initial states used to produce the forecast. In addition, the noise from seasonal forecasting systems is filtered by the application of large ensembles to produce the forecasts, but usually some of the signal is also filtered away. Statistical postprocessing techniques can be applied to enhance this signal, and to adjust the modelled correlations between large scale climate characteristics (such as the North Atlantic Oscillation; NAO) and local weather phenomena (rainfall) using observed correlations.

Two post-processing steps were applied to output from the GloSea5 seasonal forecasting system operated by the MetOffice to improve the forecast skill of precipitation. In the first step the forecast signal in the NAO prediction is increased by fitting a linear regression between the ensemble mean NAO index and the NAO index derived from observations, and scale up the predicted signal by the slope of this regression, increasing the signal-to-noise ratio of the NAO forecast. In the second step, observations are used to replace the forecasted precipitation in Europe by analogues from the historical record, to improve the local precipitation prediction. Results in the dry Eastern Iberian area, where two case studies explore the use of seasonal forecasting for water resource management in the basins, show that a small improvement in local precipitation forecasts can be seen for winter, but not in summer. Further testing and adjustment to the operational Decision Support Systems is still required.



Seasonal rainfall anomalies for a NAO-positive year (2016) for the Jucar basin. The improvement of the forecast by using the empirical relationship between the NAO index and precipitation anomalies is evident with the adjusted forecast ensemble (yellow) much better reflecting the observed anomalies (red) compared to the raw model output (grey).

Regional climate projections

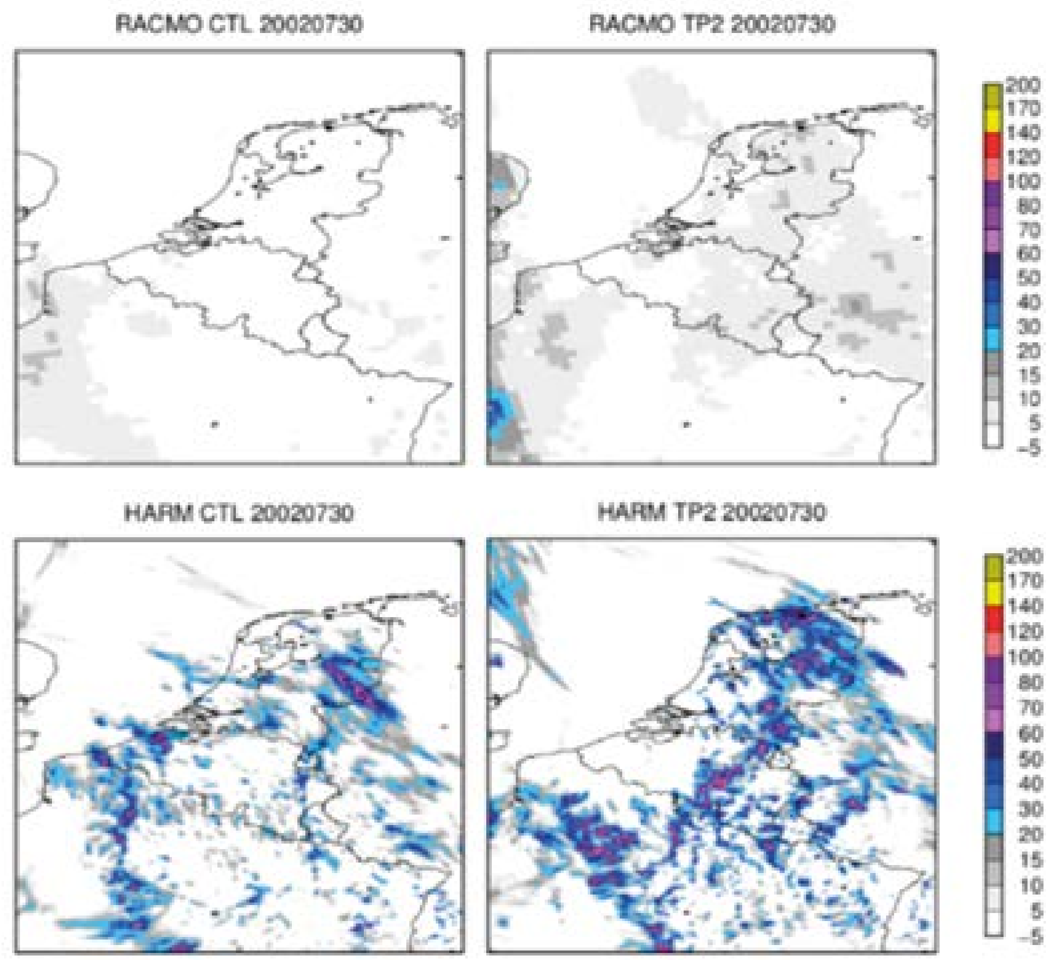
Development of convection permitting climate models for heavy rainfall

While most regional climate models (RCMs) are still operated on a relatively coarse spatial resolution, climate change effects on heavy precipitation are governed by processes at a much smaller spatial scale. In the international CORDEX community a coordinated development of so-called Convection Permitting RCMs (CPRCM) is taking place, in order to improve the climate projections for these high-impact heavy precipitation phenomena. In simulations with a CPRCM for 10 historical summer seasons covering Scandinavia, West-Central Europe, East-Central Europe and Southwestern Europe it is shown that the model produces stronger high-intensity precipitation extremes than coarser scale RCMs. Comparison to observations reveal that deficiencies in both the models and the (relatively coarse-scale) reference data sets contribute to a pertaining bias in these simulations, and further work is needed.

A simple "surrogate warming" experimental set-up

A disadvantage of the high resolution CPRCMs is that their considerable computational power demand limits their application in comprehensive climate change assessments. Running long time slices of present-day and future climate is costly, and requires substantial data processing capabilities to deal with the large data volumes. Alternative climate change assessments make use of so-called "surrogate warming" experiments. In this set-up, a CPRCM is set-up to reproduce a number of historical events or shorter episodes, and reruns of these episodes are carried out after changing the initial and boundary conditions of the CPRCM to represent a warmer world. The results are thus indicative to answer the question: "how would this episode or event have looked like if the world would have been warmer?"

The surrogate climate change experiments indicate that precipitation will increase in a two-degree warmer situation. The results show that the change in the local maximum hourly rainfall in a given region exceeds the area averaged rainfall amount, which is an indication of the added value of the CPRCM over the RCMs. However, the experimental design focuses on exploration the potential climate change influence of particular events, and findings from these analyses cannot always be generalized to depict a representative climate change signal. Sometimes a very strong amplification of the precipitation extreme is shown, while in other cases no changes are seen at all. The application of the method to a substantial number of events helps to interpret "Future Weather" simulations in terms of climate change.



Example of a heavy precipitation event in the control climate (left panels) and the simulations corresponding to a 2° warmer world (right panels). The top panels show results with a coarse resolution RCM, while the bottom panels depict results from the CPRCM.

[4] *Arnal, L., Wood, A. W., Stephens, E., Cloke, H. L., and Pappenberger, F., 2017. An Efficient Approach for Estimating Streamflow Forecast Skill Elasticity, J. Hydrometeorol., 18, 1715–1729, https://doi.org/10.1175/JHM-D-16-0259.1*

[5] *https://hypeweb.smhi.se/explore-water/forecasts/seasonal-forecasts-europe*

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Graphic design by Arctik.

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IMPREX has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641811.

IMPREX is designed to help reduce Europe's vulnerability to hydrological extremes by achieving a better understanding of the intensity and frequency of potential disrupting events. Enhancing our forecasting capability will increase the resilience of European society as a whole, while reducing costs for strategic sectors and regions at the same time. The research project brings together 23 partners from 9 countries and has received funding from the European Union's Horizon 2020 Research and Innovation Programme.