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# An evaluation of the combined benefits of post-processing forcing and flow ensembles when conducting ensemble streamflow prediction, with application to the River Rhine

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Hydrologic ensemble prediction systems (HEPS) routinely model the total uncertainty in hydrologic predictands as a combination of specific sources of uncertainty, such as atmospheric forcing, and hydrologic model initial conditions, structure and parameters. In practice, some of the sources of uncertainty, as well as the interactions (statistical dependencies) between them, are unknown or poorly specified. This can lead to biases in HEPS that are relevant for many practical applications, such as flood forecasting and water supply forecasting.

Hydrologic post-processing is increasingly used to produce unbiased and skillful probability forecasts from "raw" hydrologic predictions, whereby the historical performance of the HEPS (e.g. determined via hindcasting) is used to inform future behavior. Statistical post-processing provides a flexible framework for the estimation of predictive probability distributions, conditionally upon the HEPS (or attributes thereof, such as the ensemble mean, spread or members) and other useful predictors, such as deterministic forecasts or auxiliary variables.

There are, however, significant conceptual and practical challenges for the successful application of statistical post-processing to HEPS. These include parameterizing strongly non-normal (and often non-stationary) probability distributions, accounting for sampling and observational uncertainties, and modeling the biases contributed by specific components of the HEPS. For example, bias correction of the atmospheric forcing ("pre-processing") is generally more complicated than hydrologic post-processing, and the combined benefits on hydrologic prediction are not always demonstrated.

In this paper, we examine the need for separate bias-correction of the atmospheric and hydrologic components of the HEPS by verifying post-processed hydrologic predictions both with and without bias correction of the atmospheric forcing. We focus on a HEPS of the River Rhine basin, whereby precipitation and temperature reforecasts from the ECMWF EPS are used to force the HBV hydrological model. The atmospheric forcing is rescaled to the hydrologic sub-basins used in the HBV model and bias-corrected using the normal regression and Indicator Cokriging (ICK) techniques for temperature and precipitation forcings respectively. The hydrologic forecasts are post-processed and evaluated at multiple forecast lead times and for sub-basins of the River Rhine, as well as the outlet at Lobith. The Hydrologic Uncertainty Processor is used to bias-correct the streamflow ensemble forecasts. Comparisons are made between the bias-corrected flow ensembles with and without the forcing post-processing for several attributes of forecast quality, including the unconditional bias, Type-I conditional bias (reliability), Type-II conditional bias, and forecast skill.