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A refined description of climatic signal transformation by hydrosystems using spectral analysis

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Time series of hydrological variables, such as river discharge or groundwater levels, have only little resemblance with the effective precipitation signal that feeds a watershed. Even more disturbing is the fact that catchments undergoing similar climatic conditions do not produce similar hydrological responses. Deciphering how a climatic signal is altered and re-transcribed into hydrological signals according to local characteristics is a difficult task. However, a number of past works have shown that all time scales of variability of the input signals are not altered in the same way by a given watershed: large time scales tend to be preserved, whereas shorter time scales are generally smoothed out depending on the flow processes taking place in the watershed. Hence, understanding how catchments react to different time scales of climatic forcing remains an important challenge for water management, as it is key to predicting extreme events (severe droughts and floods). In the last decades, several authors have used the spectral analysis framework to tackle these challenges. Indeed, some fundamental 1D flow equations have been solved in the frequency-domain and applied to the interpretation of Fourier-transformed data in order to describe hydrosystems, as well as characteristic time scales of flow processes. However, these approaches either neglected surface flow or flow through the unsaturated zone, which may have a considerable role in transforming the input signal into river discharge.

Here, we build upon previous mathematical developments to derive a new transfer function (TF) for an idealized 1D hydrosystem, incorporating diffuse surface runoff, flow through the unsaturated zone and through a Dupuit aquifer. This new TF is called HYMIT for "Hydrological Minimalist Transfer function". In particular, we aim at exploring what hydrological structure or physical properties of watersheds are responsible for altering or not the climate input signals on different time scales up to interannual to interdecadal time scales. By comparing available theoretical TFs to synthetic data generated by a distributed pseudo-3D hydrological model, we show that previously developed TFs are often unable to reproduce the observations and lead to severe mis-estimations of catchment dynamical properties. However, the new function HYMIT is well able to capture all features observed in the spectra of synthetic data, for a wide range of plausible settings. We further show that HYMIT is sensitive to the spectral signature of all fundamental compartments, and thus to their filtering effect. Having validated HYMIT, we apply it as interpretation tool of real hydrological data from several catchments with distinct behaviors in Northern France. We thereby demonstrate that we may refine the description of such common datasets in the spectral domain, and that we are able to estimate key properties of each functional compartment in the system. Finally, we conclude that our approach is a practical way to understand which processes are responsible for the observed variability in catchment responses, and that the frequency-domain analysis of data has potential in assisting calibration procedures of more realistic 3D distributed hydrological models.