Supporting Information for "Identifying and quantifying the impact of climatic and non-climatic drivers on river discharge in Europe"

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Introduction

This supplementary information file contains a complementary explanation of the sensitivity and robustness tests done for the study. It also includes a map of the catchments specifically referred to in the article. Finally, it includes a detailed illustration of the methodology at the catchment scale for a given catchment in Northern Spain.

Complements on validation and robustness of the method

a- Adequacy of the framework

The method aims to compare the trends in river discharge Q_{LSM} from the model, which represents the climatic conditions only, and Q_{obs} deduced from observations, which represent all conditions at once, the actual conditions. They are not compared directly but through their substitutes Q_{climat} and Q_{actual} determined with the Budyko framework, which facilitates the interpretation of partial trends. We, therefore, need to attest to the quality of the Budyko framework to reproduce Q_{LSM} and Q_{obs} through their parametric representation.

We use the Nash-Sutcliffe coefficient (NSC) and the Percent bias (PBIAS) (Fig. S1). The Budyko fraemwork is able to reproduce correctly the annual mean of observed river discharge over all European basins with a very good PBIAS (<10 % for all river basins) (Fig. S1d) and a good NSC > 0.5 for 569 stations out of 849, except for north-eastern Europe, where we locate the majority of stations which fail this test (Fig. S1c). This second test is more demanding and attests to the quality of Budyko framework to reproduce the inter-annual variations of discharge. It is also efficient to reproduce the climatic river discharge from the model (Fig. S1a and S1b) with $NSC > 0.5$ and $PBIAS \leq 15\%$ except for a few basins and still an under-performance for NSC over Eastern Europe.

Therefore, the Budyko framework is an adequate parametric representation of annual mean discharge in both systems and we can use Q_{climat} and Q_{actual} derived from this framework to compare the climatic behavior of the watershed and its actual behavior.

In this study, we filter out the stations for which NSC < 0.5. We only keep the 569 stations for which the Budyko framework is efficient for both reproducing Q_{LSM} and Q_{obs}. Therefore, the analysis when comparing Q_{climat} and Q_{total} will not be tinted by the ability of Budyko framework to effectively reproduce Q_{LSM} and Q_{obs} respectively.

b- Robustness to climate data

We also tested the method's robustness and its sensitivity to data driving the LSM by comparing its application with different forcing datasets. Three independent atmospheric datasets are available over the 1979-2010 period.

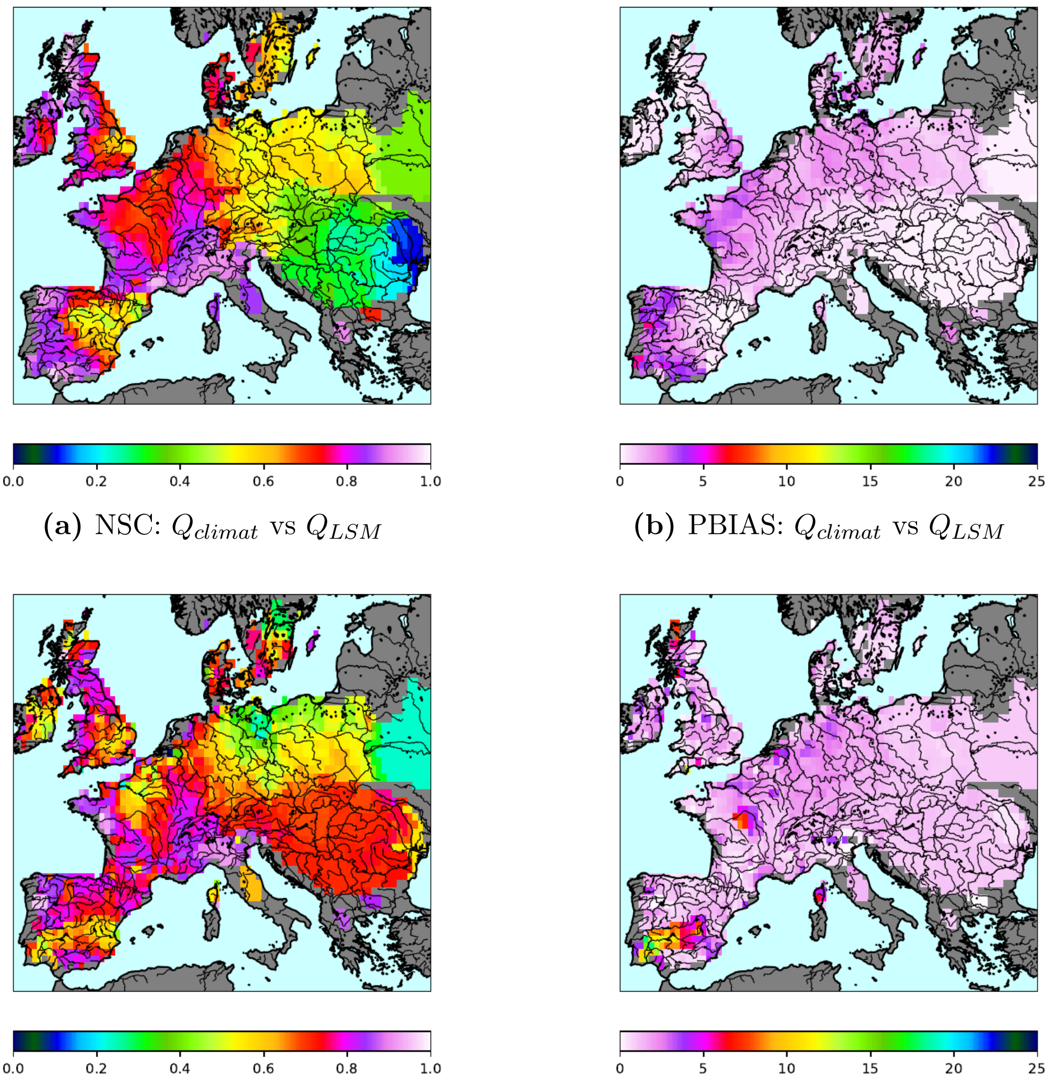
Over such a short period, trends are mostly non-significant and can't be appropriately statistically compared. However, for all forcings considered, the patterns are very similar. Here we focus on the efficiency parameters ω_c and ω_a correlation and variance for each forcing, to analyze the impact of the forcing choice on how our method attributes variations of ω to climatic behavior with our LSM.

Comparing ω_c and ω_a obtained for the three forcings over the common period and for each system, we obtain very similar results when looking at the average variance over all basins for each evapotranspiration efficiencies time-series and the two-by-two correlations (Tab. S1).

The variances have a similar order of magnitude no matter the forcing used to calculate ω_c and ω_a, consistently producing ω_a larger than ω_c by a factor of ten with all forcings. E2OFD has a finer resolution, increasing the results' variability relative to the other two coarser climate datasets. The forcing datasets are not fully independent given the limited number of observations. For instance, GSWP3 and WFDEI use the same precipitation product to bias correct the re-analyses on which they are based. E2OFD and WFDEI use the same re-analysis but interpolated to different resolutions and corrected with two distinct observational precipitation estimates. Given that the results are closer for GSWP3 and WFDEI, we can hypothesize that the method is more sensitive to the precipitation data used than the other variables.

These results show globally that the method is robust, since it is not very sensitive to the forcing used. The differences in variance between forcings are smaller than those between the variance of ω_a and ω_c for all tested forcings. The poorest correlation is between E2OFD and GSWP3 (the forcings most different from each other) and mostly for ω_c, which has the smallest average variance. Therefore, it will impact our results less when comparing trends. However, the absolute values of ω are significantly different depending on the forcing used, comforting the idea that this method can only be used to assess and compare trends.

Results presented in the article are obtained with the forcing dataset GSWP3, which covers the longest time period 1901-2012 and is thus most relevant for evaluating the driver of river discharge trends.



(a) NSC: Q_{climat} vs Q_{LSM}

(b) PBIAS: Q_{climat} vs Q_{LSM}

(c) NSC: Q_{actual} vs Q_{obs}

(d) PBIAS: Q_{actual} vs Q_{obs}

Figure S1. Using Nash-Sutcliffe coefficient (NSC) and absolute Percent bias (PBIAS) to compare river discharge modelled Q_{LSM} or observed Q_{obs} to river discharge Q_{climat} and Q_{actual} calculated with Fu's equation, to attest the quality of the Budyko framework. Colors from yellow to pink are considered as satisfactory.

Table S1. Comparison of the evaporation efficiencies time-series calculated with the different forcings for each system over the period 1979-2010: ω_c for the climatic system and ω_a for the actual system.

Average variance over all catchments

	ω_c	ω_a
GSWP3	0.0023	0.039
WFDEI	0.0033	0.036
E2OFD	0.0110	0.031

Correlations:

% of stations with average correlation > 0.6 and median correlation between all catchments

	ω_c		ω_a	
E2OFD/GSWP3	38%	0.50	53%	0.65
WFDEI/GSWP3	73%	0.75	77%	0.99
E2OFD/WFDEI	64%	0.70	59%	0.73

Map of the specific catchments referred to in the study

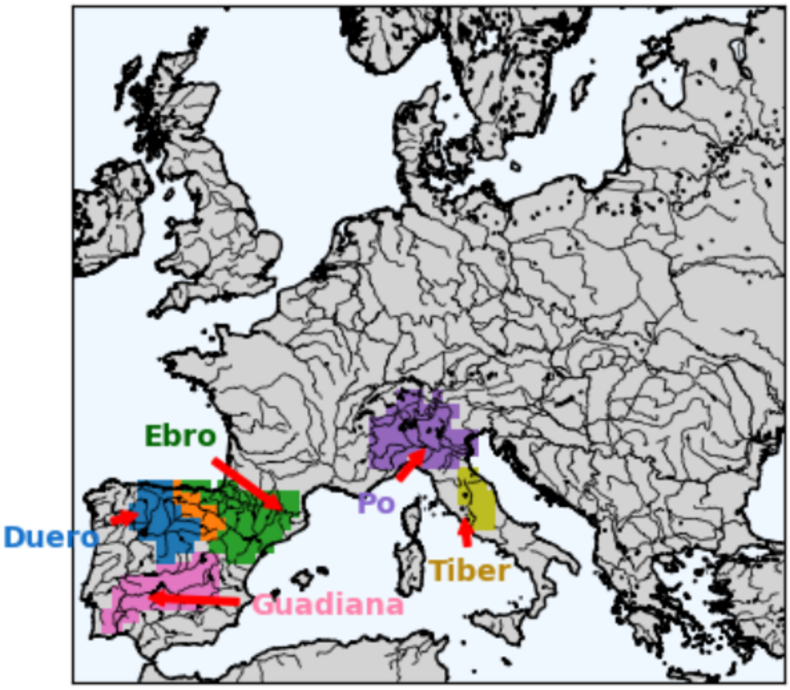
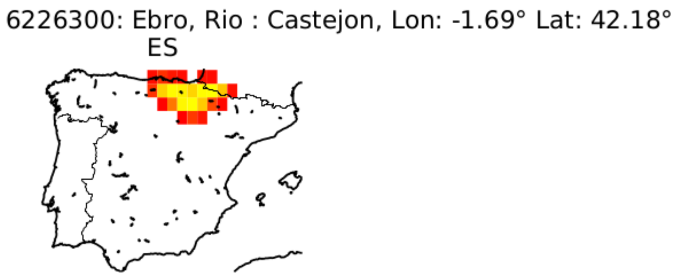


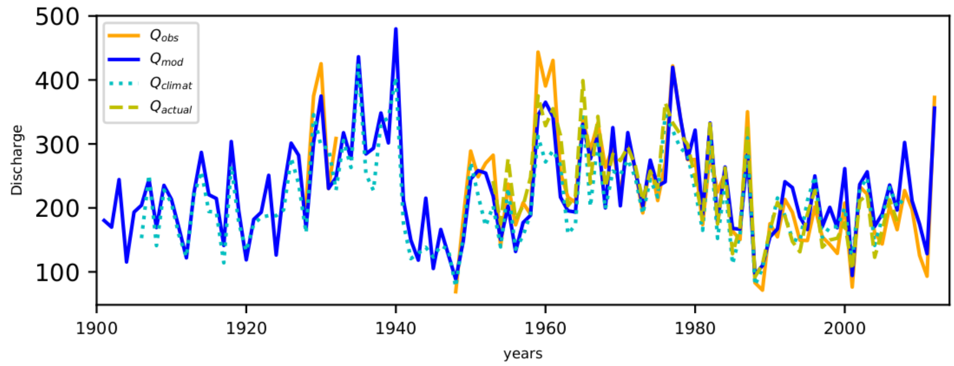
Figure S2. Catchments of specific rivers in Spain (Ebro, Duero, Guadiana) and Italy (Tiber, Po), referred to in the article as specific examples of some results and hypotheses.

Illustration of the analysis at the catchment level

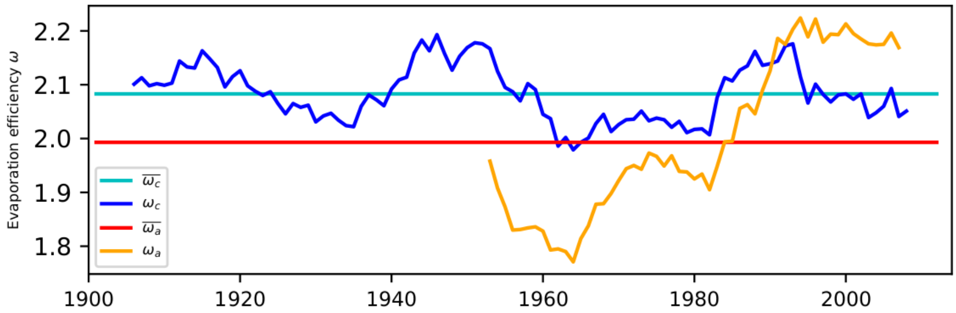
The discharge (Fig. S3b) at the station level has continuous observations from the 1950's (Q_{obs}). We see that if the variability of Q_{obs} and Q_{mod} are very similar (Fig. S3b), we see that over the observation period covered by the observation, at the beginning of the period (1950-1970), $Q_{obs} > Q_{mod}$ while at the end of the period (1990-2010), $Q_{obs} < Q_{mod}$. Both tend to decrease but Q_{obs} has a steeper decrease. Looking at the variations of ω (Fig. S3c) in both systems helps to explain that difference. ω_c is not constant over time but its variability is smaller than that of ω_a. There are other non-climatic factors inducing higher trends. For the particular case of Castejon, there are two time periods at the end of the 1960's end in the 1985-1995 period where there are trends in ω_a with a slope which is higher than 90% of all of ω_c slopes over the entire century (Fig. S3d). Therefore, there is a high probability that these slopes can not be explained only by climatic phenomena. They are positive trends: non-climatic factors tend to increase evaporation efficiency (associated with a decrease in discharge, not significant, however, at the decadal scale).



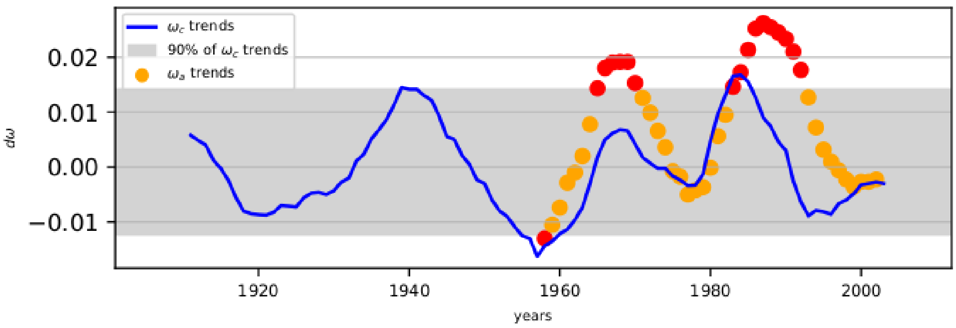
(a) Watershed of the gauging station Castejon on the Ebro river



(b) Discharge at the station outlet: Observed discharge Q_{obs} (orange), modeled discharge from the LSM ORCHIDEE Q_{mod} (blue) and from the Budyko framework fitted on the model Q_{climat} (dotted blue) and on the observations Q_{actual} (dashed orange)



(c) ω fitted on the model outputs (ω_c (blue) corresponding to the "climatic" ω, compared to ω_a (orange) fitted on the observations).



(d) Slopes of ω calculated with an 11-year time moving window (slope calculated over 11 years, 5 years prior and after the referenced year), for ω_c (blue) and for ω_a (orange). The red points corresponds to years for which the absolute slope of ω_a is different from 90% of all ω_c slopes (grey area).

Figure S3. Example of the results at the station level for the gauging station Castejon on the Ebro river in Spain