Identifying and quantifying the impact of climatic and non-climatic drivers on river discharge in Europe

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Key Points:

- Attribution of streamflow trends to climate drivers
- Larger effect on streamflow of non-climatic drivers
- Strong impact of human activities, especially over Spain

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Abstract

Our water resources have changed over the last century through a combination of water management evolutions and climate change. Understanding and decomposing these drivers of discharge changes is essential to preparing and planning adaptive strategies. We propose a methodology combining a physical-based model to reproduce the natural behavior of river catchments and a parsimonious model to serve as a framework of interpretation, comparing the physical-based model outputs to observations of discharge trends. We show that over Europe, especially in the South, the dominant explanations for discharge trends are non-climatic factors. Still, in some catchments of Northern Europe, climate change seems to be the dominating driver of change. We hypothesize that the dominating non-climatic factors are irrigation development, groundwater pumping and other human water usage, which need to be taken into account in physical-based models to understand the main drivers of discharge and project future changes.

Plain Language Summary

Water is an essential resource. Its access and management are key challenges in the context of climate change. Changes in precipitation distribution and intensity and other climate effects lead to a change in the water availability and in the discharge of rivers. On top of that, humans intervene to uptake water from rivers and change streamflow dynamics. To better assess management practices and prepare for future climate conditions, it is important to understand which part of discharge evolution is due to climate and which part is due to human intervention. In this article, we present an innovative methodology to do so. We show that over Europe, if discharge in the North is mostly impacted by the evolution of climate, in the rest, water management practices are the main cause of discharge changes. This is especially the case for the drying discharge trends in the South. Therefore, the evolution of management practices must be particularly of interest when constructing adaptation pathways to future climate conditions.

1 Introduction

Water is an essential resource for both ecosystems and human needs. Floods or water scarcity can lead to environmental catastrophes, conflicts and economic hardships. Understanding the evolution of water availability is a key challenge in the context of climate change and a highly managed continental water cycle. To study the evolution of water resources, one key variable is streamflow. Being at the surface, it is directly related to freshwater available to humans and ecosystems (Dai, 2016). In order to optimize its availability and reduce the impacts of floods and hydrological droughts, mankind has managed it over the last millennia. Because of its central role in our water resources, it has also been well observed over the last century.

From a geophysical perspective, streamflow provides a comprehensive overview of the water dynamics of catchments as it is the result of the catchment-integrated balance between water storage, precipitation and evapotranspiration (Milly et al., 2005; Rottler et al., 2020). These last two fluxes are dominated by climate processes and thus driven by atmospheric variability and trends (Christidis & Stott, 2022; García-Ruiz et al., 2011). On the other hand, it is through the management of water storage (reservoirs or groundwater pumping) and evaporation (land use and irrigation) that humans optimize the benefits they take from surface water and modify streamflows (Schneider et al., 2013; Riedel & Weber, 2020).

All of these processes have confounding effects on river discharge, which makes it difficult to detect and attribute trends in water resources (Rottler et al., 2020; Ficklin et al., 2018). With climate change, precipitation distribution, frequency and intensity are evolving, along with an increase in atmospheric water demand due to increased en-

ergy available at the surface and atmospheric water holding capacity and to changes in turbulences (Douville et al., 2021; Christidis & Stott, 2022; García-Ruiz et al., 2011; Ribes et al., 2019; Dezsi et al., 2018). In turn, human activities and management, through abstractions (for irrigation, domestic uses...) and regulations (dams, reservoirs...), directly impact the partitioning of water between runoff and evapotranspiration along with flow seasonality, due to additional water uptakes and to controlled water releases (Rottler et al., 2020; García-Ruiz et al., 2011; Ficklin et al., 2018). Therefore, streamflow changes are driven by climate change and anthropogenic activities, both influencing catchment dynamics and equilibrium.

To project future streamflow changes and adapt water management strategies to climate change, it is essential first to understand the relative weight of these different drivers in streamflow dynamics. Being able to attribute past changes in river discharge to either climatic factors or human intervention on the land surface processes provides invaluable information to water managers in an evolving water cycle.

Physical-based land surface models (LSMs) and global hydrological models (GHMs) have been developed to understand streamflow dynamics, reproduce land surface processes and predict the evolution of the water cycle using different scenarios for the future (W. Zhao & Li, 2015; Nazemi & Wheater, 2015). They have grown more complex over time and represent, at best, the current understanding of surface/atmosphere interactions, vegetation dynamics and hydrological processes under the control of climate (Tafasca et al., 2020; Quintana-Seguí et al., 2020; Stephens et al., 2023). These models are very useful to study patterns of change and trends and link them to specific processes (Douville et al., 2021; Zanardo et al., 2012; Alkama et al., 2010; Do et al., 2020). However, to this day, they fail to effectively include most anthropogenic water usage and management, even if progress is being made in that direction (F. Wang et al., 2018; Nazemi & Wheater, 2015).

In view of the complexity of land surface processes and the lack of data, another class of models has also been developed: parsimonious or calibrated models. Based on the perceived functioning of the surface hydrology (Beven & Chappell, 2021), relations and parameters are selected and then adjusted over a period to represent, at best, actual streamflow characteristics. These models have demonstrated their value for operational short-term predictions and to represent and detect current trends in discharge with a simplified interpretation tool (Jiang et al., 2015; Andréassian et al., 2016; Perrin et al., 2003). However, they are limited in their ability to predict changes associated with specific drivers due to the difficulty of physical interpretation of the adjusted parameters and the undetermined sensitivity of these parameters to the drivers (Zheng et al., 2018; Andréassian et al., 2016; Coron et al., 2014; Nicolle et al., 2021). Still they have been used to try and separate the effect of anthropogenic activities from climatic drivers, often comparing a reference "untouched" period or area to a post-change period or to a similar but highly anthropized area (Ficklin et al., 2018; W. Wang et al., 2020; Palmer et al., 2008; Ahn & Merwade, 2014; Zheng et al., 2018; Luo et al., 2020; J. Zhao et al., 2018). However, these methods all rely on the debatable assumption that the adjusted parameters are independent of climate variability (Coron et al., 2014; Andréassian et al., 2016; Reaver et al., 2022).

Using both classes of models, we propose a method to analyze observed annual river discharge and decompose observed trends into climate-driven changes and those caused by human intervention on the continental water cycle. The LSM is chosen as the climatic reference as it represents the behavior of catchments and land surface dynamics, responding to changes in climate variables only. Due to the incomplete representation of the complex land surface processes and the lack of representation of human water management, the direct validation of the predicted river discharge to observation is difficult (Hagemann & Dümenil, 1997). The Budyko space and the one-parameter parsimonious model proposed by Fu's equation (Zhang et al., 2004) is used as a framework for interpreting both

the LSM's simulated and the observed historical discharge. This parsimonious model introduces a parameter allowing to isolate the partial trends in discharge (Q) due to a change in catchment evaporation efficiency from the partial trend due to changes in the two main average climate variables precipitation (P) and potential evapotranspiration (PET) (Collignan, Polcher, Bastin, & Quintana-Segui, 2023). Projecting the LSM output onto this framework allows to derive the climate sensitivity of the adjusted parameter of the parsimonious model. In turn, comparing these results to the interpretation of observed historical records by the Budyko model allows to isolate the trends due to changes in evaporation efficiency and land characteristics not represented by the LSM. This separates the observed changes in streamflow into a component that can be attributed to climate variations and another that can be linked to human activities.

2 Method

The Budyko framework is a relatively simple empirical framework which relies on balancing the water and energy fluxes through only a few variables (precipitations P and potential evapotranspiration PET) to express the partitioning of water between evapotranspiration E and runoff. As opposed to other simple empirical models such as linear regression models, it accounts for physical boundaries: the water limit and the energy limit on the system. For the framework to work, it needs to be applied to a closed system where the boundaries can be defined, such as a watersheds at an equilibrium state (the variations of water storage within the catchment are supposed to be small). It is simple enough to be applicable to a wide variety of observed catchments as only basic variables are needed. In this study we used the parametric equation of Fu-Tixeront (Zhang et al., 2004) (Zhang et al., 2008) (Zheng et al., 2018). It reduces for each catchment its evaporation efficiency to a single specific parameter ω (Equ. 1), fitted over hydrological year averages, in a given period. For the same climatic conditions P, PET, a catchment with a higher ω will evaporate more than another one with a smaller ω.

In the original framework, this parameter is assumed to be constant since the watershed is considered to be in a stationary state and only driven by climate.

$$\frac{E}{P} = 1 + \frac{PET}{P} - \left(1 + \left(\frac{PET}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} \tag{1}$$

E is the actual evaporation at the scale of the catchment. With the same assumption of a closed system and no water storage change, the water continuity yields for discharge $Q = P - E$.

Here, we consider only that the system is piece-wise stationary and that the parameter can be assumed to the constant over a short period (11 years) (Han et al., 2020). This introduces a time-dependence in the parameter ω by successive fits over an 11-year time-moving window. We therefore capture the long-term effects of climate change and anthropogenic activities, both influencing catchments responses.

As a result, both the annual mean of P and PET, regrouped in the variable C later on, and for the evaporation efficiency ω are time dependent. This allows to construct a framework of interpretation, with a simple decomposition of discharge trends Q: a partial trends due to long-term changes in average climate variable and a partial trend due to changes in catchment responses. More details for this methodology are given in (Collignan, Polcher, Bastin, & Quintana-Segui, 2023). In this framework, the anthropogenic water management and water usage will only change the catchment responses and not the climate variables.

By applying the method to the observed catchments and the representation of these catchments in a land surface model, the relative contribution of climate to trends in discharge can be quantified. The two systems considered are :

- **A climate-driven system, referred as climatic system**: An LSM is used to estimate the climate induced changes in the evaporation efficiency (ω_c). The LSM stands as our climatic reference. It provides us with the following information:

  - $\Delta Q_{climat}(C, \omega_c)$: defined as the climate driven discharge trends.
  - $\Delta Q_c(C, \overline{\omega_c})$: partial trend due to fluctuations in annual averages of climate variables (C), where $\overline{\omega_c}$ is the average evaporation efficiency over the entire period.
  - $\Delta Q_c(C_{rand}, \omega_c)$: partial trend due to climatic impact on evaporation efficiency ω_c, where C_{rand} is a random climate with no trends.

- **The observation-based system, referred as actual system**: the framework is used to decompose the observed discharge changes. We successively fit the framework to discharge observations, getting another time series of the evaporation efficiency parameter ω_a. This provides the following information:

  - $\Delta Q_{actual}(C, \omega_a)$: overall trend in Q in the actual system.
  - $\Delta Q_a(C, \overline{\omega_a})$: partial trend due to changes in C.
  - $\Delta Q_a(C_{rand}, \omega_a)$: By randomizing the climate, the partial trend due to the evolution of evaporation efficiency ω_a can be estimated. In that case, all changes in the watershed characteristics (anthropogenic as well well as its climate induced) are considered.

We illustrate the differences in both systems over a given catchment, with a figure of Q_{climat}, Q_{actual}, ω_c and ω_a, for the station of Castejon, upstream of the Ebro river in Spain (in supplementary materials, Fig. S3).

We consider that the LSM accurately reproduces dynamic changes in an idealized natural catchment driven by observed climatic conditions, even if it might have biases in the absolute values of discharge. Therefore we only compare trends between both systems. All trends are computed using the Mann-Kendall non-parametric test, associated with the Thiel-Sen slope estimator (Xiong et al., 2020), with a 0.05 p-value threshold for significance.

3 Data

3.1 The Land Surface Model ORCHIDEE

The LSM used in this study is the Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) (Krinner et al., 2005) from the Institut Pierre Simon Laplace (IPSL). The current version of the model simulates the global carbon cycle and quantifies terrestrial water and energy balance through biophysical and natural biogeochemical processes. It can include some anthropogenic interference such as land cover changes, forest and grassland management or irrigation (Guimberteau et al., 2012). Here the model is used without these options, as only the climatic dependences of hydrology are sought. Used in off-line conditions, the atmospheric conditions are forced by a given data-set.

3.2 Forcing datasets

Three different climatic datasets are used to drive the LSM. These datasets are used as input to the off-line LSM and provide the variables needed in Fu's equation 1. The main one is the forcing dataset GSWP3 (Hyungjun, 2017), covering the 1901-2012 period at a 3-hourly resolution with a geographic resolution of 0.5°x 0.5°. It is a dynamical downscaling of 20th Century Reanalysis using a Global Spectral Model. It is bias-corrected using Global Precipitation Climatology Center (GPCC) (Rudolf et al., 2005) and Climate Research Unit (CRU) observational data (Harris et al., 2020). The results presented later on are obtained with this forcing dataset.

206 We also use two other forcings, WFDEI-GPCC (Weedon et al., 2014) and E2OFD
207 (Beck et al., 2017), both covering the 1979 to 2014 period. Testing the methodology with
208 different independent climate datasets allows to verify the robustness of our results com-
209 paring the two systems and their sensitivity to the choice of climate forcing used (see
210 supplementary materials).

3.3 Watersheds and discharge observation datasets

212 The river discharge observations collected by the Global Runoff Data Center (GRDC)
213 from gauging stations all over Europe (GRDC, 2020) are the base of the current study.
214 They were completed over Spain with data obtained from the Geoportal of Spain Min-
215 isterio (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020) and over
216 France with data from the database HYDRO (Ministere de l'ecologie, du developpement
217 durable et de l'energie, 2021).. In the final analysis, only 814 stations were kept with at
218 least 50 years of observations and for which we were able to satisfyingly reproduce the
219 upstream catchment in the hydrological routing of the LSM (Polcher et al., 2022; Nguyen-
220 Quang et al., 2018), based on the dataset HydroSHEDS (Hydrological Data and Maps
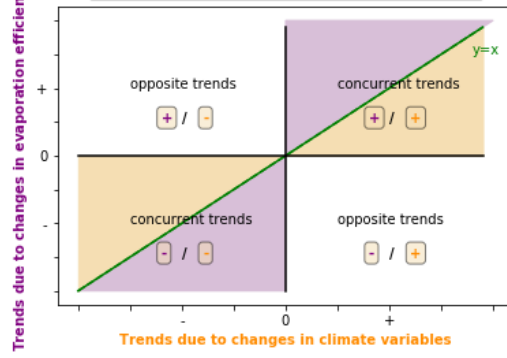221 Based on Shuttle Elevation Derivatives at Multiple Scales) (Lehner et al., 2008).

4 Results

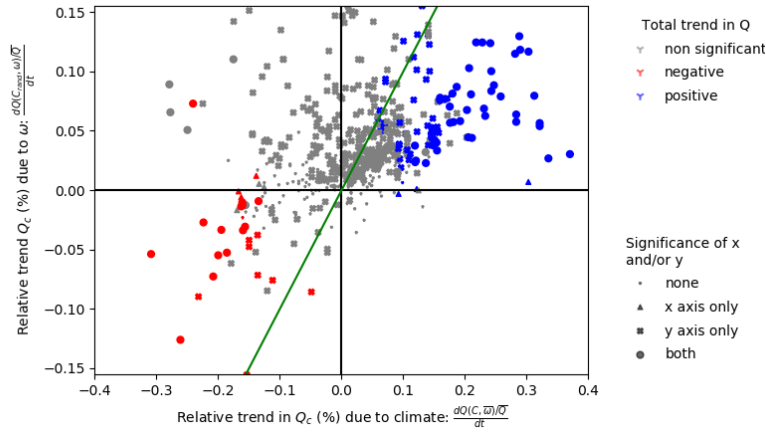### 4.1 Decomposing the trends in river discharge over the past century

224 The framework defined by the parsimonious model chosen allows to separate trends
225 in river discharge (Q) into the part explained by the evolution of climate C (x-axis) and
226 a partial trend due to changes in the catchment affecting evaporation efficiency (ω) (y-
227 axis). Figure 1a allows to illustrate the relative importance of both components of the
228 trends as estimated with the methodology presented above, using a 100-year-long sim-
229 ulation with an LSM and the observed discharge at 569 gauging stations.

230 Positioning the results for one catchment in Fig. 1a allows to illustrate the mag-
231 nitudes of the partial trends due to each component and whether they are concurrent
232 or opposite and if they tend to increase or decrease discharge. Two different systems are
233 projected on this framework for comparison (see Method): the climatic system (Q_{climat})
234 based on the LSM outputs and the actual system (Q_{actual}) based on observed records.
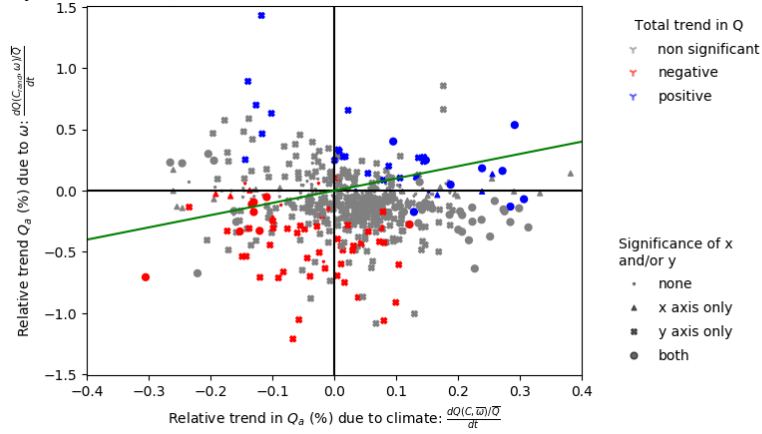
235 Our results show that in the case of the climatic system (Fig. 1b), the changes in
236 annual mean climate variables have about a four times larger impact than the changes
237 in evaporation efficiency on relative annual mean discharge trends. Overall, almost all
238 catchments where Q_{climat} has significantly changed (catchments with significant trends
239 correspond to colored points) have concurrent trends in both components. A high co-
240 variance between these two components allows to better detect the trends. More gen-
241 erally, there is a dominance of the trends in annual mean in climate variables P, PET,
242 amplified by the response of evaporation efficiency of the catchment induced by climate
243 change. These cases correspond to catchments where an increase in P and/or a decrease
244 in PET tends to increase annual mean discharge or inversely for a decrease. For instance,
245 if an increase in P is inhomogeneous, with an even stronger increase in winter precip-
246 itation, the partitioning towards runoff is usually higher, which translates into a decreased
247 evaporation efficiency and thus an even stronger increase of Q_{climat} (top right quadrant,
248 Fig. 1b). Therefore in this example, the increase in the annual mean Q_{climat} is not only
249 due to an increase in annual mean P but is amplified by the more contrasted seasonal-
250 ity and its impact on evaporation efficiency. More generally, there are fewer catchments
251 where the changes in the evaporation efficiency tend to decrease discharge in the climatic
252 system, except when they concur with a high decrease in relative discharge due to a de-
253 crease in P and/or an increase in PET. This is coherent with the increasing intensity
254 and contrasted seasonality of precipitation events observed over Europe (Christidis &

(a) Interpretation scheme: comparing significant trends due to climate variables or due to ω. The graphs have four quadrants: the top right and the bottom left ones correspond to area of the graph where the climatic trend and the area due to ω are complementary/ going into the same direction. The top left one contains the basins for which the trends due to ω are positive and the trends due to climate variables are negative and the bottom right quadrant the opposite.

(b) Climatic system Q_{climat}: relative trends (%/yr over the century) due to changes in ω_c versus relative trends due to changes in climate variables C

(c) Actual system Q_{actual}: relative trends (%/yr over the century) due to changes in ω_a versus relative trends due to changes in climate variables C

Figure 1. Comparing the relative trends ($\frac{dQ}{dt}/\overline{Q}$) due to a change in climate variables or due to a change in evaporation efficiency ω in the evolution of discharge, for both system Q_{climat} and Q_{actual}. One point corresponds to a basin with at least 50 years of river discharge observations over Europe. The scale of trends due to ω_a in the actual system is ten times larger than the one for trends due to ω_c in the climatic system. The green line is the line $y = x$. The color scale represents the significance of the trend in Q when all factors are considered. The markers indicate whether the partial trends are significant due to changes in C (x-axis), in ω (y-axis), or both.

Stott, 2022; Riedel & Weber, 2020; Zveryaev, 2004; Ribes et al., 2019; Douville et al., 2021), which would logically tend to decrease evaporation efficiency by increasing local runoff, and therefore lead to a positive partial trend in discharge.

In the case of the observed system (Fig. 1c), the relationship between the two partial trends looks very different. The one linked to changes in evaporation efficiency is larger than the partial trends linked to the annual mean in P and PET by a factor of 3. More generally, the total trends in Q_{actual} (catchments with significant trends correspond to colored points) follow the partial trends due to changes in the catchments' evaporation efficiency. Therefore, in the actual system, the trends in discharge are mainly due to changes in catchment behavior due to non-climatic factors. Contrary to when only climate change is considered for natural catchments, land use changes and human water management tend to increase the evaporation efficiency of catchments and, therefore, decrease Q_{actual}. This is coherent with activities such as irrigation, or agriculture in general, which aim at optimizing the evapotranspiration over catchments.
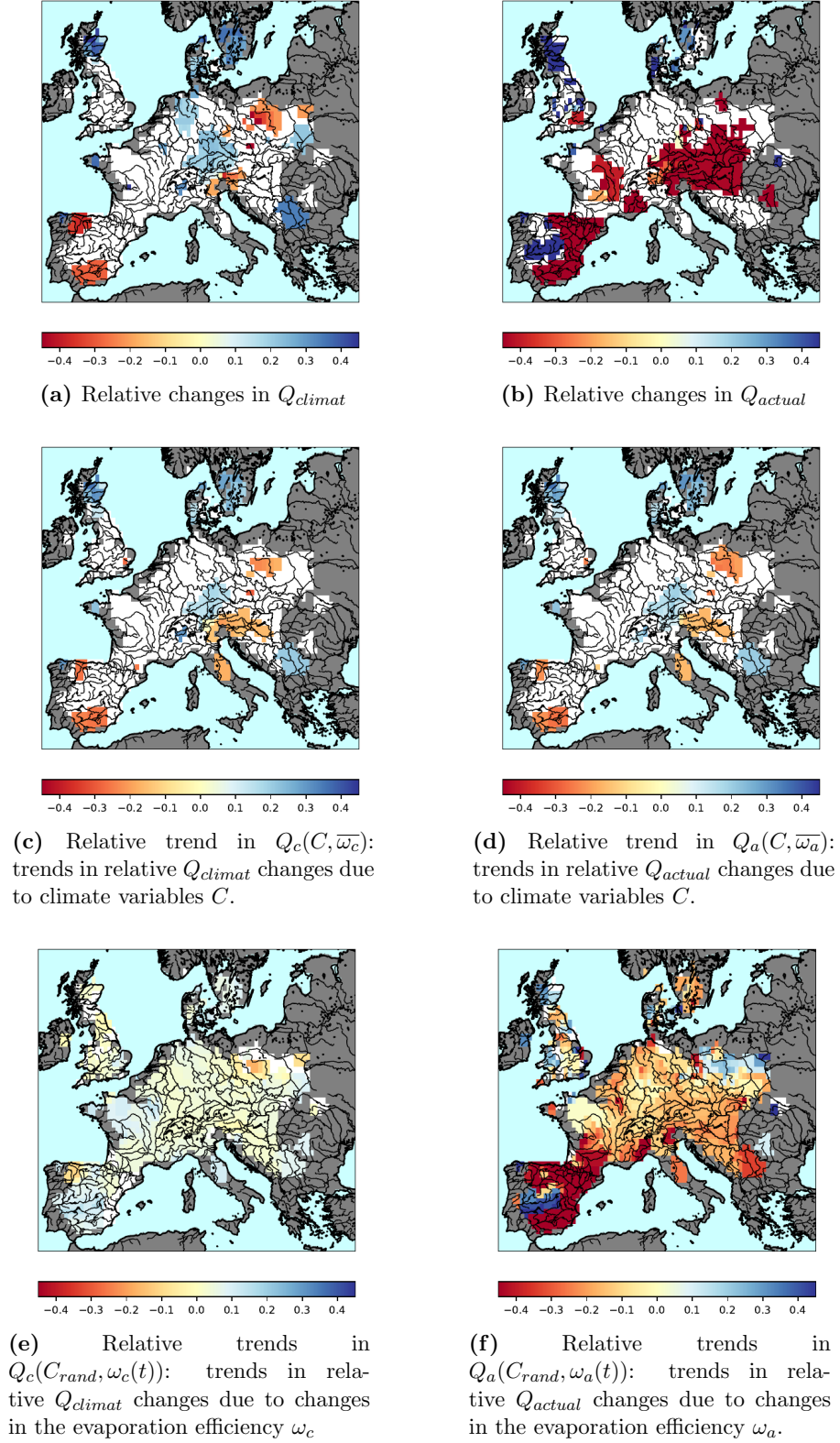
4.2 Geographical distribution of discharge trend characteristics

The spatial distribution of the significant relative trends (Fig. 2) is spatially coherent, which also attests to the method's robustness. When some specific catchments are referred to, the geographic location of these catchments is illustrated in supplementary material (Fig. S2).

In the climatic system (Fig. 2a), basins in eastern Europe and Spain are getting dryer with trends in discharge between -0.2%/yr and -0.5%/yr over the past century. In central and northern Europe, the climatic discharge is increasing with trends of +0.2%/yr to 0.5%/yr over the past century. Similarly to the previous results, we observe that in this system, the trends in discharge Q_{climat} (Fig. 2a) are mostly driven by changes in average climate variables C (Fig. 2c) and not to changes in evaporation efficiency ω_c (Fig. 2e). These partial trends due to changes in the evaporation efficiency ω_c (Fig. 2e) are small (between -0.2%/yr to +0.2%/yr) and are mostly positive. Their effect is negligible when looking at the total trends in discharge (Fig. 2a). It can however amplify the partial trend due to changes in the annual average of climate variables C. It corresponds to the top-right and bottom-left quadrants in Fig. 1b. This effect is illustrated in the Duero basin in north-western Spain, where both partial trends concur to a decrease in Q_{climat}. They can also cancel each other out, for instance, in the Tiber River in Italy, where the decrease in Q_{climat} due to changes in C is not significant in the overall changes in Q_{climat}.

Again, for the actual system, our results show that the discharge trends (Fig. 2b) are mostly explained by changes in the evaporation efficiencies (Fig. 2f). Here the changes in the evaporation efficiency ω_a encompass all changes in the catchment's evaporative behaviors, those induced by climate and those by changing water usage. Similarly to results from other studies (Vicente-Serrano et al., 2019) over Western Europe, we find the highest negative trends are over Southern Spain and are mostly driven by non-climatic factors. To facilitate the comparison, scales of the Fig. 2 are fixed thus for Fig. 2d and Fig. 2f they saturate, not showing that the trends are a lot higher in Spain, with up to -4.4%/yr change over the past century in Q_{actual}. Over the rest of Europe, trends are lower and less significant, with positive trends generally in northern Europe, Great Britain and Sweden and negative trends over central Europe. The south of Spain corresponds to an area where both climate changes and changes related to human activities led to a significant decrease in river discharge over the past century. There, mainly, the changes in evaporation efficiency result in decreasing trends in Q_{actual} (Fig. 2f). This is coherent with increasing irrigation water uptakes. However, the Guadiana River stands out in our results. It seems that over that specific catchment, the overall effect of human water management and land use changes tend to increase Q_{actual}, contrary to the rest of

(a) Relative changes in Q_{climat}

(b) Relative changes in Q_{actual}

(c) Relative trend in $Q_c(C, \overline{\omega_c})$: trends in relative Q_{climat} changes due to climate variables C.

(d) Relative trend in $Q_a(C, \overline{\omega_a})$: trends in relative Q_{actual} changes due to climate variables C.

(e) Relative trends in $Q_c(C_{rand}, \omega_c(t))$: trends in relative Q_{climat} changes due to changes in the evaporation efficiency ω_c

(f) Relative trends in $Q_a(C_{rand}, \omega_a(t))$: trends in relative Q_{actual} changes due to changes in the evaporation efficiency ω_a.

Figure 2. Significant trends in the relative river discharge $Q/\overline{Q}$ over the time period 1901-2012 (%/yr over the century). The scales have been forced to be the same for all maps for comparison purposes but the extrema can go higher or lower.

Spain. As discussed later, this could be linked to unsustainable groundwater pumping (Holtz & Pahl-Wostl, 2012), which invalidates the hypothesis of no water storage change and, therefore, results in a lower apparent evaporation efficiency and an artificially underestimated evapotranspiration, increasing the resulting discharge. More generally, there are several basins over Europe where the trends induced by changes in the evaporation efficiency lose their significance when the climate variability is considered in the reconstructed discharge. See, for instance, western France, northern Germany, Serbia.

Interestingly, when we draw similar maps for sub-periods of 10 years, the impact of evaporation efficiency changes on discharge is not dominant anymore. At the decadal scale, the climatic variability is high. This climatic noise covers the effect of changes in the catchment's evaporation efficiency in discharge trends. At the scale of the century, the signal-to-noise ratio is higher, bringing to light the long-term role of changes in the catchment's evaporation efficiency and catchment's behavior on discharge.

5 Discussion

Our method uses a parsimonious hydrological model to decompose the observed river discharge trends into climate-driven processes, as estimated with a state-of-the-art LSM, and non-climatic changes that can be attributed to human activities. It can be generalized to the use of any couple of calibrated parsimonious model and physical-based model and be an effective operational tool to estimate and illustrate the effect of non-climatic drivers and land surface changes not well accounted for in current models and which may have a strong direct impact on water resources.

We show that the dominant explanation for river discharge trends is non-climatic factors, especially in Southern Europe. In some catchments of Northern Europe, climate change seems to be the dominating driver of change. Still, in accordance with previous studies (Gudmundsson et al., 2017), our results highlight the fact that not accounting for non-climatic trends leads to high under-estimation of discharge changes in the physical-based model used and therefore to high uncertainties in projections of future water resource trends, especially when looking at long-term trends.

With this methodology, we can only estimate the magnitude of non-climatic trends but not attribute them to specific processes. In some areas where a dominant process can be hypothesized, such as irrigation, correlation with indicators can allow to verify the plausibility of the assumed cause. For instance, over Spain, especially over the Ebro basin, the strong increase in evaporation efficiency and reduced discharge is correlated to the development of dams with a coefficient above 0.7 when correlating ω_a to reservoirs levels for 6 sub-basins in this catchment. Dams water storage is an indicator for human management of water resources impacting the evaporation efficiency of watersheds. More generally, we see that the changes in the evaporation efficiency intensified over the second part of the century, where areas equipped for irrigation have been developed (Angelakɩs et al., 2020; Siebert et al., 2015). However, the available data are insufficient to attest to a correlation with that latter factor or with the effective amount of water used for irrigation. Groundwater pumping and glacier melt can explain positive trends in discharge due to additional sources of water not accounted for in the climatic system, which lead to artificially low evaporation efficiencies in our framework. For the Guadiana River in Spain, the unsustainable groundwater pumping (Holtz & Pahl-Wostl, 2012; Llamas et al., 2015; Esteban & Albiac, 2012) can explain the positive trend. In a similar way, for the Po river in Italy, which is highly irrigated (Siebert et al., 2015), we would expect a strong decrease in discharge as in most of Spain, but glacier melt brings additional water to the system (Schaner et al., 2012; Vincent et al., 2017; Huss & Hock, 2018), explaining a reduced detected negative trend over the end of the century. Other phenomena, such as soil sealing and river management, would be expected to have similar effects due to a decrease in evapotranspiration or to an artificial enhancement of runoff.

Changes in land use as represented in ORCHIDEE (Lawrence et al., 2016) are shown to have little effect on discharge over the studied period and area but could have a more significant effect at finer scale over small catchments.

Quantifying the contribution of climatic and non-climatic factors to changes in river discharge is an important first step. But it should be followed by an attribution. The use of the LSM in its current state allows to attribute the changes due to climate. However, the non-climatic factors remain challenging to attribute to specific processes, especially since most factors have concurring and competing effects. Detection and attribution methods have been developed in climate studies to assess anthropogenic climate change. They have allowed to determine the role of different factors by reproducing them first in GCMs (Hegerl & Zwiers, 2011; Douville et al., 2021). Similarly, we would need to simulate water usage such as irrigation, dam management, groundwater pumping and other missing phenomena such as glacier melting in the LSMs so that their impact on the evaporation efficiency can be identified and their contribution to the non-climatic trend quantified.

Understanding and quantifying the contribution of various processes contributing to observed discharge changes over the past century is an essential step in developing adaptation strategies to face climate change. In the future, changes in climatic variables are expected to increase even further, with increase in intense precipitation events (Ribes et al., 2019; Douville et al., 2021), an increase in evaporative demand and especially a decrease in average precipitation leading to water scarcity over southern Mediterranean Europe (Gudmundsson et al., 2017; Alkama et al., 2013). Concurrently, in Europe, human water management is expected to evolve to adapt to climate change and other constraints, such as changes in water and energy demand and regulations (Arheimer et al., 2017). For instance, the extent of irrigated land in Europe peaked at the end of the 20th century and the future irrigation evolution is expected to follow new goals and mostly rely on improved efficiency (Adeyeri et al., 2020). Therefore, the balance between the different terms influencing catchment evaporation efficiency and discharge may change. If non-climatic factors dominated over the past century to explain discharge trends, it may not be the same in the future. Attribution needs to be tested over the documented past to improve the representation of non-climatic processes and allow the effective projection of future evolutions and eventual changes in this balance.

Open Research Section

The outputs of the LSM ORCHIDEE for each catchment used in this study with the forcing GSWP3 are gathered in a file freely available on Zenodo.org (Collignan, Polcher, Bastin, & Quintana-Seguí, 2023). This file also contains the description of the stations used in the study: their location, the size of the upstream area used to position the station on the grid and annual averages of streamflow observations.

Acknowledgments

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