

# Attributing European runoff changes to climatic drivers under future conditions

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## ABSTRACT

Understanding the impact of climatic drivers on future catchment runoff is crucial for assessing how climate change will influence hydrological regimes. This knowledge is essential for evaluating water resources at the local and regional scales. Here, we assessed the contributions of climatic drivers to runoff changes under future conditions across Europe by analyzing the sensitivity of runoff to changes in precipitation and potential evapotranspiration using the Budyko framework. This analysis was conducted for 35,408 basins and based on ensembles of bias-adjusted climate projections and hydrological data. We further explored the link between runoff changes and catchment hydrological similarities, investigating the impact of climatic drivers on runoff across different hydrological regimes in three future periods (early, mid and late century) and emission scenarios. Results indicate precipitation as the primary driver of runoff changes across Europe under low and medium emission scenarios. However, by the mid and late century in high emission scenarios, potential evapotranspiration's contribution becomes comparable to precipitation, significantly influencing runoff variations in central and southern Europe. Finally, the sensitivity of the runoff changes to climatic drivers is linked to the regime of the river systems. Runoff changes in basins with slow response to precipitation tended to show a more balanced contribution from both precipitation and potential evapotranspiration under high emission scenarios, while basins that are very responsive to precipitation, changes in precipitation primarily led to runoff changes. This Budyko-based diagnosis provides new insights into attribution analysis by linking hydrological regimes to runoff changes under global warming, supporting more effective local adaptation strategies.

## 1. Introduction

Global warming is a crucial issue with widespread impacts across multiple water-dependent sectors. The understanding of these effects is essential for developing effective adaptation strategies. Shifts in precipitation patterns, frequency and intensity of extreme weather events, and altered evaporation rates highlight the potential vulnerability of surface and subsurface water resources to climate change (IPCC, 2022). These variations influence the timing, location, and intensity of water availability, impacting both water quality and quantity. For instance, changes in precipitation can lead to intensified flooding (Blöschl et al., 2019) or droughts (Brunner and Tallaksen, 2019), affecting water supply for human consumption, agriculture, and energy production (Byers et al., 2018).

Due to the complex nature of climate and hydrological systems, predicting the impact of climate change on water resources includes dealing with uncertainties from, e.g., greenhouse gas emission

scenarios, climate model structures and their parameterizations, downscaling techniques and bias-adjustment methods. Ensemble climate projections are widely used to consider uncertainties, involving a collection of models to generate a range of possible future scenarios. This approach enhances the robustness of the predictions by accounting for intrinsic model biases and uncertainties. While ensembles expand the range of represented uncertainties, they are not exhaustive, underlining the need for recurrent refinement and model development (Giorgi and Gutowski, 2015). Climate variables from global climate models (GCMs) are typically dynamically downscaled using regional climate models (RCMs) to represent features and dynamics at regional and local scales (Christensen et al., 2019). Bias-adjustment methods are further utilized to reduce residual biases in the GCM/RCM modelling chain, ensuring the resulting data is suitable for climate impact studies (Krysanova et al., 2017). However, the dependence of historical data for bias adjustment and the lack of observations for future periods pose challenges in assessing the credibility of simulated climate change impacts (Kiesel

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et al., 2020). Efforts to understand the uncertainty propagation on hydrological impact assessments have included identifying uncertainty weights between GCMs/RCMs and hydrological models (Pechlivanidis et al., 2017; Samaniego et al., 2017; Vetter et al., 2017), as well as testing methods to provide informative and representative subsets of climate models for decision-making (Kiesel et al., 2020; Pechlivanidis et al., 2018; Sebok et al., 2022). Additionally, there has been a focus on improving hydrological model calibration strategies (Hundechea et al., 2020).

Several studies have examined hydro-meteorological changes across the pan-European domain, highlighting significant changes in runoff patterns, which are expected to be more pronounced due to increasing temperatures and the varying precipitation regimes (IPCC, 2022).

Investigations of historical observations detected regional variations, with patterns of positive trends in annual streamflow in western, central and northern Europe (Gudmundsson et al., 2019; Stahl et al., 2012, 2010) and negative trends in southern and parts of eastern Europe. On an intra-annual scale, wetting trends in the winter and decreasing streamflow in the spring and summer months were observed (Stahl et al., 2012, 2010). Spatial patterns of seasonal and annual runoff changes within regions, i.e. in lowland and mountainous areas, further emphasize the complexity of climate change impacts at the local scale. Increased winter runoff and decreased late spring runoff were associated with an increase in air temperature, a decrease in snowfall (Blahušáková et al., 2020; Yang and Huang, 2023) and a combination of snow cover alterations and human interventions, such as reservoir constructions (Rottler et al., 2020). Additionally, changes in land use, such as forest regrowth after damage, have been found to reduce runoff, in addition to decreased rainfall and increased potential evapotranspiration (Renner and Hauffe, 2024). Drier conditions and reduced precipitation across the year in the Mediterranean areas are projected for the future (Schneider et al., 2013; Yeste et al., 2021) impacting streamflow magnitudes in these areas and in the boreal climate zone due to opposite climatic conditions (Donnelly et al., 2017; Schneider et al., 2013). In addition, hydrological extremes are expected to rise in intensity and frequency affecting the socio-economic impact of floods (Thober et al., 2018) and droughts (Forzieri et al., 2014; Gu et al., 2023; Roudier et al., 2016). Despite advancements in understanding climate-induced hydrological changes, a key challenge remains in precisely attributing the changes to specific climate drivers (Slater et al., 2021). Disentangling these influences is essential for developing effective adaptation and mitigation strategies that account for both natural and anthropogenic factors.

A variety of methodologies have been developed to attribute observed hydrological changes to climate change. Statistical methods, such as correlation-based approaches and qualitative explanations, have been widely used to attribute detected hydrological changes to climatic drivers, typically precipitation and temperature, assuming limited human influences (Hannaford et al., 2013; Krakauer and Fung, 2008; Schneider et al., 2013; Stahl et al., 2012). Moreover, hydrological models have been used to simulate streamflow under different conditions, comparing scenarios with and without changes of each climatic driver (Hundechea and Merz, 2012). The difference in model outputs is then attributed to the influence of the modified factor. Moreover, the Budyko framework has been used for attributing hydrological changes to climate factor variations. The framework estimates the contributions of the climate drivers to runoff change through the sensitivity of hydrological variables to the basin's precipitation and potential evapotranspiration changes during impacted and natural periods based on the water balance equation (Liu et al., 2021, 2017; Roderick and Farquhar, 2011).

Attribution methodologies have been commonly applied in single river systems and although such studies are informative and detailed on attributing drivers (Tramblay et al., 2019), they cannot capture similar spatial patterns and link them to their common underlying physiographic characteristics. In contrast, large-scale analyses provide a more

comprehensive view of transboundary climate and hydrological processes (Stahl et al., 2012). Although they may not offer the same level of fine scale resolution, they enable insights on emerging patterns to be drawn from large sample hydrology and comparative analysis.

This study seeks to bridge these knowledge gaps by attributing European runoff changes to changes in specific climatic drivers, while also accounting for uncertainties under future conditions leading to more targeted and effective mitigation and adaptation strategies. To achieve these, we pose the following questions: (1) *What is the sensitivity of runoff changes to precipitation and potential evapotranspiration across Europe?* (2) *How do precipitation and potential evapotranspiration changes relatively contribute to runoff changes under future conditions?* and (3) *How are these runoff changes linked to the local hydrological regime across Europe's hydro-climatic gradient?* To address these questions, we: (a) adopt a theoretical elasticity Budyko framework to quantify and attribute runoff changes to precipitation and potential evapotranspiration under different future periods and emission scenarios and (b) identify how the relative contribution of precipitation and potential evapotranspiration to runoff changes varying across different hydrological regimes in European river systems. In total 35,408 basins lying across Europe diverse regimes were analysed and intercompared using data from the E-HYPE hydrological model and bias-adjusted Euro-CORDEX climate projections.

## 2. Hydro-climatic data and models

### 2.1. Present and future climate data

Daily precipitation (P) and air temperature data at catchment scale over Europe were provided by nine bias-adjusted regional climate simulations from the European Coordinated Regional Climate Downscaling Experiment, Euro-CORDEX (Table 1). Three representative concentration pathways (RCPs) are included, representing low, medium and high emission scenarios (RCP2.6, 4.5 and 8.5, respectively). The ensemble includes three different emission scenarios, three global circulation models (GCMs) and five regional climate models (RCMs). The dataset is divided in a reference period (1971–2000) and three future periods: 2011–2040, 2041–2070, and 2071–2100, referred to as early, mid, and late century (Berg et al., 2021b). Note that the ensemble does not fully cover all sources of uncertainty within the modeling chain. In particular, the ensemble is biased with the EC-EARTH GCM and the CCLM4-8-17 RCM being over- and under-represented within the ensemble, respectively. Moreover, some model combinations were used more than once; projections 8 and 9 were produced using different initial Earth system states of the GCM scenarios. Nevertheless, we assumed that all available climate models are equally probable in representing future conditions, meaning that they are free of systematic errors and have acceptable historical performance. Different methods for ensemble subsetting have been proposed to minimize potential bias, with comparative analyses indicating that the method selection is critical (Kiesel et al., 2020). The

**Table 1**

The ensemble of Euro-CORDEX projections used to produce hydrological impacts. All members are available for the RCP2.6, 4.5 and 8.5 emission scenario.

| # | RCP           | GCM         | RCM        |
|---|---------------|-------------|------------|
| 1 | 2.6, 4.5, 8.5 | EC-EARTH    | CCLM4-8-17 |
| 2 |               |             | RACMO22E   |
| 3 |               |             | RCA4       |
| 4 | 2.6, 4.5, 8.5 | HadGEM2-ES  | HIRAM5     |
| 5 |               |             | RACMO22E   |
| 6 |               |             | RCA4       |
| 7 | 2.6, 4.5, 8.5 | MPI-ESM-LR* | RCA4       |
| 8 |               |             | REMO2009   |
| 9 |               |             | REMO2009   |

Note: RCMs have a 0.11 degree (about 12.5 Km) horizontal spatial resolution.

\*The GCM model MPI-ESM-LR has two realizations indicating different initial Earth system states of the GCM scenarios (projection 8 and 9).

selection of representative subsets of projections may also differ based on the geographic regions evaluated and the temporal periods analyzed (Pechlivanidis et al., 2018). Testing all the different methods for each location of interest poses comparative challenges at the Pan-European scale; therefore, we did not consider ensemble subsetting in our analysis.

## 2.2. Hydrological model and data

The Hydrological Predictions for the Environment (HYPE) model (Lindström et al., 2010) is a semi-distributed, process-based hydrological model designed for basin-scale simulations of key processes such as snow and ice dynamics, soil moisture, groundwater flow, and water routing. Rainfall and snowmelt infiltration are modeled based on soil type, and potential evapotranspiration is calculated using the modified Jensen-Haise model. Runoff and water percolation are triggered by soil moisture thresholds, while groundwater levels reflect the saturation of soil zones. The model also routes streamflow through sub-basins, regulates lake and reservoir outflows with rating curves, and simulates irrigation based on crop water demands. The European configuration, E-HYPE (Hundecha et al., 2016), spans 8.8 million km<sup>2</sup> across 35,408 sub-basins (~215 km<sup>2</sup> each) and runs on a daily time step. Built on open datasets, it integrates land use, river networks, soils, lakes and reservoirs, and irrigation data, providing a comprehensive framework for pan-European hydrological modeling.

The precipitation and temperature projections were also bias-adjusted using a method that separates both data into two time scales and applies an empirical quantile mapping, as described by (Berg et al., 2021b). The approach involves calculating a 30-day running mean and anomalies, which are then adjusted through empirical transfer functions for each day of the year. Mean and anomaly data are, then, merged to create the final adjusted time series for both precipitation and temperature. Bias-adjustment was conducted using EFAS-Meteo as reference, allowing the cumulative distribution of daily precipitation and temperature projections to follow that of the reference dataset closely. Daily runoff simulations (Q) in the reference period were obtained by forcing the pan-European E-HYPE hydrological model with the nine bias-adjusted precipitation and temperature simulations (Berg et al., 2021a). Potential evapotranspiration (E<sub>0</sub>) was estimated by the Jensen-Haise method based on daily mean air temperature. Daily P, E<sub>0</sub> and Q data were aggregated into mean values over a 30-year time period for both the reference and future periods. The relative changes of precipitation and potential evapotranspiration were calculated between the future and the reference periods for the early, mid and late century (Fig. 1).

## 3. Methodology

### 3.1. Climatic drivers attribution – Budyko framework

In this study, we applied a Budyko-based framework to quantify and attribute future runoff changes to precipitation and potential evapo-

transpiration as the primary climatic factors (Fig. 1). The Budyko-based framework describes the partitioning of precipitation (P) into evapotranspiration (E) and runoff (Q) as a functional balance between the water supply from the atmosphere and the water demand from it (potential evapotranspiration, E<sub>0</sub>). Following previous studies on the attribution of runoff changes (e.g. Liu et al., 2021, 2017; Roderick and Farquhar, 2011), the water-energy balance equation by (Yang et al., 2008) is given in equation (1). This equation expresses E changes as a function of climate drivers (P, E<sub>0</sub>) incorporating a basin-specific parameter, *n*. This parameter enhances the partitioning between E and P as its value increases and is associated with basin properties. This formulation is substituted in the water balance equation for long-term runoff changes  $Q = P - E$ , where negligible storage changes over long time scales (e.g. multi-decadal periods) and stationary conditions are assumed.

$$Q = P - \frac{PE_0}{(P^n + E_0^n)^{\frac{1}{n}}} \quad (1)$$

The total differentiation of the equation (1) describes the sensitivity of runoff to changes in P and E<sub>0</sub>. First-order approximation assuming only the impact of climate drivers in the future runoff relative changes resulted in:

$$\Delta Q = \varepsilon_P \Delta P - \varepsilon_{E_0} \Delta E_0 \quad (2)$$

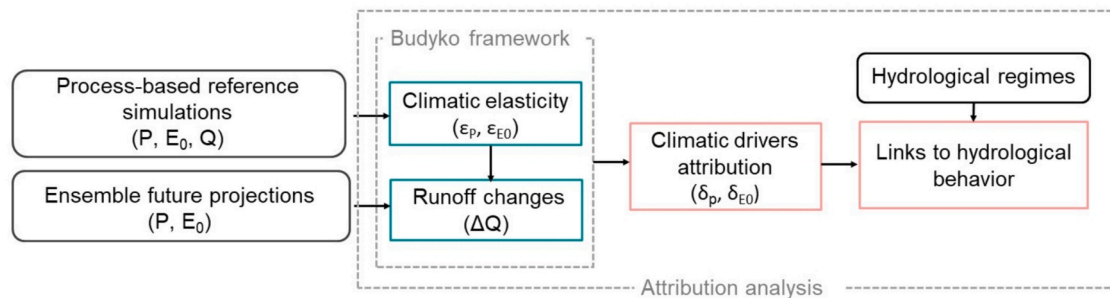
where  $\varepsilon_P$  and  $\varepsilon_{E_0}$  are the elasticity coefficients of the runoff changes to precipitation and potential evapotranspiration changes, respectively. These coefficients are functions of the reference period climate and are calculated by the method proposed by (Roderick and Farquhar, 2011) with the parameter *n* being optimized by minimizing the error between E estimations of Yang's equation and the E-HYPE output. The elasticity coefficients regulate the proportion of runoff changes due to changes in P and E<sub>0</sub> (Fig. 1) and quantify the runoff response. Elasticity coefficients equal to 1 in equation (2) imply that a 1 % increase in precipitation would increase the runoff by 1 %, while a 1 % increase in potential evapotranspiration would cause a runoff decrease of 1 %.

Following (Liu et al., 2017), the contribution of each climate factor ( $\Delta Q_P$ ,  $\Delta Q_{E_0}$ ) on runoff changes in the early, mid, and late century was then obtained by multiplying the already defined elasticity coefficient by the relative change of the climatic factor to the reference period ( $\Delta P$ ,  $\Delta E_0$ ):

$$\Delta Q_P = \varepsilon_P Q \Delta P; \Delta Q_{E_0} = \varepsilon_{E_0} Q \Delta E_0 \quad (3)$$

The attribution of runoff changes to climate changes was then expressed by the relative contribution of the influencing climate factor to runoff changes ( $\delta_P$ ,  $\delta_{E_0}$ ), i.e. the ratio between  $\Delta Q_P$ ,  $\Delta Q_{E_0}$  and the total climatic contribution ( $\Delta Q_P + \Delta Q_{E_0}$ ):

$$\delta_P = \frac{\Delta Q_P}{\Delta Q_P + \Delta Q_{E_0}}; \delta_{E_0} = \frac{\Delta Q_{E_0}}{\Delta Q_P + \Delta Q_{E_0}} \quad (4)$$



**Fig. 1.** Workflow for attributing runoff changes to climatic drivers and linking to basin hydrological behavior. Rounded and rectangular boxes indicate workflow inputs and processes including outputs, respectively. Dashed boxes indicate methodologies used in the workflow.

In the climate attribution analysis with the Budyko-based framework, we also considered the ensemble robustness of the different simulations in the three future periods and emission scenarios (section 2). To identify basins in the pan-European domain with robust changes, we adopted the criterion that at least 80 % of the climate ensemble members must agree on the sign of the changes between the period of interest and the reference period (Tebaldi et al., 2011).

### 3.2. Linking attribution to local hydrological behavior

To analyze the link between the attribution of runoff changes and the hydrological behaviors, eleven clusters were adopted to represent various hydrological characteristics of the European river systems (Pechlivanidis et al., 2020), as shown in Table 2 and Fig. A1. The clusters were obtained based on 15 hydrological signatures describing different aspects of the streamflow regime on the inter-annual (e.g. mean annual specific runoff, baseflow index, runoff coefficient) and intra-seasonal (e.g. slope of duration curves and range of Pardé coefficient) runoff dynamics, high and low streamflows and runoff hydrographs (e.g. flashiness, normalized peak distribution, rising and declining limb density). Basins with high baseflow and not very responsive to precipitation are found in cluster 1, 8 and 9. These basins are mainly located in Poland and Denmark (cluster 1, 2694 basins), central Europe with temperate continental climate (cluster 8, 4450 basins) and Scandinavia and Russia (cluster 9, 3658 basins). Basins responsive to precipitation, yet with long recessions in the hydrological response (cluster 2, 4827 basins) are mainly found in France, Germany, Sweden, south Finland, and Russia. Cluster 3 includes 2870 basins where the streamflow is controlled by snow melting and dampened by lakes and wetlands, mainly found in north-central and northwestern Russia. Basins with a highly seasonal regime due to snowmelt impact (cluster 4, 1983 basins) and those with high precipitation contribution (cluster 5, 3798 basins) are located in

**Table 2**

Characteristics of the 11 hydrological regimes (clusters) identified across Europe.

| # Cluster (no. of basins) | Geographic region                                                                      | Hydrological regime                                                                   |
|---------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| 1 (2694)                  | Eastern and Northern Europe (Poland and Denmark respectively)                          | Baseflow dominated, not very responsive to precipitation due river and lake dampening |
| 2 (4827)                  | Western Europe (France and Germany), Scandinavia (south Finland and Sweden) and Russia | Responsive to precipitation with long recession                                       |
| 3 (2870)                  | Mainly north-central and northwestern Russia                                           | Interannual highly variable, snowmelt dominated and dampened by lakes and wetlands    |
| 4 (1983)                  | High-elevated basins in Norway, Alps, Iceland, Spain, western Ireland and western UK   | Very responsive to precipitation, occasionally regulated for hydropower production    |
| 5 (3798)                  | Mountainous basins in Scandinavia (Norway, Sweden, Finland) and Russia                 | Highly variable regime and snowmelt or precipitation-driven response                  |
| 6 (3906)                  | Spread around Europe                                                                   | Highly variable regime with long recession                                            |
| 7 (1853)                  | Elevated basins in the Mediterranean regions (Spain, Italy, Albania, and Greece)       | Highly variable regime and high runoff coefficients                                   |
| 8 (4450)                  | Central Europe                                                                         | Baseflow dominated, small annual variability                                          |
| 9 (3658)                  | Scandinavia and Russia                                                                 | Highly baseflow dominated, not very responsive to precipitation                       |
| 10 (2558)                 | Low-elevated basins in Mediterranean regions (Portugal, Spain, Greece and Turkey)      | Low streamflow-dominated and low runoff coefficients                                  |
| 11 (2811)                 | Eastern Ukraine and southeastern Russia                                                | Quickly responsive to precipitation and recession, influenced by irrigation           |

high-altitude regions or cool continental climates. Cluster 6 includes 3906 basins very responsive to precipitation and generally distributed around Europe. Basins with sensitive streamflow responses to precipitation but low evapotranspiration (cluster 7, 1853 basins) are found in high altitude basins within warm and temperate Mediterranean climates. Basins in Mediterranean countries, including Portugal, Spain, Greece, and Turkey, are characterized by low streamflows and relatively low runoff coefficients due to increased evapotranspiration (cluster 10, 2558 basins). Finally, cluster 11 includes 2811 basins in eastern Ukraine and southeastern Russia showing low runoff and high annual variability, mainly influenced by human activities, e.g. irrigation.

## 4. Results

### 4.1. Precipitation and evapotranspiration changes under future conditions

We first investigated precipitation and potential evapotranspiration changes over Europe in the early, mid and late centuries and under low (RCP 2.6), medium (RCP 4.5) and high (RCP 8.5) emission scenarios (see Figs. A2 and A3 in the Appendix). Under low emission scenarios, precipitation in northern Europe changed up to 10 mm y<sup>-1</sup>, while central Europe experienced a slight increase of 25–50 mm y<sup>-1</sup> by the mid century. The relative increase of precipitation in these regions ranged from 1 % to 5 %. This pattern persisted into the late century, with more spatially homogeneous positive relative change from northern to central Europe. In contrast, precipitation decreased 10–25 mm y<sup>-1</sup> in southern Europe, especially in Spain, in the early century and, additionally in southern Italy and Greece in the late century. Under the medium emission scenario, a clear north–south contrast was observed, with precipitation increasing 25–50 mm y<sup>-1</sup> in northern Europe and decreasing at the same magnitude in southern Europe, particularly, in the early and late centuries. This contrasting spatial behavior, with increasing precipitation in northern Europe and decreasing precipitation in southern Europe, was more substantial (50–100 mm y<sup>-1</sup>) under the high emission scenarios with relative changes reaching 25–50 % in the late century.

Potential evapotranspiration showed an overall increasing trend in Europe compared to the reference period (Fig. A3 in the Appendix). Under the low emission scenario, northern Europe experienced an increase of 10 mm y<sup>-1</sup> with changes ranging from 1 to 5 % throughout all the future periods. Relative changes in some regions remained minimal, including southeastern Europe in the early century and southwestern Europe in the middle century. Under the medium emission scenario, potential evapotranspiration increased by 1–5 % in most parts of Europe. Northern Europe, in particular, experienced an increase of 10 to 25 mm y<sup>-1</sup>, with a more pronounced 5 to 10 % increase, especially in the late century. Under the high emission scenario, projections indicated a significant rise in potential evapotranspiration in the late century. This trend was particularly notable in northern Europe and the Alps, reaching increases of 25 to 50 mm y<sup>-1</sup> and a relative change of 25 % to 50 %. Central and southern Europe also experienced increases, with magnitudes reaching up to 100 mm y<sup>-1</sup>, however, the relative changes were more modest, ranging from 5 % to 10 %, especially in the late century.

### 4.2. Sensitivity of runoff changes to climatic drivers

We next analyzed the theoretical runoff sensitivity to precipitation and potential evapotranspiration over the reference period in the 35,408 basins, using the relative elasticity coefficients,  $\epsilon_p$  and  $\epsilon_{EO}$ , of the Budyko-based framework (Fig. 2). In 98 % of the investigated basins, the median ensemble elasticity coefficients of runoff to precipitation changes over Europe ranged between 0.5 and 3.6 (Fig. 2a), whereas for potential evapotranspiration, it ranged between 0.1 and 2.4 (Fig. 2b). The results imply that 1 % increase in precipitation would cause a runoff increase of between 0.5 % and 3.6 %, while a 1 % increase in potential evapotranspiration would decrease the runoff from 0.1 % to 2.4 % in these basins. The elasticity coefficients exhibited spatial variations; for

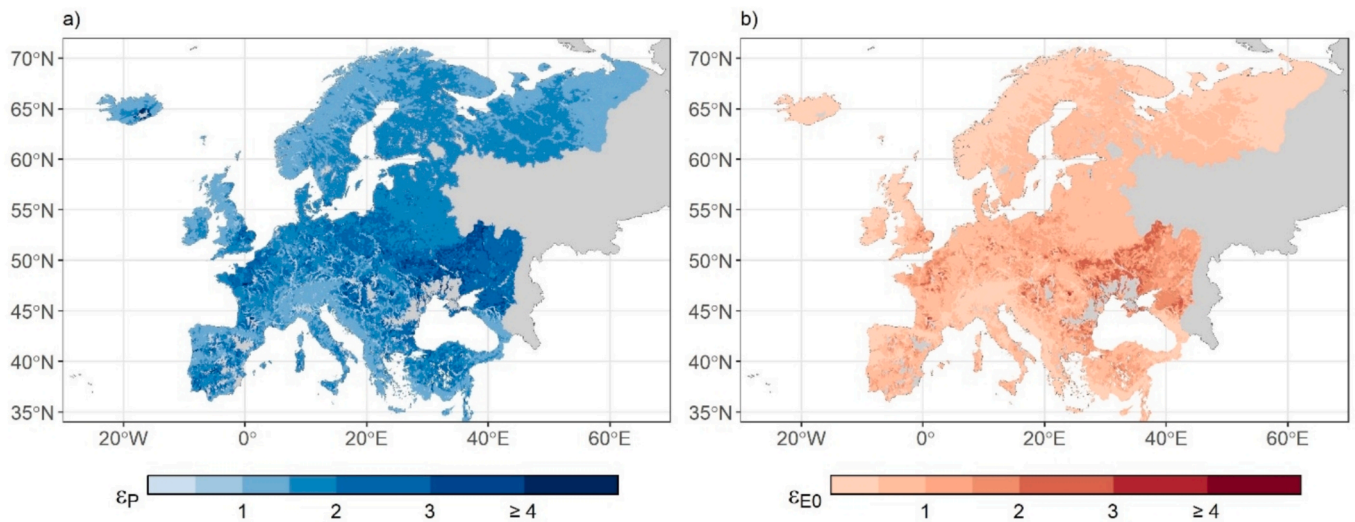


Fig. 2. Elasticity coefficients of runoff changes to a) precipitation ( $\varepsilon_P$ ) and b) potential evapotranspiration ( $\varepsilon_{E0}$ ) across Europe.

instance, northern and central Europe showed greater sensitivity to precipitation changes than to changes in potential evapotranspiration. This result implies that in this region, the relative contribution of precipitation to future runoff changes will be bigger for similar projected percentage changes of precipitation and potential evapotranspiration. In some regions the sensitivity to both climatic factors was higher than in others, such as in eastern Europe. The basins in regions with high runoff

sensitivity to changes in climatic drivers are characterized by water-energy balances close to the water and energy limits, with high basin-specific parameters determining high elasticity coefficients.

#### 4.3. Spatial variability of runoff changes under future conditions

We next quantified the expected runoff changes based on the

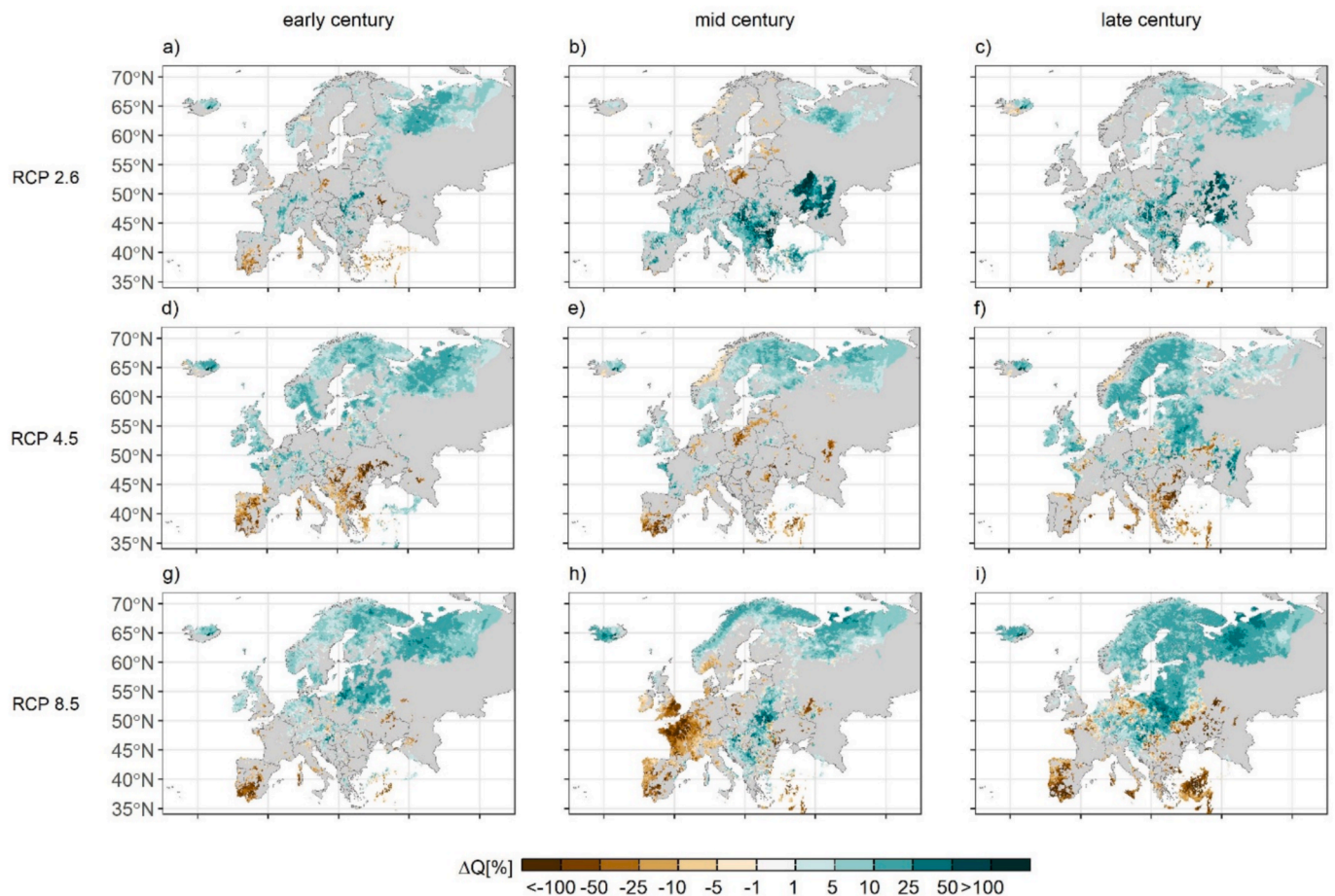


Fig. 3. Ensemble median of projected runoff changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe.

theoretical runoff sensitivity, expressed by the elasticity coefficients, and the relative changes in the climatic drivers. We present variations in runoff under future conditions, focusing on low, medium, and high emission scenarios (Fig. 3). Additionally, results for the entire domain, including those without robustness, are shown in Fig. A4. Under low emission scenarios, runoff increased by 5–25 % in most of central Europe across all three future periods compared to the reference period. In eastern Europe, more substantial increases were observed, reaching up to 50 % in the late century. This region experienced greater runoff increases than central Europe, even though precipitation and potential evapotranspiration increased similarly, due to its high elasticity coefficients. Conversely, some regions in southern Europe showed a decline in runoff during the early and late centuries.

Under the medium emission scenario, runoff in northern Europe increased by 5–10 % in the early century and 10–25 % in the late century. Runoff in southern and eastern Europe, in contrast, experienced a decrease of 25 % across all future periods. This contrasting spatial variability was even more pronounced under the high emission scenario than under the medium emission scenario. Additionally, under high emission scenario, runoff decreased in central Europe in the mid century.

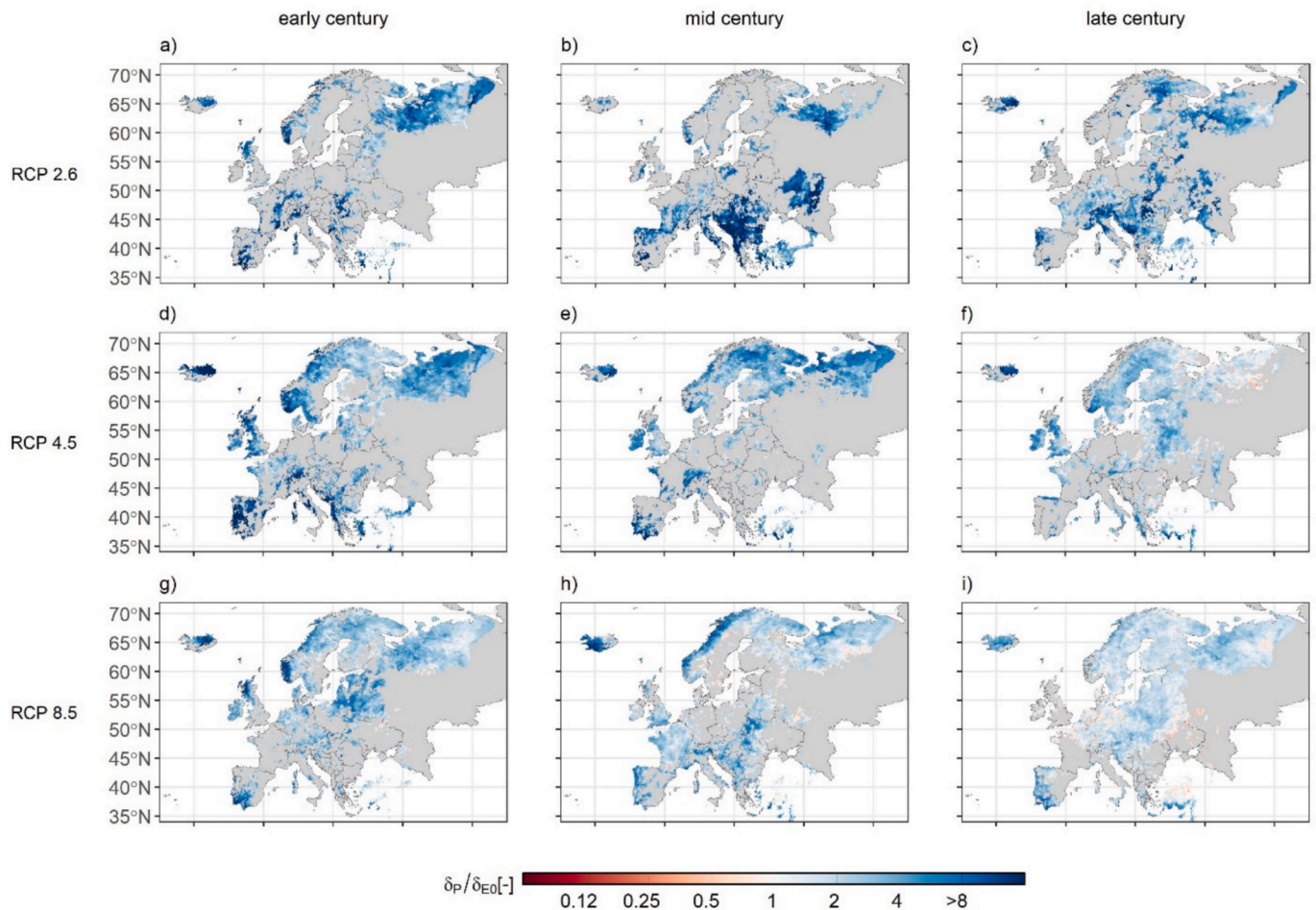
The ensemble variability of the runoff changes showed temporal consistency from the early to the late century for all emission scenarios (Fig. A5). Runoff changes showed low (0–5 %) to moderate (5–10 %) variability in the ensemble across northern Europe. In contrast, the ensemble variability of runoff changes ranged from moderate (10–25 %) to high (>25 %) across central, eastern and southern Europe. This result

indicates that the ensemble predictions agreed more closely on quantified runoff in northern Europe, where runoff increased, compared to central and southern Europe, where runoff either increased or decreased under high emission scenarios.

Applying the robustness criterion, that requires at least 80 % agreement among climate models on the direction of changes (see section 3.1), resulted in a varying number of displayed basins across different future periods and emission scenarios. The spatial consistency of the model ensemble improved from the low emission scenario to the high emission scenario, and from the early to the late century. This finding suggests a reduction in uncertainty among the ensemble models regarding the direction of changes and, thus, a more spatially consistent signal of increased runoff in northern Europe and decreased runoff in central and southern Europe under extreme warming.

#### 4.4. Attribution of precipitation and evapotranspiration to runoff changes

Here, we analyzed the relative contributions of precipitation ( $\delta_p$ ) and potential evapotranspiration ( $\delta_{E0}$ ) to runoff variations across Europe and presented the results as the ratio of these two contributions for the early, mid, and late centuries under low, medium, and high emission scenarios (Fig. 4). Additionally, results for the entire domain, including those without robustness, are shown in Fig. A6. Under the low emission scenario, precipitation was the primary factor influencing runoff changes across Europe, contributing up to eight times as much as potential evapotranspiration. In central and eastern Europe, precipitation changes had a positive contribution to runoff variations during the early and late



**Fig. 4.** Ensemble median ratio between the relative contribution of precipitation ( $\delta_p$ ) and potential evapotranspiration ( $\delta_{E0}$ ) to runoff changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe.

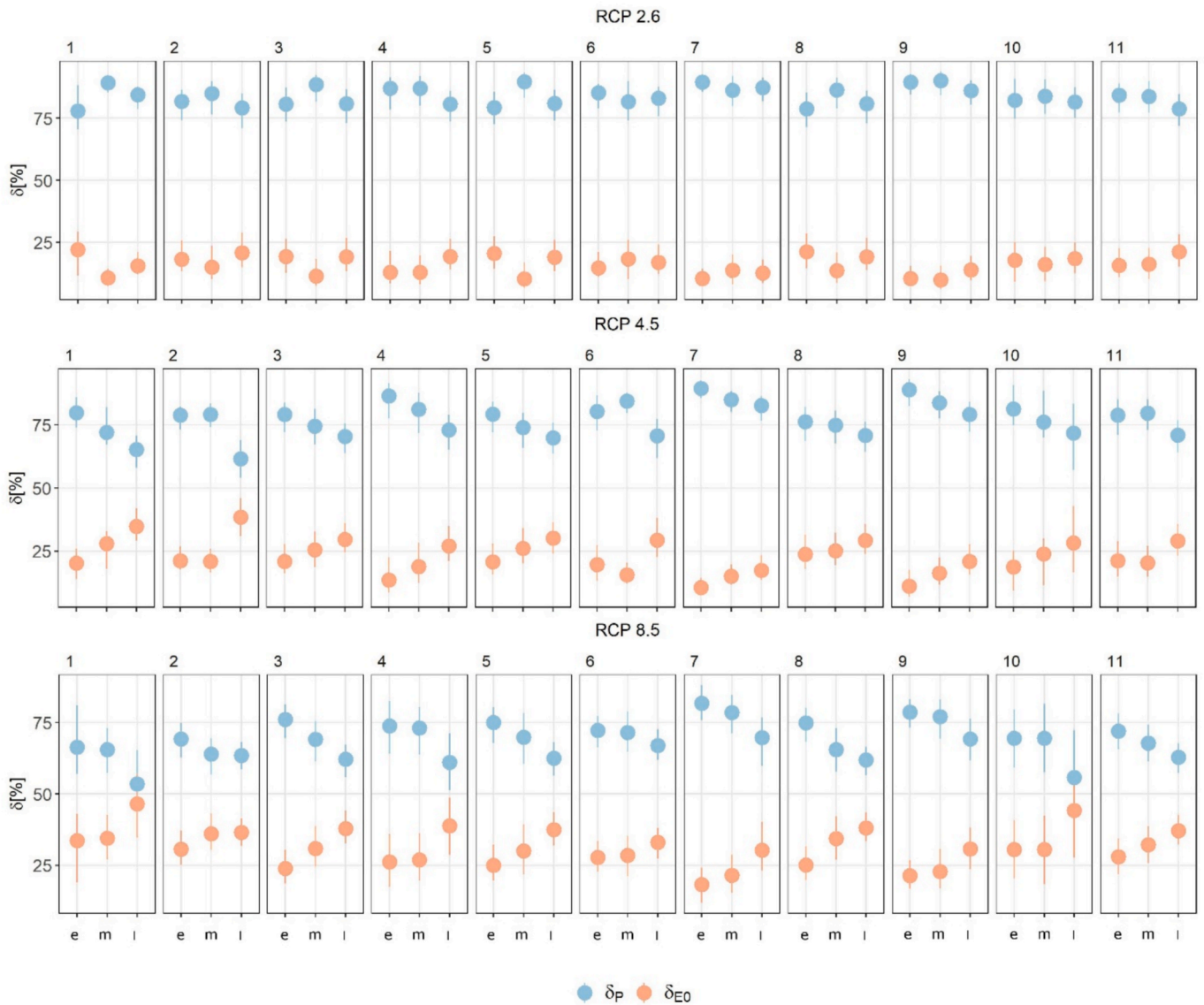
centuries. The same positive effect was found in Scandinavia and northeastern Europe, particularly under medium and high emission scenarios. In these regions, runoff showed greater sensitivity to precipitation (Fig. 2a) than to potential evapotranspiration (Fig. 2b); hence, increases in precipitation resulted in runoff increases. Conversely, in southern Europe, precipitation had a negative contribution to runoff variations, especially under the medium emission scenario.

Under the high emission scenario, the positive precipitation contribution on runoff increases remained evident in northern Europe during the early and mid century, whilst in southern Europe, precipitation decreases had a predominant negative contribution to runoff during the early and mid century. However, as we progressed in the mid and late century, potential evapotranspiration emerged as a significant negative factor influencing runoff variations in continental western and central Europe. The ratio of precipitation to potential evapotranspiration, which became nearly equal or even shifted to have potential evapotranspiration as a more dominant factor influencing runoff variations, reflected this change. In continental western Europe, potential evapotranspiration contributed to decreased runoff in the mid century, while in central Europe, it either reduced runoff or moderated its increase in the late century (Fig. 4).

#### 4.5. Linking climate attribution to hydrological behavior

We finally investigated the link between the attribution of runoff to climatic drivers and basin characteristics by decomposing the relative contributions of precipitation and potential evapotranspiration within the eleven predefined hydrological clusters (Fig. 5). These clusters were based on 15 hydrological signatures that grouped basins with similar streamflow characteristics into the same cluster (see Table 2). The number of basins with consistent model ensembles in each cluster for the different periods and scenarios was also calculated to show the robustness of the attribution results (Fig. A7 in the Appendix). Overall, across different hydrological clusters in Europe, runoff variations were mainly attributed to changes in precipitation, especially in the low emission scenario. However, the relative difference between the contribution from precipitation and potential evapotranspiration decreased in the high emission scenario, indicating a strengthened influence of evapotranspiration. Changes in the relative contribution of the two climate drivers varied among the hydrological clusters, with their magnitude influenced by both the emission scenario and future time period.

In basins within clusters 1, 4, and 10, precipitation is the primary contributor to runoff changes under the low emission scenario.



**Fig. 5.** Ensemble median of the relative contribution of precipitation ( $\delta_p$ ) and potential evapotranspiration ( $\delta_{EO}$ ) changes for the RCP 2.6, RCP 4.5 and RCP 8.5 emission scenarios in the early (e), mid (m) and late (l) century relative to the reference period (1971–2000) in the eleven hydrological clusters (1–11).

However, under the high emission scenario (hence high temperature increases), the contribution of potential evapotranspiration nearly equals that of precipitation, indicating that both climatic drivers are important for runoff changes. These basins are characterized by low streamflow dominance, low runoff coefficients and limited response to precipitation. As a result, an increased influence from potential evapotranspiration could significantly impact, particularly, energy-limited basins. In such basins, more energy will become available for the evapotranspiration process, which reduces the amount of water available, even if precipitation remains constant. In clusters 2 and 6, where the basins are highly responsive to precipitation, the contribution of precipitation remained the most significant factor for future runoff changes.

In clusters 3, 5, 8 and 11, precipitation was the dominant driver of runoff changes in the low and mid emission scenarios. However, under high emission scenarios, the precipitation contribution decreased towards the late century, while the contribution of potential evapotranspiration increased. These basins are mainly snow- and rainfall-driven, characterized by low runoff coefficient and high inter-annual variability. A similar pattern was also observed in cluster 7, where streamflow is sensitive to precipitation. However, in these basins, precipitation remained to be the dominant driver for runoff changes, despite the increased influence from potential evapotranspiration. These results are considered robust, as they are supported by a large number of basins (260–7978) showing consistent model ensemble results (see Fig. A7 in the Appendix), highlighting the significance of the differences observed among the clusters.

## 5. Discussion

### 5.1. Methodological remarks

Different studies used Budyko-based frameworks to assess the relative contribution of changes in climatic and other factors (e.g. topography, land use and human activities) to streamflow changes between past and present conditions at the regional and global scale. In this study, we used the framework to calculate the elasticities of a catchment runoff to precipitation and potential evapotranspiration changes and quantitatively attribute future runoff changes to these climatic drivers in the pan-European domain.

We found that, on average, elasticities of runoff changes to precipitation were higher than in potential evapotranspiration changes in the reference period (1971–2000). This result is in agreement with previous studies at the global scale and their findings in temperate and humid areas (Berghuijs et al., 2017; Liu et al., 2021). The previous studies analyzing the observed runoff changes at the global scale and over Europe indicated precipitation as the main driver in northern Europe, while evapotranspiration and other factors are the main drivers of streamflow changes in central Europe in the present conditions (Liu et al., 2021). Here, analyzing future scenarios, we found that similar changes will continue to occur, with increased runoff in Scandinavia and north-eastern Europe, and precipitation as the main driver of this change. In addition, we found that in southern Europe, decreased precipitation will contribute to runoff decreases, especially under the medium emission scenario. At the same time, potential evapotranspiration will be an equally prominent driver under the high emission scenario, particularly in basins with low streamflow and runoff coefficient and not responsive to precipitation. In these basins, the shift of the relative influence towards potential evapotranspiration on runoff changes appears abrupt across time, occurring mainly in the late century.

The uncertainty of climate projections is one of the primary sources of uncertainty in estimating runoff changes in future conditions. In contrast with previous studies using climate outputs obtained from global climate models (Liu et al., 2017), we used an ensemble of bias-adjusted projections from multiple GCMs and RCMs to account for this source of uncertainty. In addition, we considered runoff change

consistent across Europe when climate projections showed a consistent change of direction. This approach differs from the study by (Liu et al., 2017) that used the Budyko framework to assess the impact of projected streamflow across China, but addressed uncertainties considering a consistent change of streamflow directions between the future and reference periods.

Applying the Budyko-based framework to assess the driving factors behind future runoff changes has its limitations, as the sensitivity may not accurately reflect real-world changes (Liu et al., 2019). Compared to process-based models, for example, that involve the representation of physical processes, this empirical approach is limited by the case and time-specific validity. The potential evapotranspiration method could potentially impact the magnitude of the runoff changes. Temperature-based models tend to overestimate potential evapotranspiration with high emission scenarios compared to other methods (Lemaitre-Basset et al., 2022). These overestimations could have an impact where evapotranspiration will be an equally prominent driver. However, the impact is expected to be small in water-limited and not responsive to precipitation (cluster 10) compared to not responsive in energy-limited catchments (cluster 1). In addition, the assumption of negligible storage changes in the water balance of a system can be valid for long-term attribution, but limits the framework's applicability for attributing runoff changes to drivers in the case of single events such as floods and droughts. However, for long-term climate impact assessments over typical 30-year periods, the Budyko framework can be a more efficient way to assess the impact of climatic drivers on runoff than sensitivity analyses by forcing process-based hydrological models with multiple ensembles of climate projections. Another limitation of the framework lies in the stationary assumption, i.e. changes in land cover, human activities and population are assumed not to change in the future. This assumption is used in the other assessment approaches and represents a standard limitation in climate impact assessment studies. To address this limitation in future work, one option would include using CMIP6 climate projections that are based on Shared Socioeconomic Pathways (SSP) scenarios (Eyring et al., 2016). Additionally, integrating land surface models with the Budyko framework could help disentangle the impacts of climatic drivers from those of other factors influencing runoff changes, as demonstrated by (Collignan et al., 2025) under present climatic conditions. This approach would benefit from explicitly predicting land cover evolution, using land surface models and conducting paired simulations (i.e. with and without land use and land cover changes) similar to hydrological modelling experiments, to quantify their contribution to future runoff changes. A more empirical alternative would be to incorporate projected changes in basin characteristics derived from land use and land cover scenarios, after establishing robust relationships between basin-specific Budyko parameters and vegetation properties.

### 5.2. Evolving climate services towards attribution analysis

Attribution refers to the understanding of the causes or processes that drive change. In climate science, attribution refers to quantifying the human impact on the climate extremes (Trenberth et al., 2015). In hydroclimatology attribution has the broader sense of investigating and separating the multiple factors contributing to hydroclimatic variations and extremes, including climate variability, changes in land cover, and interactions between land and the atmosphere (Slater et al., 2021). The interplay among these factors poses a significant challenge to attributing hydrological variations to climate change. However, attributing hydrological modifications (their trends and/or specific events) to climate change and human activities is crucial. It influences and supports policy-making at the continental and global scales and consequently relevant mitigation and adaptation efforts at the national or regional scales (Clarke et al., 2023; Kreibich et al., 2019).

Attribution methodologies for hydrological changes and hazards (floods and droughts) have not to this date been established under a

common robust scientific framework. The attribution of streamflow changes and extremes to climatic drivers and land use changes has been mainly addressed by water balance-based methods at the multi-decadal time scale (Liu et al., 2021, 2017), simulations-based experiments with hydrological models testing the effect of a set of potential drivers (Harrigan et al., 2014; Hundecha and Merz, 2012) and data-based statistical methods (Bertola et al., 2021; De Niel and Willems, 2019; Mal-lucci et al., 2019). However, these approaches have limitations when applied at different time scales (seasons and events), such as hypothesis holding, availability of time-extended datasets or when dealing with the complexity of the underlying relations. To this latter point, new techniques, including machine learning and data-driven models, can contribute in detecting the complex interactions between drivers and impacts and enhance the attribution efforts towards operational services. Moreover, attribution analyses involve dealing with uncertainties inherent in both climate and hydrological models and observational data. The quantification and reduction of these uncertainties may involve exploring ensemble-based modeling approaches, incorporating uncertainty propagation techniques, and assessing the robustness of attribution findings through sensitivity analyses (Clark et al., 2016). Efforts are thus needed towards refining and reconciling existing methodologies with new approaches to attribute hydrological changes to underlying drivers.

Attribution analysis is typically conducted on large scales—national, continental, and even global. However, there is a growing demand for analysis and services at regional and local community levels (Ziogas et al., 2021). Efforts should be directed towards local customization of such services, accounting for local climate dynamics, topography, and socio-economic factors. In this regard, the availability of comprehensive and high-quality observational data is of high relevance. Integrating various observational data (from traditional and non-traditional sources), including local in-situ observations and satellite data, could enhance the reliability and usability of attribution analysis. This integration involves addressing data gaps, ensuring data quality, and developing methods to merge different data types for attribution.

Another challenge in attribution analysis comes from compound and cascading events, where multiple climate-related hazards occur either simultaneously or consecutively. These events can lead to intensified impacts that are difficult to directly attribute to climate change (Slater et al., 2021). To develop a robust attribution service, an interdisciplinary approach that incorporates climatology, hydrology, environmental science, and social sciences can provide a more comprehensive understanding. Such diagnosis can set the pathways to meet the UN's Sustainable Development Goals related to climate extremes and impacts.

## 6. Conclusions

In this study, we explored the attribution of runoff changes to the main climatic drivers (precipitation and potential evapotranspiration) under different future conditions (future periods and emission scenarios) in the pan-European domain using a Budyko-based framework. We linked climatic impacts on runoff changes and basin hydrological signatures, providing new insights into the attribution analysis. A total of 35,408 basins across Europe's diverse hydrological regimes were analyzed and intercompared using data from the E-HYPE hydrological model and bias-adjusted Euro-CORDEX climate projections. The main conclusions are as follows:

- Precipitation showed a noticeable contrasting pattern, increasing notably in northeastern Europe and Scandinavia, while decreasing significantly in southern Europe from the low to the high emission scenario. Additionally, potential evapotranspiration showed a positive trend over the whole Europe, intensified with the high emission scenario.
- Overall precipitation elasticity (the theoretical sensitivity of runoff to precipitation changes) was higher than potential evapotranspiration in northern and central Europe, indicating potential higher impact from precipitation on runoff changes. This is particularly observed in northern and central Europe, while in other regions, the elasticity to both climatic factors was more comparable.
- Precipitation was the main driver of the increasing runoff in Scandinavia and northeastern Europe especially under the medium and high emission scenarios. In contrast, precipitation contributed to decreased runoff in southern Europe, especially under the medium scenario.
- The relative contribution of precipitation and potential evapotranspiration to runoff changes varied across basins of different hydrological regimes. In basins where runoff is highly responsive to precipitation, precipitation remained the most significant driver for future runoff changes. Meanwhile, in basins with low streamflow dominance, low runoff coefficients and limited response to precipitation, a more balanced impact of precipitation and potential evapotranspiration on runoff changes was identified.

Our results highlight the importance of considering hydrological signatures in the attribution analysis of future runoff variations to the climatic driver changes. This approach can enhance climate services by offering insights into common spatial patterns and shifts in climatic influences. It can support water resource planning in transboundary river systems and climate hotspots, enabling more targeted and effective adaptation strategies on a regional to a continental scale. For instance, it can improve water management practices to optimize precipitation use in highly responsive basins, while also integrating methods that balance water conservation and evapotranspiration management in less responsive basins.

## CRedit authorship contribution statement

**Ilaria Clemenzi:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yiheng Du:** Writing – original draft, Investigation. **Ilias Pechlivanidis:** Writing – original draft, Visualization, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

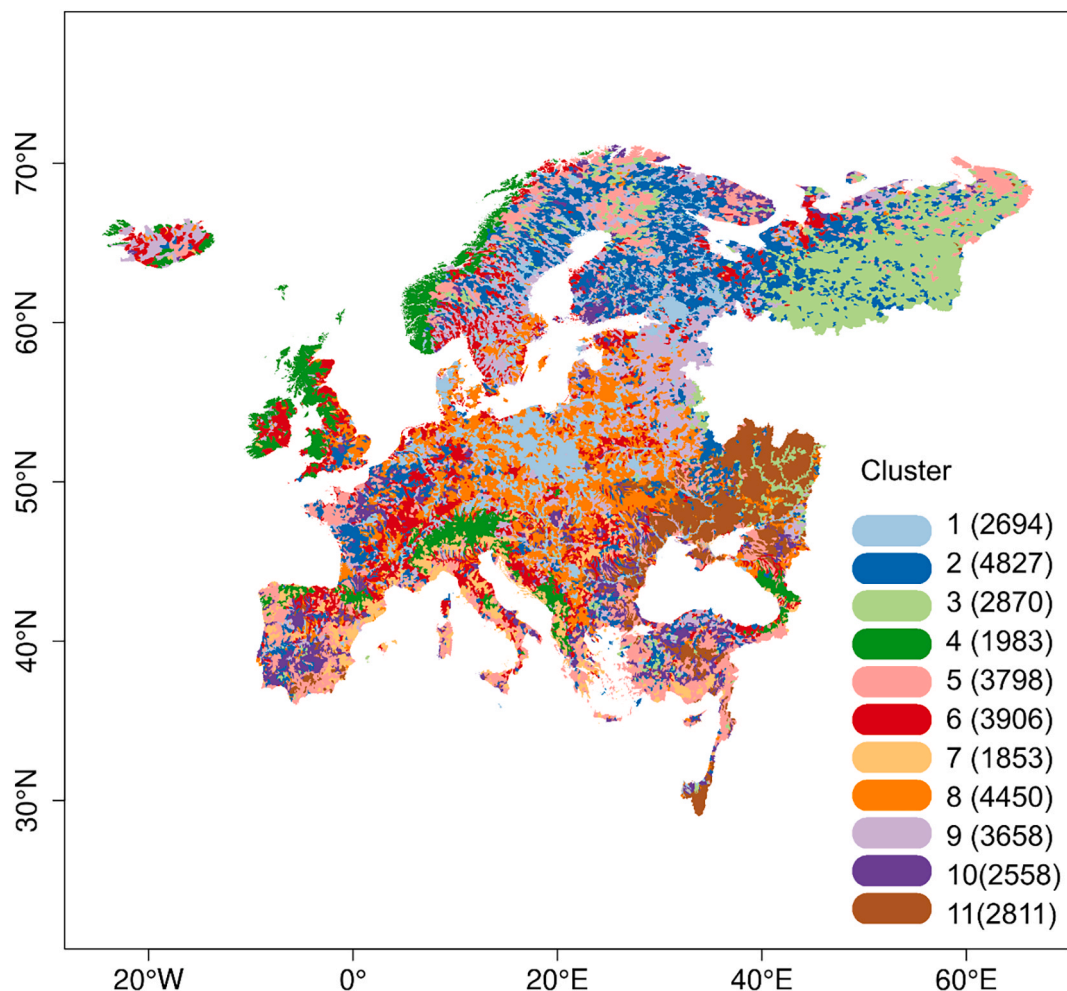
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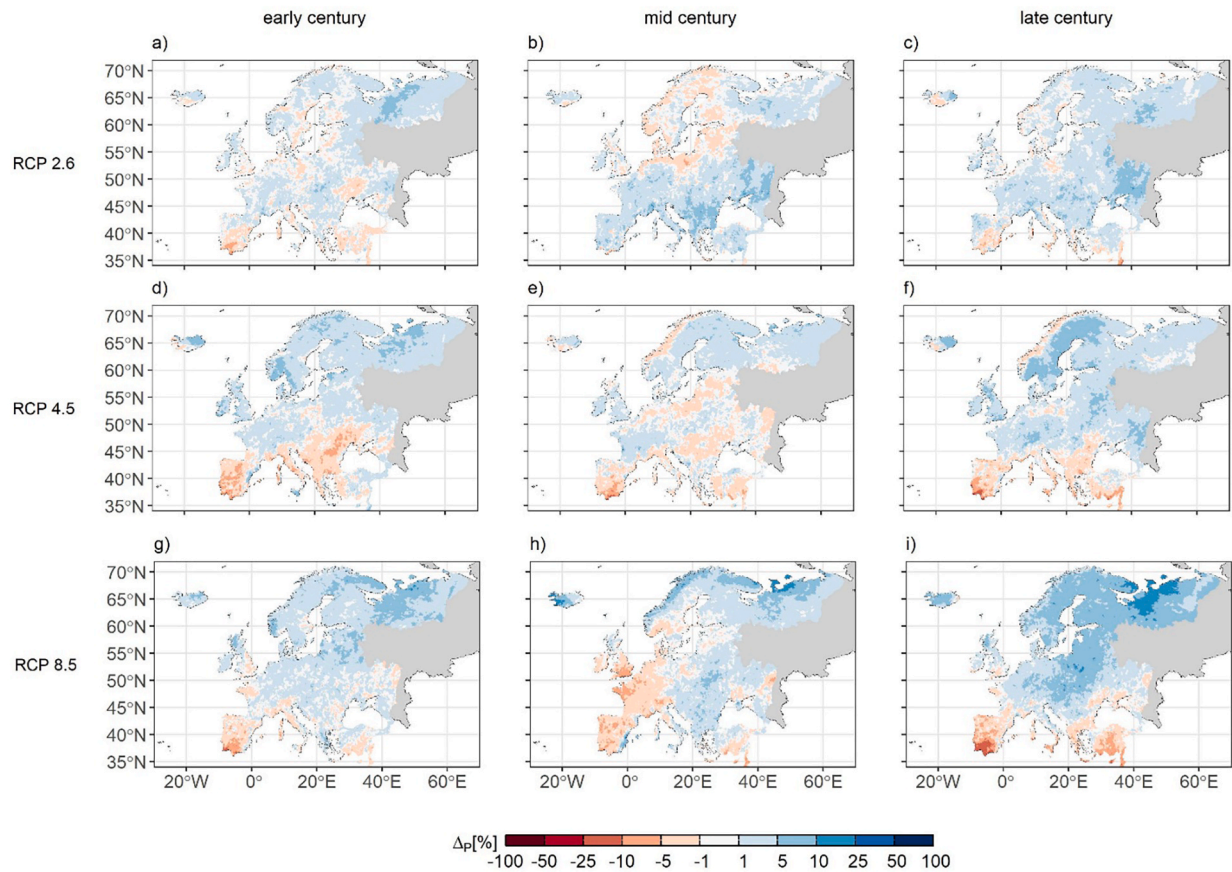
## Appendix

We present figures referenced in Sections 3.2, 4.1, 4.3, 4.4, and 4.5. These figures support our findings on the spatial variability of runoff changes and their attribution to climatic drivers under future conditions. Specifically, the figures illustrate the spatial distribution of hydrologically similar

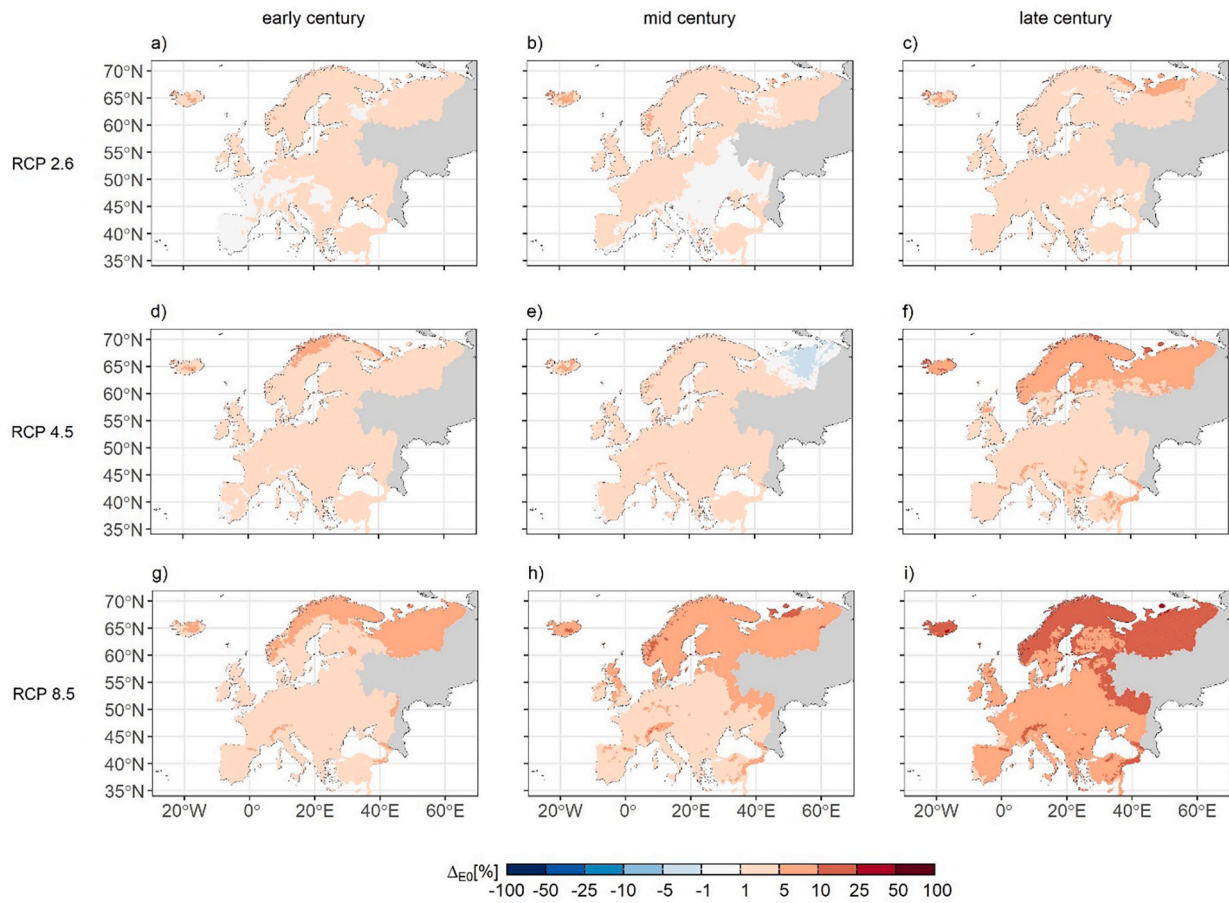
basins over Europe (Fig. A1), the spatial variability of model ensemble precipitation (Fig. A2), and potential evapotranspiration (Fig. A3). We also present the spatial variability of ensemble projected runoff changes (median in Fig. A4 and spread in Fig. A5) and of the ratio of climatic driver contributions, including no robust results (Fig. A6). The number of basins within each hydrological cluster (Fig. A7) is relevant to the results on climatic impacts on runoff changes and basin hydrological signatures (see Fig. 5) under low, medium and high emission scenarios.



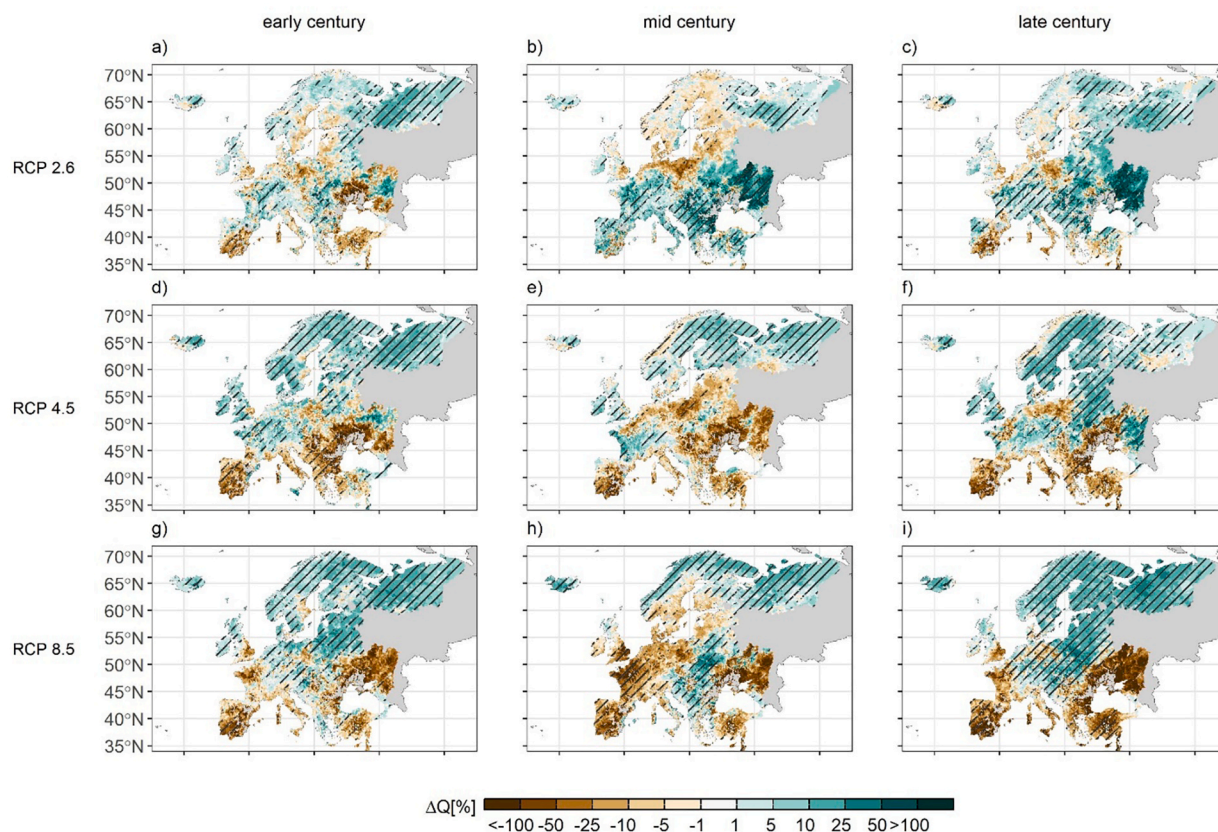
**Fig. A1.** Spatial distribution of hydrologically similar (clusters) basins over Europe including in brackets the number of sub-basins in each cluster. Note. From “Hydrological regimes explain the seasonal predictability of streamflow extremes” by Du et al 2023, Environ. Res. Lett. 18, 094,060 (<https://doi.org/10.1088/1748-9326/acf678>). CC BY 4.0)



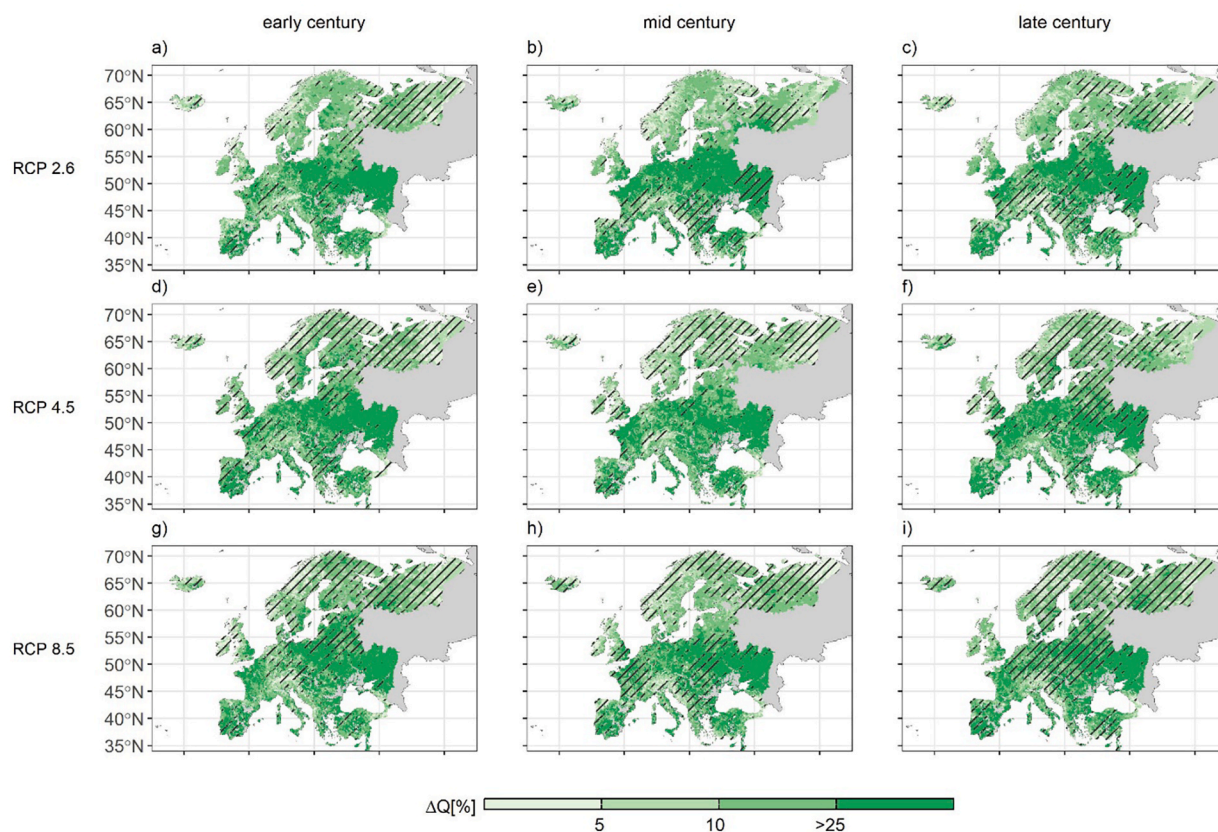
**Fig. A2.** Model ensemble median of precipitation percentage changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe.



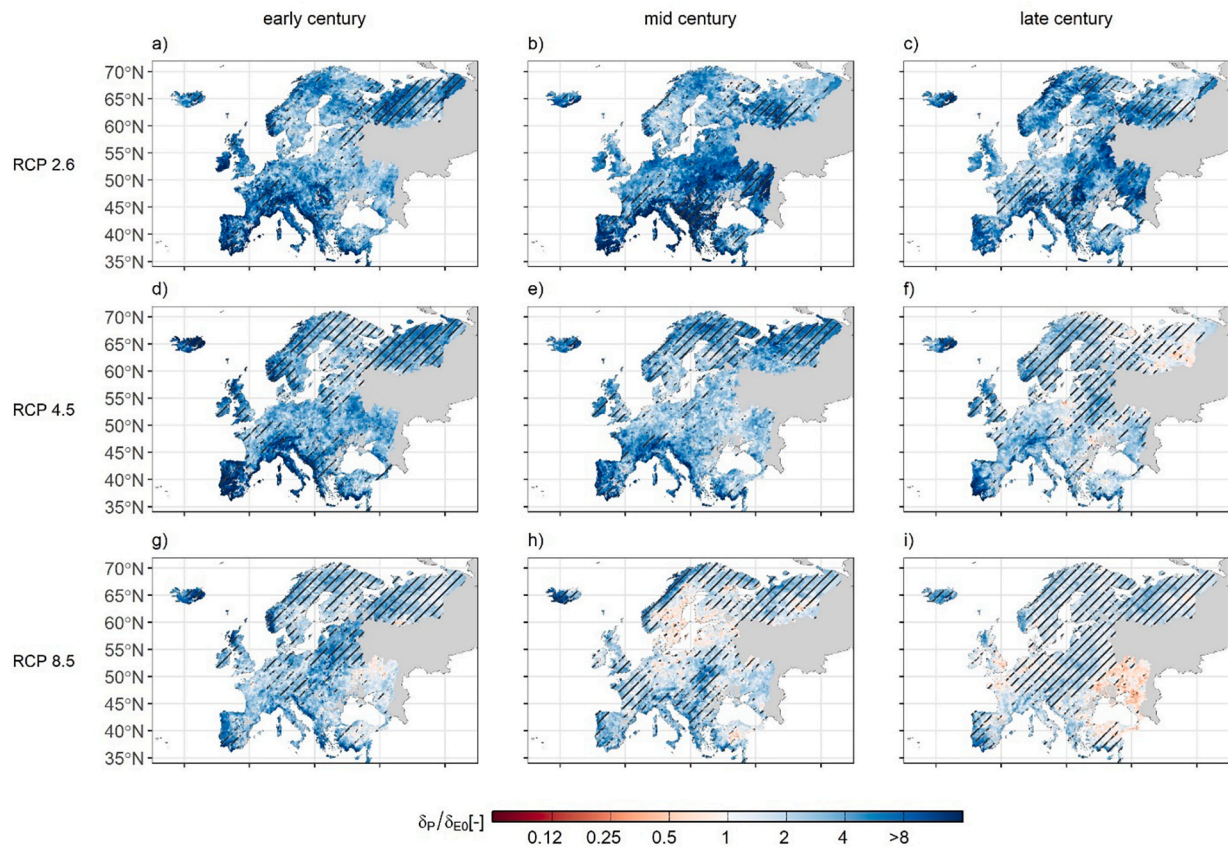
**Fig. A3.** Model ensemble median of potential evapotranspiration percentage changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe.



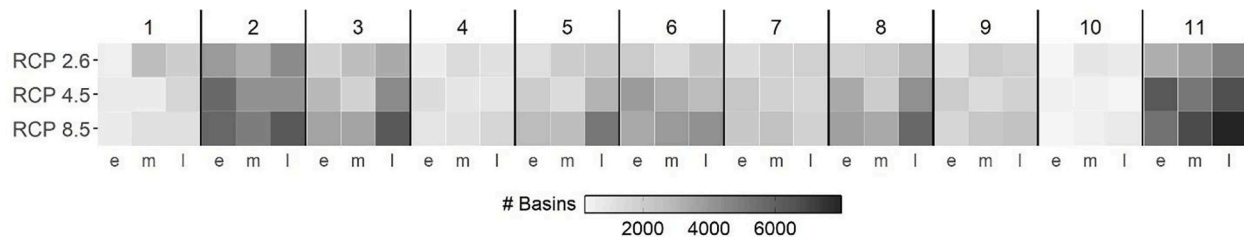
**Fig. A4.** Ensemble median of projected runoff changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe. Striped regions indicate robust changes in Fig. 3.



**Fig. A5.** Ensemble interquartile range of projected runoff changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe. Striped regions indicate robust changes.



**Fig. A6.** Ensemble median ratio between the relative contribution of precipitation ( $\delta_P$ ) and potential evapotranspiration ( $\delta_{EO}$ ) to runoff changes for the RCP 2.6 (a,b,c), RCP 4.5 (d,e,f) and RCP 8.5 (g,h,i) emission scenarios in the early (a,d,g), mid (b,e,h) and late (c,f,i) century relative to the reference period (1971–2000) across Europe. Striped regions indicate robust changes in Fig. 4.



**Fig. A7.** The number of basins for each hydrological cluster (1–11) with consistent model ensemble used for precipitation ( $\delta_P$ ) and evapotranspiration ( $\delta_{EO}$ ) attribution to runoff changes in Fig. 5. The results are presented for each RCP scenario and in the early (e), mid (m) and late (l) century.

## Data availability

The climatic projections are freely accessible from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/#/home>). The HYPE model code is available from the HYPEweb portal (<https://hypeweb.smhi.se/model-water/>). Hydro-climatic projections obtained through E-HYPE are openly available also on the HYPEweb portal (<https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/>).

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