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# Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble

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## Abstract

An overall appraisal of runoff changes at the European scale has been hindered by “white space” on maps of observed trends due to a paucity of readily-available stream-flow data. This study tested whether this white space can be filled using estimates of trends derived from model simulations of European runoff. The simulations stem from an ensemble of eight global hydrological models that were forced with the same climate input for the period 1963–2000. A validation of the derived trends for 293 grid cells across the European domain with observation-based trend estimates, allowed an assessment of the uncertainty of the modelled trends. The models agreed on the predominant continental scale patterns of trends, but disagreed on magnitudes and even on trend directions at the transition between regions with increasing and decreasing runoff trends, in complex terrain with a high spatial variability, and in snow-dominated regimes. Model estimates appeared most reliable in reproducing trends in annual runoff, winter runoff, and 7-day high flow. Modelled trends in runoff during the summer months, spring (for snow influenced regions) and autumn, and trends in summer low flow, were more variable and should be viewed with caution due to higher uncertainty. The ensemble mean overall provided the best representation of the trends in the observations. Maps of trends in annual runoff based on the ensemble mean demonstrated a pronounced continental dipole pattern of positive trends in western and northern Europe and negative trends in southern and parts of Eastern Europe, which has not previously been demonstrated and discussed in comparable detail.

## 1 Introduction

Europe’s climate is changing and with it the spatial and temporal characteristics of its hydrology. In recent decades, precipitation has decreased around the Mediterranean and increased in parts of Northern Europe (e.g. Zhang et al., 2007; Klein Tank et al., 2002). Climate assessments and environmental reports for Europe often contain

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are commonly calibrated to represent average conditions over a period of time and are rarely tested for their ability to simulate transient changes in time. However, strong recent changes suggest that transient time trends appear to provide useful benchmarks against which simulated runoff from large-scale models can be tested (e.g. Stahl et al., 2011; McCabe and Wolock, 2011).

Furthermore, as with climate models, model intercomparison studies have shown that different models (land surface and hydrological models) show considerable variability in the magnitude and timing of the hydrological variables simulated (e.g. LUCHEM: Breuer et al., 2009; PILPS: Cornwell and Harvey, 2007; GSWP: Dirmeyer et al., 2006; WaterMIP: Haddeland et al., 2011; Prudhomme et al., 2011; Gudmundsson et al., 2012). Some studies suggest that the ensemble mean (of all models) provides a more reliable estimate than any single model (Guo et al., 2007; Gudmundsson et al., 2012).

A key objective of this study is to assess the ability of a multi-model ensemble of eight large-scale hydrological models to simulate relatively detailed spatial patterns (0.5° grid-scale) of runoff trends in Europe. Hence, the study included a validation of modelled trends against previously published trends from observed streamflow records from a substantial number of small rivers with near-natural flow across Europe (i.e. from the same dataset used in the observation-based trend study by Stahl et al., 2010). As described in detail in Sect. 2 the models were forced with the same input data and the model runs reflect “naturalized” conditions – i.e. human impacts, such as water storage in man-made reservoirs and agricultural water withdrawals, are not included in the model runs. This setup allowed an assessment of (i) the sensitivity of trend estimates to the hydrological model, and (ii) the validation of spatial patterns of modelled runoff trends against trends in observed streamflow records. This validation complements and adds to modelling studies that have assessed past streamflow trends at the mouth of a few continental river basins (e.g. Dai et al., 2009). In these large basins, anthropogenic disturbances (e.g. impoundments and water withdrawals) may impact streamflow magnitude and transient trends to a degree often not represented by the

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hydrological models. In contrast, given the high spatial resolution of the mapped trends, small catchments enable the focus to be on processes (in both the climate and hydrological system) controlling changes in runoff generation in space and time.

In addition to the immediate, obvious scientific benefit of an improved assessment of the capability of large-scale hydrological models to reproduce historical runoff changes, a major benefit of this validation exercise is that, contingent on the utility of the models in reproducing observed trends, the model outputs can be used to “fill the white space” on current maps of recent runoff changes on a European scale (e.g. Stahl et al., 2010). This paper thus presents and discusses, for the first time, detailed maps of modelled runoff changes for the whole European continent, along with a consideration of the uncertainties resulting from differences among models, and between models and observations.

## 2 Data

This study used simulated daily runoff from eight large-scale hydrological models that were part of the model intercomparison experiments within the EU funded Water and Global Change (WATCH) project (<http://www.eu-watch.org>). Details of the models included, i.e. GWAHA, HTESEL, JULES, LPJml, MATSIRO, MPI-HM, Orchidee, and WaterGAP, can be found in Haddeland et al. (2011) and Gudmundsson et al. (2012), including an overview of the schemes used for simulation of evapotranspiration, runoff generation and snowmelt. All eight models were run for the period 1958–2000 on a global 0.5° grid and forced by the WATCH Forcing Data (WFD). The WFD were derived from the ERA-40 reanalysis product, interpolated to half-degree resolution and bias-corrected based on Climate Research Unit (CRU) and Global Precipitation Climatology Centre (GPCC) data (Weedon et al., 2011). The size of a grid-cell varies depending on the latitude, between 1065 km<sup>2</sup> (at 70° N) and 2387 km<sup>2</sup> (at 39.5° N). The first five years of the ERA-40 period (starting in 1958) were used for model spin-up and disregarded from the analysis. With the exception of WaterGAP, the models were not calibrated

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specifically for this experiment and models use their default soil and vegetation information (Haddeland et al., 2011). The variable used in this study is daily total runoff (sum of fast and slow component) simulated for each grid cell in Europe (4425 land cells).

5 Streamflow observations from across Europe were available from the combined dataset of the European Water Archive of the UNESCO IHP FRIEND programme (<http://www.unesco.org/new/en/natural-sciences/environment/water/ihp/ihp-programmes>) and the WATCH project. This dataset contains over 400 near-natural streamflow records for the period 1962 to 2004. Further details on the derivation of the dataset are provided in Stahl et al. (2010). With the majority of catchment areas below 2000 km<sup>2</sup> (see Stahl et al., 2011) most of the catchments are subscale to the size of the model grid-cells. Therefore, each gauged catchment was first assigned to the model grid cell in which its centroid lies. For model grids with more than one catchment, only the record from the largest catchment within a grid cell was kept for the analysis, resulting in a dataset of 293 daily streamflow records that could be paired with model simulations of the runoff from the corresponding grid cells. All daily simulated runoff and observed streamflow data were converted to mm of runoff per unit area. Grid cell simulated runoff was used directly and not routed to larger river basins as the focus was on spatial patterns of trend in runoff generation as represented by the catchments. The finest temporal resolution used was a 7-day average, which is longer than the typical runoff concentration time in small catchments. A bias between the magnitudes of observed and simulated runoff amounts as discussed in Gudmundsson et al. (2012) will not affect the present analysis, which only considers relative time trends in the individual variables and does not directly compare modelled and observed runoff values.

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distribution or not). The second and third measures relate to trend pattern and magnitude. The Pearson correlation coefficient  $r$  and its significance at 5% was computed to assess the similarity of the trend pattern across the 293 paired trend values for each model. The mean absolute error  $e$  was chosen as a measure of the magnitude of the difference between modelled and observed trends. The performance measures were derived for the trends in annual and monthly runoff, high and low flow for the eight individual models, as well as for the model ensemble mean (i.e. the mean of individual models'  $T$ ).

Spatial patterns in runoff trends were then visualized on maps. A grid-by-grid comparison of the direction of trends indicates areas where the uncertainty is high: grid cells where less than six out of eight (<75%) of the models agree on the direction of the trend are highlighted. In addition, grid cells where the trend direction of the ensemble mean is opposite to the observed trend are highlighted.

This study does not aim to discuss the performance of the individual models and hence does not reveal the identity of individual models in the results; rather, the variability in modelled trends given the same climate input is the primary interest. The attribution of a particular model behavior to a particular characteristic or model structure has previously proven extremely difficult for the same ensemble of large-scale models, which points to the limits of a diagnostic model evaluation given a high model complexity (Gudmundsson et al., 2012).

## 4 Results

### 4.1 Trend validation

The first performance measure compared the cumulative distribution of trend magnitude in the paired observed and modelled annual runoff trends (Fig. 1). The KS test revealed similar distributions for only one model for the annual trends, one model and the ensemble mean for the high-flow trends, and none of the models for the low flow



models, with values in the range  $0.1 < r < 0.7$  and  $12\% < e < 34\%$  (Fig. 2). Some of the correlations were weak, but they were all significant (5% level). The measures showed a decreasing agreement of observed and modelled trends from annual mean runoff, to high flow, and to summer low flow (Fig. 2). The ensemble mean performed better than any individual model for high and low flow trends and was among the best models for annual trends.

For the monthly runoff trends the two measures ( $r$  and  $e$ ) showed large seasonal differences and a large variation among the models (Fig. 3). Correlation coefficients were weak for some models and months, but significant with the exception of one model in April. Throughout the year, the ensemble mean trend agreed better with observed monthly trends than any individual model's trend. Performance was best in the period December to April, but dropped from April to June (both  $r$  and  $e$ ). In July, the correlations temporarily increased and notably lower errors were found. The errors remained low in August, but the correlation dropped again. In the autumn months, September to November, there was a shift to higher errors and the correlation remained relatively low. In December, the performance improved considerably. Overall highest (lowest) correlations were found in February and March (May and June), whereas lowest (highest) errors were observed in July and August (March and June). The worst model performance was found in May and June.

## 4.2 Spatial patterns of trends

The maps in Fig. 4 present the spatial distribution of trends in annual runoff, high flow, and summer low flow for the observations (Fig. 4a, d, g), the model ensemble mean at the locations of the observations (Fig. 4b, e, h), and the ensemble mean trend for the whole European domain (Fig. 4c, f, i).

The trends in observations of annual flow showed a broadly similar pattern, but a higher local variability in the observations than in the modelled trends. Deviations were found from the modelled trend pattern in regions of predominantly positive trends, specifically in the UK, Germany, the Alps, and Norway. The dominant pattern of

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modelled low flow trends. The disagreement among models for low flow trends was similar to the high flow trends and larger than for the trends in annual flow. Disagreement was mainly found in regions with weak trends and along the transition from areas with trends towards wetter to trends towards drier low flows. Overall weak trends were found for all three runoff indices in the Alps.

Monthly runoff trends based on the ensemble mean are shown in Fig. 5. Months with stronger trends appear to have resulted in a higher agreement with the observations (ref. Fig. 3). This includes the distinct trend patterns from December to April, which were even stronger than those for the annual trends, and show similarities to the pattern of annual trends, but also some regional differences. From December to March, different trend directions in the paired observed and modelled grid-cells occurred mainly along the boundary between areas of positive and negative trends, in northern Scandinavia (in Dec only), and for selected locations throughout Europe. From April to July, however, when negative trends started to increasingly dominate in the observations (as discussed in detail in Stahl et al., 2010), many modelled trends in central Europe point in the opposite direction. Negative trends, which dominated the results for the summer months, were generally less reliably modelled, both according to the large differences among models and when compared to observations. Trends in the autumn months September to November, being the weakest of all seasons, showed the largest disagreement in trend direction among models, and also had the largest disagreements with observations.

## 5 Discussion

### 5.1 Spatially distributed trend validation

Key systematic differences that emerged from the comparison of modelled trends with paired grid-cell observations from catchments include: (i) a shifted distribution in the trend magnitude with an overestimation of the number and magnitude of increasing (wetter) trends and an underestimation of the number and magnitude of decreasing

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(drier) trends, and (ii) a considerably higher local spatial variability of trends in the observed than in the modelled trends. These differences can have various sources, including errors in the forcing data, limitations related to model resolution and model concepts or physics, quality of the input data to derive model parameters and quality and availability (spatial coverage) of streamflow gauging stations (observed runoff).

The good agreement between modelled and observed runoff trends in annual runoff, high flow and winter month runoff in rain-dominated hydrological regimes, implies that the WATCH forcing data is reliable. This assessment agrees with other catchment-scale applications (Van Huijgevoort et al., 2010). The increasing trends found in high flow are located in areas that coincide with areas of increasing rainfall (Klein Tank et al., 2002; Zhang et al., 2007) and with increasing wet spell length (Zolina et al., 2010), which will likely enhance runoff generation. The comparison with observations in this study shows that the models likely exaggerate this effect at the grid scale, causing steeper trends than observed in the catchments. Within the dataset used no scaling effect was evident, but further studies may want to consider nested subcatchments within larger river basins (not available in the EWA) to explore scaling effects. However, potential human influences and the necessity to introduce a routing model will then add considerable uncertainty to the attribution of errors to runoff generation (e.g. Balsamo et al., 2009).

Larger differences between modelled and observed trends were found in regions with snow influence. This is consistent with the results of Gudmundsson et al. (2012) who found a systematic lower model performance of the mean annual cycle for snow-dominated regimes in Europe. Similarly, Haddeland et al. (2011) highlighted that significant differences in simulated monthly flow between land surface and global hydrological models are related to the relative partitioning between rainfall and snowfall and the snow accumulation and melt scheme employed. The present study shows that these differences have strong implications for the detection of trends in monthly runoff and in annual 7-day high-flow, which occur during snowmelt in some regions. In Scandinavia and Northeastern Europe trends in the high flow observations are negative, but the

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modelled trends are predominantly positive. In areas with complex topography like in Norway, the modelling of snow processes is challenging due to a sub-grid scale elevation dependence of the climate variables. Around the Baltic Sea, where there is snow but little topographic relief, unfortunately, available observations were sparse.

In addition to the differences between models in representing snow processes, a further reason for model disagreement with observations in mountain areas is the localised small-scale variability of terrain, geology and climate. Unsurprisingly, observed trends in relatively small mountain headwater catchments appear to be more variable than in other regions. Heterogeneity of observed trends in mountainous and snow-influenced areas has been reported previously, with patterns being highly dependent on the dominant process controls of the hydrological regimes. In the Nordic countries Wilson et al. (2010) found no coherent pattern of high flow trends and seasonal flow, partly due to temperature-driven changes affecting the timing of snowmelt and the seasonal distribution of flow. A study of trends in snowmelt season flow in the Alps found a similar heterogeneity except for glacial regimes (Bard et al., 2011). Rivers with differing degrees of rain and snow dominance on runoff occur side by side in mountainous regions. Model grid cell sizes of 0.5 degrees cannot resolve such differences and therefore may provide, at best, a rather generalized picture of reality of hydrological change in mountain regions.

Model disagreements with observations in the winter months are concentrated along the transition areas of the large continental regions of predominately positive and negative trends. This result, which may be related to model resolution or to a spatial offset between a model parameterization based on coarse thematic maps of land properties and reality, may be expected. The result suggests that modelling of hydrological change in these areas is particularly challenging and additional downscaling and improved representation of local hydrological processes are required to determine changes reliably. However, for the trends in the summer months and transition seasons as well as for derived indices such as high and low flow, the disagreements are not limited to these transition areas (and are also not as pronounced). This suggests that,

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## 5.2 Regional trend patterns and uncertainty

The large-scale hydrological models have shown considerable variability in their representation of the runoff trends. The variability is largest in the magnitudes of transient runoff trends, but there are also large areas where the trend direction differs for many of the indices, suggesting a high uncertainty even in the hindcasting of hydrological change. The generally larger variability among the models found in the dry season and for low flow trends in regions where a validation was possible, suggests a higher uncertainty in simulating trends under dry conditions. Overall, the model validation confirms the findings of other studies that the ensemble mean tends to outperform individual models. Examples include the evaluation of continental-scale summaries of high and low flow with the same datasets (Gudmundsson et al., in press), and numerous studies on runoff from large basins (e.g. Hagemann and Jacob, 2007; Matera et al., 2010) and other variables of the terrestrial water cycle, e.g. Guo et al. (2007).

Notwithstanding the inherent uncertainties, the maps of modelled trends elucidate spatial details not available from previously published observation-based trend maps from specific European analyses of modelled changes. Key “white space” now mapped with modelled trends includes persistent negative trends throughout the year in the southeast, the Iberian Peninsula and Italy. For the Iberian Peninsula, the few observations in the north show some deviations for the winter months, but otherwise agree with the modelled trends. Several other studies from the Iberian Peninsula have previously documented widespread negative runoff trends in which the climate component is still discernable despite a considerable additional impact of water management in the region (Lorenzo-Lacruz et al., 2012). For Italy and southeastern Europe no streamflow observations were available to confirm the modelled patterns, although the findings accord with climate trends, which have shown a long-term drying in these areas of the Mediterranean (Sousa et al., 2011). This further underlines the need for future extension of the observed streamflow dataset into southern regions of Europe in particular.

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It should also be kept in mind that the trends were derived for the period 1963–2000 and any trend calculation depends strongly on the period of record, as highlighted in numerous previous studies (e.g. Chen and Grasby, 2009). Further work is underway by the authors to establish how representative this shorter period is of longer-term variability, using a selection of long (>90 yr) records within the dataset (Hannaford et al., 2011). Whether the trends shown here are due to long-term variability or recent climate change (or a combination) remains to be investigated.

However, the spatial patterns throughout the year with predominantly positive trends in winter and negative trends in summer agree with other hydroclimatological studies as well as with future climate projections of a drier southern and wetter northern Europe (e.g. Bates et al., 2009; EEA-JRC-WHO, 2008). In addition, the north – south gradient may reflect the increased prevalence of the positive phases of the North Atlantic Oscillation (NAO) over the period considered by this study, which has previously been associated with increased rainfall, mean runoff and high flow (particularly in winter) in northern Europe (Shorthouse and Arnell, 1997; Hannaford and Marsh, 2008), and concomitant decreases in rainfall and river flow in the Mediterranean (e.g. Lopez-Moreno et al., 2008, Lorenzo-Lacruz et al., 2011). The two factors are not mutually exclusive, as NAO variability may itself be heavily influenced by anthropogenic warming (Dong et al., 2011). A detailed attribution was beyond the scope of this paper, however, hopefully it will spark interest in the study of atmospheric causes for the specific patterns of change and variability of change found.

## 6 Conclusions

Previous continental-scale assessments of recent hydrological change in Europe have had to rely on a sparse coverage of streamflow observations and disparate regional studies, which used very different methodologies and study periods. As such, there is typically “white space” on previously published maps of streamflow change, where observations are unavailable (e.g. southeastern and northeastern Europe), and limited

consistency in published trend results across Europe. This study evaluated the potential for creating useful, high-resolution, continuous and regionally consistent maps of runoff changes for the whole of Europe by extrapolating in space using large-scale models, and thus demonstrated the current limitations of the approach. The results suggest that care should be taken when interpreting these maps for seasons and regions where temporary or long-term storage processes influence the propagation of climatic trends and for regions where the spatial variability is higher than that resolved by the models.

Generally, a higher confidence in model simulations should be sought through validation. Consequently, additional observation networks are encouraged to contribute to this important task of model validation at different scales to improve future confidence in areas where data availability or accessibility is currently limited – many of which are apparent “hot spots” where model simulations suggest recent changes are strong and regionally consistent (for example, the general tendency towards strong drying trends in southeastern Europe).

The considerable variability among simulated trends for the different large-scale hydrological models is a strong reminder of the uncertainty of projected future changes in runoff if limited to only one such model. Thus, the study makes a case for multi-model approaches that include different land surface hydrology schemes, and for the improvement of process conceptualization and resolution of large-scale hydrology models. The WATCH model output is available globally and similar studies may be carried out on other continents. The results herein may potentially not only advance our understanding of hydrological change; they may further guide the assessment of the uncertainty of future scenario runs with those models, and thus assist future efforts to improve them.

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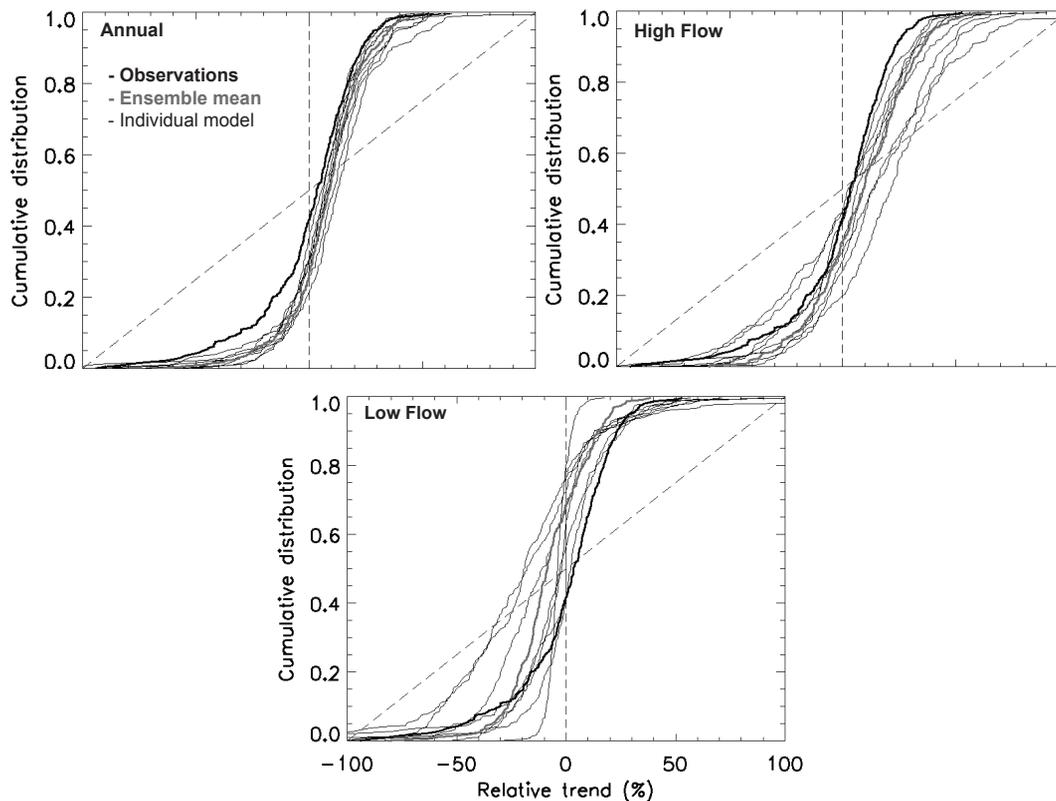
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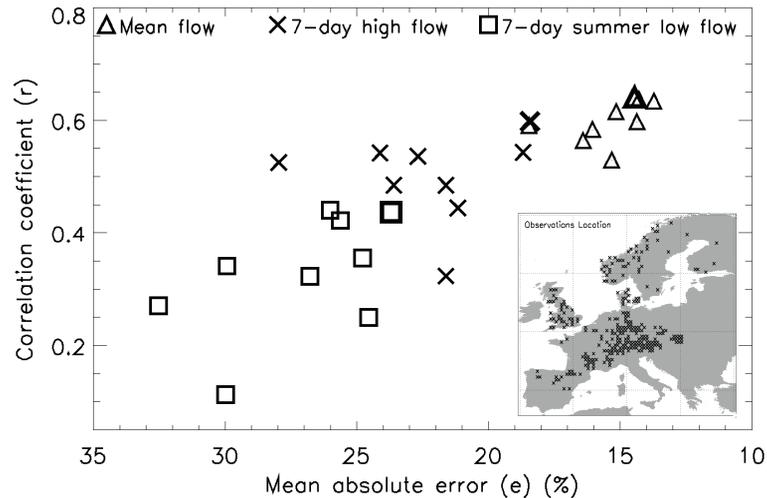


**Fig. 1.** Distribution of trend in annual runoff (upper), high flow (middle) and summer low flow (lower) from observations, individual models and the ensemble mean trend.

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**Fig. 2.** Comparison of correlation  $r$  (pattern) and error  $e$  (difference in trend magnitude) between observed and modelled trends in annual flow, high flow, and low flow all paired basins and grid cells (location in inset). Bold symbols are the ensemble means. Best performing models plot in the top right corner.

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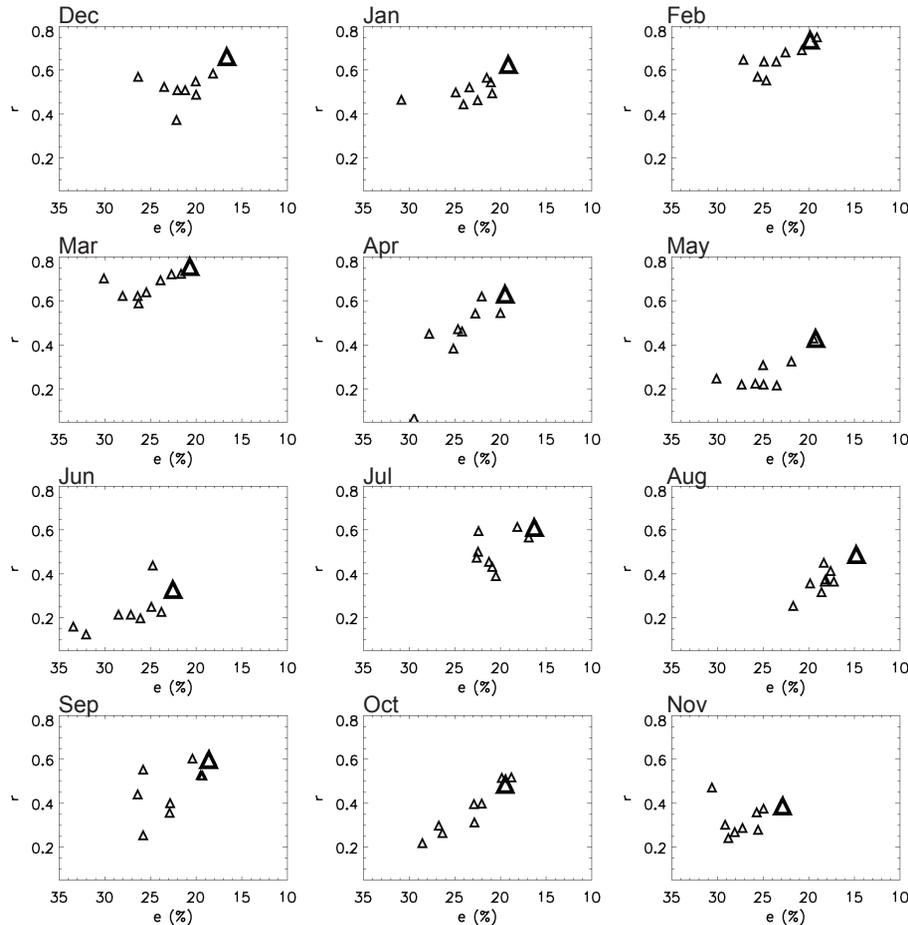
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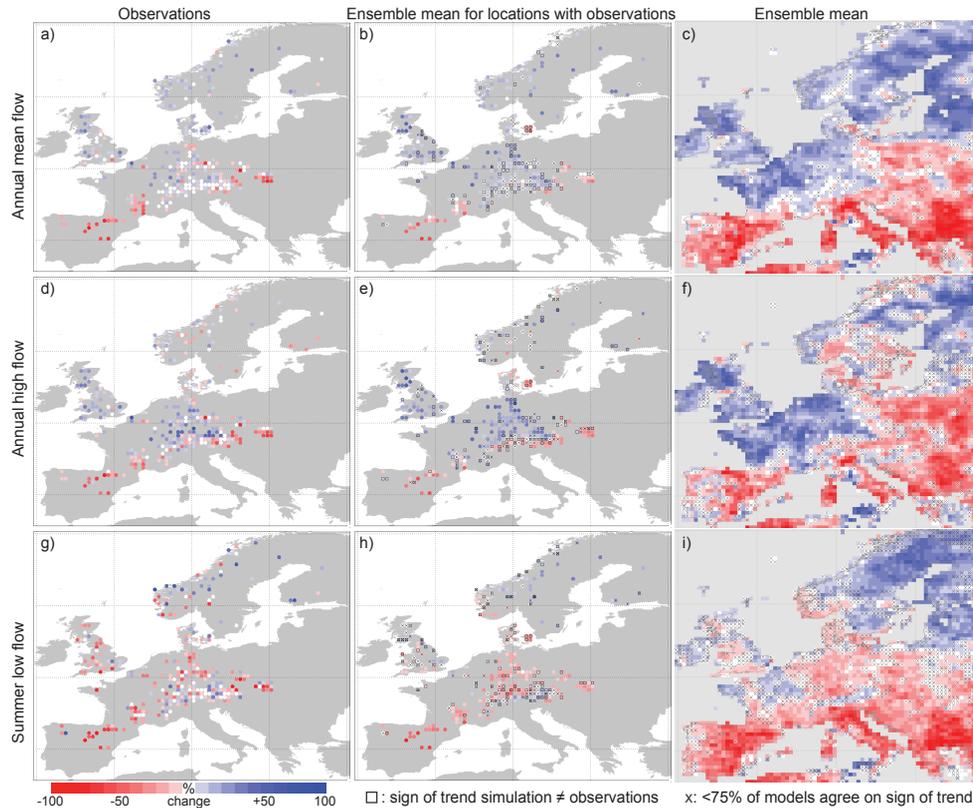
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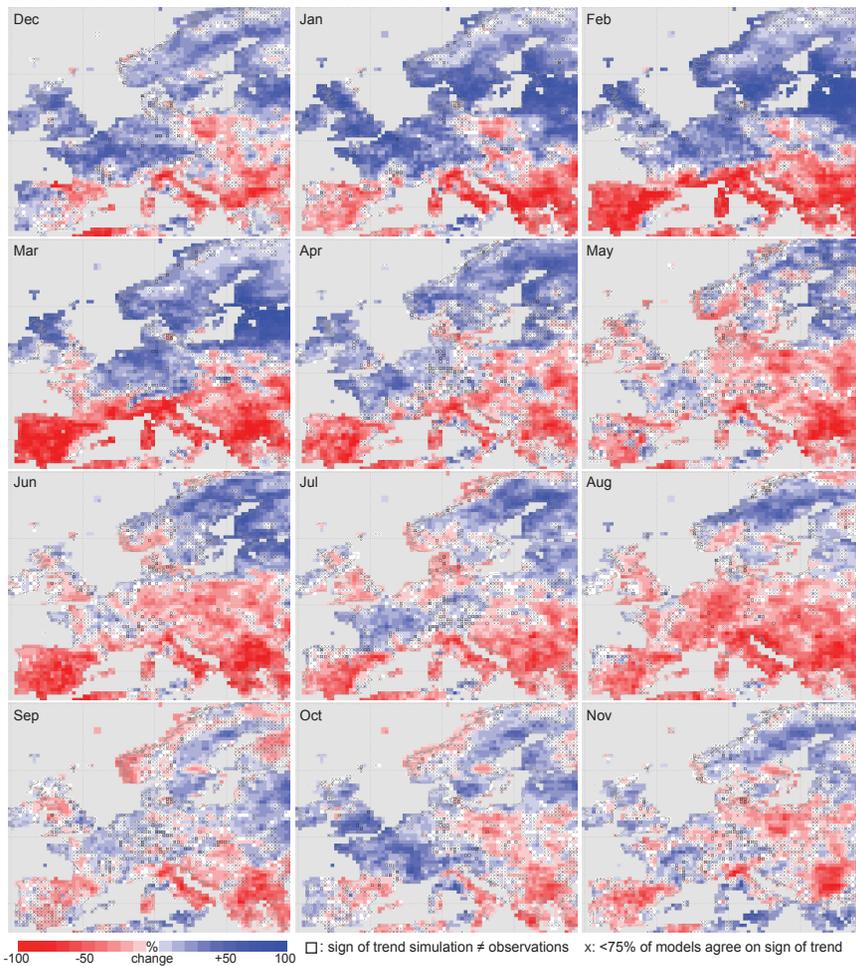


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**Fig. 4.** Spatial distribution of the ensemble mean trend in annual runoff (upper panel), high flow (middle panel) and summer low flow (lower panel).



**Fig. 5.** Spatial distribution of the ensemble mean trend in monthly runoff.

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