Response to the comments to the manuscript **hess-2019-523**

"Flood trends in Europe: are changes in small and big floods different?"

by Miriam Bertola, Alberto Viglione, David Lun, Julia Hall and Günter Blöschl

We wish to thank the Editor and the three Reviewers for the time they spent on our manuscript and for the positive and constructive comments. For the sake of convenience, we reproduce and number in the following document all the comments of the Reviewers in *italic characters*, followed by our answers. Together with the revised manuscript in PDF we also send the Marked Manuscript in PDF in which all the changes in the text are tracked (deleted in ~~red~~ characters, while new text is in blue characters). Numbers in brackets (highlighted in yellow) indicate the line numbers in the Marked Manuscript.

Editor

Comments to the Author:
Dear Authors,
Three reviewers evaluated your manuscript and gave useful feedback to improve your manuscript. The overall evaluation is positive, although some changes/improvements/clarifications are needed. Please adjust the manuscript according to the reviewers suggestions. The manuscript will be sent out for another round of review.
Sincerely,
Albrecht Weerts

We thank the Editor Albrecht Weerts for this chance to improve our manuscript; we have carefully considered and addressed all the comments provided by the Reviewers as detailed in the following pages.

Referee #1: Dominik Paprotny

The manuscript "Flood trends in Europe: are changes in small and big floods different?" analysed changes in return periods of extreme river discharges between 1960 and 2010. The study is largely a follow-up to "Changing climate both increases and decreases European river floods" by Blöschl et al. (I will refer to it, for brevity, as the "Nature" paper). This doesn't compromise the novelty or importance of the submission, which is overall a well-written and important contribution. I have three major comments, and some very minor points.

We want to thank the Referee Dominik Paprotny for the time he spent on our manuscript and for the useful and constructive comments. We have carefully considered and addressed all his comments in the following.

Major comments:

1. The analysis in section 3.2 includes the uncertainty ranges of the trends, but their ranges look in most cases proportional to the magnitude of the trend. I therefore find it not informative. It would be much more clear if instead of showing the uncertainty, to providing information whether the trends are statistically significant (at alpha of 0.1, or 0.05) by recolouring cells with insignificant trends grey. The text in section 3.2 could then be adjusted accordingly to the modified figures 5 & 6. The problem needs to be addressed as in the Nature paper as much as 72% of station trends were *found to be insignificant. Also, in some areas the large uncertainty comes from the very limited number of stations. Though the stations are shown in Figure 1, a supplemental figure with the number of stations included in each 600 km box could be added, maybe even separately for large and small catchment sizes. This extra figure(s) is only a recommendation.*

We thank the Referee for raising this issue; we understand it deserves additional explanation and changes to the manuscript. In the Authors' opinion, it is more informative to show the uncertainty associated with the estimated regional flood trends (represented in figures 5 and 6 through the width of the 90% credible bounds), rather than discarding the statistically not significant trends. This is because, on the one hand, we are interested in showing the absence of the trend when it is associated with small uncertainties (i.e. cells where the estimated trend is close to zero and the credible bounds are narrow). In this case, the trend would result as statistically not significant from a trend test and the corresponding pixel would be shown in grey, as for those pixels where there is not enough information to reject the null hypothesis. In reality we have accurate information about the absence of the trend. On the other hand, when the estimated trend is statistically significant, but it is associated with very large uncertainties (e.g. in figure 5 in eastern Europe), we are interested in showing how much this estimate is uncertain (i.e. the width of the credible bounds). For these reasons we do not think that redrawing Figures 5 and 6 with grey pixels will improve them. However we have added to the text the number of pixels for which the 90% credible bounds do not include the value of zero trend, which is analogous to performing a trend test with alpha 0.1 (even though, strictly speaking, null-hypothesis significance testing is not a tool of Bayesian statistics). The additional sentences (lines 288-292) are: "Overall, in more than half of the cases the 90% credible bounds do not include 0 (i.e. 68.9%, 59.2%, 58.5% and 50.2% respectively in panel a, b, c and d). Positive (negative) trends occur in 26.3 to 34.95% (65 to 76%) of the cases and their credible bounds do not include zero in 4.9 to 20.8% (39.5 to 48.1%) of the total cells. These percentages depend on the assumptions made, such as regional homogeneity and no spatial cross-correlation, and may, therefore, be overestimated".

As the Referee correctly says, there is a tendency of having larger uncertainties in the regions where the trend magnitude (in absolute value) is larger. The Authors believe that this is due to extrapolation of the trends to catchment sizes not well represented in these regions, which results in large flood trend magnitudes (in absolute value) which are indeed very uncertain. According to the Referee's suggestion, we have one extra figure to the Appendix (Fig. A1) showing the number of stations in each 600x600 km cell, with a distinction of catchment size. Furthermore, thanks to this comment we understood that figures 5 and 6 drove the attention of the reader to the stronger trends only (represented by the darker colours), without giving the right weight to the uncertainties (represented by the white circles). We have therefore replaced figure 5 and 6 with an alternative representation that better balances between the importance of the two types of information, i.e., the estimated flood trends and their uncertainties.

2. The analysis in section 3.3 includes three manually derived regions, which creates several problems. For one thing, no proper explanation for the choice is given. The Nature paper is cited as the source, but that paper also gives no real explanation apart for the attempt for homogenic regions (elliptical and overlapping for some reason). The other cited reference, Kotlarski et al. (2014) shows very different regional divisions (and not "not dissimilar" – btw. please avoid double negation). The regions omit, according to Table 1, one-third of stations in Europe, including most of the Danube catchment and northern Europe. Further, for some reason, the number of stations in each region is different than in the Nature paper, despite the ellipses being the same and the total number of stations as well. In summation, the authors should make a new derivation of regions, preferably based on actual geographical divisions of Europe (Fennoscandia, East European Plain, etc.), Koeppen's climate zones or drainage divides. Alternatively, cluster analysis could be used for this purpose. This would provide better connection between climate, topography and observed trends.

In the Nature paper, the 3 elliptical regions were identified by visual inspection of the flood trend and flood seasonality patterns and by the selection of large homogeneous regions in terms of changes in the mean annual flood discharges. In this study (which, as the Referee correctly says, is a follow-up of the Nature paper), the same regions are analysed in terms of changes in flood quantiles, to allow a more detailed assessment of existing research and to allow for ready comparability of the results. Furthermore, the location and extension of these three macro-regions are comparable with some of the climate zones of the Köppen-Geiger classification, suggested by the Referee. Northwestern Europe (region 1), in fact, roughly corresponds to the temperate oceanic climate zone, in southern Europe (region 2) hot and warm summer Mediterranean climate zones prevail, and eastern Europe (region 3) is dominated by the warm summer humid continental climate zone. For these reasons we decided to maintain the original regions, however, we have clarified this choice and corrected the sentence with double negation in lines 192-202: "Figure 1 shows three macro-regions (numbers 1-3) located over northwestern Europe, southern Europe and eastern Europe, respectively. These regions were identified in Blöschl et al. (2019) by visual inspection of the flood trend and flood seasonality patterns and represent large homogeneous regions in terms of changes in the mean annual flood discharges. According to Köppen-Geiger climate classification (Köppen, 1884), northwestern Europe (region 1) corresponds approximately to the temperate oceanic climate zone, in southern Europe (regions 2) the hot and warm summer Mediterranean climate zones prevail, and eastern Europe (region3) is dominated by warm summer humid continental climate. Table 1 shows some related regional summary statistics. In this study the same regions are analysed in terms of changes in flood quantiles, to allow a more detailed assessment of existing research and to allow for ready comparability of the results." We thank the Referee for noticing the difference in terms of number of stations in each region in table 1. We have corrected the table and reproduced figure 7 with the correct number of stations.

3. Not really a comment on paper, but an important question to the authors nonetheless. The authors provided an online dataset, and I noticed that it was updated recently in order to fix the errors in station coordinates. I wonder whether those errors affected the paper's results and figures in any way, and whether they could account for the difference between the number of stations in Table 1 and the Nature paper. I suggest the authors check their data and code to ensure that there is no data-processing error present in their paper.

We thank the Referee for spotting this and allowing us to check. The correction of the released flood data did not affect our analysis, as we used the original data. This correction was about an error occurred while producing the csv file for the public release.

Minor comments:

Title: the study deals with floods understood as extreme river discharge, rather than floods as occurrence of losses. I know that's the hydrological vs natural hazards perspective issue, but even in HESS, the title could be more precise by mentioning "Flood discharge trends" rather than "Flood trends".

We understand the Referee's point of view; we have clarified and emphasized in the abstract (lines 3-4) the fact that this study analyses river flood discharges, by changing the sentence from: "The aim of this study is to assess whether trends also occurred for larger return periods accounting for the effect of catchment scale. We analyze 2370 flood records […]" to "The aim of this study is to assess whether trends in flood discharges also occurred for larger return periods accounting for the effect of catchment scale. We analyze 2370 flood discharge records […]". However, we prefer to keep the original title.

L4, L41, L128: the flood database is mentioned as "newly-available", but it has been compiled 4 years ago already. If it wasn't released publicly recently, the "newlyavailable" moniker should be removed.

In the manuscript (L41 and L128) we cite an article about the compilation of the flood database (i.e. Hall et al., 2015) which was, at that time, ongoing. The flood database was instead publicly released in August 2019.

L20-21: please correct this sentence, it's very ungrammatical.

We have rephrased the sentence (lines 20-24) to: "Increasing flood hazard in Europe has become a major concern as a consequence of severe flood events experienced in the last decades, as, for instance, the extreme floods occurred in central Europe in 2002 (e.g. Ulbrich et al., 2003) and 2013 (e.g. Blöschl et al., 2013a), and the winter floods in northwest England in 2009 (e.g. Miller et al., 2013) and 2015-16 (e.g. Barker et al., 2016)."

L41-L44: when referring to the Nature paper, the names of regions from this submission are used instead of the Nature study. Especially the location of the "Atlantic" region, used throughout (including the abstract), is unclear until section 2.3.

We have re-named the "Atlantic" and "Mediterranean" regions into "Northwestern Europe" and "Southern Europe" throughout the manuscript and the abstract.

Section 2.1: the similarity report noticed some overlaps in text with the author's other recent paper, which is not cited. Some comment in the section whether the presented methodology was used before or not would be beneficial.

The main similarity with the Author's other recent publication is in the description of the tool used (i.e. rstan). Thank you for noticing it; we have rephrased the sentences at lines 134-139.

L134-135: the authors repeat the explanation of station selection from the Nature paper, but given the methodological differences between the papers, I think the need for more even spatial distribution is much reduced here. Maybe some better explanation would do here.

Since this work is a follow-up of the Nature paper and complementary analyses are presented, we should be consistent with this previous study by analysing the same flood data, in order to produce comparable results. We have better explained it in lines 161-162: "For comparability with Blöschl et al. (2019), only the stations satisfying the following selection criteria, based on record length and even spatial distribution, are considered for the estimation of the regional trends".

L216: "British-Irish Isles" should be replaced with "British Isles", as this term encompasses Ireland.

According to the interactive comment of the Referee #2, we have maintained the original inclusive term "British-Irish Isles".

L410: the reference to the Nature paper should be updated, as it is no longer "under review".

The reference has been updated.

I am looking forward to the authors' revision of their paper.

We want to thank the Referee for his comments that helped to improve the quality of the manuscript.

Referee #2: Duncan Faulkner

The paper makes an interesting and valuable contribution to the large volume of literature on trends in flood magnitude. The pan-European focus is particularly valuable, as is the separation by flood rarity and catchment size.

We thank the Referee Duncan Faulkner for the time he spent on our manuscript and for the useful and constructive comments that helped to improve the quality of the manuscript. We have carefully considered and addressed all his comments in the following.

Main comments

1. The paper acknowledges that no allowance is made for spatial correlation of floods, and that this may affect the estimation of uncertainty. It claims that the regional model is more robust than the at-site trend analysis. This raises the question of the extent to which the apparent increase in robustness is due to the same information being repeated several times over, if trends at nearby gauges are reflecting essentially the same flood events. I recommend that the authors consider ways of accounting for spatial correlation when quantifying uncertainty, such as a spatial nonparametric bootstrap or a likelihood correction (Sharkey and Winter, 2019). The authors quote a cross-correlation length of about 50km (section 4) which seems rather short in comparison with the spatial scale of some flood-producing weather systems.

The referee is right, spatial cross-correlation between flood timeseries at different sites is not accounted for in this study and it may affect the estimation of sample uncertainty. In particular, if the flood timeseries at different sites are strongly correlated, we expect the uncertainties to be larger than the uncertainties estimated in this paper. Therefore, we state that the estimated credible bounds should be intended as lower limits (lines 386-389). However, we do not expect the trend estimates (i.e., in this case, the posterior median) to change, when cross-correlation is taken into account (Stedinger, 1983; Hosking and Wallis 1988 and 1997).

We thank the Referee for suggesting possible ways to account for spatial dependence in flood data. We have applied the magnitude adjustment to the likelihood (described in Sharkey and Winter, 2019) to the example region of section 3.1, in order to quantify, for this specific case, the increase in the width of the credible bounds when spatial cross-correlation is taken into account. Figures 3 and 4 have been updated accordingly. Additional text has been added to the manuscript:

- In section 2.1 (lines 144-154): "Spatial cross-correlation between flood time series at different sites is not accounted for in this model (i.e. it assumes independence of flood time series in space), however, it is possible to quantify its effects in first approximation in a Bayesian framework through an approach based on a magnitude adjustment to the likelihood (Ribatet et al., 2012). This approach consists in scaling the likelihood with a proper constant exponent to be estimated between 0 and 1, that results in inflating the posterior variance of the parameters and consequent increase of the width of parameter uncertainty intervals, reflecting the overall effect of spatial dependence in the data. In the case of spatial independence the magnitude adjustment factor is 1, whereas values of the magnitude adjustment factor close to 0 indicate strong inter-site correlation of floods and substantially larger sample uncertainties resulting from the adjusted model, compared to the model where spatial cross-correlation is not accounted for. For further details about the method and its application to hydrological data, see Smith (1990), Ribatet et al. (2012) and Sharkey and Winter (2019). We apply this method to an example region in central Europe, in order to quantify the magnitude of the uncertainty underestimation associated with the model assumption of spatial independence in flood data."
- In section 2.3 (lines 211-213): "In this example region we also investigate the effect of spatial dependence in flood data on the width of the estimated credible bounds, with an approach based on the magnitude adjustment to the likelihood".
- in section 3.1 (lines 243-246): "In this case, the overall effect of spatial cross-correlation between flood time series at different sites is investigated through the magnitude adjustment to the likelihood. The credible bounds of the regional trends obtained with the likelihood adjustment (dashed lines in Fig. 3) are 17.6 to 23.8% larger compared to the case where spatial cross-correlation is not accounted for (estimated magnitude adjustment factor 0.669)" and (lines 257-258) "The credible bounds obtained with the likelihood adjustment (dashed lines) result slightly wider (about 20%) compared to the case where spatial cross-correlation is not accounted for."
- in section 4 (lines 370-376): "A possible way of taking into account spatial cross-correlation between sites is a magnitude adjustment to the likelihood, that reflects the overall effect of spatial dependence and results in increased width of uncertainty intervals of the estimated quantiles (see Ribatet et al., 2012). The application of this approach to the specific example region in central Europe shows that the 90% credible bounds of the regional trends in q2 and q100 result, on average, 20% wider compared to the case where the likelihood is not adjusted. However, further research is needed to properly characterize the effect of spatial dependence between flood peaks in regional frequency analyses."

At lines 369-370 we have stated how the cross-correlation length of about 50 km has been calculated: "[…] calculated from flood timeseries and distances between catchment outlets using a nonlinear regression model proposed by Tasker and Stedinger, 1989 […]".

2. The discussion (Section 4) makes various statements that go some way towards attributing trends. These vary from confident assertions (flood trends in the Mediterranean are negative due to …) to more informal or speculative comments *using wording like "linked with", "suggest that", "could be found". I think many of us tend to use language like this when discussing trends, but in this context I would suggest the authors state more explicitly whether they are attempting a formal attribution of the trends or merely providing some hypotheses (or somewhere in between).*

Thank you for pointing this out. This work does not aim at formally attributing the observed flood trends to drivers and the statements in the discussion section, about the potential causes of the observed flood trends, are intended to be hypotheses or interpretation of the results, based on the literature and on the Authors' understanding of these processes. We have mitigated the statements about the trend attribution that sound like confident assertions throughout the discussion section 4. Additionally, in order to avoid misunderstandings, we have removed the last sentence from the abstract (line 18) and we have clarified it in section 4 (lines 447-451): "This study provides a continental-scale analysis of the changes in flood quantiles that have occurred across Europe over five decades, however further research is needed to formally attribute the resulting regional change patterns to potential driving processes".

Minor comments

The paper makes frequent use of the return period terminology. This is conceptually awkward in non-stationary conditions. I would suggest that the authors at least acknowledge this, and perhaps refer to some of the literature on alternative ways of expressing flood rarity.

We understand that the use of the return period terminology in a non-stationary context may sound ambiguous to some readers. In the manuscript we refer to the return period (rather than to the annual exceedance probability) because, in the engineering practice, it is widely understood what a 100-year flood is. Examples of return period terminology used in a similar non-stationary context in the literature are Renard et al. (2006), Machado et al. (2015), Šraj et al. (2016). For these reasons we prefer to maintain the return period terminology in the manuscript. However, we have clarified the terminology used in lines 123-124: "We investigate changes in flood quantiles associated with fixed annual exceedance probability 1-p, or, equivalently, with fixed return period T=1/(1-p)".

The Gumbel parameters are modelled as varying with time according to a log-linear relationship. Perhaps the authors could comment on any alternative ways they considered of modelling trend, such as other mathematical forms of the relationship with time, or inclusion of physical covariates in an attempt to improve the identification of the time trends.

Thank you for pointing this out. We have introduced additional text about alternative ways of modelling trends in section 4 (lines 352-354): "The two parameters are modelled as varying in time according to log-linear relationships. Other relationships with time could be investigated as well as the use of physical covariates.". The use of physical covariates in order to attribute the trends in flood quantiles is actually planned in the next phase of our research.

The meaning of gamma and S in the equations around lines 103-4 was not clear to me.

Thank you for spotting this lack of clarity in these lines. The gammas are parameters of the model that control the scaling with catchment area and S is catchment area. We have specified the meaning of S in line 112 and of gamma in line 118.

The assumption of homogeneity of the windows (section 2.3) seemed to me to need some justification.

Thank you for rising this point; we have better explained it in section 2.3 (lines 180-181): "The rationale behind the homogeneity assumption is that the spatial windows, given their size, are characterized by comparatively homogeneous climatic conditions (and hence flood generation processes) and processes driving flood changes". Additionally, we discuss the homogeneity assumption in section 4 (lines 387-395): "We have not assessed the statistical homogeneity of the regions in terms of the flood change model used here. One reason is that formal procedures to assess the regional homogeneity, such as for example those used in regional flood frequency analysis (e.g. Hosking and Wallis, 1993; Viglione et al., 2007), are not available at the moment. Also, while deviation from regional homogeneity would probably invalidate estimates of local flood change statistics from the regional information (e.g., as in the prediction in ungauged basins, see Blöschl et al., 2013b), we expect its effect on the average regional behavior to be less relevant. This is because we have not observed significant differences in the spatial change pattern when changing the size of the moving windows (not shown here). As a limiting case, the results obtained using the three macro-regions (Sect. 3.3) are consistent with those obtained by the moving window analysis across Europe (Sect. 3.2)."

I was impressed with the design of Figs 2 and 3, which pack in a great deal of information. I would suggest that the authors either remove or justify the extrapolation of the model to catchment areas ten times smaller and ten times larger than those included in the dataset.

We agree with the Referee's suggestion of removing the extrapolation of the model to very small and very large catchment areas. We have modified Figures 2 and 3 accordingly.

The description of Fig 5 mentions larger positive trends in NW France for big floods than for small floods. I could not see that effect from comparing the pairs of maps.

Thank you for noticing it; we have corrected the description of Figure 5 by removing "and north-western France" from line 268 and 272.

Anonymous Referee #3:

The article is very nice, and contains a lot of information and results. One thing which is not clear from is the catchment size. For example, the Rijn has a catchment size of 180.000 km2, and contains also smaller catchments. How is this handled in this paper? Can smaller catchments be part of larger catchments? This is important, because large catchments do show a negative trend. This is not explained, and maybe there is no explanation, but has to be investigated in the future, this , however, can be stated more explicitly. The following citation does NOT explain why the large catchment show different results: "Furthermore, in medium and large catchments the magnitude of the trends is in general smaller compared to the small catchments. This may be due to long-duration synoptic weather events, producing floods in medium and large catchments, in contrast to small catchments in western Europe where the largest peaks are often caused by summer convective events with high local intensities". Does this suggest that "long-duration synoptic weather events" do show a negative trend?

We thank the Anonymous Referee #3 for the time she/he has spent on our manuscript and for the useful and constructive comments.

In this study, we analyse flood data from 2370 hydrometric stations in Europe, each one corresponding to a specific catchment size/area. Consequently, multiple smaller catchments can be part of a larger catchment. We have clarified it in lines 158-160: "Their contributing catchment area ranges from 5 to 100 000 km^2 and several nested catchments are included in the database". As explained in section 2.3, the Gumbel regional model is fitted to flood records that are pooled over regions. In each region, the regional trend corresponding to a large (hypothetical) catchment area is an output of the model and is determined by the flood records, within the region, that correspond to large catchment areas. The trend in large catchments is shown in Figure 5b and d and its sign and estimated magnitude varies according to the location and the flood quantile considered.

In this work we do not aim at investigating the causes of the observed flood trends (this is actually planned for the next phase of this research). However, in the discussion section, we make hypotheses on the possible drivers of the resulting flood trends, based on the literature and on our understanding of these processes. The sentences pointed out by the Referee refer to the Atlantic region, where large catchments exhibit, in general, smaller trends (positive for the 2-year quantile and negative for the 100-year quantile) compared to the smaller catchments. We do not intend to attribute this difference to specific drivers, nor to suggest negative trends in long-duration synoptic weather events. These aspects will be investigated in future work. In these lines we hypothesize that different types of weather events could affect the flood trends in catchments of different size in different ways. We have changed these sentence (lines 407-411) from: "This may be due to long-duration synoptic weather events, producing floods in medium and large catchments, in contrast to small catchments in western Europe where the largest peaks are often caused by summer convective events with high local intensities" to: "This could be explained by different types of weather events and their changes affecting the flood trends in catchments of different sizes in different ways, for example, long-duration synoptic weather events are probably more influential in producing floods in medium and large catchments, in contrast to small catchments in western Europe where the largest peaks are often caused by summer convective events with high local intensities […]".

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Flood trends in Europe: are changes in small and big floods different?

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Abstract.

Recent studies have revealed evidence of trends in the median or mean flood discharge in Europe over the last five decades, with clear and coherent regional patterns. The aim of this study is to assess whether trends in flood discharges also occurred for larger return periods, accounting for the effect of catchment scale. We analyze 2370 flood discharge records, selected from a newly-available pan-European flood database, with record length of at least 40 years over the period 1960-2010 and with contributing catchment area ranging from 5 to 100 000 km^2. To estimate regional flood trends, we use a non-stationary regional flood frequency approach consisting of a regional Gumbel distribution, whose median and growth factor can vary in time with different strengths for different catchment sizes. A Bayesian ~~Monte Carlo Markov Chain~~ Markov chain Monte Carlo (MCMC) approach is used for parameter estimation. We quantify regional trends (and the related sample uncertainties), for floods of selected return periods and for selected catchment areas, across Europe and for three regions where coherent flood trends have been identified in previous studies. Results show that ~~, in the Atlantic region, the~~ in northwestern Europe the trends in flood magnitude are generally positive. In small catchments (up to 100 km^2), the 100-year flood increases more than the median flood, while the opposite is observed in medium and large catchments, where even some negative trends appear, especially ~~over the southern part of the Atlantic region. In the Mediterranean region~~ in northwestern France. In southern Europe flood trends are generally negative. The 100-year flood decreases less than the median flood and, in the small catchments, the median flood decreases less compared to the large catchments. ~~Over Eastern~~ In eastern Europe the regional trends are negative and do not depend on the return period, but catchment area plays a substantial role: the larger the catchment, the more negative the trend. ~~The process causalities on the effects of return period and catchment area on the flood trends are discussed.~~

1 Introduction

Increasing flood hazard in Europe has become a major concern as a consequence of severe flood events experienced in the last decades~~. Examples of such events are~~ , as, for instance, the extreme floods occurred in central Europe in 2002 (e.g. Ulbrich et al., 2003) and 2013 (e.g. Blöschl et al., 2013a), and ~~in northwest England~~ the winter floods ~~of~~ in northwest England in 2009 (e.g. Miller et al., 2013) and 2015-16 (e.g. Barker et al., 2016). Hence a growing number of flood trend detection studies has been published in recent years. These studies typically analyse a large set of time series of flood peaks in a region and test them for the presence of significant gradual or abrupt changes in flood magnitude or frequency. For example, Petrow and Merz (2009) analysed eight flood indicators, from 145 gauges in Germany over the period 1951-2002, and detected mainly positive trends in the magnitude and frequency of floods. Villarini et al. (2011) tested ~~the~~ flood time series of 55 stations in central Europe, with at least 75 years of data, for abrupt or gradual changes and found mostly abrupt changes associated with anthropogenic intervention (such as the construction of dams and reservoirs and river training). Mediero et al. (2014) detected a general decreasing trend in the magnitude and frequency of floods in Spain, with the exception of the north-west. Prosdocimi et al. (2014) investigated the presence of trends in annual and seasonal maxima of ~~flow peaks~~ peak flows in the UK and found clusters of increasing trends for winter peaks in northern England and Scotland, and decreasing trends for summer peaks in southern England. These studies are highly heterogeneous in terms of flood data types, period of records and detection approaches and it is therefore not trivial to deduce regional patterns of flood regime change at the larger continental scale. Despite this fragmentation, Hall et al. (2014) summarized ~~their findings in a qualitative~~ the findings of previous studies in a map of increasing, decreasing and not detectable flood changes for Europe, ~~where~~ and showed the existence of consistent regional patterns~~emerge~~. In particular, ~~over~~ in central and western Europe flood magnitude ~~appears~~ appeared to increase with time, while it ~~appears to decrease over~~ seemed to decrease in the Mediterranean catchments and in eastern Europe.

More recently, thanks to the availability of European and global high spatial resolution databases, large-scale investigation studies across Europe have been published. Mangini et al. (2018) extracted 629 flood records ~~,~~ from the Global Runoff Data Center database (GRDC, 2016) ~~,~~ and compared the detected trends in magnitude and frequency of floods from different approaches (annual maximum flood and peak over threshold) for the period 1965–2005. Blöschl et al. (2019) analysed 2370 flood records from a newly available pan-European flood database ~~,~~ consisting of more than 7000 observational hydrometric stations and covering the last five decades (Hall et al., 2015) ~~,~~ and revealed consistent spatial patterns of trends in the magnitude of the annual maximum flood, with clear positive trends ~~over the Atlantic regions~~ in northwestern Europe and decreasing trends ~~over eastern Europeand the Mediterranean~~in southern and eastern Europe.

~~Most of the existing~~ Existing studies typically analyse catchments individually and investigate whether spatial clusters or coherent regional patterns of flood trends can be observed (e.g. Petrow and Merz, 2009; Prosdocimi et al., 2014; Mangini et al., 2018). Based on predefined regions or obtained change patterns, some studies aggregate flood records and local test results in order to assess their field significance (e.g. Douglas et al., 2000; Mediero et al., 2014; Renard et al., 2008). The main limitation of most ~~of the~~ at-site studies is the ~~limited~~ short length of the flood peak records locally available for the detection of trends, resulting in low signal-to-noise ratio and hence high uncertainties in the detected trend. Increasing the signal-to-noise ratio can be achieved by pooling flood data ~~over~~ from multiple sites within ~~a homogeneous region~~homogeneous regions, as in regional frequency analyses (Dalrymple, 1960; Hosking and Wallis, 1997). Several studies propose non-stationary regional frequency analyses for changes in precipitation extremes and flood trends, that consider the dependency of ~~the~~ regional estimates on time (e.g. Cunderlik and Burn, 2003; Renard et al., 2006a; Leclerc and Ouarda, 2007; Hanel et al., 2009; Roth et al., 2012) or on climatic and anthropogenic covariates (e.g. Lima and Lall, 2010; Tramblay et al., 2013; Renard and Lall, 2014; Sun et al., 2014; Prosdocimi et al., 2015; Viglione et al., 2016). Other approaches analyse coherent regional change by testing for the presence of trends in regional variables, as the number of annual floods in the region (e.g. Hannaford et al., 2013), or with regional tests (e.g. Douglas et al., 2000; Renard et al., 2008).

Most of the above cited studies however However, most of the cited studies investigate changes in the mean annual (or median) flood only, and few examples exist where observed trends in different flood quantiles are analysed. Typically, flood quantiles obtained with stationary and non-stationary flood frequency approaches are compared (see e.g. Machado et al., 2015; Šraj et al., 2016; Silva et al., 2017). The detection of changes in the magnitude of flood quantiles is much more common for precipitation (e.g. Hanel et al., 2009) or in flood projection studies (e.g. Prudhomme et al., 2003; Leander et al., 2008; Rojas et al., 2012; Alfieri et al., 2015).

To address this research gap, the aim of this study is to assess the changes occurred in small vs. big flood events (corresponding to selected flood quantiles) across Europe in the last five decades over five decades (i.e. 1960-2010), and to determine whether these changes have been subjected subject to different degrees of modification in time. Moreover, given that the impacts of different drivers of change on floods are expected to be strongly dependent on spatial scales (Blöschl et al., 2007; Hall et al., 2014), it is here also of interest to assess the effect of catchment area, by comparing changes of flood quantiles in small and large catchments for catchments of different sizes. Since the length of at-site flood records is often not sufficient to enable the reliable estimation of flood quantiles associated with high return periods (i.e. low probability of exceedance, e.g. the 100-year flood)to be reliably estimated, we adopt , in this study we adopt a (non-stationary) regional flood frequency approach, which pools flood data of multiple sites in order to increase the robustness of the estimated regional flood frequency curve with and its changes over time. The methods and the flood database are described in detail in Sect. 2. The results are presented in Sect. 3, where we show the estimation of the flood quantiles and their trends in one example region (Sect. 3.1), the patterns of flood regime change changes emerging from a spatial moving window analysis over across Europe (Sect. 3.2) and the flood regime changes in three relevant regions, emerging from the change patterns macro-regions (Sect. 3.3).

2 Methods

2.1 Regional flood change model

We aim In order to quantify the changes in time in the flood frequency curve by calculating the relative change in time of flood flood quantiles corresponding to different return periods for catchments of different size. To this aim, we propose a regional flood change model that is more robust than local (at-site) trend analysis, in particular regarding trends associated to large quantiles of the flood frequency curve. We assume the flood peaks to follow a Gumbel distribution We assume annual maximum flood peak discharges to follow the Gumbel distribution (i.e. Extreme Value distribution type I), whose cumulative distribution is defined as:

$$F_X(x) = p = \exp\left(-\exp\left(-\frac{x-\xi}{\sigma}\right)\right) = \exp\left(-\exp\left(-y\right)\right),$$

where ξ and σ are the location and scale parameter and

$$y = \frac{x-\xi}{\sigma} = -\ln(-\ln p),$$

is the Gumbel reduced variate. The corresponding quantile function, i.e., the inverse of the cumulative distribution function, is:

$$q(p) = \xi - \sigma \ln(-\ln p) = \xi + \sigma y,$$

In this paper we consider two alternative parameters ~~,~~ which better relate to the literature on regional frequency analysis, ~~specially~~ especially to the Index-Flood method of Dalrymple (1960) and Hosking and Wallis (1997). The alternative parameters are: (1) the ~~2-years~~ 2-year quantile or median q_2 (which corresponds to the index-flood), and (2) the ~~100-yr~~ 100-year growth factor x'_{100}, which gives the ~~100-years~~ 100-year quantile as $q_{100} = q_2(1+x'_{100})$ in a similar fashion to the modified quantiles in Coles and Tawn (1996) and Renard et al. (2006b). The relationships ~~of~~ linking these alternative parameters ~~with~~ to the Gumbel location and scale parameters are:

$$q_2 = \xi + \sigma y_2$$

$$x'_{100} = \sigma(y_{100} - y_2)/(\xi + \sigma y_2)$$

where $y_2 = -\ln(-\ln(0.5))$ and $(y_{100} - y_2) = -\ln(-\ln(0.99)) + \ln(-\ln(0.5))$. The quantile function, with the alternative parametrisation, is here expressed as a function of the return period ~~T as:~~ $T = 1/(1-p)$ as:

$$q_T = q_2\left(1 + a_T x'_{100}\right), \tag{1}$$

where $a_T = (y_T - y_2)/(y_{100} - y_2)$ and $y_T = -\ln(-\ln(1-1/T))$. In particular, a_T=0 for T=2 and a_T=1 for T=100.

In the following we estimate the parameters of the Gumbel distribution both locally and regionally. For the local case, we allow the parameters to change with time according to the following log-linear relationships:

$$\ln q_2 = \ln \alpha_{2_0} + \alpha_{2_1} \cdot t$$

$$\ln x'_{100} = \ln \alpha_{g_0} + \alpha_{g_1} \cdot t$$

$$\ln q_2 = \ln \alpha_{2_0} + \alpha_{2_1} \cdot t$$
$$\ln x'_{100} = \ln \alpha_{g_0} + \alpha_{g_1} \cdot t \tag{2}$$

For the regional case we introduce the scaling of q_2 and x'_{100} with catchment area ~~of the parameters~~ S, according to the following relationships:

$$\ln q_2 = \ln \alpha_{2_0} + \gamma_{2_0} \ln S + (\alpha_{2_1} + \gamma_{2_1} \ln S) \cdot t + \varepsilon$$

$$\ln x'_{100} = \ln \alpha_{g_0} + \gamma_{g_0} \ln S + (\alpha_{g_1} + \gamma_{g_1} \ln S) \cdot t$$

$$\varepsilon \sim \mathcal{N}(0, \sigma)$$

$$
\begin{aligned}
&\ln q_2 = \ln \alpha_{2_0} + \gamma_{2_0} \ln S + (\alpha_{2_1} + \gamma_{2_1} \ln S) \cdot t + \varepsilon \\
&\ln x'_{100} = \ln \alpha_{g_0} + \gamma_{g_0} \ln S + (\alpha_{g_1} + \gamma_{g_1} \ln S) \cdot t \\
&\varepsilon \sim \mathcal{N}(0, \sigma)
\end{aligned}
\tag{3}
$$

where the α and γ terms are parameters to be estimated (the γ terms control the scaling with area) and the ε term accounts for the fact that additional local variability, on top of the one explained by time and catchment area, is affecting the index flood but not the growth curve. In our model, a homogeneous region is thus formed by sites whose growth curve depends on catchment area and time only, and whose index flood also depends on other factors which determine an additional noise (here assumed normal). ~~Spatial cross-correlation between flood timeseries at different sites is not accounted for in this study.~~

~~In order to quantify the changes in time in the flood frequency curve, we calculate the~~ We investigate changes in flood quantiles associated with fixed annual exceedance probability $1-p$, or, equivalently, with fixed return period $T = 1/(1-p)$. The relative change in time of the generic flood quantile q_T ~~(defined in Eq. 1), which~~ is thus derived, for the local case~~is:~~, from Eq. 1 and Eq. 2:

$$
\frac{1}{q_T}\frac{dq_T}{dt} = \alpha_{2_1} + \alpha_{g_1} - \frac{\alpha_{g_1}}{1 + a_T x'_{100}},
\tag{4}
$$

and, for the regional case~~is:~~, from Eq. 1 and Eq. 3 :

$$
\frac{1}{q_T}\frac{dq_T}{dt} = \alpha_{2_1} + \alpha_{g_1} + (\gamma_{2_1} + \gamma_{g_1}) \ln S - \frac{\alpha_{g_1} + \gamma_{g_1} \ln S}{1 + a_T x'_{100}}.
\tag{5}
$$

The ~~alternative~~ model parameters, the quantiles and their local and regional relative trends are estimated by fitting the local and regional models to flood data with Bayesian inference through a Markov ~~Chain Monte Carlo~~ chain Monte Carlo (MCMC) approach. One of the advantages of the Bayesian MCMC approach is that the credible bounds of the distribution parameters (and other estimated quantities) can be directly obtained ~~in the estimation procedure~~ from their posterior distribution, without any additional assumption. The MCMC inference is performed using the R package *rStan* (Carpenter et al., 2017)~~is used to perform the MCMC inference. It makes use of~~. It generates samples with a Hamiltonian Monte Carlo ~~sampling, which speeds up convergence and parameter exploration by using the gradient of the log~~ algorithm, that uses the derivatives of the density function being sampled to generate efficient transitions spanning the posterior (Stan Development Team, 2018). For each inference, ~~we generate~~ 4 chains~~of length N_{sim}=~~, with 100 000 ~~, eachstarting from different parameter values , and check~~ simulations each, are generated with different initial values of the parameters and checked for their convergence. An improper uniform prior distribution over the entire real line is set for the parameters, with the exception of α_{2_0} and α_{g_0} for which we use an improper uniform prior distribution over the entire positive real line. When fitting the regional model we make the assumption of regional homogeneity with regards to the distribution of flood peaks, allowing local variability of the median value and its changes in time.

Spatial cross-correlation between flood time series at different sites is not accounted for in this model (i.e. it assumes independence of flood time series in space), however, it is possible to quantify its effects in first approximation in a Bayesian framework through an approach based on a magnitude adjustment to the likelihood (Ribatet et al., 2012). This approach consists in scaling the likelihood with a proper constant exponent to be estimated between 0 and 1, that results in inflating the posterior variance of the parameters and consequent increase of the width of parameter uncertainty intervals, reflecting the overall effect of spatial dependence in the data. In the case of spatial independence the magnitude adjustment factor is 1, whereas values of the magnitude adjustment factor close to 0 indicate strong inter-site correlation of floods and substantially larger sample uncertainties resulting from the adjusted model compared to the model where spatial cross-correlation is not accounted for. For further details about the method and its application to hydrological data, see Smith (1990), Ribatet et al. (2012) and Sharkey and Winter (2019). We apply this method to an example region in central Europe, in order to quantify the magnitude of the uncertainty underestimation associated with the model assumption of spatial independence in flood data.

2.2 European flood database

In this study, we analyse annual maximum discharge series from a newly available pan-European flood database, consisting of more than 7000 observational hydrometric stations and covering ~~the last~~ five decades (Hall et al., 2015). Their contributing catchment areas range from 5 to 100 000 km^2 ~~. The flood discharge data are accessible at~~ and several nested catchments are included in the database.

~~Only~~ For comparability with Blöschl et al. (2019), only the stations satisfying the following selection criteria, based on record length and even spatial distribution, are considered for the estimation of the regional trends. ~~As in Blöschl et al. (2019), we~~ We select stations with at least 40 years of data in the period 1960-2010, with record starting in 1968 or earlier, and ending in 2002 or later. Additionally, in order to ensure a more even spatial distribution across Europe, in Austria, Germany and Switzerland (countries with highest density of stations in the database) the minimum record length accepted is 49 years~~,~~; in Cyprus, Italy and Turkey 30 years are accepted, and in Spain 40 years without restrictions to the start and end of the record. Figure 1 shows the locations of the 2370 station satisfying the above selection criteria. The flood discharge data are accessible at https://github.com/tuwhydro/europe_floods.

2.3 Experimental design for the regional analyses

~~To assess the regional trends in small and large floods and in small to large catchments across Europe, we fit~~

In this study, the regional flood change model ~~, described in~~ of Sect. 2.1 ~~, to overlapping~~ is initially fitted to flood data of multiple sites that are pooled within spatial windows of ~~dimension~~ size 600x600 km, ~~assumed to be homogeneous. The overlapping length is~~ with an overlapping length of 200 km in both directions. The size and overlapping length of the windows ~~is~~ are chosen, after several preliminary tests, in order to ensure a sufficient number of gauges within each window and an appropriate spatial resolution at which to present the regional trends at the continental scale. Significant differences in ~~regime changes,~~ spatial change pattern are not observed when changing the window size ~~, are not observed~~ (not shown). ~~As the focus of the study is on the overall flood regime changes at the large scale across the continent, the selected 600x600 km windowscan~~

be considered, in this context, homogeneous with regards to geographical location and hence regional climate, which is the most important factor influencing the timing of annual maximum floods in Europe (Hall and Blöschl, 2018).

The rationale behind the homogeneity assumption is that the spatial windows, given their size, are characterized by comparatively homogeneous climatic conditions (and hence flood generation processes) and processes driving flood changes. Figure 1 shows the resulting 200x200 km grid cells. Each of the 600x600 km windows considered in the this analysis is composed of 9 neighbouring cells as represented, for example, by the black rectangular region, whose regional trend estimates are analysed shown in detail in Sect. 3.1. The example region is selected over in central Europe because of the density number of available gauges with different ranges of contributing catchment areas. In each window we estimate the regional relative trend in time of q_2 and q_{100}(i.e. percentage change of the 2-year and 100-year floods), as defined in Eq. 5, for small and big catchments catchment sizes (i.e. assuming S=100 and 10 000 km^2 in the model). Note that this analysis intends to show the estimated flood trends in hypothetical catchments with a specific size, which do not exist everywhere across Europe, based on fitting the model to existing catchments. We plot the resulting trends on a map by assigning their values to the central cell of the window respective central 200x200 km cell (e.g. the light red area in Fig. 1). The number of stations within each of the considered 600x600 km windows is shown in Fig. A1 for several ranges of catchment size.

Additionally, Fig. Figure 1 shows three regions macro-regions (numbers 1-3) that were identified by Blöschl et al. (2019) based on spatial patterns of flood trends and distinct driving processes. These regions are not dissimilar, located in northwestern Europe, southern Europe and eastern Europe, respectively. These regions were identified in Blöschl et al. (2019) by visual inspection of the flood trend and flood seasonality patterns and represent large homogeneous regions in terms of size and geographic location, to three of the European sub-domains usually considered in climate modeling studies, which represent comparatively homogeneous climatic conditions (Kotlarski et al., 2014)changes in the mean annual flood discharges. According to Köppen-Geiger climate classification (Köppen, 1884), northwestern Europe (region 1) corresponds approximately to the temperate oceanic climate zone, in southern Europe (regions 2) the hot and warm summer Mediterranean climate zones prevail, and eastern Europe (region3) is dominated by warm summer humid continental climate. Table 1 shows some related regional summary statistics. We also fit the In this study, the same regions are analysed in terms of changes in flood quantiles, to allow a more detailed assessment of existing research and to allow for ready comparability of the results. The regional change model to each of these is consequently fitted to the pooled flood data of the sites within each of the three regions and trends in small and big floods for small to large catchments are analysed (Sect. 3.3).

In summary, the following regional analyses are carried out:

- In Sect. 3.1 regional flood regime changes over in central Europe are investigated. The As an example, the regional model is fitted to the black rectangular region of Fig. 1, taken as an example and containing which contains 601 hydrometric stations. The For this example region, the regional model flood quantiles and their trends in time are shown , for this region, as a function of catchment area and of return period (as defined in Eq. 1 and Eq. 5, respectively). The regional trends in q_2 and q_{100} are finally compared for five hypothetical catchment sizes (S=10, 100, 1000, 10 000 and 100 000 km^2) . Additionally, and local trend estimates (as in Eq. 4) are shown together with the regional trends. In this example region we also investigate the overall effect of spatial dependence in flood data on the width of the estimated credible bounds, with the approach based on the magnitude adjustment to the likelihood.

– In Sect. 3.2 regional flood regime changes across Europe are investigated. The regional model is fitted to overlapping windows across Europe, of size 600x600 km, and the regional trends in q_2 and q_{100} are estimated for small and big hypothetical catchments (S=100 and 10 000 km^2, respectively). Maps of the estimated trends are shown, where the trend values are plotted in the respective central 200x200 km cell of each region. Differences among the estimated trends across Europe are additionally calculated for further comparison.

– In Sect. 3.3 regional flood regime changes in the Atlantic, Mediterranean and eastern European regions are investigatedare investigated in three macro-regions, i.e. (1) northwestern Europe, (2) southern Europe and (3) eastern Europe. The regional model is fitted to the three regions (1-3) of Fig. 1, resulting from the change patterns, these regions and the regional trends in q_2 and q_{100} are estimated and compared for five hypothetical catchment sizes (S=10, 100, 1000, 10 000 and 100 000 km^2).

Region	**No. of stations**	**Mean catchment area (km^2)**	**Mean outlet elevation (m a.s.l.)**	**Mean record length (years)**
1. AtlanticNorthwestern Europe	855 895	1301.1 1300.0	248.8 274.4	49.5 49.6
2. MediterraneanSouthern Europe	382 458	2662.8 2900.2	344.9 327.9	45.2 45.7
3. Eastern Europe	340 282	4667.4 4959.4	104.8 101.5	49.6 49.7
Europe	2370	2472.3	286.0	48.8

Table 1. Regional summary statistics (number of stations, mean catchment area, mean outlet elevation, mean record length) of the 2370 selected stations in Europe. The regions flood database for the considered macro-regions (1-3 correspond to those shown in Fig. 1) and for Europe.

3 Results

3.1 Regional flood regime changes over in central Europe

In this section, we show a detailed example of the (local and) regional model estimates for the black rectangular 600x600 km window indicated in of Fig. 1, located over in central Europe and containing 601 hydrometric stations. The annual maximum discharge series of these stations are shown in Fig. 2 (with thin lines and box-plots in panels a and b, respectively). In the same

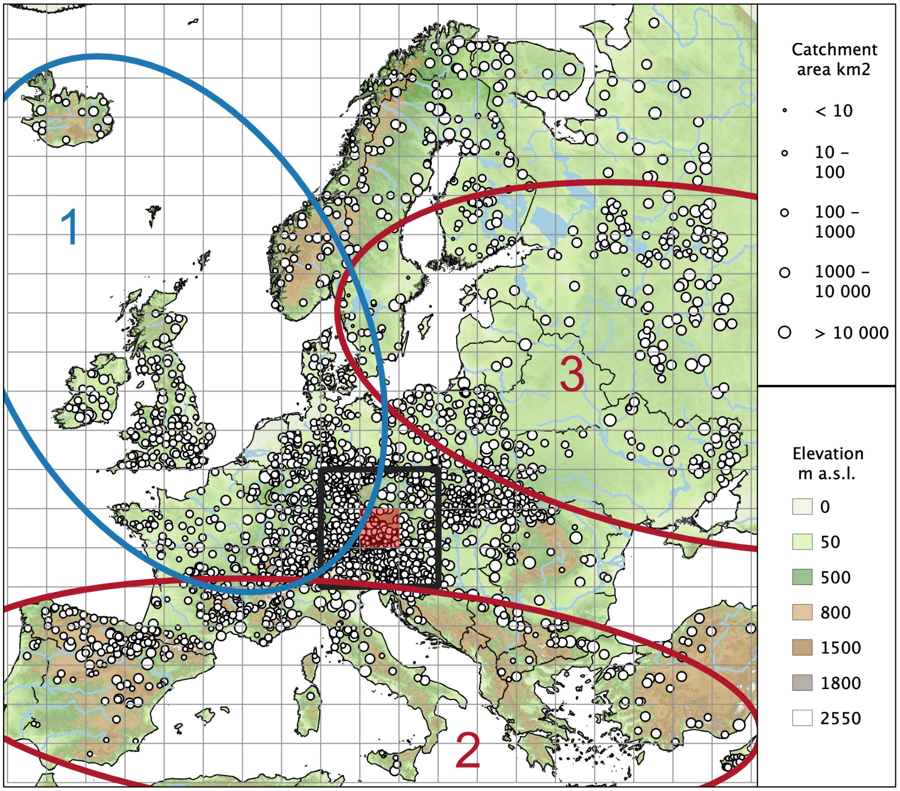

Figure 1. ~~Map~~ Location of the ~~locations of the~~ selected 2370 hydrometric stations in Europe and regions considered in this study. The size of the circles is representative for the contributing catchment area. The size of the grid cells is 200x200 km. The black rectangle shows the size of the spatial moving windows analysed in Sect. 3.2. It consists of ~~6~~ 9 cells, corresponding to 600x600 km. The three ellipses (numbers 1-3) mark homogeneous ~~sub-regions concerning trends~~macro-regions, analysed in Sect. 3.3, and consist of (1) ~~Atlantic~~northwestern Europe, (2) ~~Mediterranean~~ southern Europe and (3) eastern ~~European catchments~~Europe, respectively.

figure, the regional flood ~~peak~~ quantiles q_2 (panels a and b) and q_{100} (panel b), estimated with Eq. 1, are shown (thick lines and shaded areas) as a function of time for five selected catchment areas (S=10, 100, 1000, 10 000 and 100 000 km^2, indicated by different colours), in panel a, and as a function of catchment area for 1985 (i.e. the median year of the analyses period), in panel b. In both panels, the 90% credible bounds (shaded areas) are shown together with the median ~~value~~ (thick lines) of the posterior distribution of the regional flood quantiles. ~~Both~~ In general, both q_2 and q_{100} (not shown) increase ~~in~~ with time and their trend is larger for smaller catchment areas. The uncertainties in the quantile estimates also vary with catchment area: for very small (e.g. 10 km^2) and very large (e.g. 100 000 km^2) catchments the credible bounds get larger, reflecting the scarcity of samples with these (extremely small and extremely large) ~~size~~ sizes in the considered region (Fig. 1).

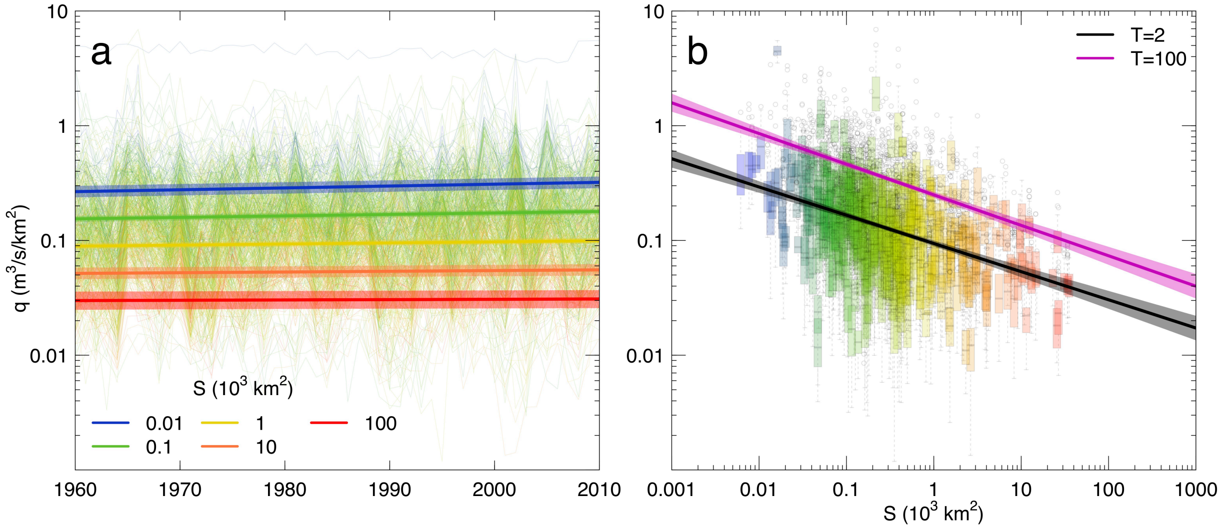

Figure 2. Fitting the regional model to flood data of ~~the~~ 601 hydrometric stations ~~within the black rectangle shown~~ in ~~Fig~~central Europe. ~~1.~~ In panel a, annual maximum ~~specific~~ discharge ~~time~~ series are shown with thin lines, with colours referring to catchment area. The thick lines and the shaded areas represent respectively the median and the 90% credible intervals of the ~~estimated~~ posterior distribution of the 2-year flood~~peak quantiles~~, ~~corresponding to a return period of 2 years,~~ for five hypothetical catchment areas (S=10, 100, 1000, 10 000 and 100 000 km^2, indicated by different colours). In panel b, the box-plots represent flood data as a function of catchment area. The thick lines and the shaded areas represent respectively the median and the 90% credible intervals of the ~~estimated~~ posterior distribution of flood ~~peak~~ quantiles, ~~with~~ corresponding to return ~~period~~ periods of 2 and 100 years. The curves are shown for 1985, i.e. the median year of the period analysed.

The two panels of Fig. 3 show the relative change in time, in % per decade, of the regional flood quantile estimates q_T (as defined in Eq. 5) as a function of catchment area and of the return period, respectively. The curves are shown for 1985, the median year of the analysed period. The trends in q_T are mostly positive and their values tend to decrease with increasing catchment area, approaching zero and moving towards negative values for higher return periods and for very large catchment areas (S=100 000 km^2). For small catchment areas (S<100 km^2) the trend tends to be bigger for floods with large return periods (q_{100}) than for small return periods (q_2). The opposite is observed for larger catchments. As in Fig. 2, we observe larger 90% credible bounds of the quantile estimates for very small and very large catchment areas. In this case, the overall effect of spatial cross-correlation between flood time series at different sites is investigated through the magnitude adjustment to the likelihood. The credible bounds for the regional trends obtained with the likelihood adjustment (dashed lines in Fig. 3) are 17.6 to 23.8% larger compared to the case where spatial cross-correlation is not accounted for (estimated magnitude adjustment factor 0.669).

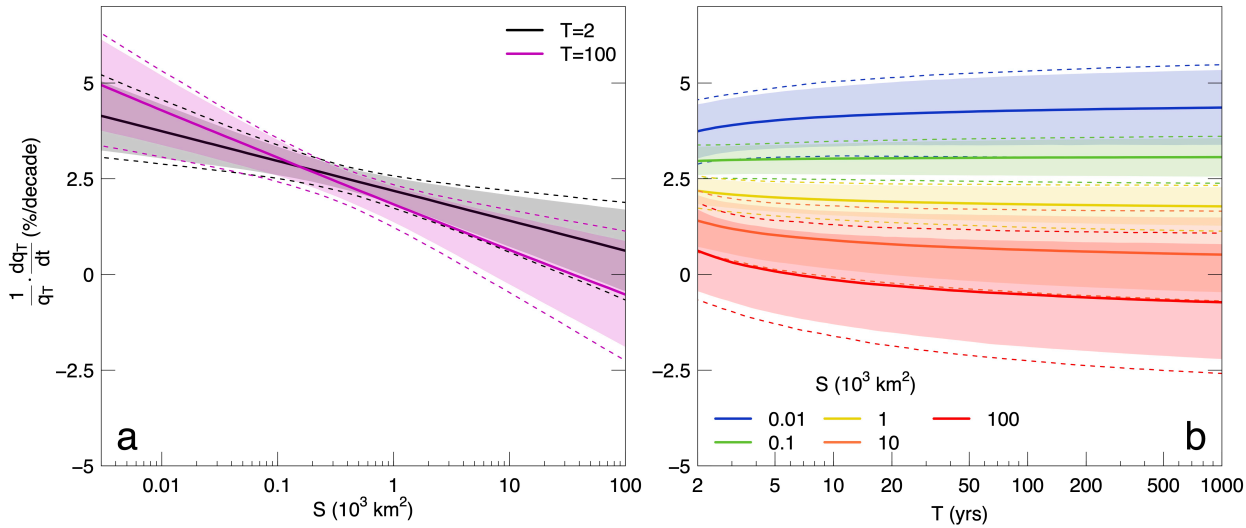

Figure 3. Estimates of the regional relative trend of q_T in %/decade as a function of catchment area and return period in central Europe. The thick solid lines and the shaded areas represent respectively the median and the 90% credible intervals of the estimated posterior distribution of the regional trends. Panel a shows the trend as a function of catchment area for selected values of the return period (T=2 and 100 years). Panel b shows it the trend as a function of return period and for five hypothetical catchment area areas (S=10, 100, 1000, 10 000 and 100 000 km^2). The curves are shown for the median year of the period analysed (i.e. 1985). As in Fig. 2, The credible bounds obtained with the region considered is magnitude adjustment to the black rectangle of Figlikelihood are shown with dashed lines.1.

Figure 4 summarizes the relative flood trends in the considered region for big (q_{100}) vs. small floods (i.e. small return periodsq_2) and for small (10 km^2) to large catchment areas . It (100 000 km^2). Panel a shows a scatter plot (light transparent dots) of the local relative trends in large (q_{100}) vs. small floods (vs. q_2), as defined in Eq. 4, with the respective uncertainties (90% credible intervals (error bars) for 1985. On top of the local valuestrend estimates, the regional relative trends, calculated with Eq. 5, are plotted (dark solid dots). Again colours refer to catchment area for both the local and regional estimates. In Fig. 4 Regional flood trends are generally positive in the considered region , with (Fig. 4b), with the exception of big floods (T=100) in the hypothesized very large catchments (S=100 000 km^2). For both big and small events, the trend is generally larger in smaller catchments and it diminishes with increasing catchment area, approaching zero, for small floods (q_2), and moving towards negative values for big floods (q_{100}, according to the credible intervals, we cannot determine if its trend for big catchments is different from zero). The credible bounds obtained with the likelihood adjustment (dashed lines in Fig. 4b) result slightly wider (about 20%) compared to the case where spatial cross-correlation is not accounted for.

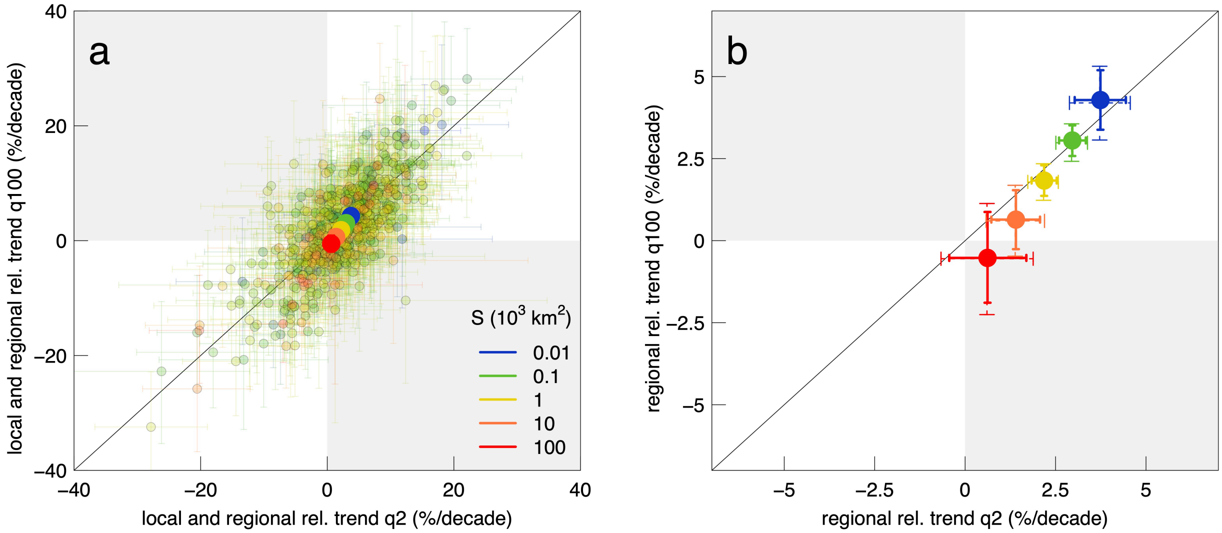

Figure 4. Local and regional relative trend in %/decade in large (q_{100}) vs. small floods (q_2) in central Europe. Panel a shows ~~a scatter plot (light colour dots in~~ the ~~background)~~ median of the posterior distribution of the local ~~relative~~ trends in ~~large (q_{100})~~ vs. ~~small floods (~~q_2 (light transparent dots in the background), with the respective 90% credible intervals (error bars). On top of them, the estimated ~~median~~ regional ~~relative~~ trends (dark solid ~~points~~dots) are shown. Panel b shows the median of the posterior distribution of the regional ~~relative~~ trends ~~(solid points)~~ in ~~large (q_{100})~~ vs. ~~small floods (~~q_2 (dark solid dots), with the respective 90% credible intervals (error bars with solid lines). Colours refer to catchment area in both panels and for both the local and regional estimates. The figure is obtained for 1985, i.e. the median year of the analyses period. ~~As in Fig. 2,~~ The credible bounds obtained with the ~~region considered is~~ magnitude adjustment to the ~~black rectangle of Fig~~likelihood are shown with dashed lines.~~1.~~

3.2 Regional flood regime changes across Europe

Figure 5 shows the results of the regional trend analysis with moving windows across Europe. It is obtained by fitting the regional model to overlapping 600x600 km windows and by plotting the estimated trend values in the respective central 200x200 km cell. Panels a and b show the percentage change of the median flood (i.e. T=2 years) and panels c and d of the 100-year flood. Panels a and c refer to small (i.e. 100 km^2) catchment area and panels b and d to big catchment area (i.e. 10 000 km^2). The white circles represent a measure of the uncertainty in the estimation of the regional relative trend, with their dimension being proportional to the width of the respective 90% credible intervals. The larger the circle, the larger the uncertainty associated with the value of flood trend provided in the map.

When analysing the panels of Fig. 5, ~~some~~ regional patterns of flood change appear: flood magnitudes increase in general in the British-Irish Isles ~~, in north-western France~~ and in central Europe, whereas they decrease in the Iberian ~~peninsula~~Peninsula, in the Balkans, in eastern Europe and in most of Scandinavian countries. The larger uncertainties associated with the regional trends are evident ~~over~~ in eastern Europe, Turkey, Iceland and ~~southern parts of the Mediterranean countries~~ the countries surrounding the Mediterranean, where the density of the hydrometric stations in the flood database is low. In the ~~British~~

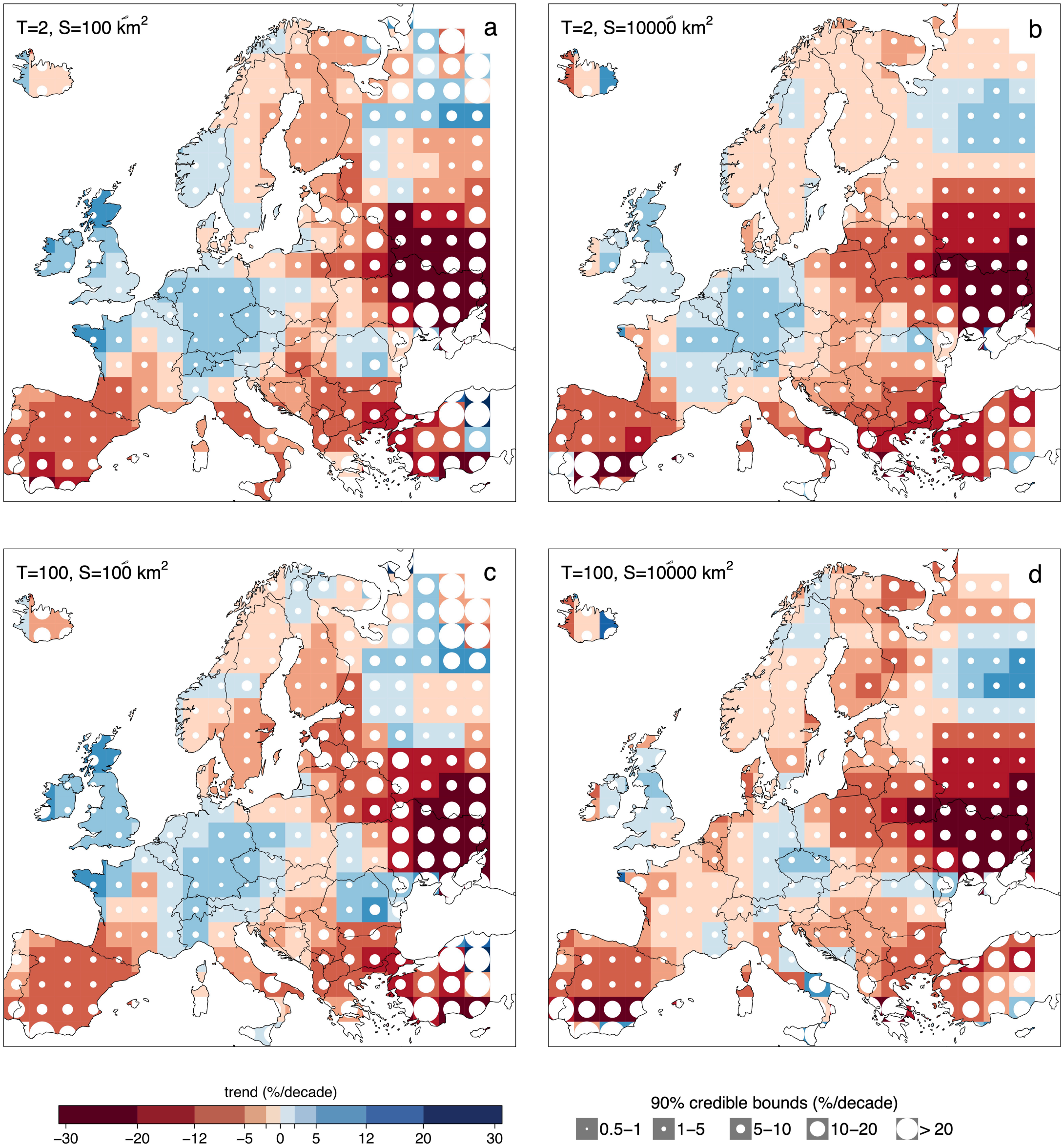

Figure 5. Flood trends in Europe: small vs big floods. The panels show the median ~~values~~ of the posterior distribution of the regional relative ~~trend~~ trends of flood ~~magnitude to~~ quantiles in time (i.e. the percentage change in %/decade). Positive trends in the magnitude of ~~floods~~ flood quantiles are shown in blue and negative trends in red. ~~The circle~~ Circle size is proportional to the width of the 90% credible intervals. ~~The results~~ Results are shown for the median flood (i.e. T=2 years), in panel a and b, and for the 100-year flood, in panel c and d. ~~The flood~~ Flood trends refer to small (i.e. 100 km^2) in panel a and c and to large catchment area (i.e. 10 000 km^2) in panels b and d.

~~Islesand north-western France~~British-Irish Isles, the positive trends in small catchments (up to 10-12% per decade, Fig. 5a and c) appear to be larger for bigger return periods (Fig. 5c), whereas for larger catchments the trends are smaller in absolute value (up to 5% per decade) and, in some cases, they ~~tend to~~ disappear or even tend to become negative. In central Europe, the magnitude of ~~the~~ positive trends (~~2.5-5~~2-5% per decade) tends to decrease for large catchments and large return periods where, in most cases, the regional trends are between 0 and ~~2.5~~2% per decade (Fig. 5b and d). Positive flood trends are also observed in northern Russia, especially in large catchments (Fig. 5b and d). These positive trends are however accompanied by strong uncertainties in the case of small catchments (Fig. 5a and c). In the Iberian ~~peninsula, south-western~~ Peninsula, southwestern France, Italy and in the Balkans, negative trends appear and they are particularly consistent for the median floods (i.e. return period T=2 years), where the regional flood trends are mostly between -5 and -12% per decade (Fig. 5a and b). ~~The trends~~ Trends in the magnitude of the big flood events (T=100 years) are less negative ~~instead~~ and some isolated positive trends do appear. The lower number of large catchments in this areas is ~~in general~~ generally reflected in larger uncertainties (Fig. 5b and d). ~~Over~~ In eastern Europe strong negative trends in flood peak magnitude are detected for ~~big and small~~ small and big floods and small and large catchments. In eastern Europe, ~~contrarily~~ contrary to the Mediterranean countries, the dataset contains mostly big catchments, hence the uncertainties are larger for small catchments (Fig. 5a and c). In Scandinavia the regional trends are, in general, ~~not~~ neither clearly positive nor negative, with spatial patterns changing with return period and catchment area. However, in Finland negative trends are prevalent (mostly between -5 and -12% per decade) and they become less negative (0-5% per decade) for big catchments and small return periods (Fig. 5b). Overall, in more than half of the cases the 90% credible bounds do not include 0 (i.e. 68.9%, 59.2%, 58.5% and 50.2% respectively in panel a, b, c and d). Positive (negative) trends occur in 26.3 to 34.95% (65 to 76%) of the cases and their credible bounds do not include zero in 4.9 to 20.8% (39.5 to 48.1%) of the total cells. These percentages depend on the assumptions made, such as regional homogeneity and no spatial cross-correlation, and may, therefore, be overestimated.

For further comparison, we estimate the differences between the regional relative trends in the panels of Fig. 5. In particular, Fig. 6a and 6b show the difference between the trend in q_{100} and the trend in q_2, for a hypothetically big (i.e. 10 000 km^2) and small catchment ~~area~~ areas (i.e. 100 km^2) respectively. Figure 6c and 6d show ~~instead~~ the difference between the trend in large and the trend in small catchments, for small (T=2 years) and big (T=100 years) return periods respectively. Positive differences are shown in blue and negative ones in red. The circle size is proportional to the width of their 90% credible intervals.

In small catchments (Fig. 6a) positive differences between the trend in q_{100} and in q_2 prevail in the British ~~isles~~Isles, the Iberian ~~peninsula~~ Peninsula and southern France, the Balkans, eastern Europe and northern Russia. This indicates that, in the small catchments of these regions, the trend of the extreme flooding events is more positive (or less negative) ~~compared to~~ than the median flood. Negative differences appear ~~instead~~ in central Europe, Baltic countries, southern Scandinavia and Turkey. The magnitude of this difference varies in a narrow range (~~-2.5~~ -2 to +~~2.5~~ 2% per decade) in most parts of Europe and it gets larger (up to -12 to +12% per decade) in ~~a number of~~ several regions in southern and eastern Europe

In the case of big catchments (Fig. 6b), negative differences between the trend in q_{100} and in q_2 are more widespread across Europe, compared to ~~the case of~~ those in smaller catchments. In the British ~~isles~~Isles, southern France, ~~north-western~~ northwestern Italy, eastern Europe and northern Russia the difference becomes in fact negative. This suggests that, in the big

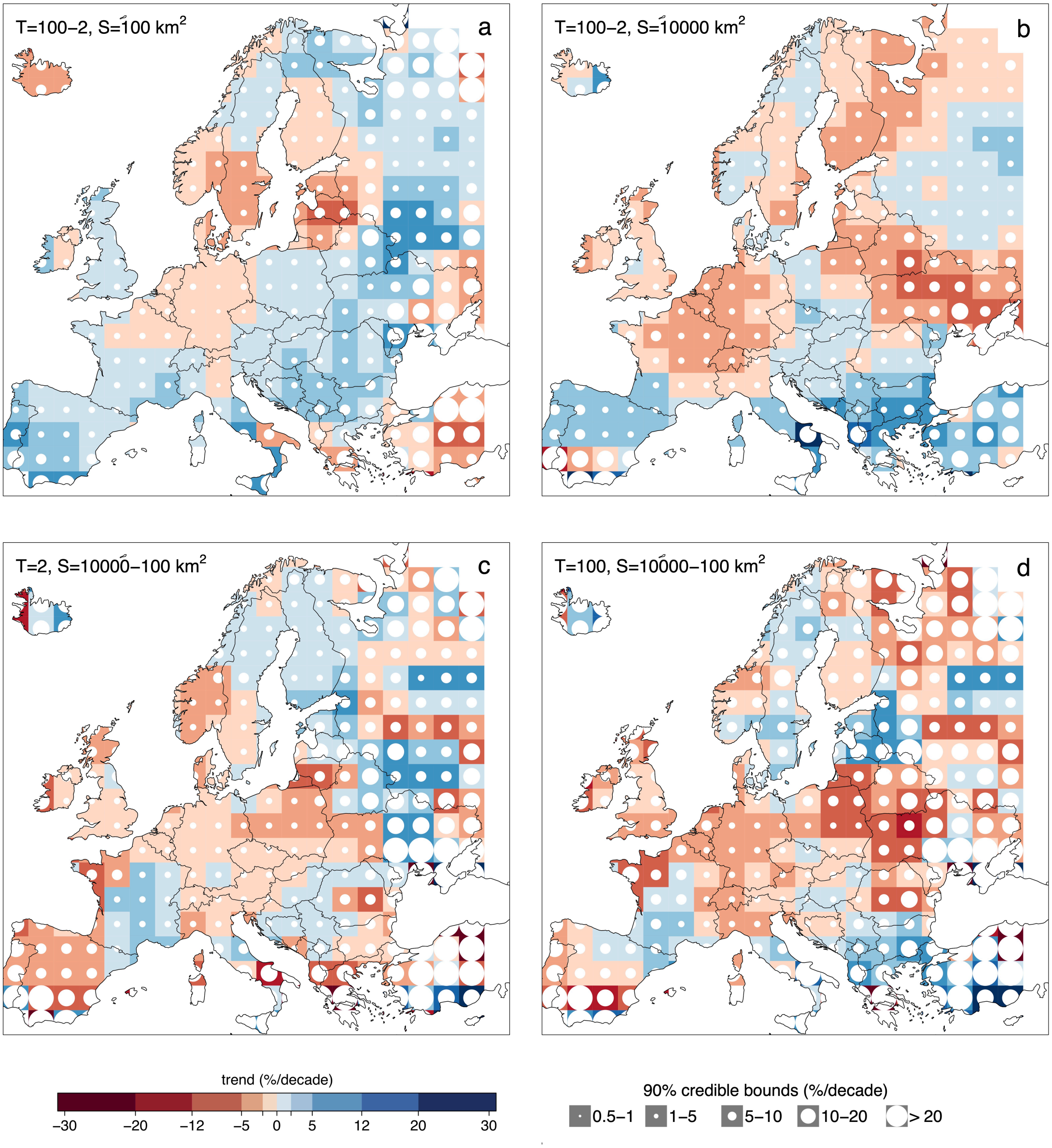

Figure 6. Differences between flood trends of big vs small floods (i.e. T=100 and 2 years, respectively) and in large vs small catchments (i.e. S=10 000 and 100 km^2, respectively). The panels show the differences (in % per decade) between the trends of Fig. 5. Positive differences are shown in blue and negative in red. ~~The circle~~ Circle size is proportional to the width of the 90% credible intervals. The panels in the first row show the difference between the trend in q_{100} and the trend in q_2 for small (a) and big catchment area (b). The panels in the second row show the difference between the trend in large and the trend in small catchments for small (c) and big (d) return periods.

catchments of these regions, the trend of the extreme flooding events is less positive (or more negative) ~~compared to~~ than the median flood. Positive values of this difference ~~instead hold~~ appear mostly in southern Europe and Russia. The magnitude of these differences, in the case of big catchments, varies in a wider range (generally from -5 to +5% per decade) with larger differences in few regions in southern and eastern Europe.

The patterns appear more fragmented when analysing the differences between trends in catchments with big and small catchment ~~area~~ areas (Fig. 6c and d) and their magnitude is generally larger (mostly from -12 to +12 % per decade). Negative differences between trends in large and trends in small catchments prevail in western and central Europe (with the exception of France), for both the median and the 100-year flood, and they extend towards eastern countries, in the case of the 100-year flood (Fig. 6d). This indicates that trends in large catchments are more negative (or less positive) than those in small catchments. Positive differences appear ~~instead~~ in central and southern France, in the Balkans, Baltic countries and northern Russia, for both T=2 and 100 years (Fig. 6c and d), and in Finland and eastern Europe, for T=100 years (Fig. 6d).

3.3 Regional flood regime changes in ~~the Atlantic~~northwestern, ~~Mediterranean~~ southern and ~~Eastern European regions~~and eastern Europe

The regional trends shown in Sect. 3.2 highlight the presence of ~~mostly~~ predominantly positive trends in ~~the Atlantic region~~ northwestern Europe and negative trends in ~~the Mediterranean and over Eastern~~ southern and eastern Europe. In this section we fit the regional model of Sect. 2.1 by pooling flood data over each of these three regions and we estimate the regional relative trends for five hypothetical catchment areas (S=10, 100, 1000, 10 000 and 100 000 km^2) and for two selected values of return period (T=2 and 100 years). The resulting trends are shown together with their 90% credible intervals in Fig. 7.

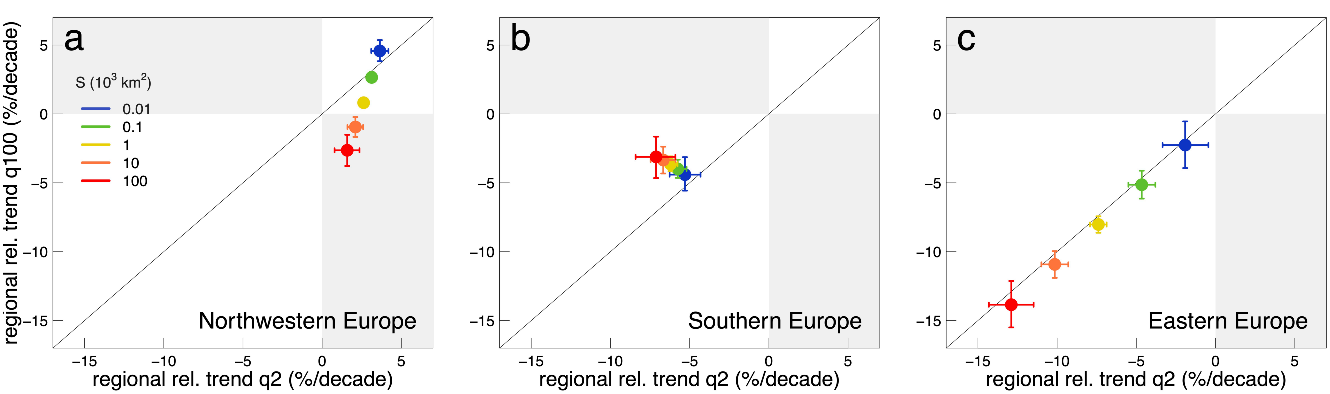

Figure 7. Regional relative trend in large (q_{100}) vs. small floods (q_2) in ~~the Atlantic~~ (a) northwestern Europe, ~~Mediterranean~~ (b) southern Europe and ~~eastern European~~ (c) ~~regions~~eastern Europe for five hypothetical catchment areas (S). The figure shows the median ~~regional relative trends~~ (solid ~~points~~dots) ~~together with their~~ and the 90% credible intervals (error bars) of the posterior distribution of the regional trends. Catchment area is shown with different colours. The figure is obtained for 1985, i.e. the median year of the period analysed.

In the Atlantic region northwestern Europe (Fig. 7a) the trends in flood magnitudes are mainly predominantly positive, with the exception of very large catchments for the 100-year flood. The magnitude of the positive trend tends to decrease with increasing catchment area for the 2-year flood, while whereas for the 100-year flood the positive trend decreases, it goes to zero for catchment size sizes of about 10 000 km^2, and then becomes negative and increases in absolute value for increasing catchment area. The trends are in general Generally, trends are bigger for the 2-year flood compared to the 100-year flood, with the exception of very small catchments (S=10 km^2). Overall there is large variability of the trend in q_{100}, which ranges from about -2.5 to 5% per decade with catchment area, while the trend in q_2 is around 2 2-3% per decade for all areas considered.

In the Mediterranean catchments the southern Europe the trends are negative in all the considered cases and larger in absolute value for the 2-year flood. This means that the more frequent flood events tend to decrease more than the rare, more extreme events. However, there is small variability of the trends (especially in q_{100}) with catchment size. In the smaller catchments the regional relative trends in q_2 and q_{100} are both about -5% per decade. As catchment area increases, the trend in q_2 decreases from -5 to -10-5.2 to -7.1% per decade, while the trend in q_{100} increases slightly from about -5.3 to -4.3 from -4.4 to -3.1% per decade.

Over Eastern In eastern Europe the regional relative trends are all negative. The estimates lay close to the 1:1 line; this , which means that the trends are roughly the same similar for big and small events and that there is no little variability with the return period. Catchment area plays instead seems to play a more important role in determining flood trends. The , as the magnitude of the negative trend appear, in fact, appears to be very sensitive to the catchment size and ranges from about -10.8 -13.8% per decade for bigger the big catchments, to 1.3 -1.9% per decade for smaller ones.

In all the regions analysed, it is also evident that the uncertainties in the trend estimates vary with catchment area: the credible bounds are in fact narrower for middle sized narrower for mid-sized catchments that are represented by more hydrometric stations in the database.

4 Discussion and conclusions

In this study we assess and compare the changes occurred in small and that have occurred over five decades (i.e. 1960-2010) in small vs. big flood eventsand in small to large catchments across Europe, during the last five decades., for catchments of different hypothetical sizes across Europe. We propose a regional flood change model that is more robust than local (at-site) trend analysis, in particular regarding trends associated with large quantiles of the flood frequency curve (e.g. the 100-year flood). Flood peaks are assumed to follow a regional Gumbel distribution, accounting for time dependency of two parameters alternative to the location and scale parameters: the 2-year flood q_2 and the 100-year flood growth factor x'_{100}. The two parameters are modelled as varying in time according to log-linear relationships. Other relationships with time could be investigated as well as the use of physical covariates. In flood frequency analysis, the Generalized Extreme Value distribution (GEV) is commonly used to estimate flood quantiles(e. g. the 100-year flood). . The suitability of the GEV distribution in the European context is discussed in detail in Salinas et al. (2014b, a)Salinas et al. (2014a, b). The estimate of the shape parameter of the GEV distribution is extremely sensitive to record length (Papalexiou and Koutsoyiannis, 2013), with strong bias and uncertainty for short records (Martins and Stedinger, 2000) , and, when corrected for the effect of record length, it varies in a narrow range (Papalexiou and Koutsoyiannis, 2013). For these reasons, in regional frequency analyses the GEV shape parameter is commonly assumed to be identical for all sites within a region (see e.g. Renard et al., 2006a; Lima et al., 2016). Here, we fix the shape parameter equal to 0 (i.e. we assume a Gumbel distribution) which leads to more robust relationships, without compromising the general validity of the study (i.e. the analysis can be repeated with a more complex GEV distribution if longer flood records are available). A Bayesian Monte Carlo Markov Chain A Bayesian Markov chain Monte Carlo (MCMC) approach is used for parameter estimation, allowing to directly obtain information about their associated uncertainties.

Spatial cross-correlation between flood timeseries time series at different sites is not accounted for in this study model and may affect the estimation of sample sampling uncertainty (see e.g. Stedinger, 1983; Castellarin et al., 2008; Sun et al., 2014). Because of this, the sample sampling uncertainties estimated in this paper should be consider considered as a lower boundary. We expect that the effect of spatial correlation on the identified spatial patterns is negligible, since the cross-correlation length is about 50 km (calculated from flood time series and distances between catchment outlets, using a nonlinear regression model proposed by Tasker and Stedinger (1989)), which is much shorter than the size of the spatial patterns. A possible way of taking into account spatial cross-correlation between sites is a magnitude adjustment to the likelihood, that reflects the overall effect of spatial dependence and results in increased width of uncertainty intervals of the estimated quantiles (see Ribatet et al., 2012) . The application of this approach to the specific example region in central Europe shows that the 90% credible bounds of the regional trends in q_2 and q_{100} result, on average, 20% wider compared to the case where the likelihood is not adjusted. However, further research is needed to properly characterize the effect of spatial dependence between flood peaks in regional trend analyses.

We analyse 2370 flood records, selected from a newly-available pan-European flood database (Hall et al., 2015). We estimate regional trends (and the related uncertainties) in the magnitude of floods of selected return periods (T=2 and 100 years) and for selected catchment areas (S=10 to 100 000 km^2), by fitting the proposed regional flood change model to flood data pooled within defined regions. Firstly, the The trend patterns are investigated at the continental scale, by fitting the model to 600x600 km^2 overlapping windows, with a spatial moving window approach. Flood trends are then analysed in three regions (Atlantic, Mediterranean and eastern European catchments, respectively), emerging from these change patterns macro-regions (i.e. northwestern, southern and eastern Europe), based on previously published change patterns of the mean annual flood magnitude and seasonality. When fitting the model to these regions, we allow for local spatial variations in the median, but assume homogeneity with regards to the growth curves of flood peaks , to changes in time and the dependency of the trends on catchment area and on the return period. The assumption is that these regions are characterized by comparatively homogeneous climatic conditions and processes (and hence flood generation processes) and processes driving flood changes. We have not assessed the statistical homogeneity of the regions in terms of the flood change model used here. One reason is that formal procedures to assess the regional homogeneity, such as for example those used in regional flood frequency analysis (e.g. Hosking and Wallis, 1993; Viglione et al., 2007), are not available at the moment. Also, while deviation from regional homogeneity would probably invalidate estimates of local flood change statistics from the regional information (e.g., as in the prediction in ungauged basins, see Blöschl et al., 2013b), we expect its effect on the average regional behavior to be less relevant. This is because we have not observed significant differences in the regime changes spatial change pattern when changing the size of the moving windows (not shown here). As a limiting case, the results obtained using the three large climatic regions macro-regions (Sect. 3.3) are consistent with those obtained by the moving window analysis across Europe (Sect. 3.2).

The results of this study show that the trends in flood magnitude are generally positive in the Atlantic regionnorthwestern Europe, where floods occur predominantly in winter (Mediero et al., 2015; Blöschl et al., 2017; Hall and Blöschl, 2018). The increasing winter runoff in UK is typically explained in the literature by increasing winter precipitation and soil moisture (Wilby et al., 2008). Recent studies show that extreme winter precipitation and flooding events over north-western in northwestern Europe are positively correlated with the North Atlantic Oscillation (NAO) and the East Atlantic (EA) pattern (Hannaford and Marsh, 2008; Steirou et al., 2019; Zanardo et al., 2019; Brady et al., 2019). Furthermore the largest winter floods in Britain occur simultaneously with Atmospheric Rivers (AR) (Lavers et al., 2011), which are expected to become more frequent in a warmer climate (Lavers and Villarini, 2013). When comparing trends in flood events associated with different return periods, we observe two opposite behaviours depending on catchment area. In small catchments (up to 100 km^2) the 100-year flood increases more than the median flood, while the opposite is observed in medium and large catchments, where even some negative trends appear, especially over the continental part of the Atlantic regionin northwestern France. Furthermore, in medium and large catchments the magnitude of the trends is in general smaller compared to the small catchments. This may be due to could be explained by different types of weather events and their changes affecting the flood trends in catchments of different sizes in different ways, for example, long-duration synoptic weather events , are probably more influential in producing floods in medium and large catchments, in contrast to small catchments in western Europe where the largest peaks are often caused by summer convective events with high local intensities (Wilby et al., 2008), which are expected to increase in a warmer climate (IPCC, 2013).

In the Mediterranean catchments southern Europe flood trends are negative, possibly due to decreasing precipitation and soil moisture, caused by increasing evapotranspiration and temperature (Mediero et al., 2014; Blöschl et al., 2019). The big flood events (i.e. T=100 years) decrease less in time compared to more frequent events (i.e. T=2 years), leading to higher flood variability and steeper flood frequency curves. The reason for this is likely may be (decreasing) soil moisture driving flood changes in southern Europe, causing dryer direr catchments and consequent negative trends in flood magnitudes, that are particularly strong for small floods (q_2), where the influence of soil moisture is stronger (as shown for e.g. by Grillakis et al., 2016). The magnitude of big flood events is also decreasing (probably, as an effect of decreasing precipitation) but in this case soil moisture is less influential, resulting in less strong negative trends compared to q_2. In small catchments, trends are less negative than in larger catchments for small return periods. For large return periods, the trends in small and large catchments are similar. Additionally, in the The flood trends do not vary significantly with catchment area. In smaller catchments we observe the same negative trend similar negative trends in q_2 and q_{100} . Notice however (about 5%/decade). With increasing catchment area the trends in q_2 become more negative, while the opposite is observed for q_{100}. Notice, however, that the small catchments analysed in the Mediterranean region southern Europe have sizes of the order of 10 km^2 , and aretherefore and are, therefore, larger than catchments where flash floods are the dominant flood type and infiltration excess runoff is the main generation mechanism (Amponsah et al., 2018). For these very small catchments (< 10 km^2), floods may become larger due to more frequent thunderstorms (Ban et al., 2015) and land management changes, e.g. deforestation and urbanisation (Rogger et al., 2017).

~~Over eastern Europe the~~ In eastern Europe trends in flood peak magnitude are strongly negative for both ~~big and small~~ small and big floods, and ~~large and small~~ small to large catchments. These negative flood trends have been linked in past studies with increasing spring air temperature, earlier snow-melt and reduced spring snow-cover extents (Estilow et al., 2015), producing increased infiltration and consequent earlier and decreasing spring floods (Madsen et al., 2014; Blöschl et al., 2017, 2019). The resulting trends in eastern Europe do not seem to depend on the return period (i.e. for a given catchment area, the trend in q_2 and the trend in q_{100} are almost identical), whereas catchment area plays a substantial role: the larger the catchment area, the more negative the trend. ~~This~~ These results suggest that, in these region, snow-melt affects flood events of different magnitude in the same way and it represents a relevant processes for flood (trend) generation especially in large catchments. The explanation for ~~that~~ the importance of these processes in large catchments could be found in the characteristics of snow-melt flooding, which originates from large-scale gradual processes, i.e. snowfall and temperature changes, that may be more influential for large scale events, compared to smaller-scale catchments, where other local conditions may prevail.

The uncertainty associated with the regional trend estimates is here assessed through their 90 % credible bounds. The results show that the uncertainties in the trend estimates varies with catchment area: the credible bounds are ~~in fact~~ generally narrower for ~~middle sized~~ mid-sized catchments, that are represented by more samples in the database, and ~~they~~ the bounds become wider for very small and very large values of catchment area, where less samples are available. Spatial patterns in trend uncertainties are also observed. As expected, the uncertainty is lower in the regions where the density of stations is very high (i.e. central Europe and UK), while the estimated trend is very uncertain ~~over~~ in the data-scarce regions (i.e. southern and eastern Europe).

This study provides a continental-scale analysis of the changes in flood quantiles ~~occurred over the last five decadesacross Europe. Our findings are relevant to flood risk managers to understand the amount of the potential over- or underestimation of the design flood at different spatial scales and in different European regions, when past flood changes are not taken into account. According to climate~~ that have occurred across Europe over five decades, however further research is needed to formally attribute the resulting regional change patterns to potential driving processes. According to flood hazard projections, the past flood regime changes found in this study, ~~will~~ are likely to further occur in the next decades, led by ~~precipitation increase over Western Europe, decrease over the Mediterranean and temperature increase~~ increasing precipitation over northwestern Europe, decreasing precipitation over southern Europe and increasing temperature in eastern Europe (see e.g. Alfieri et al., 2015; Kundzewicz et al., 2016; Thober et al., 2018). This has relevant implications since flood risk management has to adapt to these new realities.

Data availability. The flood discharge data used in this paper are available at https://github.com/tuwhydro/europe_floods. Data regarding catchment areas belong to different institutions listed in Extended Data Table 1, Blöschl et al. (2019).

Author contributions. GB conceived the original idea, and all co-authors designed the overall study. AV developed the model. MB performed the analysis and prepared the paper. All co-authors contributed to the interpretation of the results and writing of the paper.

Competing interests. The authors declare they have no conflict of interest.

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Appendix A

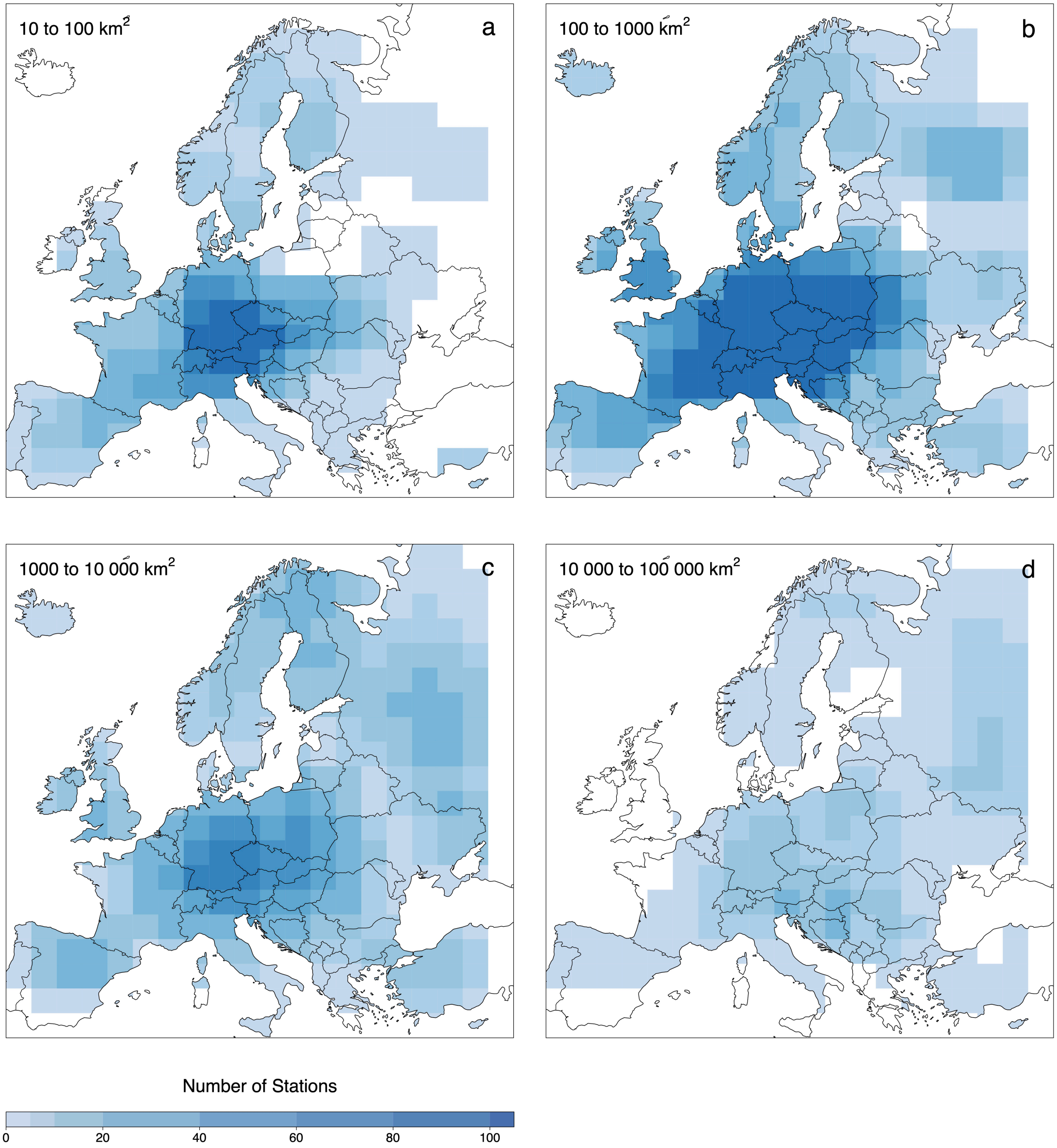

Figure A1. Number of stations in each 600x600 km region, stratified by catchment size: (a) 10 to 100 km^2, (b) 100 to 1000 km^2, (c) 1000 to 10 000 km^2 and (d) 10 000 to 100 000 km^2. The value representative for the region is plotted in the respective central 200x200 km cell.

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