1   # Changes in Mediterranean flood processes and seasonality

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Abstract

Floods are a major natural hazard in the Mediterranean region, causing deaths and extensive damages. Recent studies have shown that intense rainfall events are becoming more extreme in this region, but paradoxically without leading to an increase in the severity of floods. Consequently, it is important to understand how flood events are changing to explain this absence of trends in flood magnitude despite increased rainfall extremes. A database of 98 stations in Southern France with an average record of 50 years of daily river discharge data between 1959 and 2021 was considered, together with a high-resolution reanalysis product providing precipitation and simulated soil moisture and a classification of weather patterns associated with rainfall events over France. Flood events, corresponding to an average occurrence of one event per year (5317 events in total), were extracted and classified into excess rainfall, short rainfall and long rainfall event types. Several flood events characteristics have been also analyzed: flood event durations, base flow contribution to floods, runoff coefficient, total and maximum event rainfall and antecedent soil moisture. The evolution through time of these flood event characteristics and seasonality were analyzed. Results indicated that, in most basins, floods tend to occur earlier during the year, the mean flood date being on average advanced by one month between 1959-1990 and 1991-2021. This seasonal shift could be attributed to the increased frequency of southern-circulation weather types during spring and summer. An increase in total and extreme event precipitation has been observed, associated with a decrease of antecedent soil moisture before rainfall events. The majority of flood events are associated with excess rainfall on saturated soils, but their relative proportion is decreasing over time notably in spring with a concurrent increased frequency of short rain floods. For most basins there is a positive correlation between antecedent soil moisture and flood event runoff coefficients that is remaining stable over time, with dryer soils producing less runoff and a lower contribution of base flow to floods. In a context of an increasing aridity, this relationship is the likely cause of the absence of trends in flood magnitudes observed in this region and the change of event types. These changes in flood characteristics are quite homogeneous over the domain studied, suggesting that they are rather linked to the evolution of the regional climate than to catchments characteristics. Consequently, this study shows that even in the absence of trends, flood properties may change over time and these changes need to be accounted for when analyzing the long-term evolution of flood hazards.

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1. Introduction

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There is a growing interest in understanding the evolution of floods occurring in different regions in the context of climate change. The recent sixth report of the Intergovernmental Panel on Climate Change (Ali et al., 2022), reported a mixture of observed trends in different Mediterranean countries, with both increasing and decreasing river floods and overall, a low confidence in their attribution to climate change. Several large-scale studies on changes in flood risk (Slater et al., 2021a; Blöschl et al., 2017, 2019) have indicated for the Mediterranean region a possible decrease over the last decades. This difficulty in detecting possible changes in flood hazard is doubtless linked to the fact that there are different types of floods (Tarasova et al., 2019; Berghuijs et al., 2019; Stein et al., 2020; Tramblay et al., 2022). Indeed, a distinction can be made between floods associated with soil saturation excess, soil infiltration excess or snowmelt-driven floods and the relative frequency of these different types of floods may change over time (Zhang et al., 2022). Furthermore, these changes can occur at local to regional scales, given complex combinations of climatic and physiographic triggers, making global generalization of changes in flood risk hazardous, if not irrelevant (Whitfield, 2012; Blöschl et al., 2015).

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Only a few studies are focusing on changes in flood types over time, while it is important to understand the long-term changes in flood processes to evaluate how flood risk can evolve, in order notably to better adapt the flood mitigation strategies (Merz et al., 2014). The main limitation to perform such studies is the need for long time-series of river discharge, to have large samples of flood events to evaluate how their properties may change over time. For many regions of the world, the lack of observed river discharge data prevents this type of analysis. Some studies attempted to analyze the changes in different types of floods for different regions (Berghuijs et al., 2019; Mao et al., 2019; Kemter et al., 2020; Bertola et al., 2021; Liu et al., 2022; Tramblay et al., 2022, Tarasova et al., 2023). Most of these studies rely on flood classification schemes, with various complexity depending on the type of data available, allowing a data-based separation of floods into their distinct generation mechanisms (Tarasova et al., 2019; Berghuijs et al., 2019; Tarasova et al., 2020; Stein et al., 2020, 2021; Tramblay et al., 2022). For basins under a Mediterranean climate, several studies reported complex interactions between precipitation increases and lower antecedent soil moisture, leading to thresholds effects (Brunner et al., 201) in the catchment response to changing hydro-climatic conditions (Wasko and Nathan, 2019; Cao et al., 2020; Bertola et al., 2021). Recent large-scale studies (Jiang et al., 2022, Tarasova et al., 2023) suggested a reduction of the frequency of floods driven by soil saturation in Europe, including basins in the Mediterranean area. Yet, these studies rely on coarse resolution climate forcings provided by E-OBS and there is a need to assess whether these findings are also valid in smaller basins with high-resolution datasets, notably with a better estimation of precipitation extremes. For instance, in Bertola et al. (2021) a decrease in 7-days maximum precipitation is found with E-

117 OBS for basins in Southern France, while Ribes et al. (2019) observed an opposite increasing
118 trend using a network of about 700 rain gauges in that area. In addition, recent studies at the
119 European scale focused on annual maxima only, when to attribute changes in flood event
120 types it is also relevant to consider other metrics such as the runoff coefficient and the flood
121 event duration, that require data about flood events and not only their maxima.

123 In French Mediterranean basins, several studies reported an increase in precipitation
124 extremes (Tramblay et al., 2013; Blanchet and Creutin, 2022; Ribes et al., 2019) that did not
125 translate into increased floods (Tramblay et al., 2019). It is hypothesized that, as many regions
126 of the world, a decrease in soil moisture linked with a greater aridity can potentially offset the
127 increase in precipitation extremes and thus not increase flood severity (Sharma et al., 2018;
128 Tramblay et al., 2019; Wasko and Nathan, 2019; Wasko et al., 2021; Huang et al., 2022).
129 Excess soil moisture was previously identified as an important flood driver notably in the
130 Mediterranean (Kemter et al., 2020; Bertola et al., 2021), indicating that they can play an
131 important role. Yet, beside trend detection or changes in flood types, no study has provided
132 an in-depth analysis of the joint long-term evolution of flood processes in Mediterranean
133 basins, in relation to their drivers such as precipitation, soil moisture and the evolution of
134 synoptic weather patterns associated with floods. In particular, there is a need to assess how
135 these changes may be modulated in different catchment sizes with different land use, notably
136 in the Mediterranean context where floods are generated by rainfall events characterized by
137 a strong spatial and temporal variability. Therefore, the objective of the study is to evaluate
138 how the characteristics of Mediterranean floods are changing. A recent study (Tramblay et al.,
139 2019) indicated no significant trends on flood hazards for a large ensemble of basins located
140 in southern France. This database is used herein and expanded with a weather types
141 classification linked to floods to further analyze the possible changes in flood event
142 characteristics. This analysis provides a comprehensive view at the regional scale of the
143 evolution in time of flood-events characteristics (runoff coefficients, soil moisture, base flow
144 contribution…), flood event seasonality in relation to large scale atmospheric patterns, flood-
145 events types (excess rain floods, short rain floods...) and their respective magnitude.

147 In section 2 are presented the different datasets used for this analysis, including river
148 discharge, precipitation, soil moisture data and weather types classification. In section 3 the
149 methods are presented, for event extraction, analysis of the seasonality and changes in the
150 different flood drivers. Results are presented in section 4.

2. Data

154 We consider 98 catchments in southern France (Figure 1) where the time series of daily
155 discharge exceeds 30 years of complete data between 1959 and 2021 (Tramblay et al., 2019).
156 Among them, 48 basins have more than 50 years of data and the basins selected are not
157 influenced by reservoir or dam regulation. The catchment sizes are ranging from 14 km² to
158 3195 km², with a mean size equal to 480 km² (see Table t1 in supplementary materials).
159 Basins with a nival regime were removed, identified from the river discharge hydrographs and
160 removing basins with more than 20% of precipitation falling as snow. In addition to river
161 discharge data, the precipitation and soil moisture for each basin has been retrieved from the
162 SAFRAN-ISBA-MODCOU (SIM) reanalysis covering the whole France territory at 8 km spatial
163 resolution (Vidal et al., 2010). Precipitation and soil moisture data have been extracted and

averaged at the catchment scale. The soil moisture data extracted from SIM is a soil wetness index obtained from the normalization of the volumetric soil moisture content with the wilting point and field capacity, that ranges between 0 and 1. Land cover classes (forest, agricultural, urban) corresponding to 2018 have been extracted from the CORINE land cover inventory (Büttner, 2014). In addition, we used the weather type classification from *Electricité de France* (EDF), corresponding to a daily classification into 8 synoptic situations associated with rainfall events over France (Garavaglia et al., 2010). This classification is built on geopotential heights at 700 and 1000 hPa pressure levels associated with rainy days over France.

3. Methods

3.1 Extraction of flood events

We extracted a sample of flood events with a mean occurrence of 1 event per year using a peaks-over-threshold approach. This type of sampling is chosen since low annual maximum runoff could be observed during dry years (Farquharson et al., 1992). A de-clustering algorithm is applied to identify single events to avoid introducing autocorrelation in the analysis and ensuring that flood events are independent, using two rules (Lang et al., 1999): first a minimum of n days between events, with $n = 5 + \log(\text{catchment area})$ and second, between two consecutive peaks, runoff must drop below ⅔ of the smallest peak. The maximum daily runoff of each event is kept. This means that for an event lasting several days, only the maximum daily discharge, and the corresponding date, are kept. Then, for each flood event, we computed the total rainfall and maximum rainfall. The n-day previous precipitation is extracted. Total rainfall for each event is estimated by a cumulative sum of precipitation starting the day of the flood and this aggregation stops if there are two consecutive days with precipitation close to zero (1 mm) to account for rainfall intermittency within events. The maximum daily precipitation is extracted from the same time interval used to compute total event precipitation. The soil moisture at the beginning of the events is extracted from the previous day of the start of the rainfall event. A base flow filter has been used to separate direct runoff and base flow for each time series, using the Lyne Hollick Filter (Lyne and Hollick, 1979), with its default parameters. For each flood event, the base flow corresponding to the peak has been extracted to estimate the direct runoff, corresponding to the event rainfall contribution, in addition to base flow. Different metrics characterizing each flood event have been computed: total rainfall (mm), event maximum rainfall (mm), duration of the rainfall event (days), duration of the flood event (days), antecedent soil moisture (0-1) and runoff coefficient (0-1). The runoff coefficient was computed for each event as the ratio of direct runoff depth and total event precipitation

3.2 Analysis of the mean date of occurrence

Circular statistics (Burn, 1997; Berens, 2009) are used to analyze flood timing. The dates are first converted into an angular value, then from this sample of angular values, the mean date of occurrence (θ) can be computed, together with the concentration index (r) which measures the variability of the flood occurrences around the mean date. Using the dates of flood events, considering hydrological years starting September 1, θ and r are computed from the sample of dates. The first step in the analysis of seasonality is to test against circular uniformity. Circular uniformity refers to the case in which all angular values of flood dates around the circle are equally likely, indicative of the absence of flood seasonality. In that case, the

computation of the mean date would have little relevance. The Rayleigh (Fisher, 1993) and the Hermans-Rasson (Landler et al., 2019) tests are used to test against uniformity for unimodal distributions, to verify the presence of flood seasonality (ie. meaning that floods do not occur randomly throughout the year). To associate flood events and weather types, for each rainy day corresponding to flood events, the weather type has been extracted from the weather type's classification.

3.3 Classification of flood generating processes

A classification is applied to the flood events, adapted from a previously implemented classification at the global scale (Stein et al., 2020), in the United States (Stein et al., 2021) and Africa (Tramblay et al., 2022). This approach relates the occurrence of rainfall amounts above various thresholds to the occurrence of floods. Flood events in each catchment are classified according to three hydrometeorological generating processes, namely, the excess rainfall, short rainfall, long rainfall using a decision tree. Excess rainfall is defined as a flood event triggered by rainfall higher than average occurring over wet soils (i.e. soil moisture above than 50% saturation), short rainfall as a single daily rainfall event above high thresholds (the 95th percentile computed over the whole time series of rainfall) and long rainfall as several consecutive days (> 2 days) with rainfall above the 95th percentile of rainfall summed over 7 days. The classification first evaluates if a larger than average multi-day rainfall fell on wet soil to determine if the flood event was an excess rainfall type of flood. If that was not the case, it evaluates whether the thresholds for long rainfall and then short rainfall are exceeded. If no process could be identified, the class "other" is assigned.

3.4 Changes in flood characteristics

To assess the changes over time in flood dates and generating mechanisms, we split the records of each station into two periods of equal length. Given that most stations have records starting after the 1960s, on average the first period is ranging from 1959 to 1990 and the second one from 1991 to 2021, with a pivot year within +/- 5 years around 1991, allowing the comparison of the two time slices across the different stations. To assess the relative changes in the flood drivers, the frequency of each driver for each time period has been computed, and then we computed for each station the relative change (%) in each driver contribution (Berghuijs et al., 2019). In addition, to detect trends on the long-term frequency of event types per year pooled at the regional scale, we used the Mann-Kendall test for trends, modified to account for autocorrelation in the time series (Hamed and Ramachandra Rao, 1998).

We use the same approach to estimate changes in the different flood events characteristics, and we applied the two-tailed Wilcoxon test to check the difference in medians. In addition, to assess the regional significance of the trends, we also computed the Mann-Kendall test on flood events characteristics pooled at the regional scale. For flood dates, we computed the mean dates of occurrence for the two time periods and assessed the significance of the difference using the Watson and Williams test, which is a circular analogue to the two sample t-test (Watson and Williams, 1956). Finally, to estimate potential relationships between different flood characteristics, the Spearman correlation coefficient (ρ) is computed.

4. Results and discussion

4.1 Change in flood event characteristics

There are several changes in flood event characteristics as seen in Figure 2 between the two sub-periods, 1959-1990 and 1991-2021. On average, total event precipitation is increasing in 65 basins (66% of basins), maximum event rainfall is increasing in 76 basins, consistent with previous studies in this area (Ribes et al., 2019; Tramblay et al., 2019; Blanchet and Creutin, 2022), while on the opposite antecedent soil moisture is decreasing in 71 basins, baseflow contribution is decreasing in 75 basins and runoff coefficient is decreasing in 68 basins. These changes in soil moisture, base flow and runoff coefficients are consistent with an overall increase of aridity in southern Europe mostly driven by higher evapotranspiration (Tramblay et al., 2020) and have been also observed in other regions with a similar climate (Ho et al., 2022). The number of local statistically significant changes for each flood event characteristic is given in Table 1. These numbers remain small but it should be reminded that sample sizes are quite short for a robust statistical assessment in a context of high interannual variability. To overcome this issue, we also assessed the regional significance of these changes in flood event characteristics. We performed a regional pooling of the events and applied the Mann-Kendall test to detect trends in the regional series of event characteristics. As shown in table 1, all the detected changes are regionally significant except the decrease in base flow contribution to peak discharge during floods. Overall, an increase in total event rainfall can be observed, mostly caused by the increase of maximum rainfall during the events (the changes in the two variables are correlated, with $\rho = 0.52$), while the flood event durations are on average decreasing, consistent with studies at the global scale (Wasko et al., 2021).

These changes in precipitation are associated with a decrease of antecedent soil moisture, before the beginning of the rainfall events. This decrease is also related to a smaller contribution of base flow during floods in some basins. There is indeed a significant correlation between the relative changes in the base flow contribution to peak runoff and soil moisture ($\rho = 0.56$), indicating that the soil moisture decrease is likely the main driver of these changes. There is also for most basins a significant nonlinear relationship (exponential type) between the flood events antecedent soil moisture and runoff coefficients, as reported in many studies (Penna et al., 2011; Rogger et al., 2013; Raynaud et al., 2015; Tarasova et al., 2020). Indeed, for the first time period, 1959-1990 the median Spearman correlation between antecedent soil moisture and flood runoff coefficients (see supplementary figure S1) is equal to 0.43 and is significant at the 5% level in 56 basins (67 basins at the 10% significance level). For the second time period, 1991-2021, the median correlation is increasing to 0.45 and is significant in 64 basins at the 5% significance level (68 at the 10% significance level). These results show, contrary to popular belief, that at the catchment scale drier soils produce less runoff, and this characteristic is even slightly accentuating over time. Indeed, increased runoff coefficients induced either by hydrophobic soil conditions following droughts (Burch et al., 1989), soil crusting and sealing (Bissonnais and Singer, 1993) or compaction (Alaoui et al., 2018), are well documented processes that mostly occur at the local plot scale that do not produce discernible effects at the catchment scale. This observation is reinforced by the fact that no negative correlation between runoff coefficients and initial soil moisture was detected. About the explanatory factors of the association between soil moisture and runoff coefficients, we found stronger correlations (significant at the 5% level) between these two variables in catchments with higher percentage of urban or agricultural areas, and on the opposite weaker

correlations along with increased percentage of forests or mean catchment altitude. There is only a very small increase of the correlations for larger basins (no significant correlation with basin sizes), indicating that this relationship between soil moisture and runoff coefficient remains valid for all basins scales considered in the present study. This relationship between runoff coefficients and antecedent soil moisture remained stable between 1959-1990 and 1991-2021 (Figure 3).

4.2 Changes in flood dates

Floods in southern France tend to occur mainly during November or December for basins close to the Mediterranean, East of the Cévennes mountainous range, while for basins located on the western part of the region, they tend to occur later during winter months, centered in January or February (Figure 4). Both the Rayleigh and Hermans-Rasson tests reject the null hypothesis of uniformity at the 5% level, indicating that floods do not occur randomly throughout the year. In most cases, the seasonal distribution is unimodal, except for a few cases; in about 15 stations the maximum occurrence of floods is observed in late autumn or winter and a secondary minor peak of occurrence is observed, usually centered around the month of March or April. These floods are associated with rainfall events rather than snowmelt, since for only 3 basins the snowfall contribution reaches 19% of total precipitation whereas the snowfall contribution is much lower for the remaining 12 basins (less than 5%).

For 79 basins, floods tend to occur earlier during the year, on average by -22 days between 1959-1990 and 1991-2021 (Figure 5, left panel). On the opposite, for 19 basins the mean flood date occurs later in the second period with an average of +12 days. These changes in the mean date are significant in 26 basins at the 0.1 level according to the Watson and Williams test (18 basins at the 0.05 significance level). There are two differentiated spatial patterns: all basins where floods tend to occur earlier are located widespread in the center of the Mediterranean region, and basins where floods tend to occur later are found only in the northwestern margin of the domain. In these basins, the mean floods occur in late winter, until February and March. The same spatial patterns of changes in mean flood dates have been observed by Blöschl et al. (2017), but without providing the possible causes of these seasonal shifts. For the concentration index (i.e., the variability around the mean date) similarly two different patterns are found: for basins where floods tend to occur earlier, the concentration index is increasing, meaning more floods are clustered around the mean date, while for western basins where floods tend to occur later, the concentration index is decreasing, meaning a larger variability in flood dates (Figure 5, right panel).

To assess the regional changes in flood dates, we first separated in two regional samples the stations where floods occur earlier (sample 1) or later (sample 2). Then we used the Watson-William test, previously used to assess changes in flood dates in each station, to compare these two regional samples. The test results indicate that for the 19 stations where floods tend to occur later, the change in flood dates are not significant at the 5% level (p value = 0.0821), on the opposite, for the 79 stations where floods are occurring earlier, the change is significant (p value = $5.34.10^{-8}$).

4.3 Associations between flood occurrence and weather patterns

352 The seasonal patterns observed for the floods are closely related to the occurrence of different
353 weather types in different sub-regions. As shown in figure 6, most basins located east of the
354 Cévennes mountainous range have floods associated with WT4, Southern Circulation, and
355 western basins with WT2, Steady Oceanic. The most frequent pattern associated with 37% of
356 floods, WT4, is known to be triggering intense rainfall events in this region (Ducrocq et al.,
357 2008; Tramblay et al., 2013). Interestingly, the WT6, Eastern circulation, and WT7,
358 Southwestern circulation, are both associated to a lesser extent with floods across the whole
359 region, but without notable spatial differences in the relative frequency of floods associated
360 with these weather types. Change in flood seasonality could be ascribed to changes in the
361 seasonal occurrence of the weather types (Figure 7): WT4 tends to occur more frequently
362 from March to August during 1991-2021 compared to 1959-1990, and these changes are
363 statistically significant (see supplementary figure S2). When looking at the actual count of WT4
364 days, this change represents an increase of 69 events during that 6-month period for 1991-
365 2021, so an average of +2.2 days per year. Associated with a warmer Mediterranean Sea over
366 the last decades notably during summer (Pastor et al., 2020), the combination of these two
367 factors could explain the earlier occurrence of floods east of the Cévennes mountainous
368 range. Similarly, there is an increased frequency of WT2 in January, February and March
369 between 1991-2021 and 1959-1990, that is also significant (supplementary figure S2)that
370 could be possibly related to the later occurrence of floods west of the Cévennes range.
371 Although this change in weather types seasonality leading to heavy rainfalls is a plausible
372 cause of the observed changes in the flood seasonality, more research is needed to better
373 understand these relationships and attribute changes in flood seasonality. Notably, to analyze
374 in more detail the moisture supply from the Mediterranean or Atlantic seas, the interaction with
375 the atmospheric thermodynamics, the duration, localization and the spatial dependence of the
376 rainfall episodes inducing floods.
377
378 **4.4 Changes in flood generating processes**
379
380 When first applying the classification of flood-generating processes on all floods, we find a
381 predominance of excess rainfall events (Figure 8), followed by long rain and short rains, that
382 is consistent with the known flood-generating processes in this region (Mediterranean
383 episodes) and, in particular, the strong influence of saturated soils on runoff generation with
384 floods mostly occurring during the autumn (Tramblay et al., 2010, 2019). The category 'other'
385 regroups only 0.97% of floods and it represents mostly events with very low precipitation
386 amounts, likely due to an underestimation of rainfall in the SAFRAN database for some events.
387 It is worth noticing that despite the large sample of basins considered, the patterns are
388 remarkably consistent and homogeneous across different basin sizes and locations. There is
389 a significant, yet low, correlation ($\rho = 0.26$, p-value = 0.008) between the ratio of excess rain
390 floods and catchment size, with a larger proportion of excess rain in larger basins, while on
391 the opposite there is an even weaker and negative correlation ($\rho = -0.16$, p-value =0.09)
392 between the ratio of short rain and basin size. It should be noted that floods driven by short
393 rain episodes are potentially affecting smaller regions than floods driven by excess floods
394 (Brunner and Dougherty, 2022). For 30 basins (not necessarily the largest ones), the
395 proportion of excess rain exceeds 80% of the total number of flood events (see supplementary
396 figure S3). For short rain and long rain, the maximum contributions observed much lower, 36%
397 and 32%, respectively, but these maximum values are only found in small basins. Indeed,

398 basins when short rain or long rain exceed 30% of episodes are only found in basins smaller
399 than 100 km².
400
401 The mean date of occurrence is significantly different between the three flood types, according
402 to the Watson and Williams test. As shown on figure 9, the highest proportion of floods induced
403 by short rain is observed during September to November, while the floods induced by long
404 rain are mostly occurring during October to December, and excess rain floods are observed
405 in late autumn and winter, with a peak in February. This is consistent with the annual soil
406 moisture cycle in this region: at the end of the summer the soils are dry and it takes several
407 months to replenish the soil moisture level, which is at highest during winter. If examining the
408 long-term changes in this monthly repartition of flood types (see supplementary figure S4), the
409 frequency of excess rain is decreasing from February to April, and also in October, while
410 increasing during winter months. This implies that the season during which excess rain floods
411 are occurring is reducing in length and concentrated during wet winter months. On the
412 opposite the frequency of short or long rain floods is increasing in June and September,
413 months that are getting drier over time in this region.
414
415 The noticeable changes in flood processes over time are a reduction of Excess rainfall in 71
416 basins and an increased frequency of short rains in 53 basins and Long rains in 63 basins
417 (Figure 10), while short rain and long rain floods are decreasing for 19 and 22 basins,
418 respectively. For excess rain, there are only 16 basins where their relative proportion is
419 increasing; they are mostly located on the margins of the Alps and Pyrenees mountains. For
420 more frequent events (ie. if considering an average of 3 episodes per year instead of one), the
421 number of basins with a change is larger, with a reduction of Excess rainfall in 82 basins out
422 of 98 (results not shown). This indicates that the soil moisture depletion has more impacts on
423 small to moderate flood events, as previously observed by Bertola et al. (2021). There is no
424 relationship between the rate of change in the different flood generating processes and
425 catchment sizes indicating a clear regional pattern. The average magnitude across all basins
426 of these changes remains low, on average -4.1% for excess rain, +1.2% for short rain and +
427 2.1% long rain. Yet, the magnitude of these changes is ranging from +15% to -21% for excess
428 rain, +11% to -20% for short rain and +12% to -11% for long rain, depending on the catchment,
429 indicating that local catchment characteristics could strongly modulate the regional signal. In
430 addition, the average values over the whole domain are hiding some local changes: for
431 instance, short rainfall floods are increasing in the southeastern part of the Cévennes while
432 decreasing for the northwestern part as seen in Figure 10.
433
434 **4.5 Regional changes**
435
436 To assess whether the changes in the relative influence of the three different flood types are
437 significant at the regional scale, we computed for each year the relative frequency of the
438 different flood types, all basins together. It is indeed not possible to do this analysis for each
439 station independently, due to the small size of the samples over the two periods. These
440 changes in the occurrence of flood types are significant at the regional scale according to the
441 Mann-Kendall test (Figure 11), for the frequency of excess rain floods and short rain floods, at
442 the 5% significance level, but not for the long rain floods. All events pooled regionally, the
443 decrease in excess rain floods is equal to -13% between 1959-1990 and 1991-2021, and the
444 increase of short rain floods is equal to +36%. In addition, to assess whether these results are
445 robust to the thresholds used in the classification of flood events, a Monte Carlo experiment

446 has been also conducted. Results show (see supplementary figure S5) that regional changes
447 in excess rain and short rain floods are not dependent on classification thresholds, while it is
448 not the case for long rain floods. In terms of flood severity for the different flood types, the
449 median flood computed for each basin is strongly correlated to basin size ($\rho = 0.78$) for floods
450 caused by excess rain, short rain ($\rho = 0.80$) and long rain ($\rho = 0.75$); and very similar results
451 are found for the maximum flood. On the contrary, the specific discharge of flood peaks is non
452 linearly related to basin sizes, with a clear threshold effect for basins smaller than 500 km²
453 that have a much larger specific discharge than larger basins.
454
455 Given that there are different flood sample sizes in the different basins corresponding to
456 different flood-generating processes, we pooled regionally the flood events. To do so, we
457 computed the specific discharge for each event (i.e. the flood magnitude divided by catchment
458 area) to analyze the distributions of specific discharge for all the events associated with excess
459 rain, long rain or short rain. Specific discharge is used herein since it is a good indicator of
460 flash floods severity, notably in this Mediterranean region (Delrieu et al., 2005, Ruin et al.,
461 2008). Figure 12 shows that the short rain floods are more severe, in terms of specific
462 discharge, than excess rain or long rain floods at the regional level (as shown also by Tarasova
463 et al., 2023). The regional distributions for the different event types are different according to
464 the Kolmogorov-Smirnov test. It must be noted that for a given basin the magnitude of the
465 different types of floods may not be very different, showing the strong variability from one event
466 to another that is not solely linked to the flood trigger. When comparing the different flood
467 distributions between the time periods 1959-1990 and 1991-2021, the differences in flood
468 magnitudes between excess rain, long and short rain are reduced. This is mainly due to a
469 slight decrease in the specific discharge of short rain floods, notably for flood events with a
470 return level higher than 10 years, while the excess rain floods show very little changes in
471 intensity over time.
472

473 # 5. Conclusions

474
475 The aim of this study was to document the evolution of the characteristics of Mediterranean
476 floods, using long river discharge records in southern France, a high-resolution climate and
477 surface reanalysis that is used operationally to monitor water resources and extremes in
478 France, and a classification of weather patterns. This large regional database with an average
479 of 50 years of records allowed to detect regional significant changes on several flood events
480 characteristics. In most basins, floods tend to occur earlier during the year, the mean flood
481 date being on average advanced by one month. This seasonal shift can be attributed to the
482 increased frequency of southern-circulation weather types during spring and summer that are
483 strongly associated with the occurrence of floods in this region. Over time, floods also tend to
484 be more clustered in time over the different basins, as reflected by a decreasing variability in
485 flood occurrence throughout the year. On the contrary, for the westernmost basins influenced
486 by Atlantic circulation patterns, floods tend to occur later during the year, also due to a
487 seasonal shift of the flood-generating circulation patterns that are occurring more frequently in
488 late winter. These results indicate that changes in large-scale atmospheric circulation
489 described by weather types is the likely driver of the seasonal shift of flood dates previously
490 observed for French Mediterranean regions (Blöschl et al., 2017).

491 During floods, an increase in total and extreme event precipitation has been observed,
492 associated with a decrease of antecedent soil moisture before rainfall events, linked to a
493 smaller contribution of base flow during floods. It can be concluded that it is the depletion of
494 soil water content, due to increased aridity in south France notably related to higher
495 evapotranspiration rates (Tramblay et al., 2020), that is the likely cause of the absence of flood
496 trends in this region despite the increase in extreme rainfall. It should be also noted that over
497 all basins, dryer soils are associated with lower runoff coefficients, and this relationship
498 remains valid over time. This result contrasts sharply with the generally accepted idea that in
499 a drier climate we observe stronger runoff. While this statement could be valid at the plot scale,
500 we show herein that it is an opposite relationship found for the whole range of catchment sizes
501 considered in the present work. The majority of flood events are associated with excess rainfall
502 on saturated soils, but that proportion is decreasing over time with a concurrent increased
503 frequency of short rain, potentially leading to more severe floods, as previously shown at the
504 European scale by Tarasova et al. (2023). At the regional scale, we show that floods induced
505 by short rains are indeed of higher magnitude, but due to a lower runoff coefficient induced by
506 drier antecedent soil moisture, the specific discharge associated with short rain flood is also
507 decreasing over time. These results are consistent with those obtained in other regions of the
508 world, showing that floods do not necessarily increase with the increase in extreme
509 precipitation, and that soil moisture seems to play a key role in explaining these changes and
510 the lack of trends ultimately on flood hazard (Wasko and Nathan, 2019; Bertola et al., 2021;
511 Wasko et al., 2021). The results of the present study are rather homogeneous given the
512 different catchment sizes and land use types, indicating that changes in flood types are mainly
513 resulting from regional climate change and not only local changes, such as land cover or
514 agricultural practice changes, nor the increase of urban and peri-urban areas. Nonetheless, if
515 the observed trend in increased short rain floods is persisting in the upcoming decades, the
516 severity of floods, particularly the most important ones, could increase along with the rise in
517 rainfall extremes particularly in areas where the soil infiltration potential is low, such as in
518 mountainous or urbanized areas, that have expanded a lot in recent years in Mediterranean
519 regions. For other types of basins, notably in lowland areas with agricultural or natural
520 landscapes, caution should be exerted before extrapolating such hazards in the future, since
521 we show herein a potential reduction over time of the specific runoff even for short rain floods.
522 This aspect could be further investigated using climate scenarios.

523 One of the main perspectives of this work would be to perform a similar analysis at sub-daily
524 time steps, that would be more adapted to analyze changes in flash floods characteristics,
525 notably in terms of the flashiness response of the catchments (Baker et al., 2004; Li et al.,
526 2022). Indeed, the daily time step prevents a thorough analysis of changes in rainfall patterns,
527 notably at shorter time steps. Yet, there is no gridded dataset of hourly precipitation before the
528 2000s in Southern France, that does not allow to repeat such a similar study over 62 years.
529 However, given the availability of radar rainfall over France, it would be possible to analyze,
530 at least for the recent years after 2000, the evolution of several characteristics, such as the
531 evolution of storm hydrographs, concentration time and the flashiness response of the basins.
532 Another relevant prospective work would be to analyze the spatial extent of floods. Given the
533 future evolution of weather types associated with floods in combination with more local to
534 regional characteristics, such as soil moisture state, these types of events may impact
535 simultaneously wider, or smaller, parts of the region considered, and this could have serious
536 implications on risk management (Brunner et al., 2021; Brunner and Dougherty, 2022).
537 Therefore, the joint analysis of flood occurrence in nearby basins would be highly relevant.

Finally, there is also a need for new approaches to incorporate these changes in flood generating process into engineering practice (Slater et al., 2021b), notably to estimate the return levels for different types of infrastructure design.

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Data availability

The computed catchment-based indicators for each flood events in all basins are accessible from the online repository: https://doi.org/10.5281/zenodo.8075639

The complete time series of river runoff can be accesses freely here: https://hydro.eaufrance.fr/

The SAFRAN/ISBA outputs can be ordered freely for scientific purpose here: https://donneespubliques.meteofrance.fr

Author contributions

Y.T.: Conceptualization, investigation, data curation, formal analysis, writing—original draft preparation. YT designed the experiments, performed the analyses, and wrote the paper. PA, GA, ML, EP, LN and ES Conceptualization, data curation, writing—reviewing and editing.

Competing interests

The authors declare that they have no conflict of interest.

570 Table 1: Number of local significant changes in the median of flood events characteristics
571 detected by the Wilcoxon test and results of the regional Mann-Kendall test on flood event
572 characteristics

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Indicator	Number of significant local changes (Wilcoxon, 10%)	pvalue of the regional MK test	Regional changes between 1959 and 2022 (%)
Flood event duration	17	**0.0046178**	-0.40%
Base flow contribution to peak	15	**0.5687962**	-8.62%
Runoff coefficient	19	**0.0000002**	-14.62%
Total event rainfall	16	**0.0011851**	9.01%
Maximum event rainfall	27	**0.0000000**	13.47%
Antecedent soil moisture	12	**0.0000008**	-9.80%

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594
595
596
597
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References

Alaoui, A., Rogger, M., Peth, S., and Blöschl, G.: Does soil compaction increase floods? A review, Journal of Hydrology, 557, 631–642, https://doi.org/10.1016/j.jhydrol.2017.12.052, 2018.

Ali, E., Cramer, W., Carnicer, J., Georgopoulou, E., Hilmi, N. J. M., Cozannet, G. L., and Lionello, P.: Cross-Chapter Paper 4: Mediterranean Region, edited by: Pörtner, H. O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2233–2272, https://doi.org/10.1017/9781009325844.021.2233, 2022.

Baker, D. B., Richards, R. P., Loftus, T. T., and Kramer, J. W.: A new flashiness index: characteristics and applications to midwestern rivers and streams, J Am Water Resources Assoc, 40, 503–522, https://doi.org/10.1111/j.1752-1688.2004.tb01046.x, 2004.

Berens, P.: CircStat : A MATLAB Toolbox for Circular Statistics, J. Stat. Soft., 31, https://doi.org/10.18637/jss.v031.i10, 2009.

Berghuijs, W. R., Harrigan, S., Molnar, P., Slater, L. J., and Kirchner, J. W.: The Relative Importance of Different Flood-Generating Mechanisms Across Europe, Water Resour. Res., 2019WR024841, https://doi.org/10.1029/2019WR024841, 2019.

Bertola, M., Viglione, A., Vorogushyn, S., Lun, D., Merz, B., and Blöschl, G.: Do small and large floods have the same drivers of change? A regional attribution analysis in Europe, Hydrol. Earth Syst. Sci., 25, 1347–1364, https://doi.org/10.5194/hess-25-1347-2021, 2021.

Bissonnais, Y. L. and Singer, M. J.: Seal Formation, Runoff, and Interrill Erosion from Seventeen California Soils, Soil Science Society of America Journal, 57, 224–229, https://doi.org/10.2136/sssaj1993.03615995005700010039x, 1993.

Blanchet, J. and Creutin, J.-D.: Instrumental agreement and retrospective analysis of trends in precipitation extremes in the French Mediterranean Region, Environ. Res. Lett., 17, 074011, https://doi.org/10.1088/1748-9326/ac7734, 2022.

Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., Parajka, J., Perdigão, R. A. P., Plavcová, L., Rogger, M., Salinas, J. L., and Viglione, A.: Increasing river floods: fiction or reality?: Increasing river floods, WIREs Water, 2, 329–344, https://doi.org/10.1002/wat2.1079, 2015.

Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., Aronica, G. T., Bilibashi, A., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Fiala, K., Frolova, N., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Rogger, M., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J.,

Viglione, A., Volpi, E., Wilson, D., Zaimi, K., and Živković, N.: Changing climate shifts timing of European floods, Science, 357, 588–590, https://doi.org/10.1126/science.aan2506, 2017.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., and Živković, N.: Changing climate both increases and decreases European river floods, Nature, 573, 108–111, https://doi.org/10.1038/s41586-019-1495-6, 2019.

Brunner, M. I. and Dougherty, E. M.: Varying Importance of Storm Types and Antecedent Conditions for Local and Regional Floods, Water Resources Research, 58, https://doi.org/10.1029/2022WR033249, 2022.

Brunner, M. I., Slater, L., Tallaksen, L. M., and Clark, M.: Challenges in modeling and predicting floods and droughts: A review, WIREs Water, 8, https://doi.org/10.1002/wat2.1520, 2021.

Brunner, M. I., Swain, D. L., Wood, R. R., Willkofer, F., Done, J. M., Gilleland, E., and Ludwig, R.: An extremeness threshold determines the regional response of floods to changes in rainfall extremes. Communications Earth & Environment, 2:1, https://doi.org/10.1038/s43247-021-00248-x, 2021

Burch, G. J., Moore, I. D., and Burns, J.: Soil hydrophobic effects on infiltration and catchment runoff, Hydrol. Process., 3, 211–222, https://doi.org/10.1002/hyp.3360030302, 1989.

Burn, D. H.: Catchment similarity for regional flood frequency analysis using seasonality measures, Journal of Hydrology, 202, 212–230, https://doi.org/10.1016/S0022-1694(97)00068-1, 1997.

Büttner, G.: CORINE Land Cover and Land Cover Change Products, in: Land Use and Land Cover Mapping in Europe, vol. 18, edited by: Manakos, I. and Braun, M., Springer Netherlands, Dordrecht, 55–74, https://doi.org/10.1007/978-94-007-7969-3_5, 2014.

Cao, Q., Gershunov, A., Shulgina, T., Ralph, F. M., Sun, N., and Lettenmaier, D. P.: Floods due to Atmospheric Rivers along the U.S. West Coast: The Role of Antecedent Soil Moisture in a Warming Climate, Journal of Hydrometeorology, 21, 1827–1845, https://doi.org/10.1175/JHM-D-19-0242.1, 2020.

Delrieu, G., Nicol, J., Yates, E., Kirstetter, P.-E., Creutin, J.-D., Anquetin, S., Obled, C., Saulnier, G.-M., Ducrocq, V., Gaume, E., Payrastre, O., Andrieu, H., Ayral, P.-A., Bouvier, C., Neppel, L., Livet, M., Lang, M., du-Châtelet, J. P., Walpersdorf, A., and Wobrock, W.: The Catastrophic Flash-Flood Event of 8–9 September 2002 in the Gard Region, France: A First Case Study for the Cévennes–Vivarais Mediterranean Hydrometeorological

Observatory. Journal of Hydrometeorology, 6:1, 34–52, https://doi.org/10.1175/jhm-400.1, 2005.

Ducrocq, V., Nuissier, O., Ricard, D., Lebeaupin, C., and Thouvenin, T.: A numerical study of three catastrophic precipitating events over southern France. II: Mesoscale triggering and stationarity factors, Q.J.R. Meteorol. Soc., 134, 131–145, https://doi.org/10.1002/qj.199, 2008.

Farquharson, F. A. K., Meigh, J. R., and Sutcliffe, J. V.: Regional flood frequency analysis in arid and semi-arid areas, Journal of Hydrology, 138, 487–501, https://doi.org/10.1016/0022-1694(92)90132-F, 1992.

Fisher, N. I.: Statistical analysis of circular data, Cambridge University Press, Cambridge [England] ; New York, NY, USA, 277 pp., 1993.

Garavaglia, F., Gailhard, J., Paquet, E., Lang, M., Garçon, R., and Bernardara, P.: Introducing a rainfall compound distribution model based on weather patterns sub-sampling, Hydrol. Earth Syst. Sci., 14, 951–964, https://doi.org/10.5194/hess-14-951-2010, 2010.

Vidal, J.-P., Martin, E., Franchistéguy, L., Baillon, M., Soubeyroux, J.-M. : A 50-year high-resolution atmospheric reanalysis over France with the Safran system. International Journal of Climatology, 2010, 30 (11), 1627-1644. https://doi.org/10.1002/joc.2003, 2010.

Hamed, K. H. and Ramachandra Rao, A.: A modified Mann-Kendall trend test for autocorrelated data, Journal of Hydrology, 204, 182–196, https://doi.org/10.1016/S0022-1694(97)00125-X, 1998.

Ho, M., Nathan, R., Wasko, C., Vogel, E., and Sharma, A.: Projecting changes in flood event runoff coefficients under climate change, Journal of Hydrology, 615, 128689, https://doi.org/10.1016/j.jhydrol.2022.128689, 2022.

Huang, H., Fischella, M. R., Liu, Y., Ban, Z., Fayne, J. V., Li, D., Cavanaugh, K. C., and Lettenmaier, D. P.: Changes in Mechanisms and Characteristics of Western U.S. Floods Over the Last Sixty Years, Geophysical Research Letters, 49, https://doi.org/10.1029/2021GL097022, 2022.

Jiang, S., Bevacqua, E., and Zscheischler, J.: River flooding mechanisms and their changes in Europe revealed by explainable machine learning, Hydrol. Earth Syst. Sci., 26, 6339–6359, https://doi.org/10.5194/hess-26-6339-2022, 2022.

Kemter, M., Merz, B., Marwan, N., Vorogushyn, S., and Blöschl, G.: Joint Trends in Flood Magnitudes and Spatial Extents Across Europe, Geophys. Res. Lett., 47, https://doi.org/10.1029/2020GL087464, 2020.

Landler, L., Ruxton, G. D., and Malkemper, E. P.: The Hermans–Rasson test as a powerful alternative to the Rayleigh test for circular statistics in biology, BMC Ecol, 19, 30, https://doi.org/10.1186/s12898-019-0246-8, 2019.

743

744 Lang, M., Ouarda, T. B. M. J., and Bobée, B.: Towards operational guidelines for over-
745 threshold modeling, Journal of Hydrology, 225, 103–117, https://doi.org/10.1016/S0022-
746 1694(99)00167-5, 1999.

747

748 Li, Z., Gao, S., Chen, M., Gourley, J. J., Liu, C., Prein, A. F., and Hong, Y.: The
749 conterminous United States are projected to become more prone to flash floods in a high-
750 end emissions scenario, Commun Earth Environ, 3, 86, https://doi.org/10.1038/s43247-022-
751 00409-6, 2022.

752

753 Liu, J., Feng, S., Gu, X., Zhang, Y., Beck, H. E., Zhang, J., and Yan, S.: Global changes in
754 floods and their drivers, Journal of Hydrology, 614, 128553,
755 https://doi.org/10.1016/j.jhydrol.2022.128553, 2022.

756

757 Lyne, V. D. and Hollick, M.: Stochastic time-variable rainfall runoff modelling, Hydrology and
758 Water Resources Symposium, Institution of Engineers, Australia, Perth (1979), Barton,
759 Australia, 1979.

760

761 Mao, Y., Zhou, T., Leung, L. R., Tesfa, T. K., Li, H., Wang, K., Tan, Z., and Getirana, A.:
762 Flood Inundation Generation Mechanisms and Their Changes in 1953–2004 in Global Major
763 River Basins, J. Geophys. Res. Atmos., 124, 11672–11692,
764 https://doi.org/10.1029/2019JD031381, 2019.

765

766 Merz, B., Aerts, J., Arnbjerg-Nielsen, K., Baldi, M., Becker, A., Bichet, A., Blöschl, G.,
767 Bouwer, L. M., Brauer, A., Cioffi, F., Delgado, J. M., Gocht, M., Guzzetti, F., Harrigan, S.,
768 Hirschboeck, K., Kilsby, C., Kron, W., Kwon, H.-H., Lall, U., Merz, R., Nissen, K., Salvatti, P.,
769 Swierczynski, T., Ulbrich, U., Viglione, A., Ward, P. J., Weiler, M., Wilhelm, B., and Nied, M.:
770 Floods and climate: emerging perspectives for flood risk assessment and management, Nat.
771 Hazards Earth Syst. Sci., 14, 1921–1942, https://doi.org/10.5194/nhess-14-1921-2014,
772 2014.

773

774 Pastor, F., Valiente, J. A., and Khodayar, S.: A Warming Mediterranean: 38 Years of
775 Increasing Sea Surface Temperature, Remote Sensing, 12, 2687,
776 https://doi.org/10.3390/rs12172687, 2020.

777

778 Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., and Dalla Fontana, G.: The
779 influence of soil moisture on threshold runoff generation processes in an alpine headwater
780 catchment, Hydrol. Earth Syst. Sci., 15, 689–702, https://doi.org/10.5194/hess-15-689-2011,
781 2011.

782

783 Raynaud, D., Thielen, J., Salamon, P., Burek, P., Anquetin, S., and Alfieri, L.: A dynamic
784 runoff co-efficient to improve flash flood early warning in Europe: evaluation on the 2013
785 central European floods in Germany: Dynamic runoff co-efficient for flash flood early warning
786 in Europe, Met. Apps, 22, 410–418, https://doi.org/10.1002/met.1469, 2015.

787

788 Ribes, A., Thao, S., Vautard, R., Dubuisson, B., Somot, S., Colin, J., Planton, S., and
789 Soubeyroux, J.-M.: Observed increase in extreme daily rainfall in the French Mediterranean,
790 Clim Dyn, 52, 1095–1114, https://doi.org/10.1007/s00382-018-4179-2, 2019.

791

792 Rogger, M., Viglione, A., Derx, J., and Blöschl, G.: Quantifying effects of catchments storage
793 thresholds on step changes in the flood frequency curve: Step Changes in the Flood
794 Frequency Curve, Water Resour. Res., 49, 6946–6958, https://doi.org/10.1002/wrcr.20553,
795 2013.

796

797 Ruin, I., Creutin, J.-D., Anquetin, S., & Lutoff, C.: Human exposure to flash floods – Relation
798 between flood parameters and human vulnerability during a storm of September 2002 in
799 Southern France. Journal of Hydrology, 361:1-2, 199–213,
800 https://doi.org/10.1016/j.jhydrol.2008.07.044, 2008.

801

802 Sharma, A., Wasko, C., and Lettenmaier, D. P.: If Precipitation Extremes Are Increasing,
803 Why Aren't Floods?, Water Resour. Res., 54, 8545–8551,
804 https://doi.org/10.1029/2018WR023749, 2018.

805

806 Slater, L., Villarini, G., Archfield, S., Faulkner, D., Lamb, R., Khouakhi, A., and Yin, J.: Global
807 Changes in 20-Year, 50-Year, and 100-Year River Floods, Geophysical Research Letters,
808 48, https://doi.org/10.1029/2020GL091824, 2021a.

809

810 Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal,
811 K., Lees, T., Matthews, T., Murphy, C., and Wilby, R. L.: Nonstationary weather and water
812 extremes: a review of methods for their detection, attribution, and management, Hydrol.
813 Earth Syst. Sci., 25, 3897–3935, https://doi.org/10.5194/hess-25-3897-2021, 2021b.

814

815 Stein, L., Pianosi, F., and Woods, R.: Event-based classification for global study of river
816 flood generating processes, Hydrological Processes, 34, 1514–1529,
817 https://doi.org/10.1002/hyp.13678, 2020.

818

819 Stein, L., Clark, M. P., Knoben, W. J. M., Pianosi, F., and Woods, R. A.: How Do Climate
820 and Catchment Attributes Influence Flood Generating Processes? A Large-Sample Study for
821 671 Catchments Across the Contiguous USA, Water Res, 57,
822 https://doi.org/10.1029/2020WR028300, 2021.

823

824 Tarasova, L., Merz, R., Kiss, A., Basso, S., Blöschl, G., Merz, B., Viglione, A., Plötner, S.,
825 Guse, B., Schumann, A., Fischer, S., Ahrens, B., Anwar, F., Bárdossy, A., Bühler, P.,
826 Haberlandt, U., Kreibich, H., Krug, A., Lun, D., Müller-Thomy, H., Pidoto, R., Primo, C.,
827 Seidel, J., Vorogushyn, S., and Wietzke, L.: Causative classification of river flood events,
828 WIREs Water, 6, https://doi.org/10.1002/wat2.1353, 2019.

829

830 Tarasova, L., Basso, S., Wendi, D., Viglione, A., Kumar, R., and Merz, R.: A Process-Based
831 Framework to Characterize and Classify Runoff Events: The Event Typology of Germany,
832 Water Resour. Res., 56, https://doi.org/10.1029/2019WR026951, 2020.

833

834 Tarasova, L., Lun, D., Merz, R. Blösch, G., Basso, S., Bertola, M., Miniussi, A., Radovec, O.,
835 Samaniego, L., Thober, S., Kumar, R.: Shifts in flood generation processes exacerbate
836 regional flood anomalies in Europe. Commun Earth Environ 4, 49,
837 https://doi.org/10.1038/s43247-023-00714-8, 2023.

838

839 Tramblay, Y., Bouvier, C., Martin, C., Didon-Lescot, J.-F., Todorovik, D., and Domergue, J.-
840 M.: Assessment of initial soil moisture conditions for event-based rainfall–runoff modelling,
841 Journal of Hydrology, 387, 176–187, https://doi.org/10.1016/j.jhydrol.2010.04.006, 2010.

842

843 Tramblay, Y., Neppel, L., Carreau, J., and Najib, K.: Non-stationary frequency analysis of
844 heavy rainfall events in southern France, Hydrological Sciences Journal, 58, 280–294,
845 https://doi.org/10.1080/02626667.2012.754988, 2013.

846

847 Tramblay, Y., Mimeau, L., Neppel, L., Vinet, F., and Sauquet, E.: Detection and attribution of
848 flood trends in Mediterranean basins, Hydrol. Earth Syst. Sci., 23, 4419–4431,
849 https://doi.org/10.5194/hess-23-4419-2019, 2019.

850

851 Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S. M., Volaire, F., Boone, A.,
852 Le Page, M., Llasat, M. C., Albergel, C., Burak, S., Cailleret, M., Kalin, K. C., Davi, H.,
853 Dupuy, J.-L., Greve, P., Grillakis, M., Hanich, L., Jarlan, L., Martin-StPaul, N., Martínez-
854 Vilalta, J., Mouillot, F., Pulido-Velazquez, D., Quintana-Seguí, P., Renard, D., Turco, M.,
855 Türkeş, M., Trigo, R., Vidal, J.-P., Vilagrosa, A., Zribi, M., and Polcher, J.: Challenges for
856 drought assessment in the Mediterranean region under future climate scenarios, Earth-
857 Science Reviews, 210, 103348, https://doi.org/10.1016/j.earscirev.2020.103348, 2020.

858

859 Tramblay, Y., Villarini, G., Saidi, M. E., Massari, C., and Stein, L.: Classification of flood-
860 generating processes in Africa, Sci Rep, 12, 18920, https://doi.org/10.1038/s41598-022-
861 23725-5, 2022.

862

863 Wasko, C. and Nathan, R.: Influence of changes in rainfall and soil moisture on trends in
864 flooding, Journal of Hydrology, 575, 432–441, https://doi.org/10.1016/j.jhydrol.2019.05.054,
865 2019.

866

867 Wasko, C., Nathan, R., Stein, L., and O'Shea, D.: Evidence of shorter more extreme rainfalls
868 and increased flood variability under climate change, Journal of Hydrology, 603, 126994,
869 https://doi.org/10.1016/j.jhydrol.2021.126994, 2021.

870

871 Watson, G. S. and Williams, E. J.: On the Construction of Significance Tests on the Circle
872 and the Sphere, Biometrika, 43, 344, https://doi.org/10.2307/2332913, 1956.

873

874 Whitfield, P. H.: Floods in future climates: a review: Changing floods in future climates, J.
875 Flood Risk Manage, 5, 336–365, https://doi.org/10.1111/j.1753-318X.2012.01150.x, 2012.

876

877 Zhang, S., Zhou, L., Zhang, L., Yang, Y., Wei, Z., Zhou, S., Yang, D., Yang, X., Wu, X.,
878 Zhang, Y., Li, X., and Dai, Y.: Reconciling disagreement on global river flood changes in a
879 warming climate, Nat. Clim. Chang., 12, 1160–1167, https://doi.org/10.1038/s41558-022-
880 01539-7, 2022.

881

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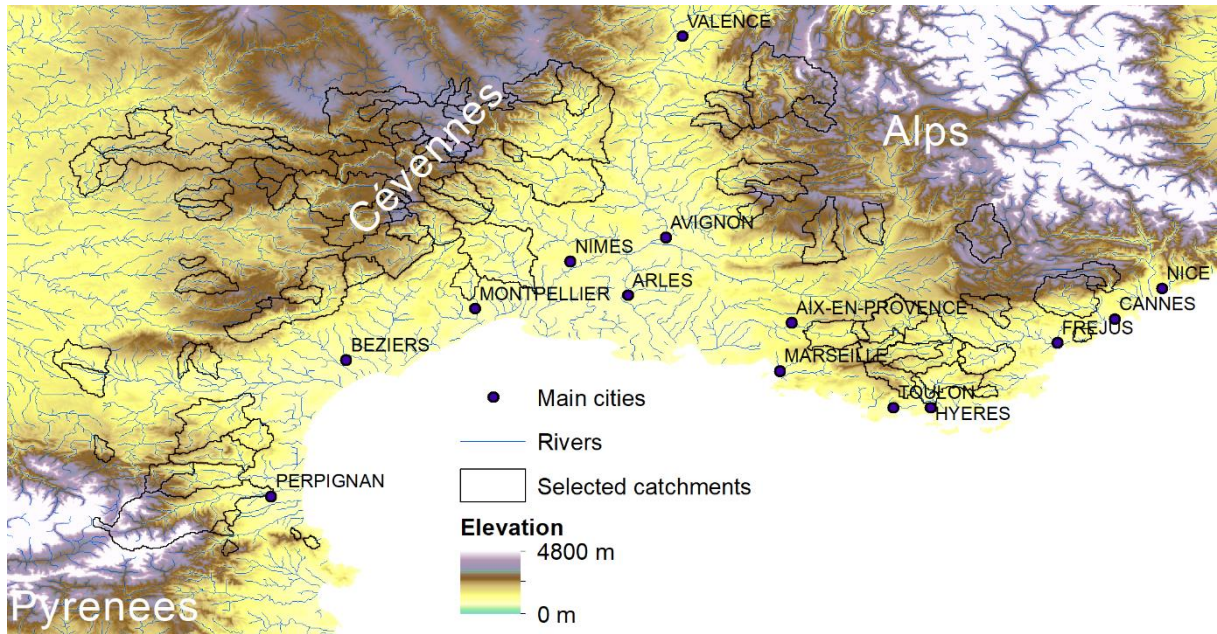
Figure 1: Map of the selected catchments
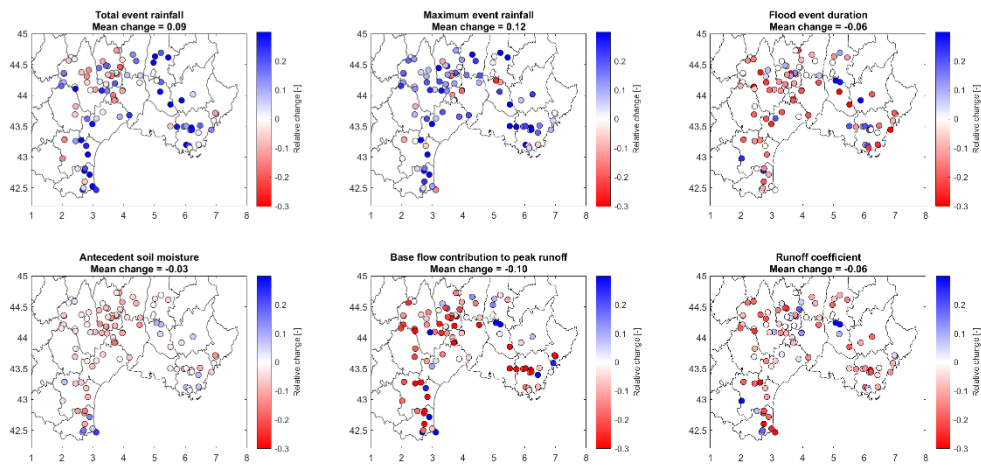
Figure 2: Relative changes in different flood event characteristics between 1959-1990 and 1991-2021
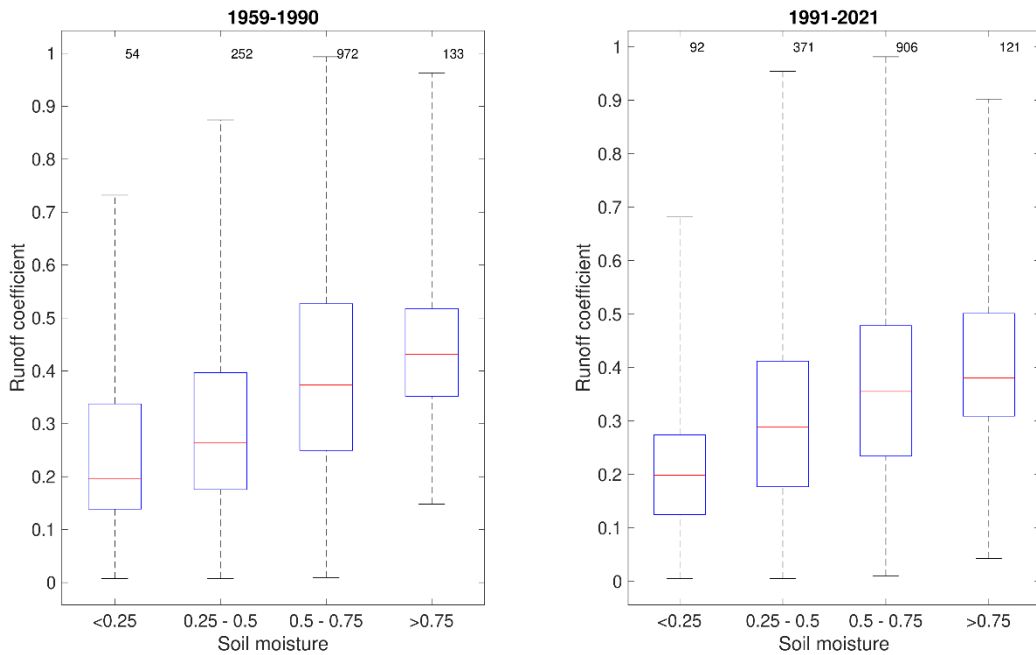
Figure 3: Relationship between the flood event runoff coefficients and antecedent soil moisture for the two time periods considered: 1959-1990 and 1991-2021. For each box, the central line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points. The numbers at the top of the figure indicate the number of events in each category.
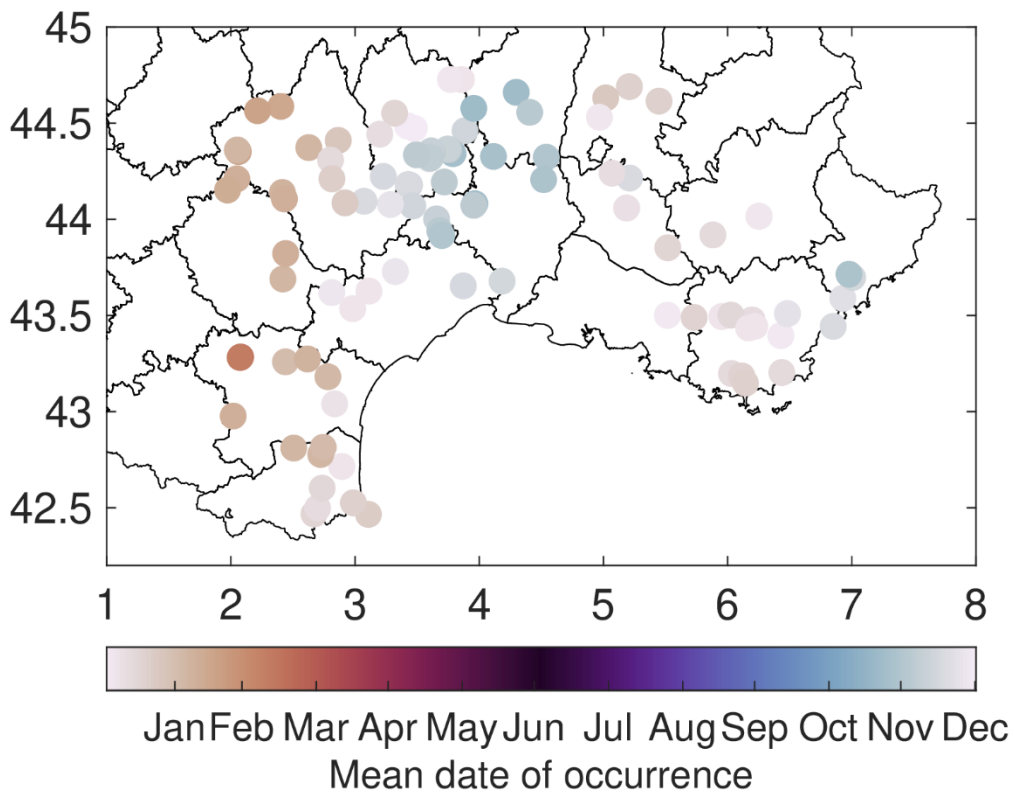
Figure 4: Mean date of flood occurrence
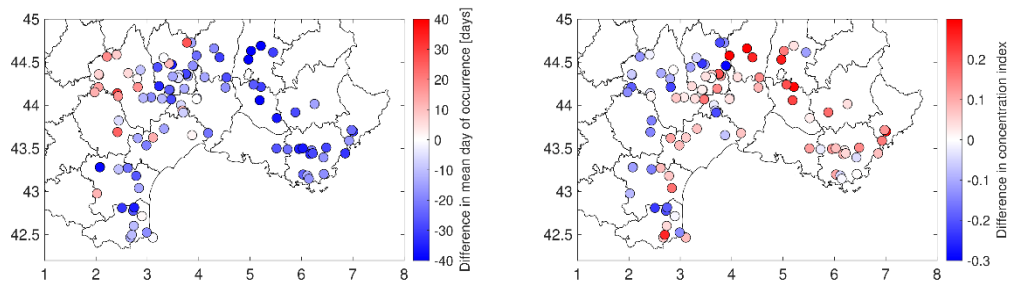
Figure 5: Changes in mean flood date (left) and changes in the concentration index (right) between 1959-1990 and 1991-2021
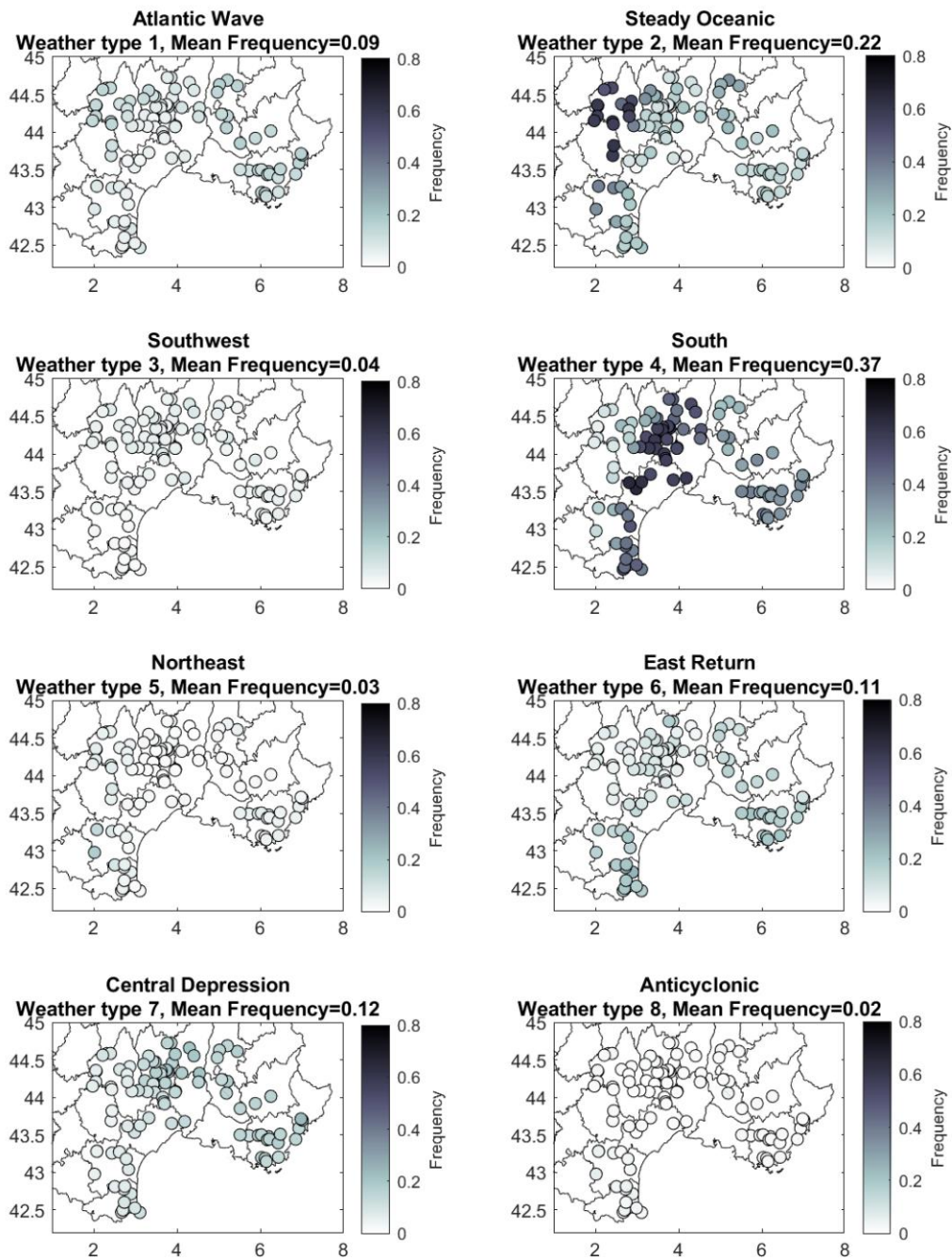
Figure 6: Frequency of the different weather types associated with flood events, the names of the different weather types are from Garavaglia et al. (2010)
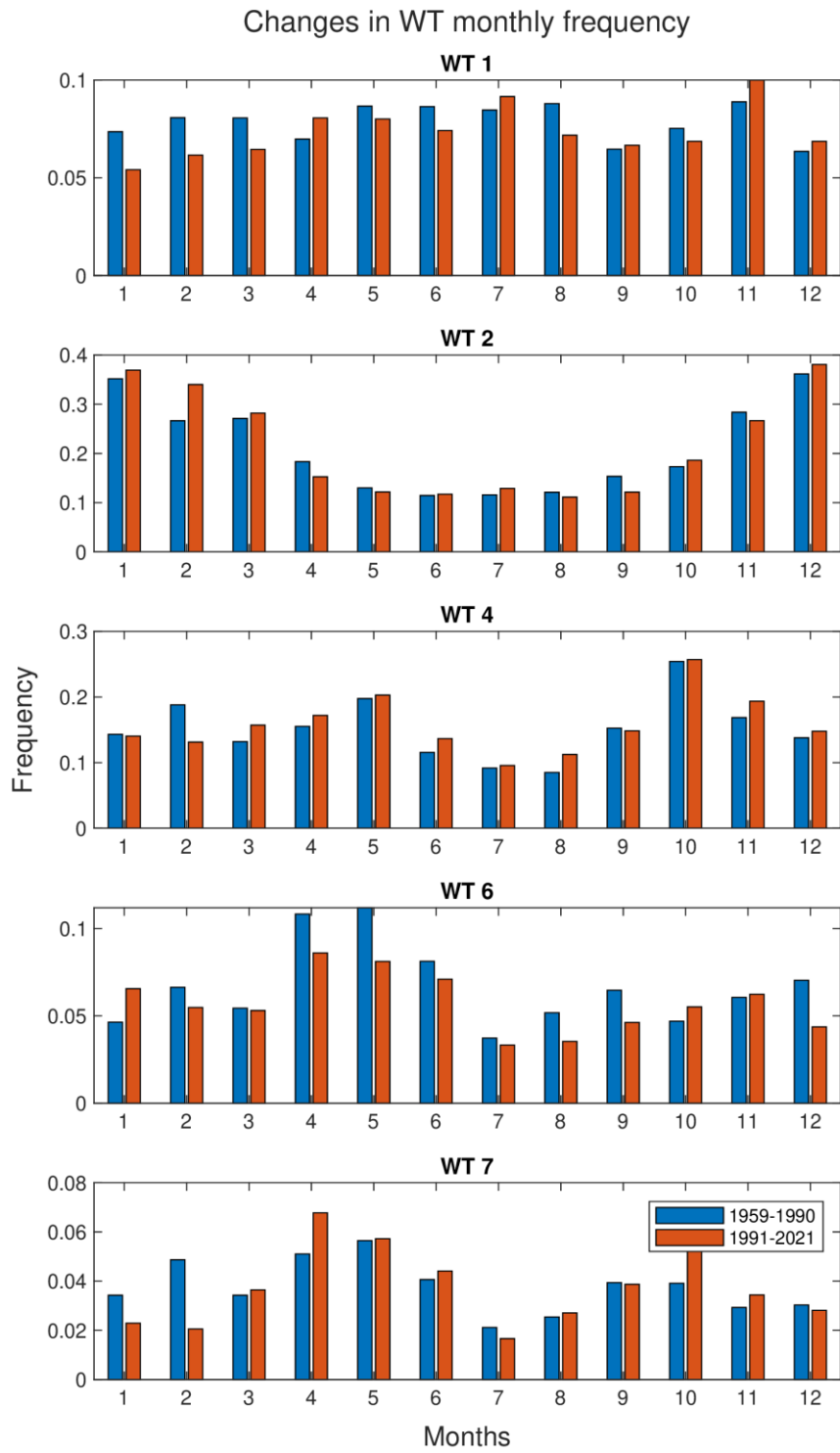
Figure 7: Change in monthly frequency of weather types 1, 2, 4 ,6 and 7 between 1959-1990 and 1991-2021
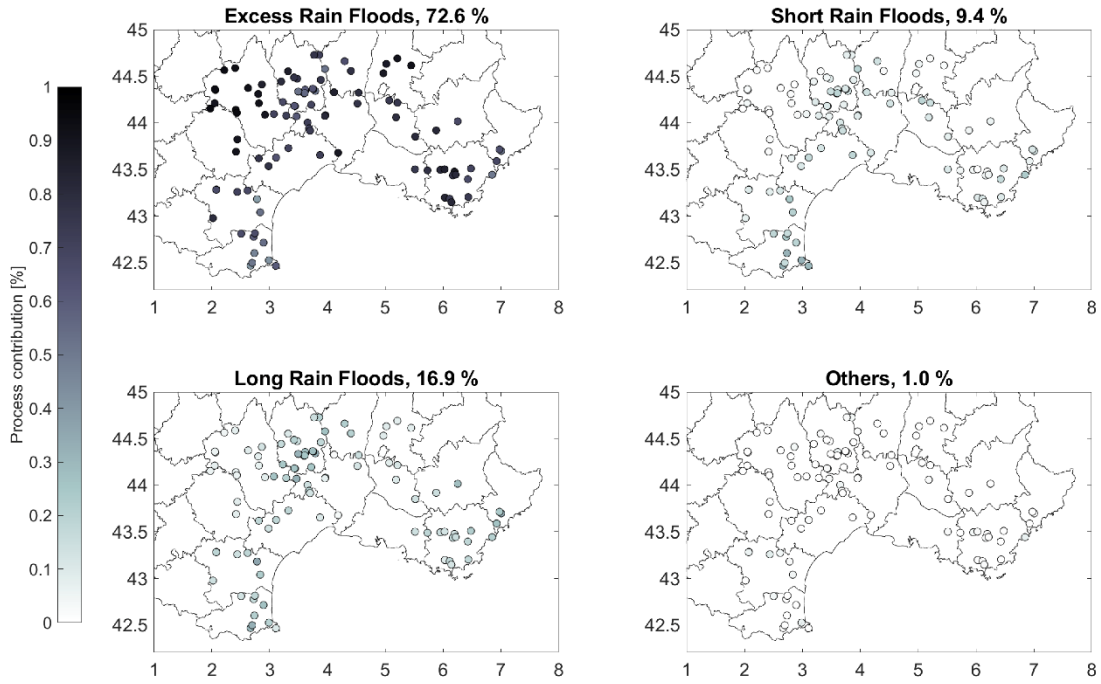
Figure 8: Flood event classification into four categories: excess rain, long rain, short rain and others
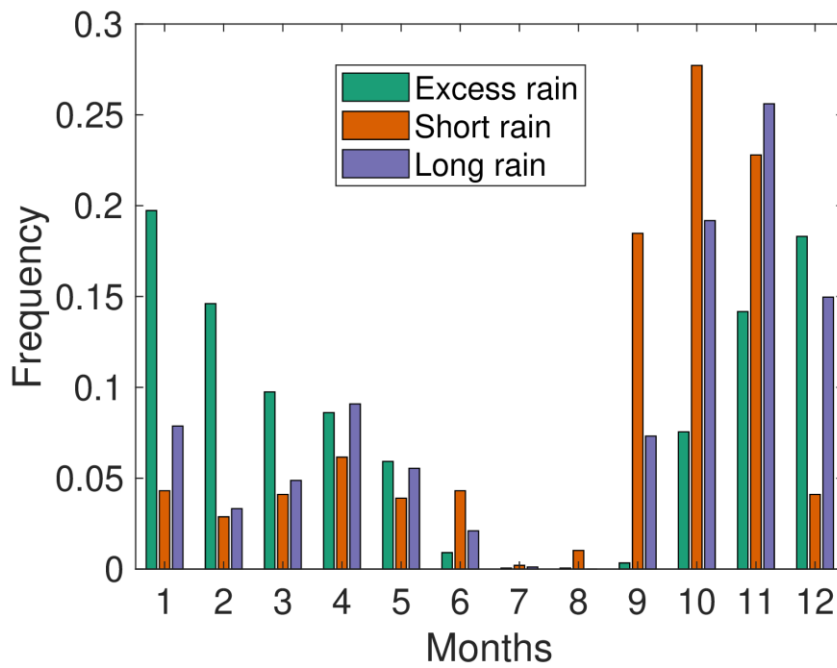
Figure 9: Mean monthly frequency of occurrence for the three flood drivers: excess rain, short rain, and long rain
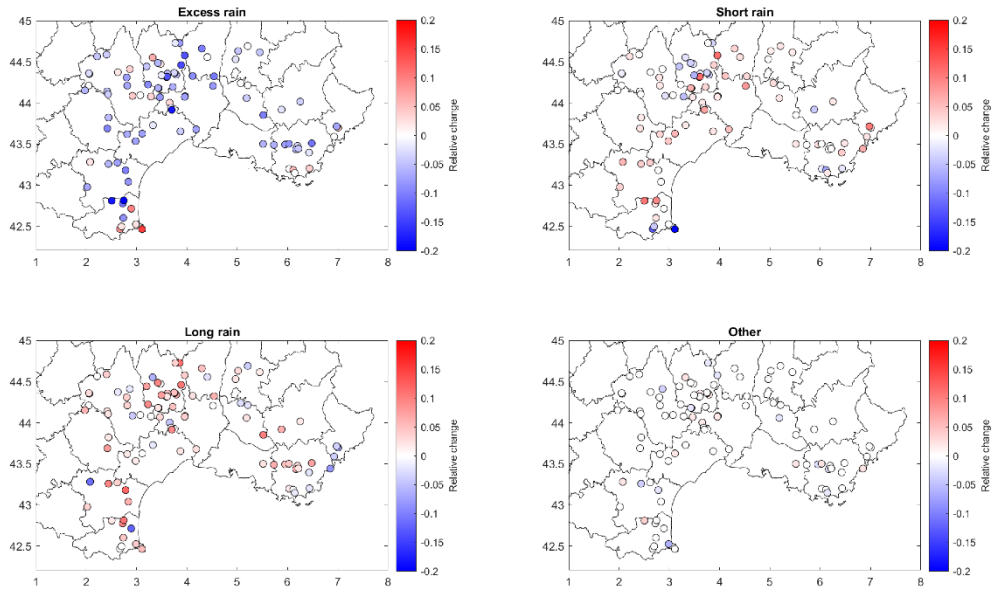
Figure 10: Relative changes in the frequency of excess rain, short rain and long rain between 1959-1990 and 1991-2021
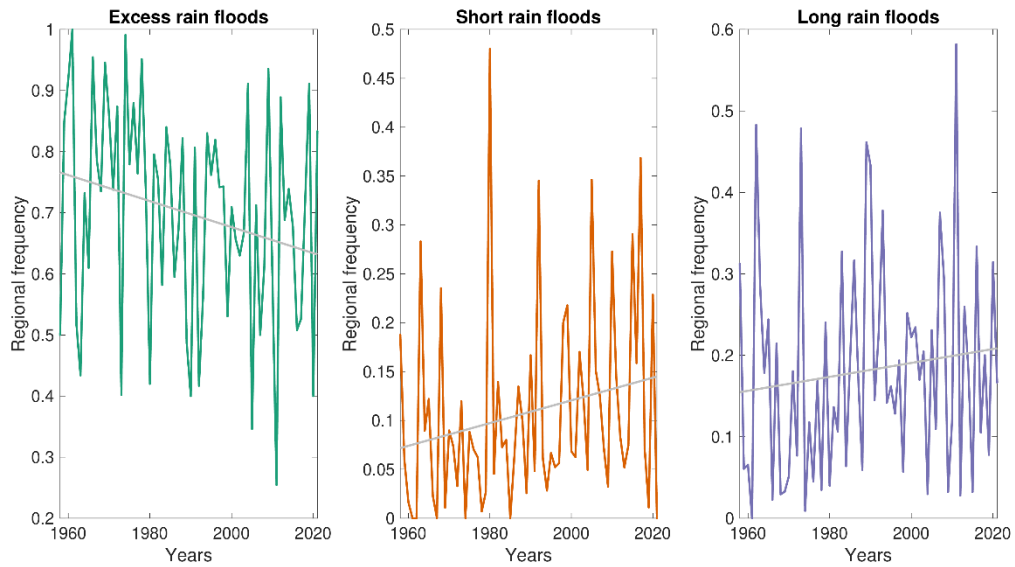
Figure 11: Regional frequency of excess rain, short rain, and long rain floods between 1959 and 2021. The gray lines denote a least-square linear fit to represent the long-term tendency
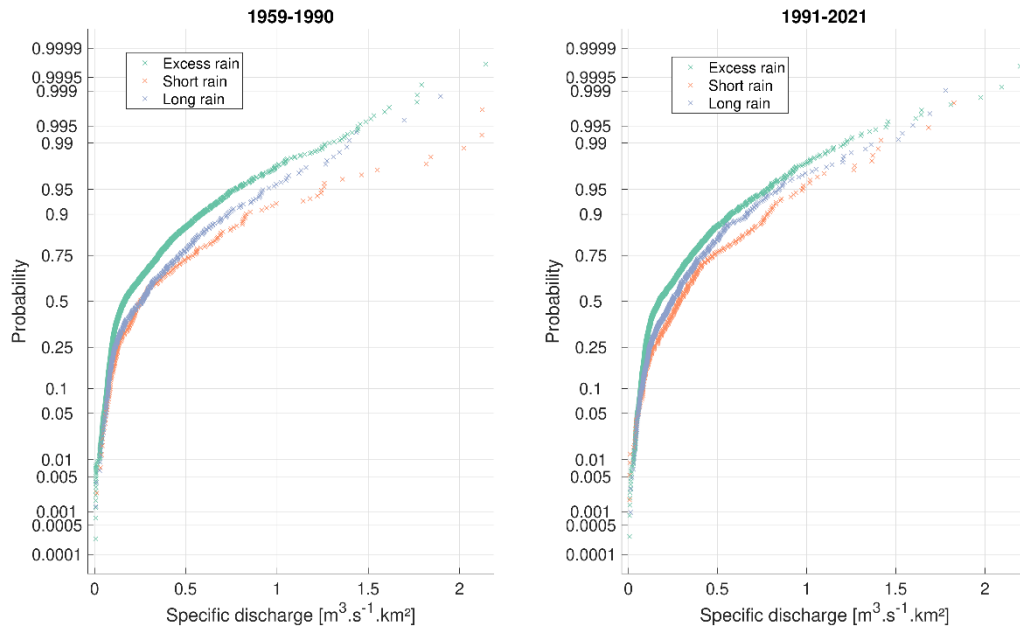
Figure 12: Distribution of regionally sampled floods corresponding to excess rain, short rain and long rain types of floods for the two time periods 1959-1990 and 1991-2021