



Climatology and trends of observed daily and hourly extreme precipitation in the French Alps

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Abstract. The French Alps are characterized by complex topography, which influences precipitation regimes and associated risks in various ways. Extreme precipitation, especially when it happens on very short timescales, can lead to flash floods and landslides with important social and economic impacts. Local stakeholders, working on prevention and protection from such events, report a perceived recent increase in sub-daily extreme precipitation intensities in the French Alps. However, to our knowledge, this has not yet been confirmed statistically. In this paper, we apply a statistical approach based on extreme value theory on long time series of in situ observations. By comparing daily and hourly observations and analysing both months and seasons, we are able to present a climatology as well as trends of precipitation extremes in unprecedented detail. Here we define 'extreme' as 20-year return levels of precipitation intensity, focusing thus on very rare events. In a first part, we use a stationary framework to provide an updated climatology of daily and hourly extremes. We make use of an existing weather pattern classification to show the dynamic influences on precipitation maxima, highlighting the strong differences between the northern and the southern French Alps as well as between seasons. In a second part, we compute trends of these extremes, for which we also find partially large differences between regions and seasons. For annual extremes of daily precipitation, we find strong positive trends in the south and negative trends in the north, mostly driven by changes in autumn. Annual trends of hourly extremes are mostly non-significant and show more of an east-west division, with positive trends in the high Alps and negative ones in the pre-Alps.

1 Introduction

A direct consequence of global atmospheric warming is a profound modification of global atmospheric circulation and the entire climate system (IPCC, 2023). One of the main indicators of this change on a global scale is the intensification of the water cycle and an increase in hydrometeorological extremes, such as extreme precipitation and droughts (e.g. Markonis et al., 2019; Trenberth et al., 2003; Trenberth, 2011). Extreme rainfall, especially when it happens on very short timescales (minutes to hours), can lead to flash floods and landslides with important social and economic impacts. In 2024 alone, many such events hit the news, for example in eastern Spain, Nepal, Afghanistan or central Europe (WMO, 2025), which shows the urgency of better knowledge of probability and potential consequences of such events. Also southeastern France was not spared from



such events recently. In June 2024, intense rainfall at high altitude contributed to major flooding in the Ecrins massif (Blanc et al., 2024). In October, locally more than 600 mm of rainfall in 48 hours lead to widespread flooding in the Ardèche province (Météo-France, 2024). And in May 2025, short but extremely intense thunderstorms (locally exceeding 120mm/h) caused widespread damage in the southern Var province (Météo-France, 2025).

The French Alps are characterized by complex topography, which influences precipitation regimes and associated risks in various ways. First, the local relief induces significant spatial variability in orographically triggered precipitation (Kieffer-Weisse and Bois, 2001; Saidi-Bououdina, 1996). Second, steep slopes, especially when combined with unstable soils prone to erosion, are more exposed to landslides and flash floods (Creutin et al., 2022; Gaume et al., 2009; Llasat et al., 2016). These events can have catastrophic consequences when they affect homes, roads, or economic and touristic infrastructure. Third, the French Alps are located at the crossroads of Atlantic and Mediterranean climatic influences. A very clear climatic difference can be found between the northern and southern part of this region (e.g. Blanchard, 1921), which is also part of a larger climatic divide of the European Alps between temperate westerly and Mediterranean subtropical climate as found by Auer et al. (2007). However, this divide, even though mainly topographically induced, is not fixed between seasons and over time. For example, a study by Blanchet et al. (2021b) showed that the Mediterranean influence on precipitation extremes is retreating in winter and spring (in favour of the Atlantic influence), but increasing in autumn. With this background, both thermodynamic (a warmer atmosphere having a higher moisture holding capacity) and dynamic (changes in the relative influence of weather patterns) are likely to be of importance for assessing changes of precipitation extremes in our study region, thus complicating the topic of assessing possible trends.

Previous studies, conducted primarily on daily precipitation extremes, have already shown trends in precipitation extremes in southeastern France in recent decades. For example, Ribes et al. (2019) used an approach that involved the analysis of a single aggregated time series of daily data from several stations in southern France. They found a temperature-intensity relationship of 1 to 3 times that expected by Clausius-Clapeyron. They also noted that the trend in annual daily precipitation maxima was non-existent until the 1990s and about 20 to 40% since then. Blanchet et al. (2021a, 2016) found an increase in daily extreme precipitation in autumn, particularly in the Mediterranean region, and a decrease in the northern Alps in winter. Studying the onset of clear trends in daily precipitation extremes, Blanchet and Creutin (2022) showed that a consensus to significant trends in observations in southern France only appeared in the 2000s. In neighbouring Switzerland, Haruna et al. (2025) showed significant positive trends of extreme daily precipitation in the Swiss pre-Alps and the Swiss Plateau in winter, spring and summer as well as in the southern cantons of Ticino and Grisons in autumn.

Local stakeholders, working on prevention and protection from such events, report a perceived recent increase in short-duration (< 24 hours) but high-intensity precipitation in the French Alps, causing landslides and floods in areas where little or no such activity has been observed before (pers. comm. from stakeholders at RTM, EDF, Météo-France). However, to our knowledge, no studies have been conducted on this topic yet. Given that in smaller catchments changes in severe flooding intensity are closely related to changes in short-duration high-intensity precipitation events (Blöschl, 2022; Haslinger et al., 2025; Llasat et al., 2016) there is an urgent need to address this knowledge gap.



This type of small-scale precipitation events is usually caused by convective processes, typically thunderstorms. Regarding extremes, it is often assumed that in first order these should scale similarly with temperature as the potential increase in the water vapour content, which according to the Clausius-Clapeyron relationship is roughly 7%/K (Trenberth, 2011). As Fowler et al. (2021b) have shown in a literature review on hourly extremes, and John et al. (2022) in a model analysis studying daily extremes, globally this assumption seems to hold true, but locally scaling rates of two to three times higher have also been observed. Furthermore, it is expected that the trends in intensity should be higher for subhourly durations (Zheng et al., 2015; Dallan et al., 2022). While this has been shown locally (Sydney, Australia: Ayat et al. (2022), Canada: Cannon et al. (2024)) it is difficult to prove on a global scale due to the very limited availability of long-term observations at such high temporal resolution. Both mechanistic and statistical explanations for these "super-CC" trends at small timesteps have been put forward (Fowler et al., 2021b, a; Loriaux et al., 2013; Da Silva and Haerter, 2025). Some studies (e.g. Loriaux et al., 2013; Fowler et al., 2021b) suggest that mechanistic reasons, i.e. an intensification of the convective system itself due to a non-linear response to an increase in temperature are responsible for these "super-CC"-scaling rates. Other studies however, most notably an analysis by Da Silva and Haerter (2025) show that this might be a purely statistical effect, resulting from an increase of the convective fraction especially of mixed stratiform-convective systems. By splitting precipitation events into convective and stratiform they show that each of the two types individually scale very closely to CC-scaling. Yet another possible explanation, especially on local to regional scales, could be a shift in prevailing circulation patterns, i.e. atmospheric dynamics (e.g. Blanchet et al., 2021a).

Unfortunately, there is no consensual definition of what characterises an 'extreme'. Some authors study what we would term 'heavy precipitation', typically intensities above the 99th percentile or seasonal/annual maxima (thus exceeded between 3-4 times a year and every two years). Others, however, look at 'extreme precipitation' as events that are rarely or never encountered in a human's life (e.g. return levels of 20 years or higher). In the present article we are mostly interested in the second class, as these events are likely to produce the strongest impacts. More precisely, we here define extremes as 20-year return levels. While studies of trends in extremes remain rare, a much larger body of literature provides insights into trends of heavy precipitation (e.g. Westra et al., 2013; Donat et al., 2016). Studies conducted in the European Alps (whole region: Menegoz et al. (2020), Switzerland: Bauer and Scherrer (2024), Austria: Haslinger et al. (2025); Schröer and Kirchengast (2018), northern Italy: Dallan et al. (2022); Giorgi et al. (2016); Brugnara and Maugeri (2019)) generally agree on the big picture: Trends in daily heavy precipitation are different depending on the region and the period studied, which is generally attributed to the complex interplay of large-scale circulation patterns and local topography (e.g. Bauer and Scherrer, 2024; Haslinger et al., 2025; Schröer and Kirchengast, 2018; Brugnara and Maugeri, 2019). Nevertheless, some regions like Austria (Haslinger et al., 2025) or the European Alps as a whole (Menegoz et al., 2020) do show significantly positive trends. On shorter time scales, trends in heavy precipitation are generally positive and follow more closely the 7%/K relation expected from the Clausius-Clapeyron relationship (Haslinger et al., 2025; Schröer and Kirchengast, 2018; Dallan et al., 2022; Bauer and Scherrer, 2024). In summary, trends in heavy precipitation on daily timescales seem to be mostly influenced by changes in large-scale circulation patterns, while short-duration high-intensity rainfall seems to be much closer correlated to air temperature through increased moisture holding capacity and increased energy available for convection (see also Giorgi et al., 2016). At this point it should also be



mentioned that a study by Barbero et al. (2017) found overall lower significance and temperature sensitivity of annual/seasonal maximum precipitation of hourly compared to daily precipitation over the contiguous United States, which is surprising given the widespread hypothesis of higher intensity trends for shorter durations. The authors attribute this to the more localised nature of high-intensity short-duration events, making them difficult to sample by ground-based rain gauge observations.

Even with the large body of literature on daily precipitation extremes and daily to hourly heavy precipitation in the European Alps summarised in the previous paragraphs, to our knowledge no study has analysed the trends of sub-daily extreme precipitation in the Alps, which is mostly due to the previously limited temporal depth of available data. Only now are observational time series becoming long enough to attempt an analysis of extreme precipitation trends on an hourly timescale, which is one of the main objectives of this study focusing on the French Alps. Previous studies of hourly precipitation extremes in the region have mainly focused on characterising spatial patterns and improving predictability. In the 1990s, the digitalisation of continuous observations (notably by Électricité de France, a French power company, as well as various other institutions) provided access to 30-40 years of data for about sixty stations, allowing the characterisation of extreme rainfall at sub-daily timescales (Garçon, 1993). This possibility has been exploited in a series of doctoral theses at the time: Saidi-Bououdina (1996) studied the influence of local relief on precipitation extremes, showing for example that the influence of altitude on precipitation intensities is much smaller for hourly than for daily extremes. Kieffer-Weisse (1998) developed interpolation methods, and Djerboua (2001) worked mostly on the predictability of such extremes. Today, with another 30 years of observations for many of the stations analysed in these previous studies as well as 25-30 years of hourly observations by the French national weather service Météo-France, we now have access to a much larger dataset of observations. With 177 stations having more than 25 years of observations (28 stations with more than 45 years, longest 70 years), we have a sufficiently large dataset to obtain updated estimates of return periods as well as, for the first time, studying trends of hourly extreme precipitation in the French Alps. Additionally, we build on and expand the work of Garavaglia et al. (2010); Blanchet et al. (2016, 2021a) to get an overview over the weather patterns behind high-intensity precipitation in the region. Together with the estimates of return periods and their trends we thus aim to obtain an updated climatology of daily and hourly precipitation extremes in the French Alps.

The remainder of this article is organised as follows: Sect. 2 introduces the study area, the datasets used and the preprocessing steps applied. In Sect. 3 we outline the methodology. The results, including estimated stationary return levels, weather patterns associated to precipitation maxima, and trends of extremes are shown in Sect. 4. In Sect. 5 we discuss the results and then conclude the paper in Sect. 6.

2 Study area and data

2.1 Study area

Our study area (shown in Fig. 1) covers the nine French *départements* (provinces) lying (at least partly) in the Alps. These are Savoie (official geographical code 73), Haute-Savoie (74), Isère (38) and Drôme (26) in the Auvergne-Rhône-Alpes region,

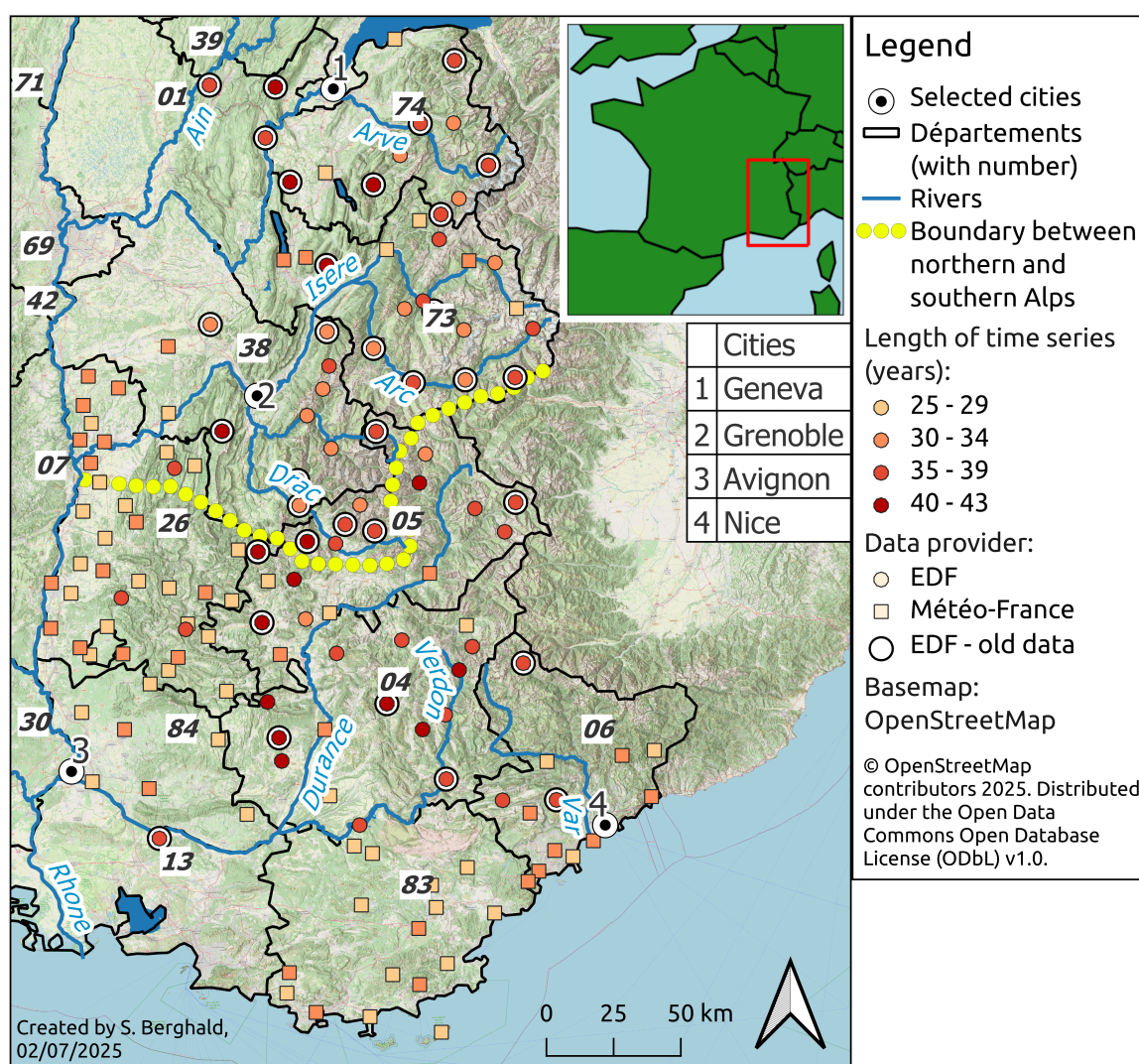


Figure 1. Study area and locations of precipitation observations used in this study. Stations maintained by EDF are shown as circles, those maintained by Météo-France as squares. Stations for which old data previous to the 1980s is available are marked by black circles. The colour of a point indicates the length of the hourly timeseries in years (old data previous to 1980 not included due to the very different data structure). The length of daily time series is not shown, but generally exceeds the length of hourly data. The boundaries of the administrative regions (*départements*) are shown in black with their respective codes (see text). Important rivers are indicated in blue, and selected cities as black dots. The yellow line shows the climatological boundary between northern and southern Alps (Blanchard, 1921; Auer et al., 2007). Inlet: Position of the study area within France. Basemap: OpenStreetMap contributors (2025), hillshade: Esri (2025)



125 as well as Hautes-Alpes (05), Alpes-de-Haute-Provence (04), Vaucluse (84), Var (83) and Alpes-Maritimes (06) in Provence-Alpes-Côte d'Azur. Due to their proximity, three stations in Ain (01) and one in Bouches-du-Rhône (13) are also included.

The French Alps are generally divided into two parts, characterized by different climatic influences (Blanchard, 1921; Auer et al., 2007). The division between the Northern Alps and the Southern Alps roughly follows a line passing through the mountain passes of Col de la Croix-Haute, Col Bayard, and Col du Lautaret, with the Écrins massif and its peaks reaching over
130 4000 meters being the main meteorological divide between North and South (Fig. 1). The Northern Alps are generally higher than the Southern Alps and very well structured: from west to east, there are first the pre-Alps (Chablais, Bornes, Bauges, Chartreuse, Vercors), followed by the central massifs (Mont Blanc, Beaufortain, Belledonne, Oisans, Pelvoux). Between the two lies the Alpine Furrow, a major north-south valley including the Grésivaudan and the Combe de Savoie valleys. To the east of the central massifs is the intra-Alpine zone, accessible via the upper Isère valley (Tarentaise), the Arc valley (Maurienne),
135 and the Romanche valley.

The Southern Alps mainly consist of the Durance watershed with its tributaries Ubaye and Verdon. They are less structured and generally lower in the outer areas (from Diois in the west to the Alpes-Maritimes in the south) and higher towards the Italian border in the east (Queyras and Mercantour).

The Northern Alps, under Atlantic influence, are among the rainiest regions in France with a mean precipitation of 1172
140 mm/year (June-August: 274 mm/3 months; mean values of our full dataset), while the Southern Alps experience a much drier Mediterranean climate (mean 855 mm/y, JJA 144 mm/3 months). The Atlantic influence in the north, with predominant westerly flows and the north-south orientation of the main mountain ranges, leads to very distinct climatic differences: the pre-Alps like Chablais or Chartreuse, being the first barrier for westerly flows, are characterized by high total precipitation amounts and comparatively low average temperatures. The Alpine Furrow, at low altitude and sheltered from westerly winds,
145 experiences a mild and much drier climate. The central massifs then form a second barrier for westerly flows. This causes the intra-Alpine regions behind these mountain ranges, the Upper Tarentaise and Upper Maurienne, to experience a very dry, sunny, and continental climate. A particular climatic phenomenon in this region is the "East Return" which can locally bring very high precipitation amounts from the Italian Po valley and the Gulf of Genoa with humidity originating from the Mediterranean Sea.

The Southern Alps are characterized by a strong Mediterranean influence that decreases from south to north. Near the
150 Mediterranean Sea, a strong seasonality between very dry summers and very rainy autumns can be observed. Rainfall intensities in autumn can locally be very high, with records exceeding 100 mm in one hour (Cannes, October 2015) and even exceeding 500 mm in 24 hours (Saint-Martin-Vésubie, October 2020). As in the wider region of the north-western Mediterranean, autumn is also the season most prone to flooding in the southern Alps (Llasat et al., 2013), which is coherent with the climatology of extremes we present in this article. Outside the typical season for high-intensity rainfall, exceptionally extreme thunderstorms
155 exceeding 120 mm/h hit the coastal Var region in May 2025 (Météo-France, 2025).



2.2 Data

In this study, we use hourly and daily rainfall observations provided by Météo-France and EDF (*Électricité de France*) and a weather pattern classification described in Garavaglia et al. (2010). In the following we give an overview over the datasets and the applied preprocessing steps.

160 2.2.1 Observations by Météo-France

The large-scale automatised of weather stations in France began in the late 1960s (Météo-France, 2020), but continuous precipitation observation was automated within the Météo-France network first in the 1990s (data availability, see also Guillou, 2018). In 1996, Météo France decided to restructure, automate, and standardize its observation network with the launch of the RADOME project (Réseau d'Acquisition de Données et d'Observations Météorologiques Etendues; Tardieu and Leroy, 2003; 165 Guillou, 2018)). Quality-controlled data from this network is publicly available at meteo.data.gouv.fr (data.gouv.fr and Météo-France, 2023). We selected all stations located in the study region for which at least 25 years of nearly complete (<10% missing data) hourly rainfall observations were available (89 stations in total, squares in Fig. 1).

2.2.2 Observations by EDF

With the post-war onset of economic growth and thus rapidly increasing need for electricity, the French national electric power 170 company EDF started to systematically assess and exploit the potential of hydropower in the French mountain ranges (Perret et al., 2012). As part of this assessment, an extensive monitoring network was established, featuring continuous observations of snow depth, river discharge and precipitation. Precipitation observations are taken since the 1950s using heated large-surface (2000 cm²) rain-gauges, with the precipitation rate registered by mechanic (past) or digital (tipping gauge, today) means. Unfortunately, we were not able to reconstruct the evolution of the network with respect to the exact timing of modifications in 175 the measurement devices. According to Garçon (1993), a change from mechanical to digital registration of observations took place in the 1980s, which seems plausible given the obtained dataset.

In the context of a common effort of several regional stakeholders (notably EDF and *CEMAGREF*) and by initiative of the regional administration, the registrations of 65 rain gauges (including 48 by EDF), some of which started measuring in the 1950s, were manually digitalized in the early 1990s (Garçon, 1993). This dataset was used and further described in Saidi- 180 Bououdina (1996); Kieffer-Weisse (1998); Djerboua (2001). Only weekly maximum precipitation totals for 1h, 2h, 3h, 6h, 12h and 24h were archived and could be retrieved for our study.

More recent data of 68 weather stations (round points in Fig. 1), covering the time from the 1980s to 2022, was made avail- able by EDF for the purpose of our study. The dataset consists of quality-controlled daily and uncontrolled hourly observations for 68 stations. A quality control of the hourly data was thus necessary. For this purpose, we scale the hourly values, i.e. we 185 multiply all hourly values of a given day by a uniform factor such that their 24-hour sum from 6am to 6am on the next day equals the corresponding daily value. The relative distribution of hourly values during the 24 hours remains unchanged in the process. Whenever the daily value is missing, or the difference between hourly sum (prior to scaling) and daily observation



is too big (more than $\pm 25\%$ of the daily value), all hourly observations of that day are set to invalid. One station (No. 2430, Abriès-Ristolas) has been removed from the dataset due to spuriously high maxima during the winter season.

190 By combining the old and recent dataset, we obtained time series of monthly maxima between 45 and 70 years long (majority: 50-60 years) for 27 stations (circled in Fig. 1), of which eight lie south of the climate divide shown in Fig. 1 and the remaining north. Where time series from the two datasets were overlapping, the more recent dataset was used due to the higher resolution.

2.2.3 Definition of seasons

195 During initial analysis we found a clear shift in seasonality of extremes in the region (see also Results and Discussion): while the traditional way of defining meteorological seasons (winter: December-January-February) still seems most logical given just the stationary results, the monthly trends we find actually motivate a different definition (winter: January-February-March). Here we decided to show the traditional seasons for the stationary analysis, and both traditional and new seasons where we show trends.

200 2.2.4 Calculation of Seasonal and Annual Maxima

From the data obtained from Météo-France and EDF (and after correction of the latter), hourly and daily maximum intensities were calculated for each station, year, and month/season. According to the criterion proposed by Blanchet et al. (2016) and inspired by Papalexiou and Koutsoyiannis (2013), a maximum is considered missing if, for a given station, month/season, and year, its rank (ascending) is less than $p_{miss} * N$, with p_{miss} being the proportion of missing data and N the number of years
205 of observations. For example, if a station has 30 years of observation and there are 20% missing values for a given season, the value of that season is not taken into account if its rank is less than $0.2 * 30 = 6$. Thus, the more missing data points there are for a given season, the higher the maximum must be to be retained. For the old dataset just including weekly maxima, monthly maxima were computed by attributing weeks between two months to the months including the larger portion of the week.

2.2.5 Subsets of the observational datasets

210 From the datasets provided by Météo-France and EDF we take two different subsets: first, a subset of 'recent' data, which consists of all timeseries by Météo-France with at least 25 years of data and the recent data from EDF. This subset thus contains 177 time series between 25 and 42 years of data starting in 1980 or later and is used for stationary extreme value analysis. For the trend analysis, we only use the 67 time series including more than 30 years of non-missing data.

2.2.6 Weather pattern classification

215 The circulation patterns bringing rainfall to southern France can be classified into eight main classes, covering a range of generating circulation modes over the Alps, the Massif Central, and the Pyrenees (Garavaglia et al., 2010, directions of flow shown in Fig. 2). These circulation modes include three types of westerly oceanic circulations (WP1 Atlantic Wave, WP2

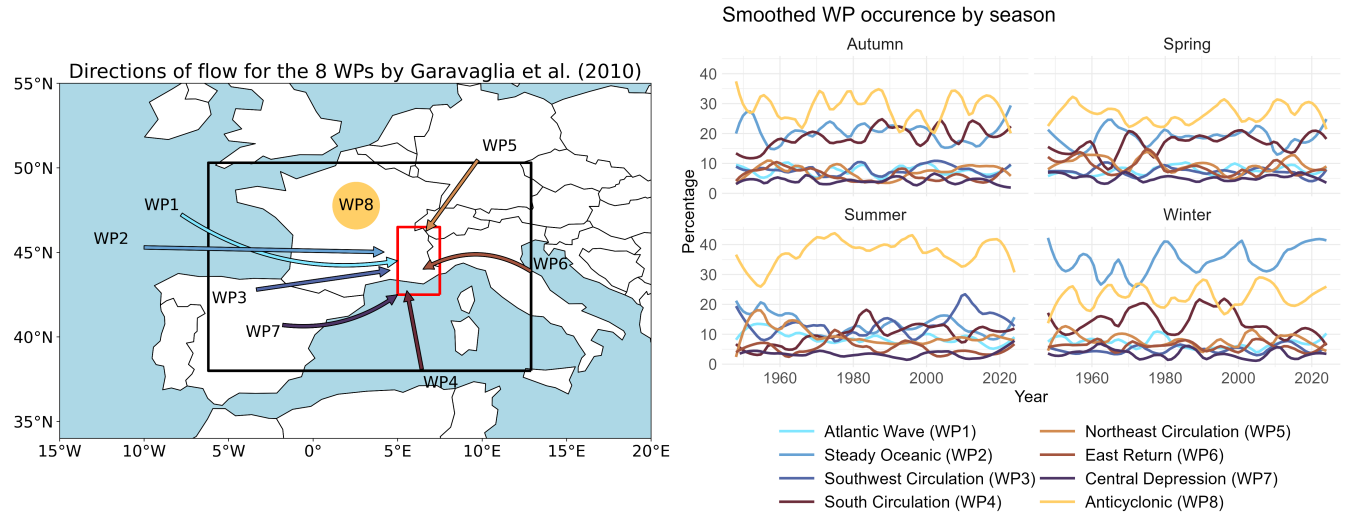


Figure 2. Left: Direction of the large-scale flow directed to the study region for the eight weather patterns by Garavaglia et al. (2010) (WP8 groups anticyclonic conditions). The black box shows the area of interest for which the classification was done, and the red box shows the French Alps, the area of interest of this study. Figure adapted from Garavaglia et al. (2010, Fig. 3 therein). Right: occurrence of the different weather patterns for each season (a LOESS smoother was applied to improve readability).

Steady Oceanic, WP3 Southwest Circulation), three types of Mediterranean circulations (WP4 South Circulation, WP6 East Return, WP7 Central Depression), Northeast Circulation (WP5), and Anticyclonic conditions (WP8). We here use the daily weather pattern (WP) classification by Garavaglia et al. (2010). In this dataset, which is regularly updated by EDF and thus includes the whole period covered in this study, each day is associated to one of the eight weather patterns, which for this day is thus the same for the whole region. Fig. 2 shows qualitatively the evolution of the relative occurrence of each WP over time. Note that in the remainder of our study we group Atlantic (WP1,2,3) and Mediterranean (WP4,6,7) influences and thus obtain four different WPs. Following the method described in Blanchet et al. (2021a, b), we first match each monthly maximum with the WP associated to that day. By doing so, we obtain series of binary variables, where $W_{t,m} = 1$ for a given weather pattern if it has generated the maximum of year t and season or month m , and 0 otherwise. In a stationary frame, we can then directly compute the relative contributions of the weather patterns to the total number of values for a given station. We call the weather pattern showing the relatively highest contribution the dominant influence for seasonal maxima at a given station.

3 Methods

We apply extreme value theory, based on block maxima (e.g., annual maxima) to characterize the general patterns and trends of extreme precipitation. Our methodology is detailed in the following paragraphs.



3.1 Extreme Value Theory

3.1.1 Stationary GEV

For the estimation of return periods, we apply extreme value theory (Coles, 2001; Katz, 2013) based on the Fisher–Tippett–Gnedenko theorem (Coles, 2001; Fisher and Tippett, 1928) which states that for sufficiently large samples (e.g., daily precipitation sums for individual years), the largest or smallest value of each of these samples (e.g., annual maximum precipitation) follows one of three possible limiting distributions, which can all be summarised in the generalised extreme value (GEV) distribution. The GEV distribution is described by location ($-\infty < \mu < \infty$), scale ($\sigma > 0$), and shape ($-\infty < \xi < \infty$) parameters:

$$P(X \leq x) = \exp\left[-\left(1 + \xi \frac{x - \mu}{\sigma}\right)^{-\frac{1}{\xi}}\right], \text{ for } x \text{ such that } 1 + \xi \frac{x - \mu}{\sigma} > 0 \quad (1)$$

A special case is $\xi \rightarrow 0$, which gives the Gumbel distribution (Coles, 2001):

$$P(X \leq x) = \exp\left\{-\exp\left[-\left(\frac{x - \mu}{\sigma}\right)\right]\right\}. \quad (2)$$

The quantiles of the distribution can now be obtained by inverting Eq. 1 or 2:

$$x_p = \begin{cases} \mu - \frac{\sigma}{\xi} (1 - \{-\log(1 - p)\}^{-\xi}), & \text{if } \xi \neq 0 \\ \mu - \sigma \log(-\log(1 - p)), & \text{if } \xi \rightarrow 0 \end{cases} \quad (3)$$

where x_p is the return level corresponding to the return period p^{-1} (e.g. $p = \frac{1}{20}$ for a return period of 20 years).

3.1.2 Non-stationary GEV

Non-stationarity is included in this concept by allowing one or more parameters of the distribution to vary with a covariate (Katz, 2013). Here we use time (in years) as covariate and redefine parameters μ and σ such that they remain constant until a breakpoint year (1985), after which they evolve linearly. This breakpoint is motivated by several considerations: (i) previous studies have shown that statistically significant trends of daily precipitation extremes in southern France start in the 1980s (e.g. Blanchet et al., 2016), (ii) this is also the time where the old dataset including only weekly maxima ends and we start to have the raw hourly observations available, and (iii) most likely, a change in instrumentation took place in the 1980s and/or early 1990s, switching from mechanical to digital registrations. Using a breakpoint, we are able to minimise potential biases stemming from the different lengths of observations while being able to take the additional data previous to 1985 into account to make the estimations more robust.

Consequently, we define the non-stationary model $\mathcal{M}_{\mu, \sigma}$ such that the linear trend starts in 1985, with stationarity before that year:

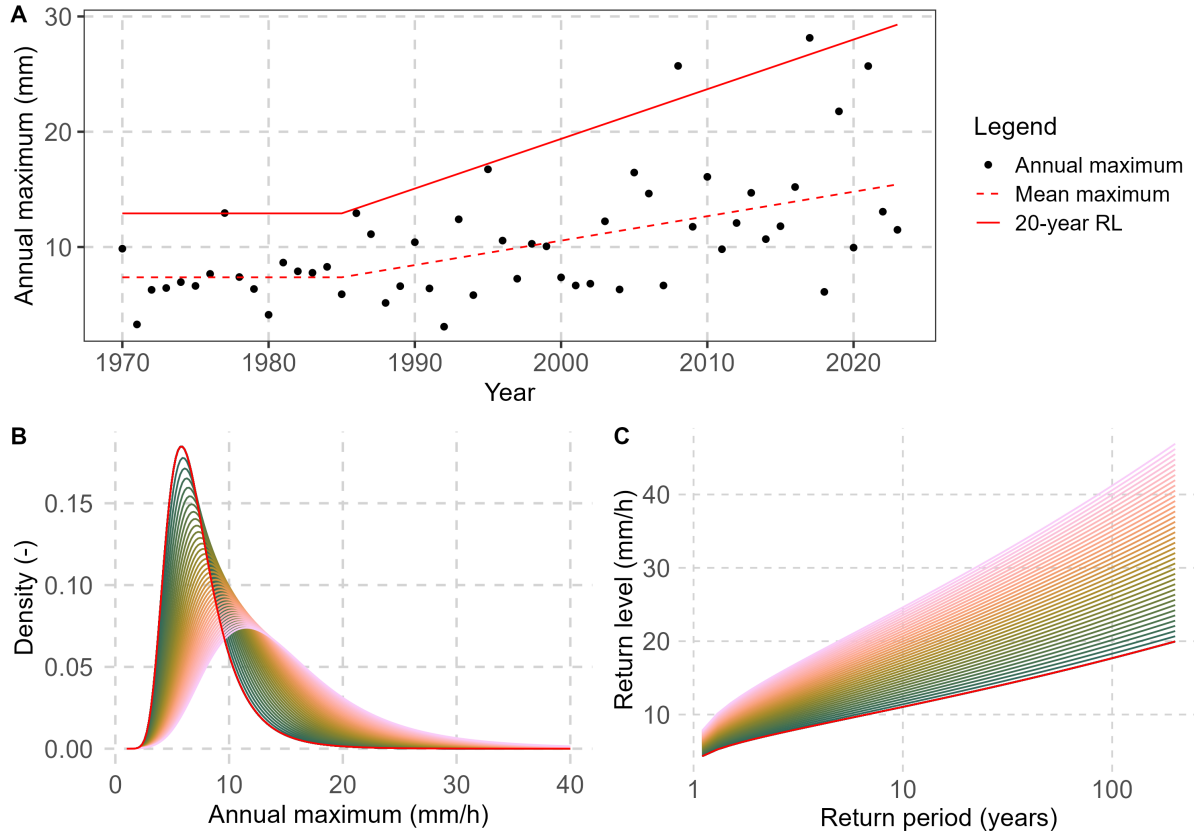


Figure 3. (A) Idealised time series of annual maxima with a linear trend in location (μ) and scale (σ) parameters after the year 1985 including mean maximum (red, dashed) and 20 year return levels (red, solid). (B) Associated GEV density plot for each year between 1970-1985 (stationary, red) and 1986 - 2023 (green to pink). (C) Associated return level plot.

$$(M_{\mu, \sigma}) \begin{cases} \mu(t) = \begin{cases} \mu_0, & \text{if } t \leq 1985, \\ \mu_0 + \mu_1(t - 1985), & \text{if } t > 1985, \end{cases} \\ \sigma(t) = \begin{cases} \sigma_0, & \text{if } t \leq 1985, \\ \sigma_0 + \sigma_1(t - 1985), & \text{if } t > 1985, \end{cases} \\ \xi \end{cases} \quad (4)$$

Because of the difficulties associated with estimating the shape parameter ξ , we choose to keep ξ constant, which is common in the literature. Fig. 3 shows the influence of a linear trend in μ and σ starting in 1985 on an idealised time series of maxima, on the density of the GEV distribution, and on the corresponding return periods. Submodels M_μ (trend only in μ) and M_σ (trend only in σ) are also considered to account for cases when all the density of maxima shifts in time (M_μ), or when only the



variability of maxima changes (M_σ). We then select at each station the best non-stationary model among M_μ , M_σ and $M_{\mu,\sigma}$ as the one minimizing the Akaike information criterion (AIC, Akaike, 1974).

To assess the significance of changes in 20-year return levels, we adopt a bootstrap approach by resampling the series of maxima 100 times with replacement, fitting the best non-stationary model to each resample, and looking if the 5%-95% confidence interval of 20-year return level changes includes zero, in which case we consider the change not significant. We prefer this method over the classical likelihood ratio test (Coles, 2001) as it specifically evaluates changes in the extremes (20-year return levels). In contrast, the likelihood ratio test assesses whether the entire distribution has changed, which could also indicate changes in heavy precipitation (e.g. in mean maxima) rather than in the extremes.

3.2 Parameter Estimation

3.2.1 Theory

Parameters are estimated using maximum likelihood estimation. For short time series, it is possible that the algorithm does not converge to a realistic result. From theoretical considerations, we consider cases where $\xi > 1$ unrealistic and, for the stationary case, impose $-\infty < \xi \leq 1$ using the L-BFGS-B method (Byrd et al., 1995). This is the case 22 times (or 0.8%) across all stations and months for daily data and 42 times (or 1.4%) for hourly data and happens mostly for summer months when entirely dry months in the south cause problems for the ML-algorithm. Not many stations are concerned in the non-stationary estimations because of the neighbourhood approach applied (see below), so these are simply discarded.

3.2.2 Neighbourhood Approach

Because of the higher number of parameters which need to be estimated in the non-stationary case, trend estimation of extremes is not robust for short time-series of just a few decades like we use here (Lang et al., 2014). One approach to circumvent this problem lies in taking into account data from neighbouring stations for a given station, thus increasing the amount of data which can be used to adjust the statistical distribution. This approach is based on the hypothesis that in an area which is not too big, the distribution of the (normalised) data, and thus the trends of extremes, should be similar for all points. Following the notation used by Blanchet et al. (2021a), we consider $R_{i,t}$ the random variable of precipitation maxima at a given point i in a year t . We then formulate the hypothesis that for a point j in the neighbourhood of i , $\mathcal{N}_i$, the distribution of

$$R_{j,t}^* = \frac{R_{j,t}}{\alpha_j}, \quad j \in \mathcal{N}_i \quad (5)$$

is equal to that of $R_{i,t}^* = \frac{R_{i,t}}{\alpha_i}$, where the α s are normalisation factors. Here, we use the mean of the annual maxima of each timeseries as normalisation factors (as Blanchet et al., 2021a), from which follows that all the $R_{j,t}^*$ have the identical mean ($= 1$). Then we can group the normalised timeseries of a station i with the normalised data of all surrounding stations j and multiply again by the normalisation factor of i , α_i to obtain a (much) larger timeseries for i (with by construction the same mean as the raw time series at station i), which allows for a more robust trend estimation. An important choice to make here is about the size of the neighbourhood: there is a bias-variance tradeoff between choosing a small radius, including few

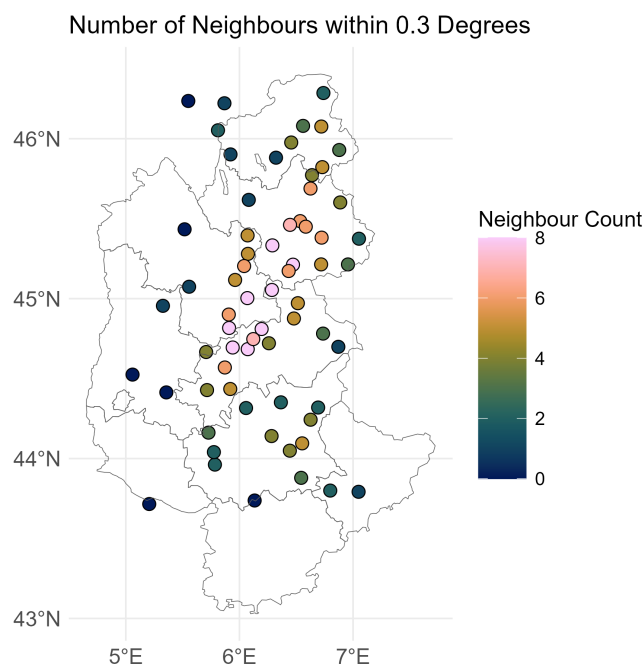


Figure 4. Number of other stations in each station's neighbourhood (0.3° radius).

observations, and a large radius, including more but potentially non-homogeneous observations. Here we chose a radius of 0.3° which results in an average of 3.9 (min 0, max 8) additional stations in each station's neighbourhood (Fig. 4). We also tested 0.2° and 0.4° , which give overall similar results (Fig. not shown). Spatial independence of observed events is sometimes ensured using a declustering technique, keeping for example only one event per day (e.g. Carreau et al., 2013). After some initial testing we decided against doing this, following Evin et al. (2016) (Sect. 7.2.3 therein). Also, as we only have weekly maxima for the old dataset (until the 1980s) any declustering could only be applied to the recent data, which in turn would introduce a potential bias between non-declustered old and declustered recent data.

300 4 Results

We start the results by showing the estimated 20-year return levels of extreme daily and hourly precipitation as well as the dominant weather patterns for each season. We then turn to the trends in extreme intensities. We do not try and interpret the results for individual stations as these can be subject to sampling problems, and constrain ourselves to analysing the regional patterns and differences. It should also be noted that 20-year return levels are generally higher for longer aggregation periods (e.g. higher for seasonal than for monthly resolution). This is expected, as annual maxima $\geq$ seasonal maxima $\geq$ monthly maxima for any given year.



4.1 Climatology of extremes

4.1.1 Daily precipitation extremes

Figs. 5 and 6 show stationary 20-year return levels of daily extremes based on the 'recent' observations (EDF and Météo-
310 France, 25-42 years, earliest starting 1980). The return levels are lowest from February to August (<70 mm/d) and higher
between September and January (autumn and winter), with the highest values in autumn. Daily 20-year return levels in autumn
and winter are also generally higher in the Rhône valley and along the Mediterranean coast. The highest values (>200 mm/d) are
found in the *département* of Alpes-Maritimes, in an area known for heavy autumnal rainfall. The lowest values of all regions
and months (<25 mm/d) in July in the southernmost areas reflect very dry conditions with almost no rainfall in this region
315 during the summer months. The annual return levels very closely resemble those of the autumn season.

In Fig. 7 we show the relative influences of the different weather patterns for monthly and seasonal maxima, averaged over
all stations north and south of the climatological divide, respectively. Fig. 8 shows the same results on maps, where just the
most important (termed dominant) weather pattern is shown for each station. In general we find again the climatological divide
between northern and southern Alps (Auer et al., 2007; Blanchard, 1921): In the north Atlantic influence is dominant during
320 the whole year. In the south there are clear differences between the seasons, with Mediterranean dominance extending far
north in spring (April and May) and autumn (September and October), while in the other months Atlantic and Mediterranean
circulations have roughly equal influence on maxima in this region. Some anticyclonic influence appears as important in the
summer months (dominant only at some stations in the south), indicating the role of convective events like thunderstorms
during this season. The annual patterns again resemble a lot the autumn patterns, showing the dominance of this season for
325 annual precipitation maxima.

4.1.2 Hourly precipitation extremes

The stationary 20-year return levels of hourly precipitation are shown in Figs. 6 and 9. The 20-year return levels are lowest (<20
mm/h) in winter (December to March in monthly resolution) and just slightly higher in spring (April and May). In summer,
the 20-year return levels are higher across the entire territory and show a distinct gradient between higher intensities in the
330 pre-Alps and lower ones in the high inner Alps (centre-east of the study area). The highest 20-year return levels of all seasons
can be found in autumn (September) on the Mediterranean coast and in the Rhône Valley, where estimates reach 75 mm/h in
some areas. Annual hourly extremes are dominated by the autumn season in the Rhône valley and along the coast, and by the
summer season in the inner Alps.

Using the long time series for the stations managed by EDF results in more robust, but overall similar patterns (not shown).
335 It is important to note that almost no EDF stations is located in the Rhône valley or along the coast, so the areas with the highest
return values cannot be compared.

As the weather pattern classification by Garavaglia et al. (2010) used here is done at daily scale, it is less relevant at hourly
scale so we choose to not show the detailed maps here. Overall, the patterns resemble the daily patterns, with a somewhat
weaker influence of Mediterranean circulations in all months and a higher influence of Anticyclonic conditions in summer.

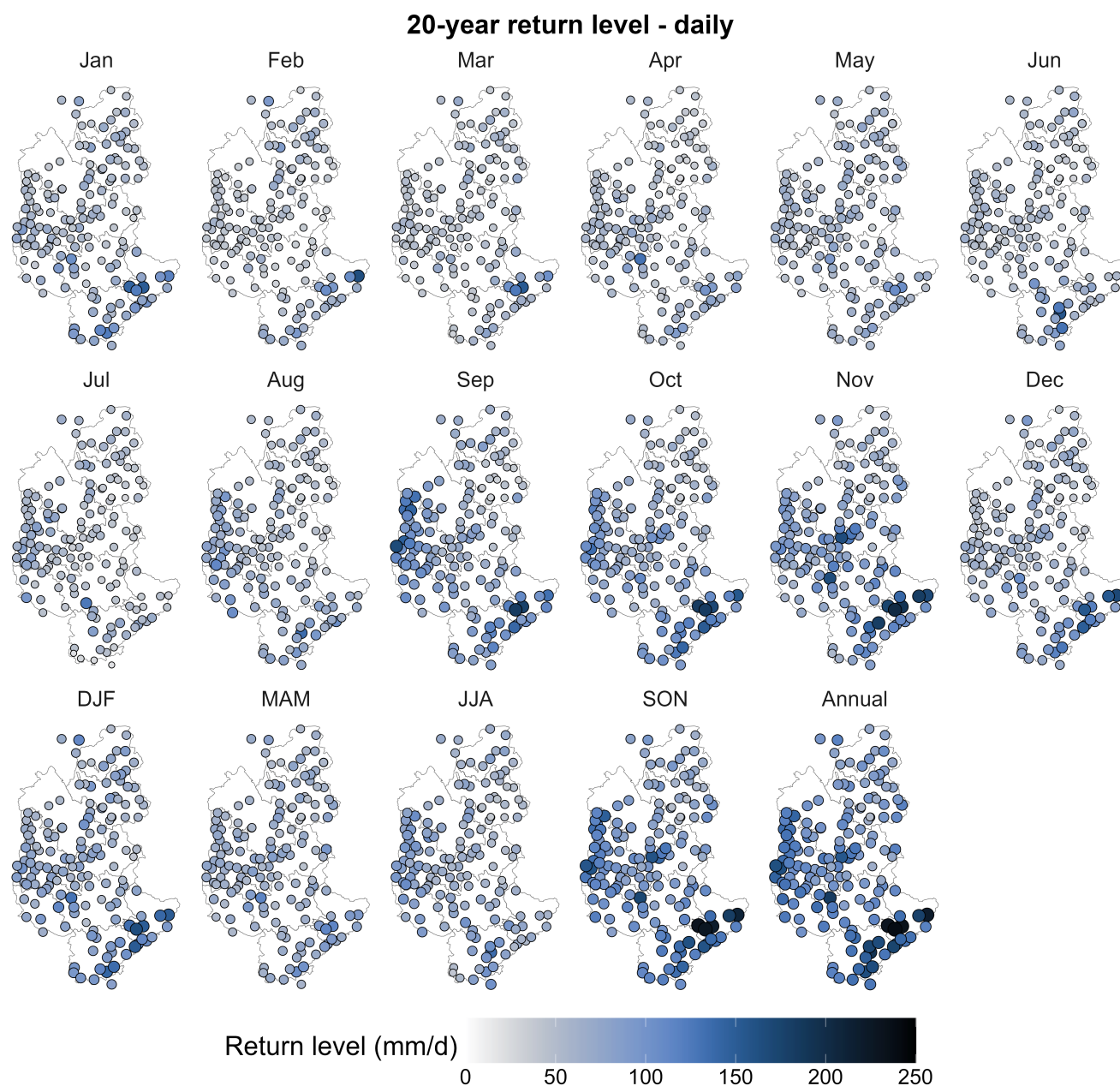


Figure 5. 20-year return levels of daily rainfall extremes for EDF and Météo-France stations for the 'recent' period (25-42 years, depending on the station). First and second row: monthly; third row: seasonal and annual

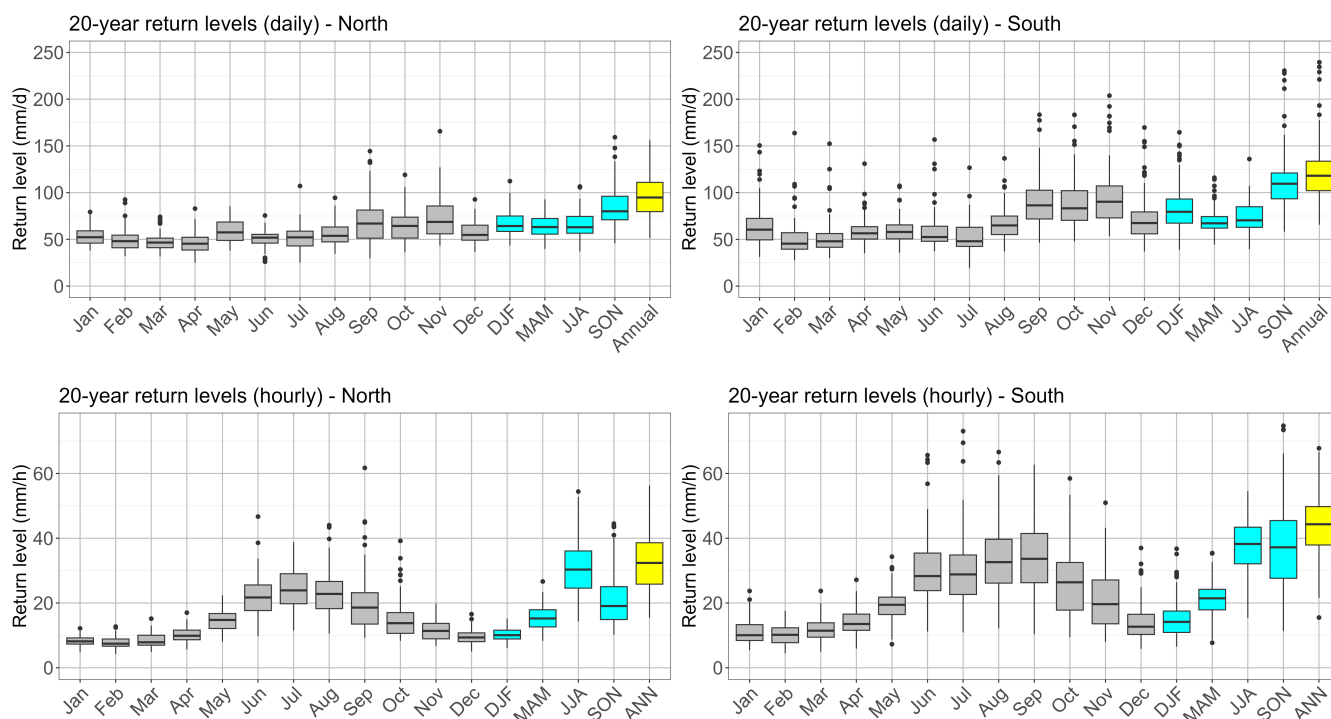


Figure 6. 20-year return levels of daily (first row) and hourly (second row) rainfall extremes for EDF and Météo-France stations for the 'recent' period (25-42 years, depending on the station), grouped into stations north (left column) and south (right column) of the climatological divide by Auer et al. (2007); Blanchard (1921).

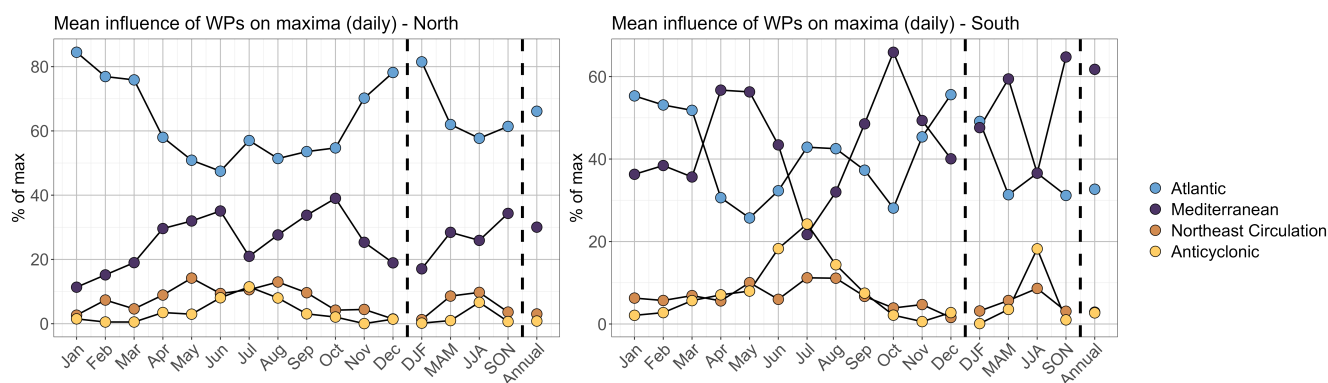


Figure 7. Relative influence of the four weather patterns on monthly/seasonal/annual maxima of daily precipitation intensity in the study region, grouped by stations north (left) and south (right) of the climatological divide by Auer et al. (2007); Blanchard (1921).

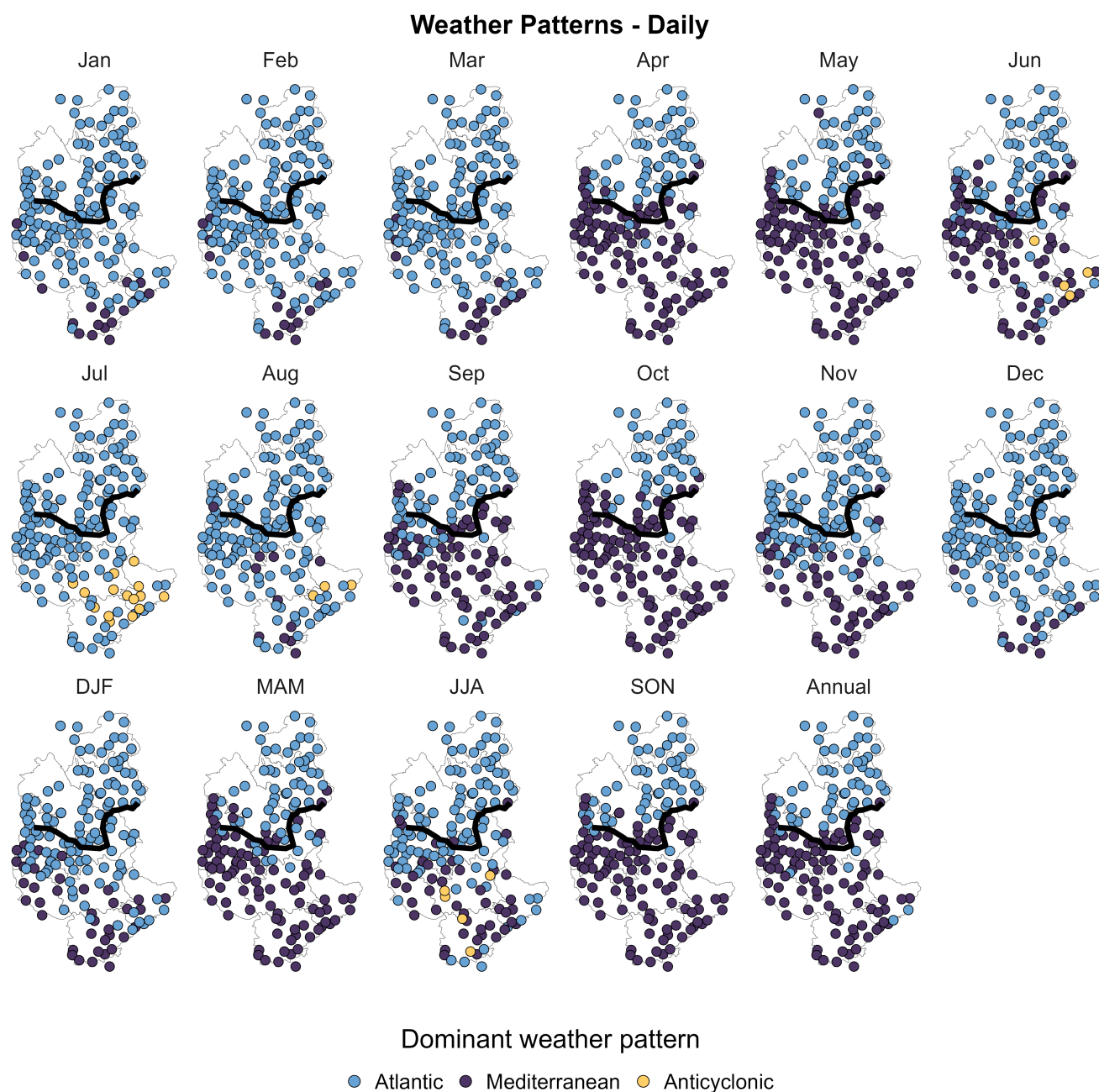


Figure 8. Dominant weather patterns generating monthly maxima at each station. Blue indicates Atlantic influence, light red Mediterranean influence, and yellow Anticyclonic conditions. Northeast circulation is not dominant at any station.

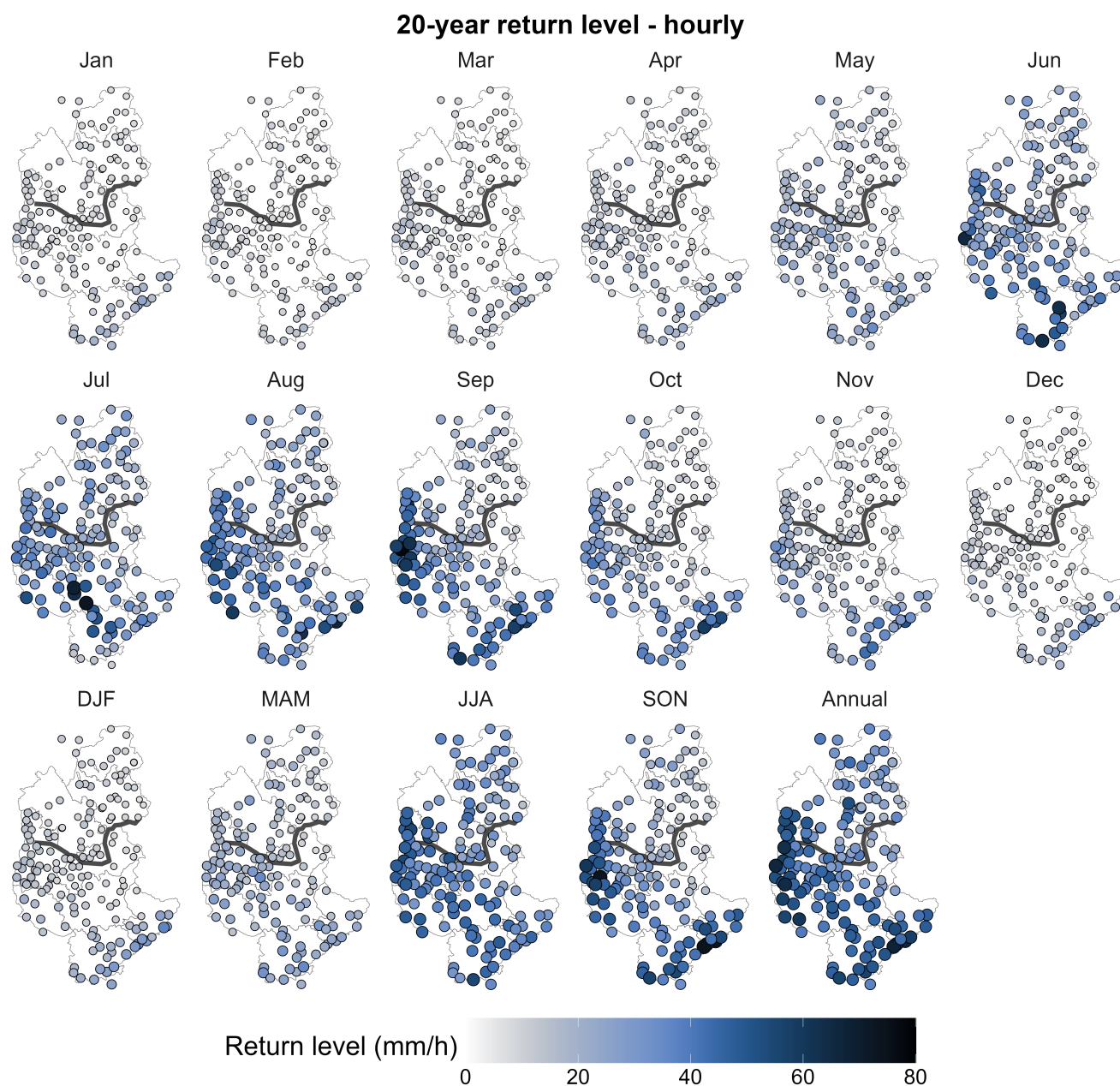


Figure 9. 20-year return levels of hourly rainfall extremes for EDF and Météo-France stations for the 'recent' period (25-42 years, depending on the station). First and second row: monthly; third row: seasonal and annual



340 4.2 Trends in extremes

We now turn to the trends in extremes (20 year return levels). Here we use the long time series (EDF stations >30 years) only which, as noted above, includes almost no stations in the Rhône valley or along the coast where stationary return levels are highest. Note that this entails that the trends shown in Fig. 11 are not for the exact same regions as the stationary return levels shown in Fig. 6. For easier interpretation we include the non-stationary 20-year return level estimates for the years 1990 and
345 2020 in the appendix, Figs. A1 and A2. We show the results in two different ways: (i) as boxplots of trends for each month and season, where stations are grouped by their location north or south of the climatological divide (Auer et al., 2007; Blanchard, 1921) and (ii) on maps, where trends are shown for each station individually. Note again that the trends for each station are computed using a neighbourhood approach (see section 3.2.2).

4.2.1 Trends in daily precipitation extremes

350 We find trends in daily extreme precipitation intensities mostly between -10 mm/d/10y and +10 mm/d/10y (Figs. 10 and 11). They show significant variability temporally (between months and seasons) but coherent patterns spatially. Notable features include positive trends in May followed by increasingly negative trends in July to September (Fig. 11, upper row). A jump to significant positive trends in October to December is present in the south, but not in the north of the domain (Fig. 11, u.r.). Looking at trends in seasonal maxima reveals large differences depending on how the months are grouped. Using the
355 traditional definition (DJF, MAM etc.) shows weakly negative trends in the north in DJF, positive trends in MAM, weak but mostly negative trends in JJA and a clear divide in SON between strong positive trends in the south and negative ones in the north. Using a different grouping of months (JFM, AMJ etc.) completely restructures the patterns with overall negative trends in JFM and JAS (higher in the south) and overall positive trends in AMJ and OND (up to 20mm/d/10y in some areas in the south in this season, Fig. 11, upper row). Finally, trends at annual scale show a transition from significant positive trends (up
360 to 24 mm/d/10y or +50% in 2020 relative to 1990) in the south to negative trends in the north (-8 mm/d/10y or -20% in 2020 relative to 1990), a pattern similar to the one found in autumn (both SON and OND, Fig. 11, upper row).

4.2.2 Trends in hourly precipitation extremes

Trends in hourly precipitation extremes (shown in Figs. 11 and 12) are highly variable both spatially and temporally (between months and seasons). In the north of the domain, trends are almost always centred around zero (September with comparatively
365 small negative trends being an exception), with the highest range of values in June and very small ranges during December to April (Fig. 11, l.l.). In the south, variability around the mean is higher for most months. Overall positive trends can be found in April to June and October to December, while they tend to be slightly negative in August and September. (Figs. 11, l.r. and 12). November stands out as the only month where a spatially coherent pattern appears showing significant positive trends in the south (up to +3,5mm/h/10y or +100% in 2020 relative to 1990, Fig. 12). Looking at seasons, trends in the north are also overall
370 centred around zero, with highest variability in summer (JJA in traditional seasons, AMJ and JAS in 'new' seasons, Fig. 11, l.l.). While the picture in the south looks similar overall, JJA/AMJ stand out with overall positive trends and highest variability

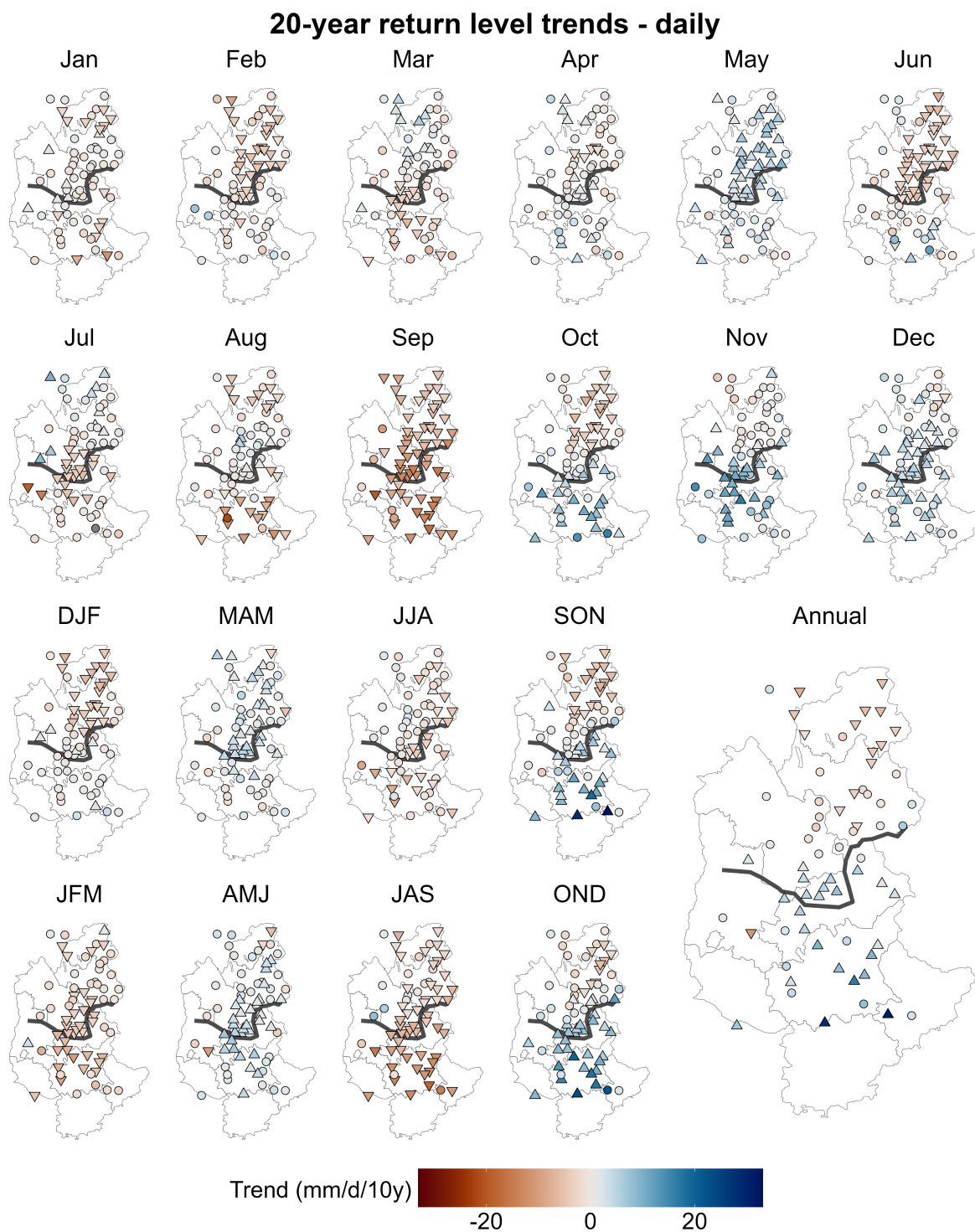


Figure 10. Trends of 20-year return levels of daily precipitation intensity using the nonstationary framework with a neighbourhood approach. Triangles indicate significant, round points non-significant trends.

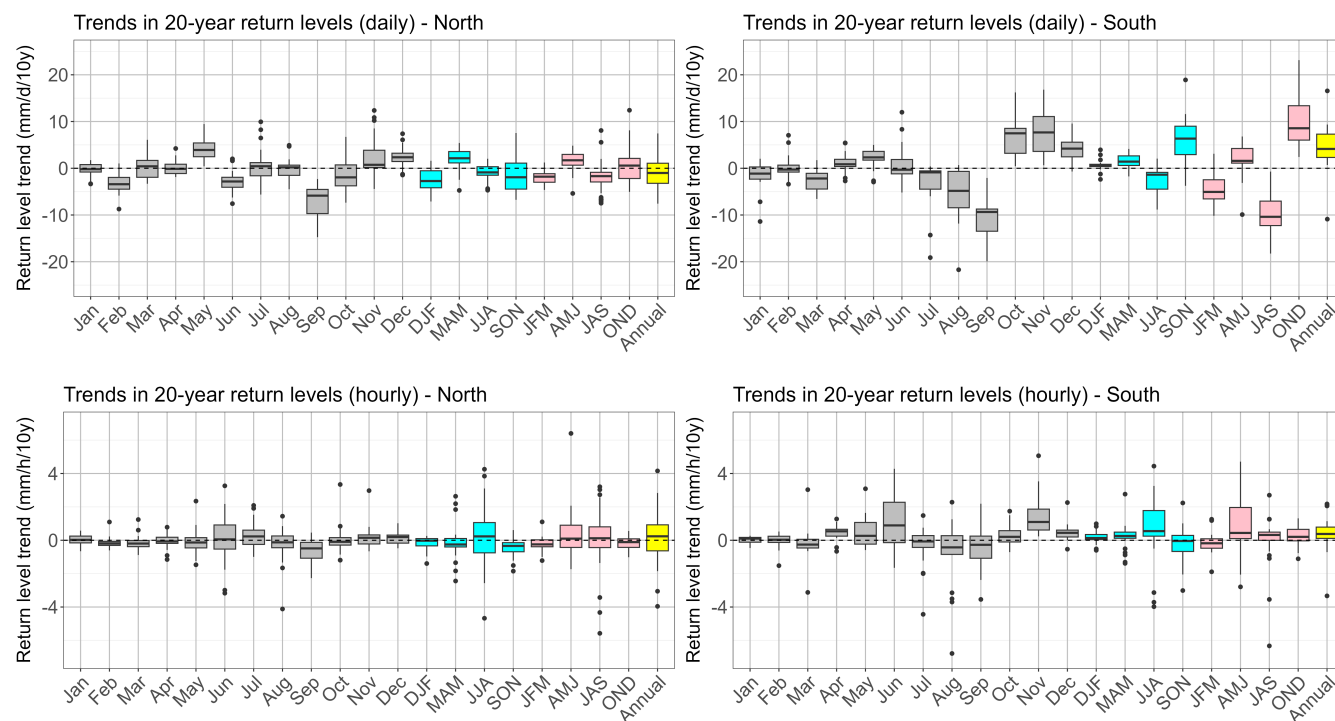


Figure 11. Trends of 20-year return levels of daily precipitation intensity using the nonstationary framework with a neighbourhood approach for daily (first row) and hourly (second row) rainfall extremes using all available timeseries of EDF stations (including 'old' data) covering at least 30 years. The results are grouped into stations north (left column) and south (right column) of the climatological divide by Auer et al. (2007); Blanchard (1921)

(Fig. 11, l.r.). Annually, trends are centred around zero with comparatively large variability in the north and overall slightly positive in the south. While we here decided to only look at the climatic north-south division of the study area, it should be noted that looking at JJA and annual extremes in Fig. 12 there seems to be an east-west pattern, with positive trends in the east (high Alps) and negative ones in the west (lower Alps),

Despite the lack of clear patterns in the trends of hourly extremes there are some systematic differences to the trends in daily extremes: in summer, trends in daily extremes are overall negative, while they are mostly positive for hourly extremes. In contrast, the clear north-south pattern in trends found for daily extremes in autumn is completely absent in the hourly data, where weakly non-significant and weakly negative trends prevail over the whole region.

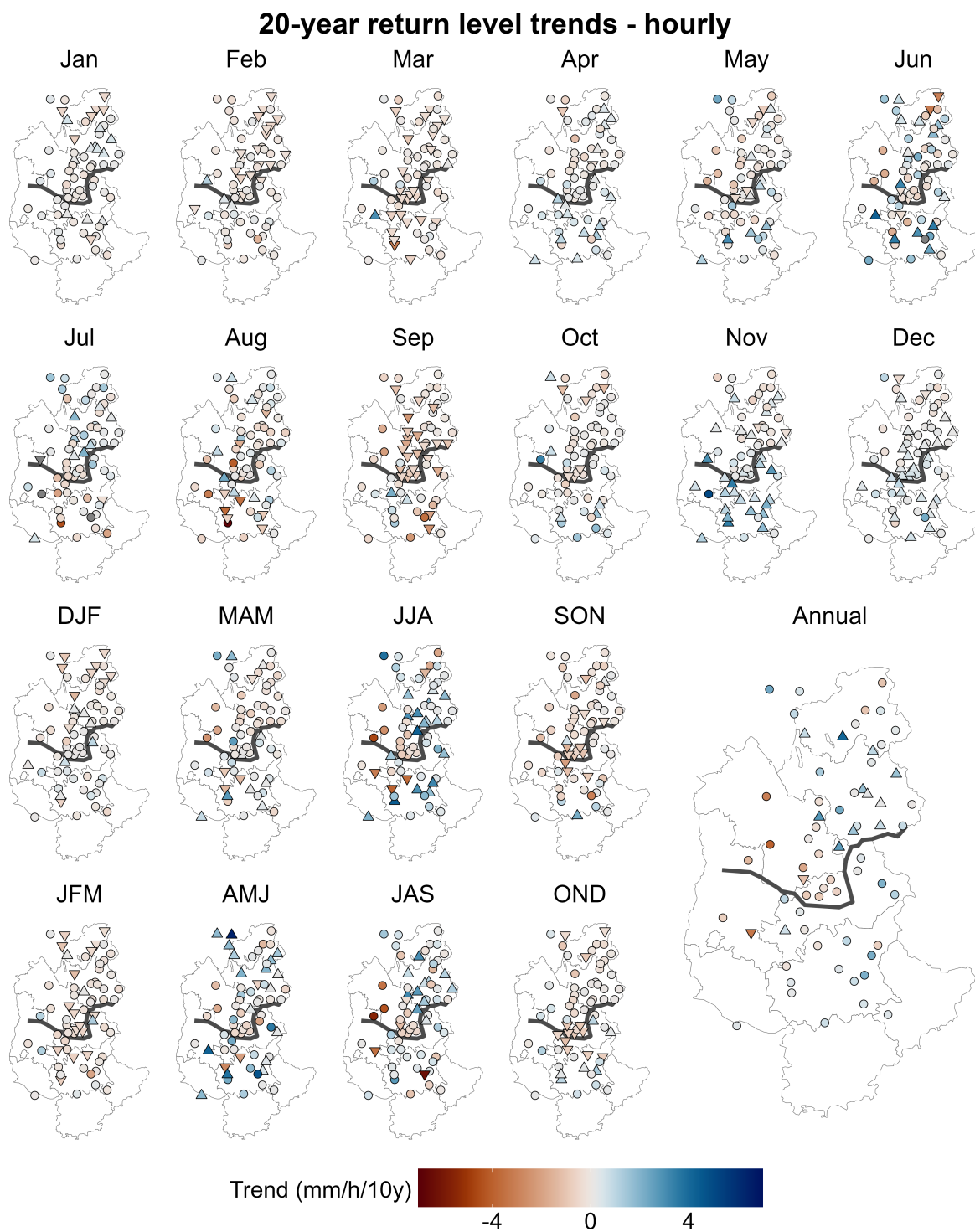


Figure 12. Trends of 20-year return levels of hourly precipitation intensity using the nonstationary framework with a neighbourhood approach. Triangles indicate significant trends.



380 5 Discussion

5.1 Methodological limitations

In this study we applied extreme value theory on time series data spanning at least 25 years of observations. While this method is widely used in the study of extremes, it also has its limitations. The return level estimates heavily depend on the quality, length, and variability of the time series. In some cases the presence (or absence) of single events can significantly influence return level estimates. For example, in Figs. 5 and 9, some individual points stand out from their surroundings, which is probably due to a sampling bias and not due to a strongly different climate of this station to its surroundings. However, as mentioned earlier, the general patterns are largely consistent, seem plausible and confirm previous studies (e.g. Djerboua, 2001), which gives us confidence in the methodology. To a certain extent, more robust return level estimations can be obtained by using a neighbourhood or region-of-influence approach, reducing the sampling bias by using more data, as we do here for the non-stationary trend estimations.

The concept of return level is based on the frequency of exceedance above a given level. However the frequency may change in the context of global warming and assuming it constant may lead to an over- or underestimation of risk. It is therefore necessary to apply a non-stationary framework to take trends into account. However, non-stationarity requires more parameters to be estimated, which adds additional uncertainties: (i) We assume that the parameter distribution changes linearly with time. In many regards this is a simplification, as there is no direct physical dependence of precipitation parameters on time. Indeed, in light of previous studies analysing the temperature–precipitation relationship (e.g. Da Silva and Haerter, 2025), temperature might seem like an obvious choice. However, which temperature to choose (e.g. local temperature at the time of the event, dew point temperature at a given pressure level, annual region-mean temperature) is a debate of its own (see also Schröder and Kirchengast, 2018; Dash and Maity, 2023), which is why we chose to keep time as the simplest covariate. (ii) From a statistical perspective, introducing time as a covariate means additional parameters to estimate, which in turn results in higher uncertainty in the estimates if the same amount of data is used. Here, we use a neighbourhood approach to overcome this problem: we combine the observed maxima at each individual station with the scaled maxima of its surroundings, thus significantly increasing the number of data points available for return level estimation. However, this approach comes with another strong assumption: We assume that the neighbourhood of each station is statistically homogeneous, which is not necessarily the case. Other studies (e.g. Carreau et al., 2013; Evin et al., 2016) have used an iterative procedure combined with a homogeneity test to find the best radius for each station. However, in our experience this is difficult to implement and not robust, which is why we decided against using this method in our study. With the radius of 0.3° we are using here we find trends that appear spatially coherent. We also tried different radii of 0.2° and 0.4° and found that the general picture remains quite similar. Thus, as long as we are mainly interested in the broader picture instead of particular values, the choice of the radius actually seems secondary to us.

However, even though the neighbourhood approach helps getting robust and spatially coherent results for daily extremes (e.g. Fig. 10), our results for hourly extremes appear much noisier (Fig. 12). This is probably due to the combination of yet relatively short timeseries of a few decades, the high interannual variability, and the very localised character of extreme short-



duration precipitation events (see also Barbero et al., 2017). Given that EDF's station network is already comparatively dense
415 with quite long observations we here arrive at the limits of studying precipitation extremes based on surface observations.
However, future studies with longer timeseries (and the additional observations from Météo-France's network starting in the
1990s starting to become long enough to be included) have the potential to result in more robust and spatially coherent trend
estimations.

Finally, estimating a single distribution over a time series assumes that all data come from the same distribution. This is
420 challenging in the real world because, for example, extreme precipitation maxima can be generated by very different meteorological
mechanisms, such as stratiform or convective precipitation (see also Da Silva and Haerter, 2025, for the consequences
of this). By using a monthly analysis, we can overcome this problem to some extent, as precipitation extremes are likely to be
caused by a dominant weather type in individual months. Another possibility would be to perform subsampling by season and
weather types as has been done for example by Garavaglia et al. (2010); Blanchet et al. (2015), but here the drawback would
425 again be the size of the obtained subsamples.

5.2 Climatology of extreme precipitation

We now turn to a discussion of the climatology of stationary return levels. Daily precipitation intensities (Fig. 5) remain quite
constant over the whole year in the north (most notably in Savoie and Haute-Savoie), which is also in line with the large
dominance of Atlantic influence on precipitation maxima in this region (Blanchet et al., 2021b, a, see also Fig. 8 in our study).
430 In the south and along the Rhône valley the months from September to December stand out with much higher 20-year return
levels than the the rest of the year, which is characteristic of the precipitation seasonality in the Mediterranean area. Here, very
dry summers are followed by rainy autumn and winter seasons, an effect enhanced by orographic uplifting of moist air masses
originating from the Mediterranean Sea along the southern and southwestern slopes of the Alps. 20-year return levels of hourly
precipitation intensities (Figs. 9, 6) follow a clear annual cycle with low values during winter and high values during summer.
435 This can be explained by the higher amount of humidity and convective available energy during the warm season, which can
trigger intense but localised convective events like thunderstorms. Comparing south to north, the peak of this cycle is higher
and occurs later in the year in the south (6). Two aspects of the geographical distributions are also worth highlighting here:
First, the very low return levels found at some stations along the coast in July, again showing the arid conditions typical for
the Mediterranean region. Second, the spatial distribution of hourly extremes, showing higher return levels along the southern
440 and western slopes and pre-Alps compared to the inner Alps, a pattern consistent with the findings of Fukutome et al. (2015);
Panziera et al. (2018) for Switzerland.

5.3 Trends in extremes

In the following section we discuss the trends found for hourly and daily 20-year return levels in the French Alps. A special
emphasis is put on the differences between trends for hourly and daily extremes, which we consider at least as informative as
445 the actual trends themselves.



First, we find clear differences between the north and the south of the region also for the trends (Fig. 11), which is in line with previous studies (Blanchet et al., 2021a, b). Overall, the southern part of the study region experiences much stronger trends, both positive and negative, for both hourly and daily extremes. In the south, daily trends tend to be negative when the Mediterranean influence is weak (January to March, July to September) and positive where it is stronger. This is a strong indication of the importance of large scale circulation patterns not only in generating extremes, but also in explaining trends in their intensity.

Especially the autumn period (October to December) deserves attention, as in this period both strong positive trends in daily extremes, a strong influence of Mediterranean circulation patterns (our study) and also a strengthening of this influence (Blanchet et al., 2021b) are observed. We thus partly attribute the positive trends to an increase in Mediterranean sea surface temperature in summer and autumn (Pastor et al., 2020), causing higher humidity in the atmosphere which is then advected to the southern French Alps by southerly/south-westerly fluxes.

While hourly extremes also show positive trends during the same months as daily extremes (Fig. 11), the clear negative trends in summer shown for daily extremes are much weaker or absent in the hourly values, which are much more variable (and for which the mean trend over all stations in the south is never much lower than zero). Indeed, between June and September, there is a very clear difference between hourly trends, which are overall small and spatially variable but also include comparatively high positive trends locally, and daily trends, which are overall negative. To a lesser extent (in June and September) this is also true in the north, showing that during this time of the year hourly and daily extremes are not experiencing the same trends.

These observed differences, together with the analysis of dominant influences shown in section 4.1 give us some ideas on the reasons of the trends. The strong negative trends of daily precipitation in summer in the south are likely to be a direct consequence of a drying in this region (e.g. Menegoz et al., 2020), which is already characterised by low precipitation totals (Joly et al., 2010). However, trends of hourly extremes in the same season show both negative and positive trends, with significant positive trends especially in the eastern part of the region, where the mountains are highest. This is clearly different to the daily trends, but also not totally in line with an increase with increasing temperature as expected by the Clausius-Clapeyron relationship. Thus, these trends might be the result of a tug-of-war between less moisture available for local recycling due to increasing aridity (Tramblay et al., 2020) and increasing energy availability due to increasing temperature (Beaumont et al., 2021), which is showing the complex interplay between dynamic and thermodynamic effects. We could then further hypothesize that the drying effect might dominate in the pre-Alps (negative trends in the western part of the region), while the increase of available energy might dominate in the interior of the Alps leading to positive trends in the eastern part (Fig. 12). This would also match the findings of e.g. Giorgi et al. (2016) showing increased convective rainfall in summer in the high massifs of the European Alps due to strong albedo feedback loops between snow cover change and temperature leading to increases in energy available for convection. In this regard, it would be interesting to also study trends on subhourly timescales. However, stations maintained by EDF unfortunately do not register at such small timesteps, and continuous observations by Météo-France are yet too short for a robust analysis of trends. At this point it should be noted that a comparatively dense network of observations by Météo-France exists in the Drôme region (*département* no. 26, Fig. 1) with continuous observations at subhourly (six minutes) resolution starting in 2005. We decided to not include this dataset here due to the short period and



the limited area covered. Another potential source of information with high spatial resolution could be radar observations. However, they also cover just a limited period of time and come with different limitations, such as masking in mountainous regions.

The month of September where a strong decrease in daily extremes is observed over the whole study region deserves special
485 attention: most likely, this result can be attributed to a shift in seasonality with a later onset of the rainier autumn season. This means that September would be shifting from being an autumn month (which is still visible in the stationary return level estimations) to being a summer month (see also Fig. A1), an observation shared by stakeholders in the region (pers. comm. from stakeholders at RTM, EDF, Météo-France). A later timing of autumnal period of high rainfall intensities might also explain the significant increase in intensity of both daily and hourly precipitation extremes in November which is small in absolute
490 numbers (+8–16mm/d/10y for daily extremes or +1–4mm/h/10y for hourly extremes, Fig. 11) but large in relative terms with increases up to +60% (daily) and +100% (hourly) between 1990 and 2020. This 'new' timing of seasons poses significant challenges for defining seasons for trend assessment, as we show for example in Fig. 11. A potential way to solve this problem might be to define the seasons dynamically, for example by using threshold values for precipitation characteristics for each season. However, this was out of the scope of our study.

495 6 Conclusion

In this study, we aimed to provide an updated climatology and an assessment of trends of daily and hourly extreme precipitation in the French Alps by applying a statistical approach based on generalised extreme value theory (Coles, 2001; Fisher and Tippet, 1928) on long time series of surface observations. Regarding the spatial and temporal of extremes, we find weak seasonality for daily 20-year return levels in the north of the study area, and a strong annual cycle for hourly extremes,
500 especially in the south. Daily extremes are highest in autumn, and hourly extremes highest in summer (and autumn in the south). While the general spatial and seasonal patterns confirm previous studies, our main contribution here lies in updating previous estimates of hourly extremes based on surface observations. To our knowledge, the last such study is by Djerboua (2001). Other methods of return level estimation exist and are applied operationally in the study region (e.g SHYREG: Arnaud et al., 2016), but they are based on gridded datasets and/or stochastic rainfall generators, which are more indirect methods than
505 the one we apply here and come with very different strengths and limitations. Regarding recent trends in extremes, we find a mixed picture of both positive and negative trends in different areas and seasons. The strongest positive trends in daily 20-year return levels tend to occur in the shoulder seasons in the south, when the Mediterranean influence on precipitation maxima is highest. Strong negative trends are observed in summer in the south, a phenomenon probably linked to the general drying of this area in summer. Trends of hourly extremes are overall small, with the most notable exception being the month of June
510 where we find locally high positive trends. In summer, hourly trends are almost systematically higher than the daily trends, which leads us to state that a decoupling is taking place between processes generating extremes on the different timescales. While a general drying of the region takes place in summer, higher potential energy as a result of a temperature increase may lead to an increase in occurrence and/or intensity of short-duration convective precipitation events. This can especially be seen



in early summer (June), when there is still enough moisture available for local recycling in convective processes. In this regard
515 it would be interesting to also study subhourly extremes. Unfortunately, the available timeseries of observations at this high
resolution (surface and radar observations) are not yet long enough to obtain robust results. Overall, the increases we find are
strongest for daily extremes in autumn (October to December) and in June and November for hourly extremes. On the other
side, September is the month experiencing strongest negative trends of extremes (although less for hourly extremes), which we
attribute to an increase of aridity in summer and a later onset of the rainy autumn season as compared to the past.

520 *Data availability.* The precipitation observations by Météo-France are publicly available at [https://meteo.data.gouv.fr/datasets?category=climatologique-](https://meteo.data.gouv.fr/datasets?category=climatologique-base)
base. The observations by Électricité de France and the weather pattern classification have been provided by Électricité de France for the
purpose of this study. While not public, these datasets could be made available to other researchers under a specific research agreement.
Requests should be sent to hydro-dtg-demande-donnees@edf.fr.



Appendix A: Non-stationary 20-year return levels in 1990 and 2022



Figure A1. 20-year return level of daily precipitation intensity in years 1990 (top) and 2020 (bottom) in the non-stationary framework (same data subset and method as in Fig. 10). Note that the colourbar is different from 5.

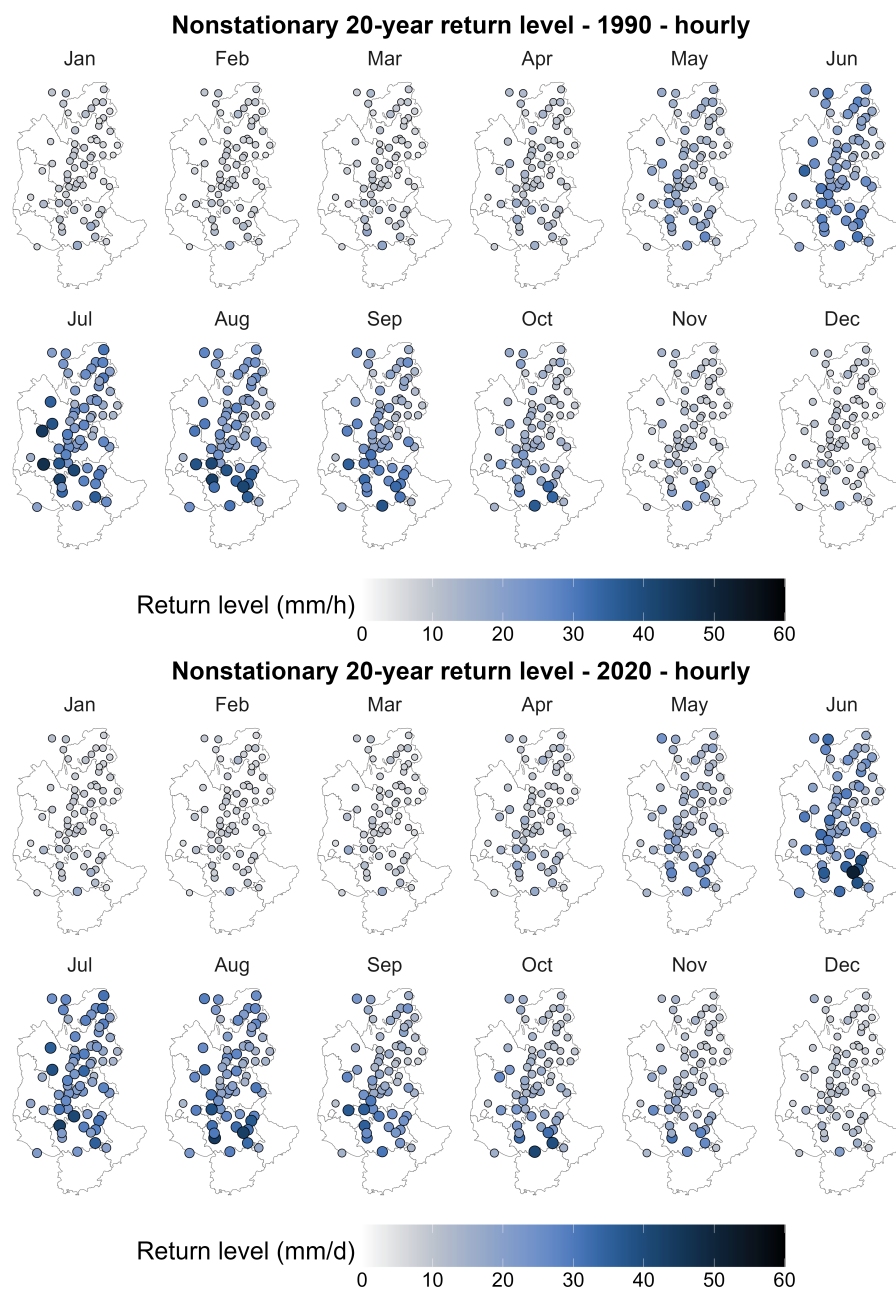


Figure A2. 20-year return level of hourly precipitation intensity in years 1990 (top) and 2020 (bottom) in the non-stationary framework (same data subset and method as in Fig. 12). Note that the colourbar is different from 9.



525 *Author contributions.* **SB:** Conceptualization, Methodology, Validation, Formal Analysis, Visualization, Writing - Original Draft, Writing
- Review & Editing. **JB:** Conceptualization, Methodology, Validation, Formal Analysis, Writing - Review & Editing, Supervision. **AB:**
Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision. **DP:** Data Curation, Resources, Methodology, Writing
- Review & Editing

Competing interests. The authors declare that they have no competing interests. It is noted that some authors are affiliated with organisations
530 that have financial and/or legal stakes in flood risk prevention within the study area. However, all authors declare that this did not influence
the outcomes of this paper.

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