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Retreating winter and strengthening autumn Mediterranean influence on extreme precipitation in the Southwestern Alps over the last 60 years

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E-mail: juliette.blanchet@univ-grenoble-alpes.fr**Keywords:** extreme precipitation, atmospheric influence, weather pattern, trend, Alps**Abstract**

This article analyzes the large-scale circulations producing daily precipitation extremes in the Southwestern Alps and their trends from 1958 to 2017. We consider a high-resolution precipitation data set of $1 \times 1 \text{ km}^2$ and the weather patterns associated to the precipitation seasonal maxima at each grid point. The high-resolution allows us to analyze in details the atmospheric influences triggering seasonal maxima. Four influences are considered—the Atlantic influence, the Mediterranean influence, the northeast circulation and the Anticyclonic situation. We show that influences on maxima are very well organized in space but their organization depends on the season. Maxima are very mainly triggered by two types of influences in the region—the Atlantic influence and the Mediterranean influence. Trends in weather patterns producing maxima are also organized in space, with opposite trends for the Atlantic and the Mediterranean influences. The Mediterranean influence retreated very significantly over the period in winter and spring, while the Atlantic influence significantly extended further south. In autumn the Mediterranean influence strengthened where it was already dominant.

1. Introduction

Many Alpine valleys are prone to extreme rainfall and resulting floods. Flooding hazard depends on rainfall accumulations at small to large scales (from urban runoff and torrents to river watersheds). Climate change has led to concerns about their recent trend and their future evolution.

Precipitation over and near mountains is related to both synoptic conditions, cloud microphysics and mountain geometry (see Roe and Baker 2006, for idealized simulations). Local topography channels and up-lifts airflow, which deeply affects precipitation formation, leading to a variety of orographic mechanisms that explain the precipitation patterns in response to mountain geometry (see for instance the 12 typical mechanisms of Houze 2012). Topography also locally modifies the vertical temperature gradient and the dispersion of anthropogenic aerosols, inducing complex modifications of cloud formation and influencing precipitation patterns (Zeng *et al* 2015).

In mountainous areas, large-scale circulation triggers orographic rainfall over a range of scales in

space and time. Linking atmospheric dynamics to rainfall statistics, a body of studies show how Alpine precipitation patterns and intensity depend on the track of Atlantic and Mediterranean cyclones. This link is essentially investigated through a bottom-up approach defining ad-hoc classes of circulation based on a precipitation pattern classification (see Garavaglia *et al* 2010, Boé and Terray 2008, for example). Other bottom-up approaches define classes of large-scale circulation for the dates of extreme precipitation events (Giannakaki and Martius 2016, Stucki *et al* 2012, Plaut *et al* 2001). The top-down approach, defining circulation patterns and looking to corresponding local meteorological parameters is used for temperature, pressure and cloudiness in the Alps in Stefanicki *et al* (1998) or for temperature in Plaut and Simonnet (2001).

In the Swiss Alpine region, the influence of large-scale flow on seasonal precipitation variability is strong in winter, moderate in spring and autumn, very low in summer. The Euro-Atlantic blocking, i.e. a breaking Rossby wave over central Europe, is by far the prevailing large-scale situation

explaining inter-annual variance of seasonal accumulation except in summer (figure 8 of Scherrer *et al* 2016). The daily rainfall patterns affecting southern France can be classified into 7 classes to cover a range of generating circulation modes on the Alps, the Massif Central and the Pyrenees (Garavaglia *et al* 2010). These circulation modes are basically westerly oceanic circulations (3 patterns), Mediterranean circulations (3 patterns), continental circulation (1 pattern). A eighth class regroups anticyclonic situations. Figure 3 of Garavaglia *et al* (2010) shows that precipitations in the western Alps are governed by two broad classes of circulation, one mostly zonal corresponds to the oceanic influence, the other one, mostly meridional corresponds to the Mediterranean influence. This view is confirmed by the seasonal Lagrangian diagnostic of the moisture transport from oceanic basins and lands to the Alps. The analysis of air parcel back-trajectories shows that, except in summer, the moisture source of northwestern Alpine precipitation is predominantly situated over the North Atlantic Ocean while the southeastern precipitations originate largely from the Mediterranean Sea (figure 9 in Sodemann and Zubler 2010). With high recycling ratios linked to local convection, the summer source of Alpine precipitation is mostly continental and quite uncertain - a large fraction of moisture enters the air parcels above the boundary layer.

Extreme precipitation events in the southern slopes of the French and Italian Alps are mainly triggered by large-scale circulations associated with Mediterranean circulations (Plaut *et al* 2001, Grazzini 2007). Over southern France, the contribution of Mediterranean anomalies in extreme daily precipitation is largely dominant (over 80%) (Tramblay *et al* 2013). Heavy precipitation events in the northern French Alps are mainly triggered by pressure anomalies associated with oceanic circulations especially for autumn and winter extreme precipitation (Plaut *et al* 2001). Extreme daily precipitation events over northern Switzerland depend on mostly the same types of large-scale atmospheric circulation with a large dominance of zonal flows with a more or less pronounced ridge over the East Atlantic and a trough over Great Britain (over 60% of the extremes), followed by meridional circulation with a breaking Rossby wave over the close Atlantic or central Europe (over 30%) and a minimal contribution of Mediterranean anomalies (Giannakaki and Martius 2016). If we consider the major historical floods of the Rhine river at Basel and in the lakes Constance, Maggiore and Zurich in Switzerland since 1868, the prevailing circulation patterns are dominantly Mediterranean situations with active cyclones centered over Italy or France (over 80%) and zonal flow plays a minimal role (Stucki *et al* 2012). The moisture back-trajectory analysis of Sodemann and Zubler (2010) points the Mediterranean Sea as a more unsteady source of precipitation for the Alps than the North

Atlantic, which suggests a major contribution of the Mediterranean Sea to precipitation extremes. At finer temporal and spatial scales, a variety of atmospheric influences impacts the different Alpine sub-regions in relation with their location and configuration in the mountain range. Giannakaki and Martius (2016) find different atmospheric influences on extreme precipitation events in northwestern versus northeastern Switzerland. Horton *et al* (2012) consider two locations located about one hundred kilometers apart on either side of the Swiss Valais. Their relevance maps show the forecasting skill of moving windows of analogy, which broadly informs on the major atmospheric influence at a given location. The maps evidence different atmospheric influences on daily precipitation variability at the two locations. Radanovics *et al* (2013) apply a similar method to about 600 climatological zones covering France. Their relevance maps evidence the large diversity of the major influence on daily precipitation depending on the location. However, to the best of our knowledge, the detailed regionalization of the various atmospheric influences—the major as the minor ones—on Alpine precipitation has been very little studied in the literature, and even less for the extremes.

This study takes benefit of a high-resolution precipitation data set to analyze the detailed regionalization of the forcing conditions producing extreme precipitation in the Southwestern Alps and their recent trends - an original way to explore the link between extreme statistics and weather patterns. We show that the contribution of the different conditions evolved in time over the last 6 decades. We also show that this evolution is not random but organized in space. In particular, we evidence that the southern flux strengthened its influence in autumn over the southern and eastern flanks of the range, while in winter the western flux dominated further southward.

2. Data and method

We use the SPAZM precipitation data set, a $1 \times 1 \text{ km}^2$ gridded interpolation of daily rainfall accumulations measured by more than 1 800 daily rain gauges over the Pyrenees, the Massif Central and the Southwestern Alps in France, Switzerland and Italy (see figure 4. of Gottardi *et al* 2012) SPAZM belongs to a large family of numerical rainfall interpolation schemes using digital elevation models to introduce statistically the influence of orography (for a review, see the introduction of Hiebl and Frei 2017, for Europe around the Alps). SPAZM shares with most of these methods the decomposition of the rainfall field into a guess (or background) field incorporating orography and residuals to this field. SPAZM originality is twofold: first the choice of guessing the field from the weather pattern mean precipitation—using the weather pattern classification of Garavaglia *et al* (2010)-, second

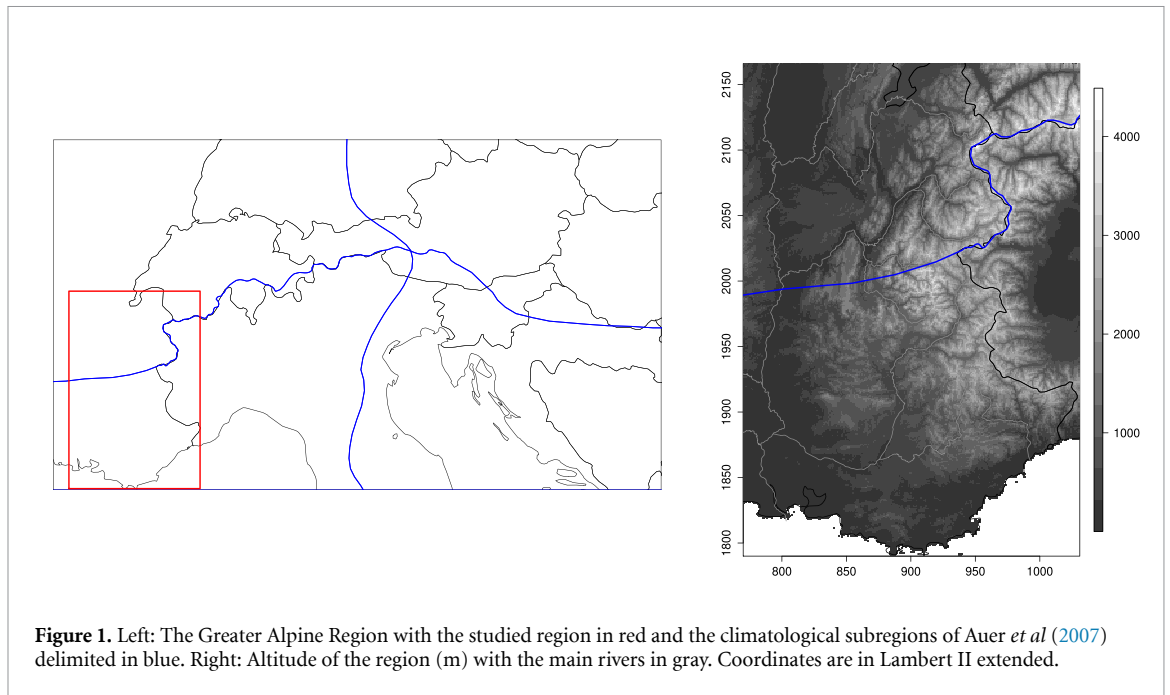


Table 1. % of WPs for the period 1958-2017. First row: daily occurrence. Second row: regional mean occurrence of the WPs producing the maxima. The percentages are rounded. Values in bold indicate when the largest value exceeds the second-largest value by at least 10%.

WP	spring				summer				autumn				winter			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Daily %	34	30	10	26	34	19	9	39	36	30	7	28	45	24	8	23
Mean % for the maxima	40	51	7	2	43	38	9	10	40	53	5	2	55	42	2	1

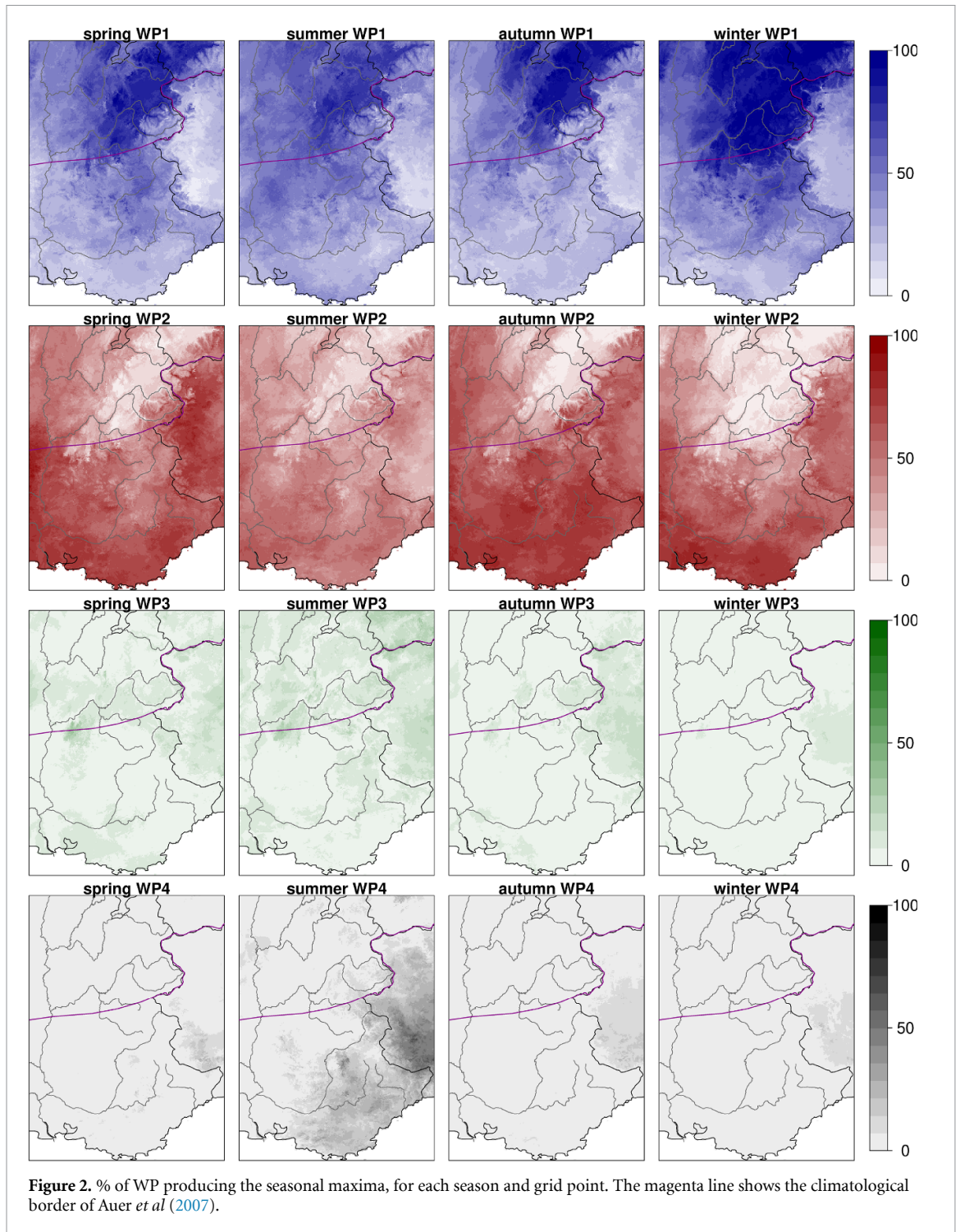
the use of the “crossing distance” that incorporates topographic features into the interpolation scheme.

Our study area is the Southwestern Alps, i.e. the mostly north-south oriented part of the chain mainly shared by France and Italy (see figure 1). The region crosses the Northwestern and the Southwestern Greater Alpine Regions of Auer *et al* (2007). The region sizes 98 000 km². Its altitude ranges from 0 on the Mediterranean coast to above 4800 m top of the Mont Blanc. Data are available at daily time scale on a 1 × 1 km² grid from January 1st, 1958 to December 31, 2017. The seasonal maxima are extracted at each grid point for March-April-May (referred as spring), June-July-August (summer), September-October-November (autumn), December-January-February (winter).

The forcing conditions are represented by the daily weather pattern classification of Garavaglia *et al* (2010). They were constructed with a bottom-up approach, starting from a classification in 7 clusters of normalized precipitation fields and 1 cluster of dry days over the French mountainous area (Pyrenees, Massif Central and French Alps), then computing the centers of gravity of the eight classes in the space of geopotential heights at 700 and 1000 hPa, and finally associating each day to its closest centroid. For the sake of conciseness, we aggregate the weather patterns according to the origin of the airflow reaching the region, by regrouping

the weather patterns corresponding to the Atlantic influence (Atlantic Wave, Steady Oceanic, Southwest Circulation) and the weather patterns corresponding to the Mediterranean influence (South Circulation, East Return, Central Depression). The two remaining weather patterns (Northeast Circulation, Anticyclonic) are unchanged. In total, our new classification contains 4 classes that we refer as weather patterns (WP): WP1 corresponds to the Atlantic influence, WP2 to the Mediterranean influence, WP3 to Northeast Circulation and WP4 to Anticyclonic conditions.

In order to study the detailed regionalization of the forcing conditions producing daily precipitation extremes, we extract at each grid point the WPs of the days when its seasonal maxima occurred. This gives a series of 60 WPs for each grid point and each season. Trend in the occurrence of a given WP producing the maxima is estimated through a logistic regression with the year as covariate, via maximum-likelihood estimation (e.g. Fox 1997, chapter 15). This estimation is made for each grid point, each season and each WP, independently. The significance of the trend in WP occurrence is assessed by the Wald test (Fox 1997, chapter 15). Note that the present study has also been applied to 220 daily rain gauges maintained by Météo-France over the French Alps. It showed very similar results, however this is not a genuine validation since SPAZM was constructed using almost all the available information over the



French Alps, including most, if not all, of these stations (see figure 4 of Gottardi *et al* 2012). This makes the validation of SPAZM with an independent dataset almost impossible. For the sake of conciseness and readability of the maps, results on the stations data are not reported here.

3. Results

At regional scale, the mean occurrence of WPs producing extremes is quite decorrelated to the daily occurrence of WPs, as shown in table 1. At daily

scale, the Atlantic influence (WP1) is the most frequent, apart in summer when Anticyclonic conditions (WP4) dominate. The second most frequent influence is the Mediterranean influence (WP2) apart in summer. Northeast circulations (WP3) occur less than 10% of the days. For the maxima, on average over the region, the Atlantic influence is the most frequent only in winter, while in spring and autumn the meridional flows produce most of the maxima. In summer both are almost as likely. Obviously Anticyclonic conditions produce very few extremes apart in summer during which

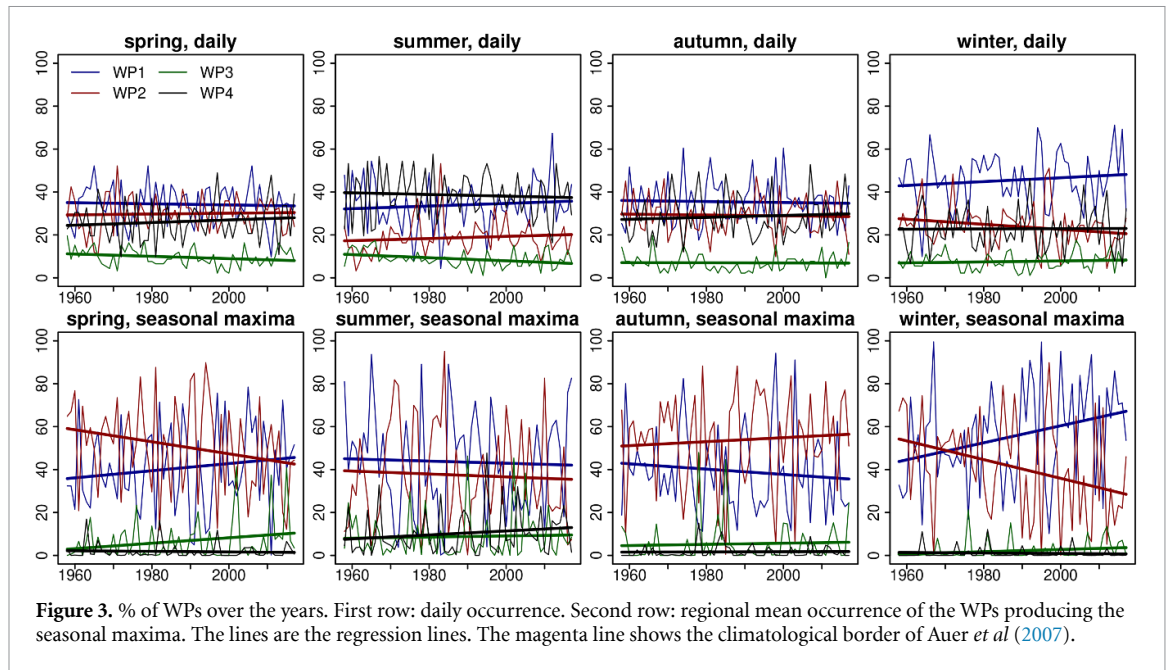


Figure 3. % of WPs over the years. First row: daily occurrence. Second row: regional mean occurrence of the WPs producing the seasonal maxima. The lines are the regression lines. The magenta line shows the climatological border of Auer *et al* (2007).

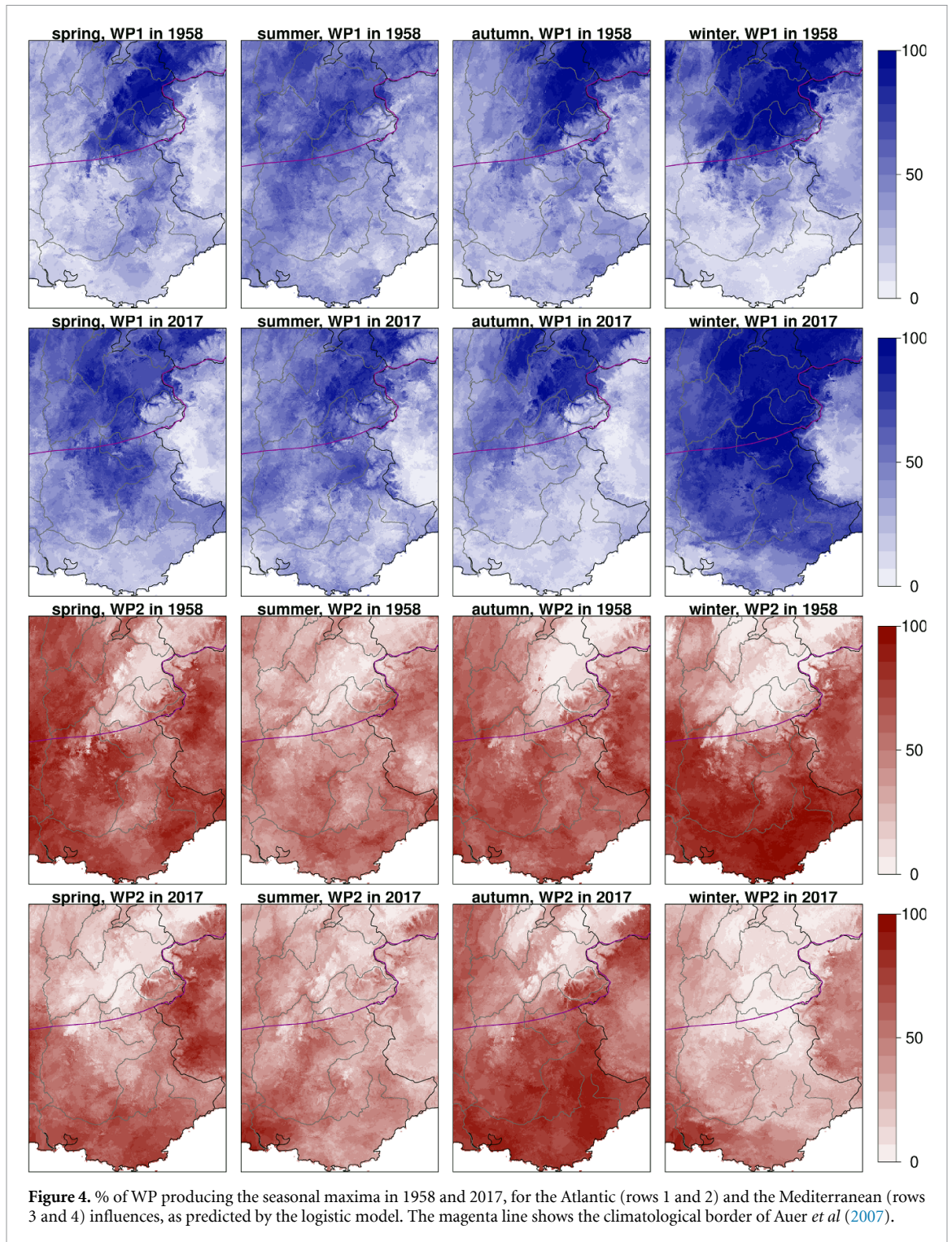
they produce 10% of the maxima due to local convection.

The high-resolution data set allows us to study the regionalization of influences in much more details than in Horton *et al* (2012) (2 stations), Giannakaki and Martius (2016) (2 regions), Plaut *et al* (2001) (6 regions), or even Radanovics *et al* (2013) (about 80 regions covering the French Alps). Figure 2 shows that the WPs for the maxima are very well organized in space. For each season, there is a clear delimitation between the Atlantic and the Mediterranean influences on the maxima. This delimitation fluctuates around the climatological border of Auer *et al* (2007) depending on the season, translating in particular southward in winter. Autumn and winter provide the clearest delineation between the northwestern flank of the Southwestern Alps (on the French side) – that is influenced by the Atlantic –, and the southeastern flank (on the Italian side) – that is under Mediterranean influence, in accordance with Plaut *et al* (2001). The Atlantic influence is more marked than any other, particularly in autumn and winter during which it produces 80 to 100% of the maxima over the northern French Alps and the Swiss Valais. Meridional flows trigger 60–80% of the maxima over the southern French Alps, the Rhône valley and the Italian Piemonte, apart in summer during which their influence is more uncertain, as also shown in Sodemann and Zubler (2010). 30–50% of the summer maxima in the southern French Alps and the Italian Piemonte relate to Anticyclonic situations and probable local convection. Contrary to the other WPs, the northeastern circulation produces maxima quite uniformly over the region in spring and summer, although with low probabilities (0–20% of the maxima). In autumn and winter, the northeastern

influence impacts mainly the Italian Piemonte, but anyway with low probabilities (0–20%).

At the regional scale, the occurrence of WPs producing the maxima is clearly non-stationary over the study period, particularly for the Atlantic and Mediterranean influences, as shown in figure 3. The daily WP occurrences show also some trends but they are much slighter. A separate analysis reshuffling the data within the WPs revealed that the nonstationarities in the WPs producing the maxima are not explained by the nonstationarities in the daily WPs. Winter shows the largest trends in WP occurrence for the maxima. At regional scale, 35% more grid points experience winter maxima during Atlantic circulation at the end of the period than at the start. These 35% are almost entirely won over the Mediterranean influence. Spring shows the same trends in sign as in winter but with lower absolute values (10 to 20%). We note that in spring the Northeastern circulations tend to be less frequent at daily scale but more productive (10% increase for the maxima). However this is mainly due to a few larger values in the last years (springs 2011, 2013, 2015). We touch here a difficulty in estimating trends over short time-series with large variability (here 60 values). In summer, influences are almost stationary although the Atlantic and the Mediterranean influences show a slight decrease (around 5%). Finally in autumn, trends are reversed but slighter than in winter and spring since the Mediterranean influence on the maxima increases of about 10% while the Atlantic influence decreases of about 15%.

We now focus on the regional details of the Atlantic and Mediterranean influences since they show the largest trends and they produce the great majority of precipitation maxima. The trends in



occurrence of WP producing the maxima over 1958–2017 are again very well organized in space, see figure 4 and the significance maps of figure 5. The trends are almost mirrored, the increase in Atlantic influence corresponding most of the time to a decrease in Mediterranean influence and vice versa. We can distinguish three phases across seasons. In autumn, the Mediterranean influence strengthens where it was already dominant. Its occurrence increases by around 10 to 30% over a large area covering the southern French Alps and the Mediterranean

coast. Changes are significant along the main ridge and its foothills south to the climatological border of Auer *et al* (2007) (see figure 5). This produces a much sharper northeast-southwest delineation between the Mediterranean and the Atlantic influenced regions in 2017 than in 1958. In winter and spring, the change is completely reversed, with a marked retreat of the Mediterranean influence and a significant southward translation of the Atlantic influence across the border of Auer *et al* (2007). In winter the very clear U shaped region of Mediterranean influence in 1958 almost

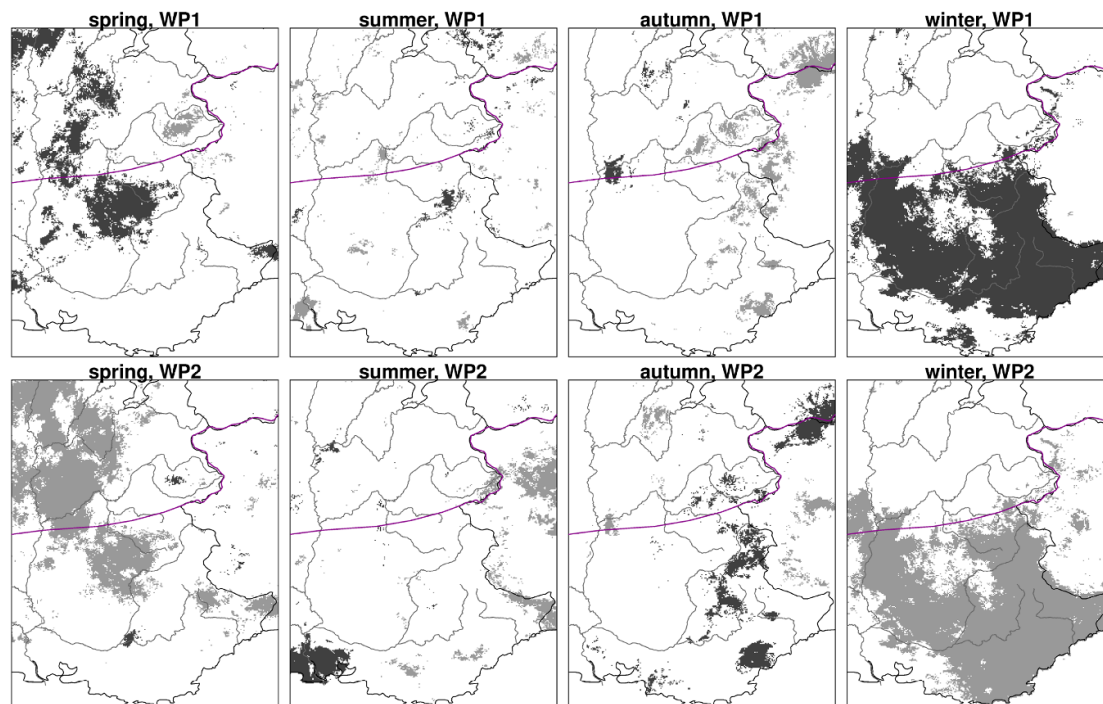


Figure 5. Significance of the trend in WP producing the seasonal maxima (Wald test at level 95%). First row: Atlantic influence. Second row: Mediterranean influence. White: non significant. Dark gray: significantly increasing. Light gray: significantly decreasing. The magenta line shows the climatological border of Auer *et al* (2007).

disappears in 2017, to the exception of the Piemonte in Italy and the Provence shore from the Rhône Delta to the Esterel Massif. In spring the retreat of the Mediterranean influence is still marked and significant but now mainly along the northern part of the Rhône valley where its occurrence decreases by about 40%. Finally in summer, the Mediterranean influence slightly retreats over the southern French Alps, the Mediterranean coast and the Italian Piemonte where it was dominant. However, contrary to winter and spring, this is not concordant with an increase in Atlantic influence but in Anticyclonic situations (not shown). At the same time the Mediterranean influence penetrates further along the Rhône valley, with significant increase over the Rhône Delta. Overall we note that despite changes of around 20 to 30% over large areas in all seasons, quite few are tested as significant (apart in winter and spring). Once again, we face the difficulty of getting significant trends over short times series. The large significance of the winter and spring trends are all the more impressive.

4. Conclusion

This article analyzed the large-scale circulation producing daily precipitation extremes in the Southwestern Alps and their trends. Considering gridded precipitation data allowed us to analyze the atmospheric influences in details, while considering a small number of weather patterns enabled us to focus on the main influences. We showed in particular that both

the influences and their trends are very organized in space. Mainly two types of circulation influence the maxima in the region—the Atlantic circulation and the Mediterranean circulation—whose delimitation varies from season to season. The Mediterranean influence retreated very significantly over the period in winter and spring, while the Atlantic influence extended further south. In autumn the Mediterranean influence strengthened where it was already dominant. Future work will compare the revealed changes in atmospheric influences with the (putative) trends in extreme precipitation, in order to assess the impact of changing atmospheric influences generating extreme precipitation on the values of extreme precipitation itself.

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