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Antoine Blanc, Juliette Blanchet, Jean-dominique Creutin. Linking Large-Scale Circulation Descriptors to Precipitation Variability in the Northern French Alps. *Geophysical Research Letters*, 2021, 48 (15), 10.1029/2021GL093649 . hal-03426611

**HAL Id: hal-03426611**

**<https://hal.science/hal-03426611v1>**

Submitted on 8 Aug 2022

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# Geophysical Research Letters

## RESEARCH LETTER

10.1029/2021GL093649

### Key Points:

- Simple descriptors of large-scale circulation explain a significant part of precipitation variability in the Northern French Alps
- NAO does not drive the pressure difference over Western Europe and weakly explains precipitation variability in the Northern French Alps

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### Citation:

Blanc, A., Blanchet, J., & Creutin, J.-D. (2021). Linking large-scale circulation descriptors to precipitation variability in the Northern French Alps. *Geophysical Research Letters*, 48, e2021GL093649. <https://doi.org/10.1029/2021GL093649>

Received 31 MAR 2021  
 Accepted 6 JUL 2021

## Linking Large-Scale Circulation Descriptors to Precipitation Variability in the Northern French Alps

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**Abstract** This work analyses the link between Western Europe large-scale circulation and precipitation variability in the Northern French Alps from 1950 to 2017. We consider simple descriptors characterizing the daily 500 hPa geopotential height fields. They are the maximum pressure difference (MPD)—representing the range of geopotential heights over Western Europe, and the singularity—representing the mean distance between a geopotential shape and its closest analogs, that is, the way this geopotential shape is reproduced in climatology. We show that the MPD and the singularity of geopotential shapes explain a significant part of precipitation variability in the Isère River catchment (9500 km<sup>2</sup>) from 10 days to 10 years, especially in winter (correlations of 0.7). These simple descriptors - that are easy to implement—provide as much information as weather pattern classification and much better performance than North Atlantic Oscillation to explain precipitation variability over a medium size mountainous catchment.

**Plain Language Summary** Precipitation accumulation over a given region varies from one year to another. This variability is governed by the atmospheric circulation, which can be viewed as the air flow on a large scale and at high elevation. In the Northern French Alps, precipitation mostly originates from the Atlantic Ocean and to a lesser extent from the Mediterranean Sea. Therefore, many studies focus on the direction of the air flow to study precipitation variability from one year to another, by classifying atmospheric circulations in different groups (Atlantic circulation, Mediterranean circulation...). These methods provide interesting information on the dominant atmospheric circulations providing precipitation, but they require several choices (notably the number of groups, the method of classification). Here, we investigate whether simple characteristics of atmospheric circulations—that are easy to implement—can also explain precipitation variability in the Northern French Alps. More specifically, we focus on the strength of the circulation, and on the way its direction is reproduced over the period 1950–2017. We show that these characteristics explain precipitation variability in the Northern French Alps as a classification method. Therefore, the evolution of these simple characteristics can give insights into the evolution of precipitation accumulation in the Northern French Alps.

## 1. Introduction

Precipitation variability is a key concern in many respects for society. In Alpine valleys, precipitation variability governs both liquid and solid water resources that are essential for touristic activities, hydroelectricity production, and agriculture. Understanding the mechanisms governing precipitation variability is, therefore, an important issue, especially in a climate change context.

In Europe, precipitation variability is often linked to different modes of large-scale circulation variability, in particular to the North Atlantic Oscillation (NAO) which is the first mode of variability over the North Atlantic and the only one that can be defined throughout the entire year (Barnston & Livezey, 1987). In winter, positive NAO phases are associated with increasing westerlies in a southwest-to-northeast direction, explaining positive precipitation anomalies over Northern Europe and negative precipitation anomalies over Southern Europe (Hurrell, 1995). The influence of NAO on precipitation variability in the Alpine region is however far less obvious (Bartolini et al., 2009; Durand et al., 2009; Schmidli et al., 2002), as the Alpine region acts as a “climatic crossroad” between Oceanic, Mediterranean, Continental, Polar, and Saharan influences (Beniston, 2005).

Linking precipitation variability to large-scale circulation, analog frameworks and weather-type classifications also provide interesting insights into the atmospheric patterns governing precipitation variability in the Alpine region. The relevance maps of Radanovics et al. (2013) and Horton et al. (2012) point out westerlies as the dominant influence producing precipitation in the Northwestern Alps, as confirmed by different weather-patterns classification established for France and the Alpine region (Boé & Terray, 2008; Garavaglia et al., 2010; Plaut & Simonnet, 2001). Focusing on the Northern French Alps, Figure 3 of Garavaglia et al. (2010) well shows that precipitations are mainly governed by zonal flows corresponding to the Atlantic influence, and a lesser extent by meridional flows corresponding to the Mediterranean influence. This view also stands for extreme precipitation in the region (Blanchet et al., 2021; Plaut et al., 2001), and is confirmed by the seasonal Lagrangian diagnosis of the moisture transport from oceanic basins and lands to the Alps (Sodemann & Zubler, 2010). With high recycling ratios linked to local convection, the summer source of Alpine precipitation is also partly continental and associated with high pressure systems (Rüdisühli et al., 2020; Sodemann & Zubler, 2010).

This work investigates the link between large-scale circulation and precipitation variability in a new way. We study whether simple characteristics of large-scale circulations—that are not associated with a circulation pattern by construction—are able to explain precipitation variability in the Northern French Alps. These “atmospheric descriptors” are quite easy to implement and rely on a limited number of choices, in comparison to weather-pattern classifications for example (choice of the classification method, number of classes). These descriptors are the maximum pressure difference (MPD)—representing the range of geopotential heights over Western Europe-, and the singularity—representing the mean distance between a geopotential shape and its closest analogs, that is, the way this geopotential shape is reproduced in the climatology. The MPD and the singularity of geopotential shapes were recently introduced and proved their relevance to characterize large-scale circulation producing extreme 3-day precipitation in the Northern French Alps (Blanc et al., 2021; Blanchet & Creutin, 2020; Blanchet et al., 2018). Here, we extend the analysis to longer time scales to investigate whether these descriptors remain relevant to explain precipitation variability, in comparison to a weather-type classification and NAO.

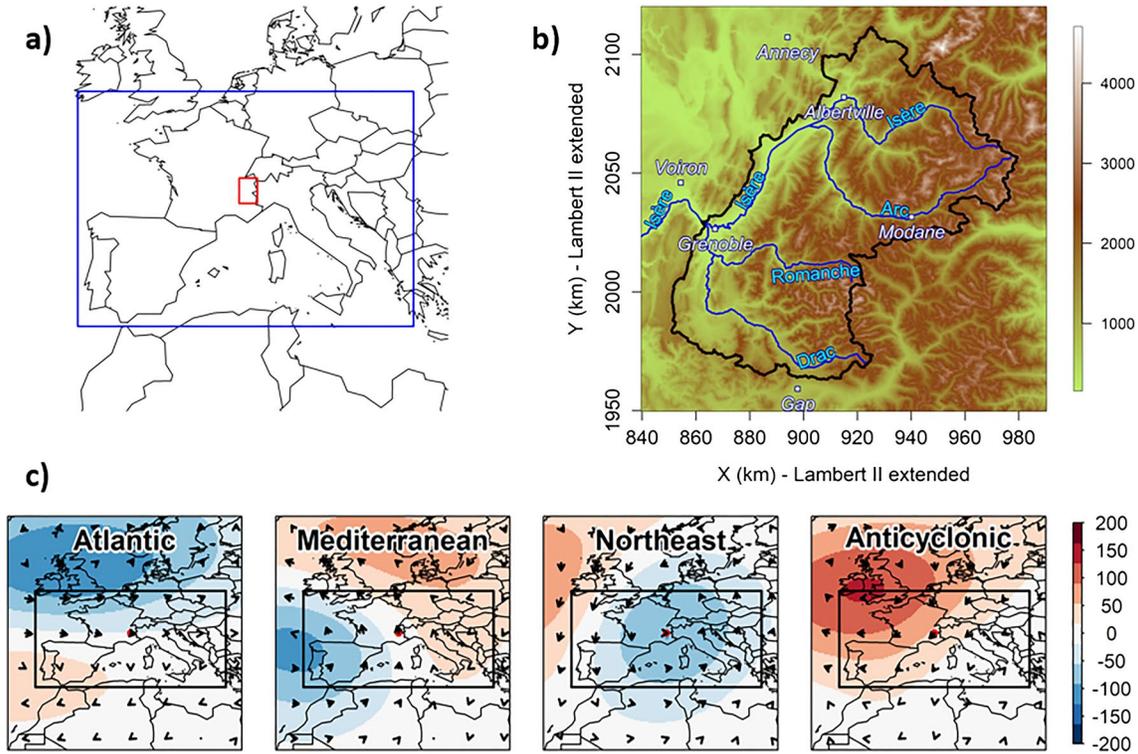
## 2. Data and Method

We use the SPAZM precipitation data set, which is a  $1 \times 1 \text{ km}^2$  gridded interpolation of daily rainfall accumulations measured by more than 1,800 daily rain gauges over the French Alps, the Pyrenees, the Massif Central, Switzerland, Spain, and Italy (Figure 4 of Gottardi et al., 2012). Like many other interpolators, SPAZM decomposes the rainfall field into a guess field incorporating orography and residuals to this field. A distinctive feature of SPAZM is that the guess field is conditional on the weather pattern of the target day, using the weather pattern classification of Garavaglia et al. (2010). This allows adjusting the altitudinal gradients according to the interaction between air flow and mountainous areas. We consider the areal precipitation over the Isère River catchment downstream its confluence with the Drac River near Grenoble, from 1950 to 2017 (Figure 1). The catchment size is  $9500 \text{ km}^2$ , with altitudes ranging from 200 m in Grenoble to 4,100 m in the Ecrins National Park.

The descriptors used, namely MPD and the singularity of geopotential shapes, are based on daily 500 hPa geopotential height fields over Western Europe ( $32^\circ \times 16^\circ$  window of Figure 1) extracted from the ERA5 re-analysis from 1950 to 2017 (Hersbach et al., 2020). First, MPD represents the range of geopotential heights (in meters) over Western Europe. Let  $z_{jk}$  denotes the 500 hPa height of grid point  $s_j$  and day  $t_k$ .  $MPD_k$  is defined as:

$$MPD_k = \max_j(z_{jk}) - \min_j(z_{jk}). \quad (1)$$

$MPD_k$  represents the MPD between weather systems over Western Europe at day  $t_k$ . It is therefore sensitive to the broad limits of the considered geographical domain (Figure 1) however not to its precise limits since geopotential height fields are quite smooth. MPD is strongly related to the spatial variance of the 500 hPa geopotential height field, but it differs from the temporal variance employed in several studies to analyze the Northern Hemisphere circulation (Blackmon et al., 1977; Sawyer, 1970). Second, the singularity measures



**Figure 1.** (a) Map of Western Europe with the window considered for computing the maximum pressure difference (MPD) and the singularity of geopotential shapes at 500 hPa (blue), and the region of study (red). (b) Altitudinal map of the Isère River catchment downstream Grenoble (in meters), with the main cities and rivers. Coordinates projection is according to the Lambert II extended system. (c) Composite 500 hPa geopotential height anomalies (in meters) of the four atmospheric influences for the period 1950–2017. The arrows represent the wind anomalies at 500 hPa. The window considered for computing the MPD and the singularity is represented by the black rectangle. The red point indicates the location of the Isère River catchment.

the way a geopotential shape is reproduced in the climatology. It is based on analogy using the Teweles–Wobus score (Teweles & Wobus, 1954). The Teweles–Wobus score between days  $t_k$  and  $t_{k'}$  is given by:

$$TWS_{k,k'} = \frac{\sum_{(j,j') \in Adj} |(z_{jk} - z_{j'k}) - (z_{jk'} - z_{j'k'})|}{2 \sum_{(j,j') \in Adj} \max(|z_{jk} - z_{j'k}|, |z_{jk'} - z_{j'k'}|)}, \quad (2)$$

where  $Adj$  ranges the set of adjacent grid points in horizontal and vertical directions in the analogy window of geopotential heights.  $TWS_{k,k'}$  measures the normalized difference between North–South and West–East gradients of days  $t_k$  and  $t_{k'}$ . It measures the similarity in shape of geopotential height fields, that is, the similarity in flow direction independently of the strength of the flow. TWS gives the same chance to a marked geopotential shape (marked westerly for instance) and to a quite flat geopotential shape (barometric swamp for instance) to find similar shapes. It has been widely used in analog frameworks to predict precipitation using geopotential height fields (Daoud et al., 2016; Horton et al., 2012; Marty et al., 2012; Wetterhall et al., 2005). As defined,  $TWS_{k,k'}$  ranges between 0 and 1. The smaller  $TWS_{k,k'}$ , the more similar the geopotential shapes/the flow directions of days  $t_k$  and  $t_{k'}$ . The singularity of day  $t_k$  is defined as the mean Teweles–Wobus score between day  $t_k$  and its  $Q$  closest analog days:

$$sing_k = \frac{1}{Q} \sum_{q \in \mathcal{A}_k} TWS_{k,q}, \quad (3)$$

where  $\mathcal{A}_k$  ranges the  $Q$  closest analogs of day  $t_k$ . Following previous optimization works,  $Q$  is set to 0.5% (Blanchet & Creutin, 2020), which represents 124 days for the period 1950–2017. The lower the singularity of a given day, the more closely reproduced its geopotential shape/its flow direction in the 1950–2017 climatology. Note that the singularity cannot be directly related to the frequency of occurrence of a given

geopotential shape since a geopotential shape is never perfectly reproduced ( $TWS_{k,k'} > 0$  even for two consecutive days). Having a very low singularity means that similar patterns are almost repeated in the climatology. However, this pattern is not necessarily frequent in the climatology, since very low singularities are rare in the climatology (Blanc et al., 2021; Blanchet & Creutin, 2020). Note also that the singularity is less direct to implement in comparison to MPD, but it still relies on a limited number of choice in comparison to a weather pattern classification.

The above atmospheric descriptors are compared to the occurrence of different atmospheric influences for explaining precipitation variability, using the weather pattern classification of Garavaglia et al. (2010). This classification into eight weather patterns was established to link daily rainfall field shapes over Southern France with synoptic situations. In order to focus on the main influences, we aggregate the eight weather patterns into four atmospheric influences according to the origin of the air flow reaching the French Alps (see the arrows in Figure 3 of Garavaglia et al. [2010]; see also Blanchet et al. [2021]). We end up with four atmospheric influences: the Atlantic influence (*aggregation of Atlantic Wave, Steady Oceanic, Southwest Circulation*), the Mediterranean influence (*aggregation of South Circulation, East Return, Central Depression*), the Northeast circulations, and Anticyclonic conditions (Figure 1). The Atlantic, Mediterranean, Northeast, and Anticyclonic influences, respectively, account for 37%, 25%, 9%, and 29% of days between 1950 and 2017.

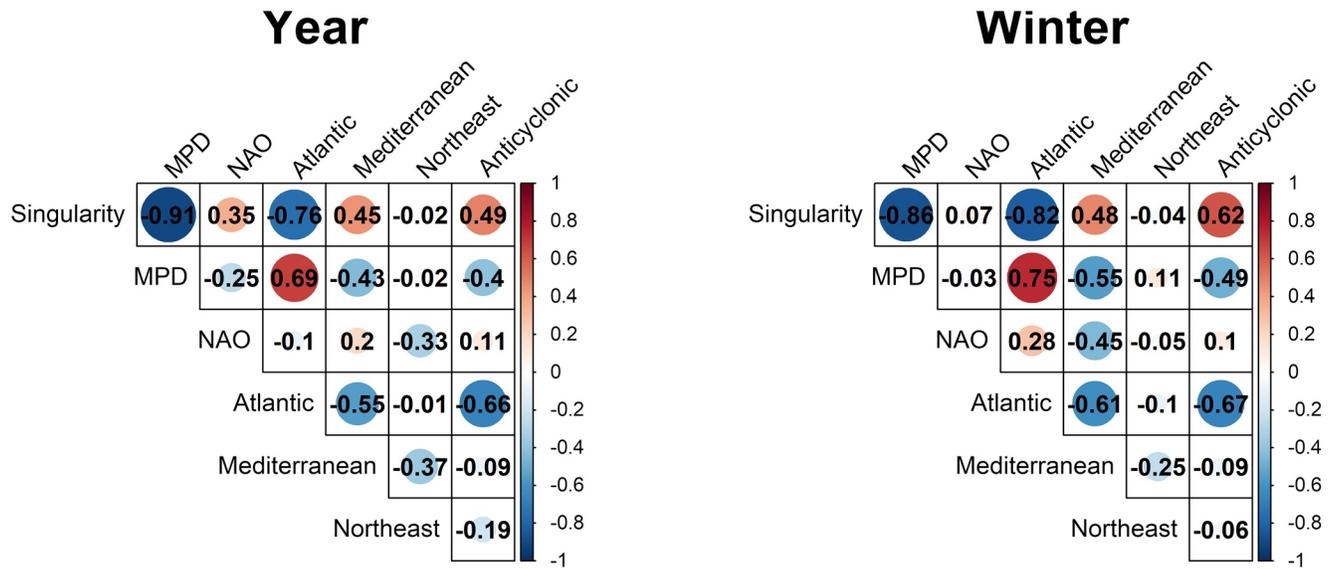
Finally, the NAO is also considered. The NAO index used here is computed by the National Oceanic and Atmospheric Administration/Climate Prediction Center (<https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>). It is the first mode of variability obtained by applying a Rotated Principal Component Analysis (RPCA) to monthly standardized 500 hPa geopotential height anomalies in the region between 20°N and 90°N, and interpolating to the day using a Least Square Regression. The RPCA is applied to each of the 12 calendar months (over a 3-month period centered on each month) to account for the annual cycle of the structure and the amplitude of NAO.

We hereafter refer to the atmospheric descriptors (MPD, singularity), the atmospheric influences (Atlantic, Mediterranean, Northeast, and Anticyclonic), and NAO as the “atmospheric indices”. The correlations given in this work are based on the Pearson correlation coefficient. The four seasons are defined as December–January–February (winter), March–April–May (spring), June–July–August (summer), and September–October–November (autumn).

### 3. Results

We first investigate the relation between the different atmospheric indices used in this study, at the interannual time-scale (Figure 2). By construction, the occurrence of the different atmospheric influences (Atlantic, Mediterranean, Northeast, Anticyclonic) is negatively correlated to each other. Furthermore, the interannual singularity, MPD, and the occurrence of Atlantic circulations appear to be strongly related to each other. This result is all the more interesting that the MPD and the singularity are not associated with an atmospheric influence by construction. The Atlantic influence is thus the influence providing the larger pressure differences over Western Europe and the most closely reproduced geopotential shapes/flow directions in climatology (Blanc et al., 2021). Note that NAO exhibits a low correlation with the other atmospheric indices, even with MPD in winter (Figure 2). Positive winter NAO phases are associated with large pressure differences between Northern and Southern Europe and pronounced westerlies (Hurrell, 1995). However they can be both associated with low and large MPDs as illustrated by the correlation of  $-0.03$  in winter, meaning that NAO does not drive the MPD in a domain spreading from the Iberic Peninsula to Southern Great Britain.

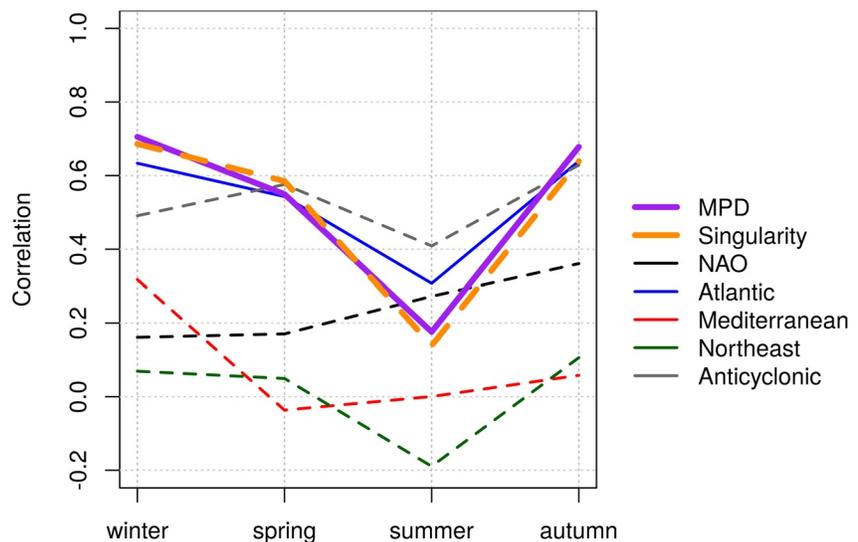
We now focus on the link between the atmospheric indices and seasonal precipitation accumulations over the Isère River catchment (Figure 3). We address this point from the least performing atmospheric indices to the best ones. Overall, correlation values are lower in summer than in the other seasons, as a part of summer Alpine precipitation is related to local convection with local moisture sources (Rüdisühli et al., 2020; Sodemann & Zubler, 2010). The occurrence of Northeast and Mediterranean circulations does not explain precipitation variability in the study area. Northeast circulations are rare and mainly carry dry continental air to the Northern French Alps, therefore weakly contributing to annual precipitation accumulation in



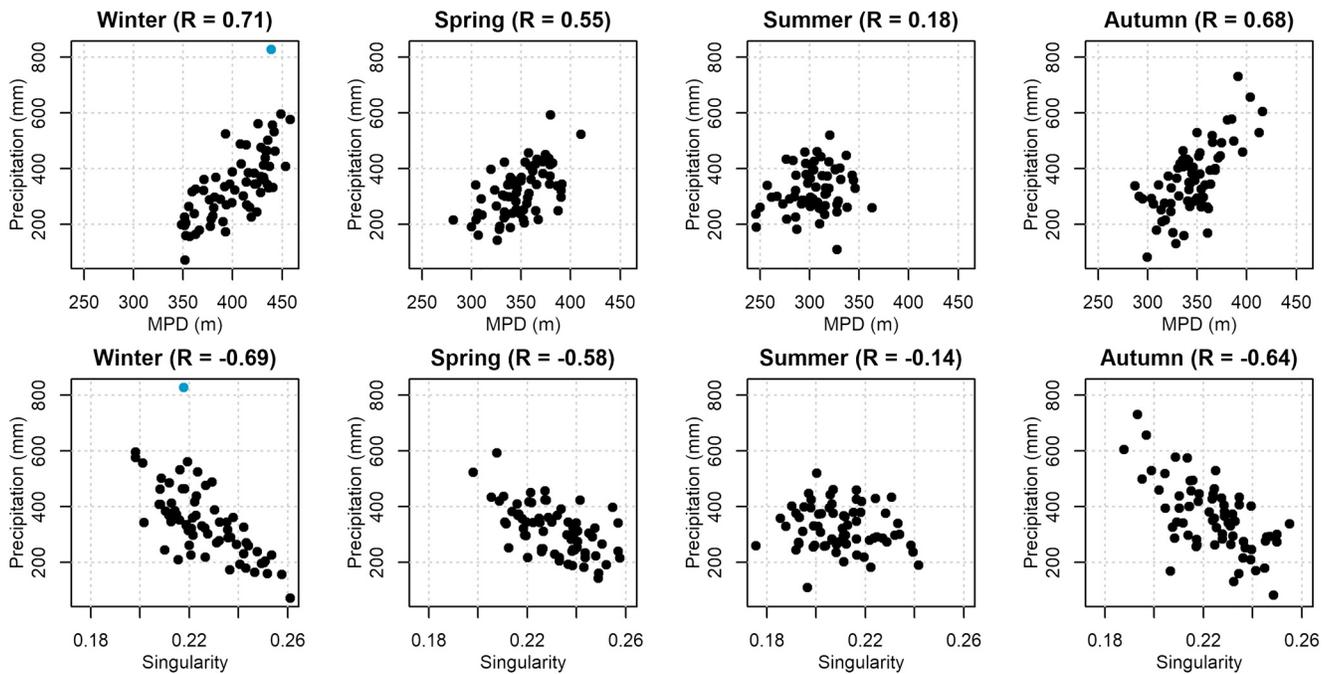
**Figure 2.** Interannual correlation between the different atmospheric indices for the period 1950–2017, for the whole year (left), and the winter season (right). For the atmospheric influences (Atlantic, Mediterranean, Northeast, Anticyclonic), the mean occurrence over the year/season is considered. The color and the size of the disk indicate the amplitude of the correlation. The color also informs about its sign.

the Isère River catchment. Mediterranean circulations are more frequent but they only represent 26% of the total precipitation over the Isère River catchment. In fact, Mediterranean circulations mainly produce precipitation in the Southern part of the catchment near the Ecrins range, which acts as a climatological barrier between the Northern and Southern Alps (Auer et al., 2007; Blanchet et al., 2021).

NAO poorly explains the interannual variability of precipitation in the Northern French Alps, in accordance with Bartolini et al. (2009), Durand et al. (2009), and Schmidli et al. (2002). As previously said, NAO does not drive the MPD in a domain spreading from the Iberic Peninsula to Southern Great Britain. This means that the pronounced westerlies associated with positive NAO phases can be associated with different storm-track latitudes, standing over Western Europe (large MPDs) or being shifted northward (low MPDs). In this way, the central position of the Northern French Alps in Europe combined with the diversity of storm-track



**Figure 3.** Interannual correlation between the atmospheric indices and seasonal precipitation accumulation over the Isère River catchment. The dotted lines represent negative correlation values.

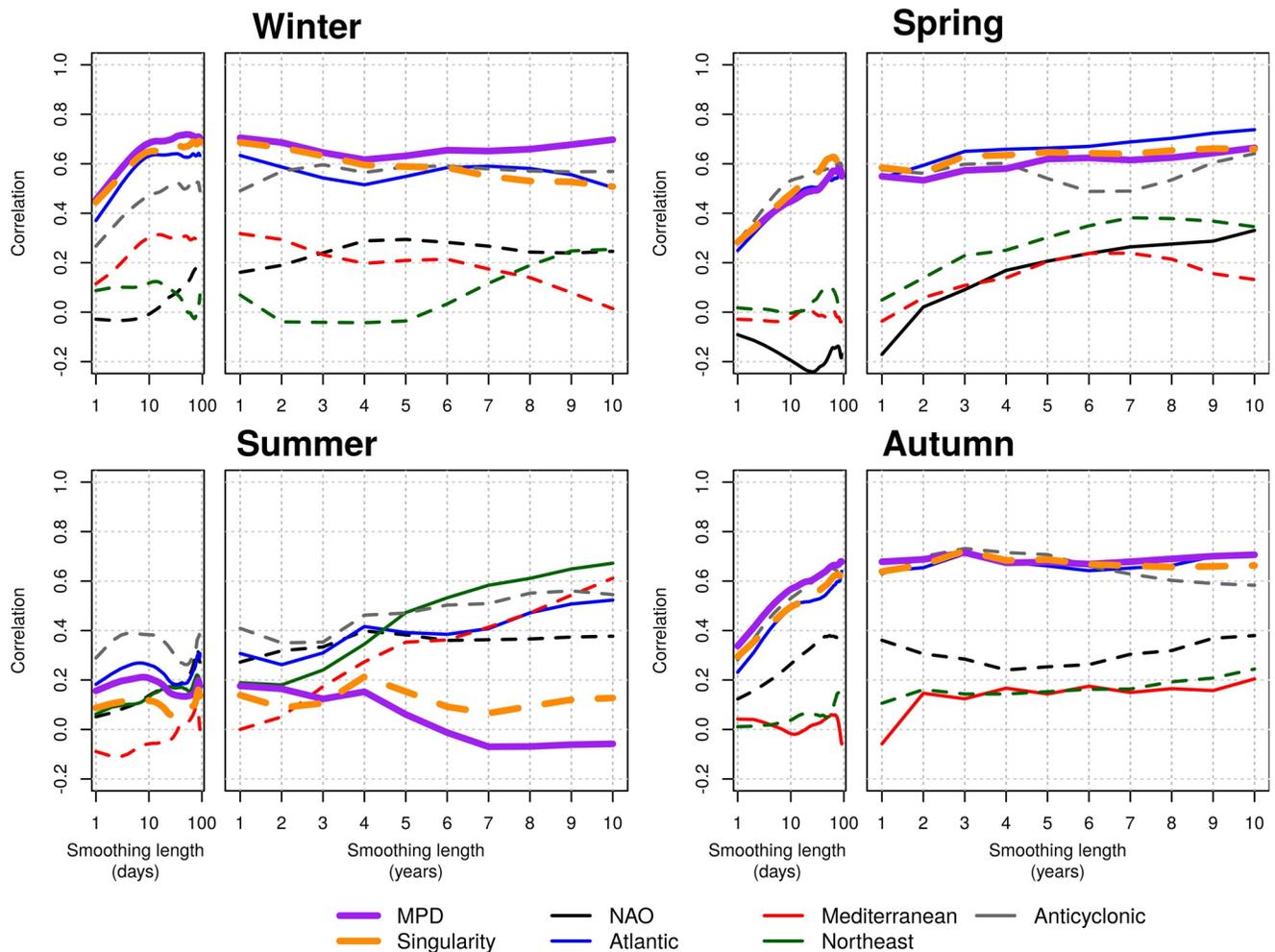


**Figure 4.** Scatterplot of the maximum pressure difference (first line) and the singularity (second line) against precipitation accumulation in the Isère River catchment, per season. Correlation values are reported above each scatterplot. Winter 1955 is represented in blue.

latitudes associated with positive NAO phases could explain the low correlation between NAO and seasonal precipitation in the Northern French Alps.

The MPD, the singularity of geopotential shapes, the occurrence of Atlantic circulations, and Anticyclonic conditions are the most performing atmospheric indices. Correlation values exceed 0.6 in winter and autumn and are close to 0.6 in spring, except for Anticyclonic conditions which less performs in winter (Figure 3). These values are consistent with the largest correlation values obtained when linking large-scale circulation patterns to precipitation variability in France and the Alpine region (Figure 4 of Boé and Terray [2008]; Table 4 of Quadrelli et al. [2001]; Figure 9 of Scherrer et al. [2016]). The occurrence of Anticyclonic conditions is negatively correlated to precipitation accumulation in the Northern French Alps, especially in spring and autumn. A large occurrence of Anticyclonic conditions in autumn and spring tends to generate low seasonal precipitation accumulation. Anticyclonic conditions are much less associated with dry days in summer due to local convection (Rüdisühli et al., 2020) and they feature a lower occurrence in winter (Blanchet et al., 2021), which could explain why the correlation of precipitation with Anticyclonic conditions is lower in winter and summer.

It makes sense that the MPD, the singularity of geopotential shapes, and the occurrence of Atlantic circulations provide similar performances knowing their link at the interannual timescale (Figure 2), although it can be noted that the singularity and MPD slightly outperform the occurrence of Atlantic circulations in winter. Seasons featuring a large occurrence of Atlantic circulations are associated with large precipitation accumulation in the Northern French Alps. This result appears to be consistent since the precipitation in the Northern French Alps is mostly related to westerlies bringing moist air from the Atlantic (Garavaglia et al., 2010; Horton et al., 2012; Radanovics et al., 2013; Sodemann & Zubler, 2010). Large seasonal pressure differences over Western Europe (large MPDs) are associated with large seasonal precipitation in the Northern French Alps. Western Europe experiences larger pressure differences during the winter (Figure 4), in accordance with the southward shift of the baroclinic zone during the winter months. We note here the benefit of using a pressure difference over a smaller region than NAO—without prescribing the location of the centers of action—to reflect the presence and the intensity of the baroclinic zone—and therefore of the storm-track—over Western Europe. Finally, seasons featuring a low singularity of geopotential shapes also feature large seasonal precipitation in the Northern French Alps (Figure 4). In other words, seasons



**Figure 5.** Correlation between the atmospheric indices and precipitation accumulation in the Isère River catchment, per season. Correlation is represented for different smoothing lengths, at daily time-scale (left, logarithmic *x*-axis) and at yearly time-scale (right, regular *x*-axis). The dotted lines represent negative correlation values.

featuring geopotential shapes/flow directions that are closely reproduced in the climatology tend to produce large precipitation accumulations, while seasons featuring singular geopotential shapes tend to produce low precipitation accumulations.

We can note that the wettest winter (winter 1955, blue point in Figure 4) is not well explained by the atmospheric descriptors. Winter 1955 features a larger seasonal accumulation than expected with its mean MPD and singularity. Further researches reveal that this discrepancy comes mainly from one specific precipitation event. More than 150 mm fell between January 11 and 14, 1955 with not-as-extreme MPD and singularity values. Among different possible explanations, the extreme stationarity in the flow direction (as measured by the celerity descriptor in Blanchet et al. [2018]) could have played a role in explaining such a precipitation accumulation. This points out that (a) extreme precipitation over few days can have a large impact in building the link between atmospheric descriptors and seasonal precipitation and (b) other atmospheric characteristics or atmospheric variables come into play to explain precipitation accumulation. It is also important to remind that the best performing atmospheric indices used in this study individually explain around 50% of the explained variance of precipitation.

We now extend our analysis to other time scales, from 1 day to 10 years (Figure 5). At the daily time-scale, nor the MPD, the singularity of geopotential shapes or the occurrence of Atlantic circulations (0 or 1 in this case) explains precipitation variability in the Northern French Alps. However, most of the gain in

correlation from 1 day to 1 year is obtained after 10 days (logarithmic scale in Figure 5) with correlation values remaining almost stable from 10 days to 10 years. The mean persistence of the Atlantic, Mediterranean, Northeast, and Anticyclonic influences are respectively of 4 days, 3 days, 1 day, and 3 days. The gain in correlation from 1 to 10 days could be explained by the fact that the atmosphere starts exploring different influences, making the occurrence of Atlantic circulation, the mean singularity, and the mean MPD over several days more relevant to explain precipitation accumulation. Furthermore, the atmospheric indices that poorly explain precipitation variability at the interannual time scale are also little explicative at shorter and longer time scales, although we can note that the occurrence of the four atmospheric influences become relevant to explain decadal precipitation variability in summer.

Although the MPD and the singularity of geopotential shape poorly explain precipitation variability under 10 days, they were shown relevant to characterize large-scale circulation producing extreme precipitation over 3 days in the Northern French Alps (Blanc et al., 2021; Blanchet & Creutin, 2020; Blanchet et al., 2018). Notably, extreme 3-day precipitation is produced by circulations featuring among the largest pressure difference over Western Europe (largest MPDs) and among the most closely reproduced geopotential shapes in the climatology (lowest singularities). Therefore, the atmospheric descriptors could be used at different timescales with different aims, focusing either on the occurrence of extreme 3-day precipitation or on precipitation variability from 10 days.

#### 4. Conclusions

This article investigated whether simple characteristics of Western Europe large-scale circulation—that are easy to implement—explain precipitation variability in the Northern French Alps. We showed that a simple pressure difference over Western Europe as well as a singularity of geopotential shapes are well related to the occurrence of Atlantic circulations, and explain part of precipitation accumulation in the Northern French Alps from 10 days to 10 years, except during the summer. In previous works, these descriptors were shown relevant to characterize large-scale circulations producing extreme 3-day precipitation in the Northern French Alps. Therefore, they appear as relevant tools to both study precipitation variability and extremes.

#### Data Availability Statement

The ERA5 reanalysis is freely available on the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu>). The SPAZM data and the weather pattern classification have been provided to the authors by Électricité de France for this research. They could be made available to other researchers under a specific research agreement. Requests should be sent to [dtg-demande-donnees-hydro@edf.fr](mailto:dtg-demande-donnees-hydro@edf.fr).

#### Acknowledgments

This study is part of a collaboration between the University Grenoble Alpes and Grenoble Alpes Métropole, the metropolitan authority of the Grenoble conurbation (deliberation 12 of the Metropolitan Council of May 27, 2016).

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