Characterizing large-scale circulations driving extreme precipitation in the Northern French Alps

Antoine Blanc | Juliette Blanchet | Jean-Dominique Creutin

Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France

Correspondence
Antoine Blanc, Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France.
Email: antoine.blanc2@univ-grenoble-alpes.fr

Funding information
Grenoble Alpes Métropole

Abstract
Extreme precipitation in the Northern French Alps are mainly associated with large-scale circulations (LSCs) bringing moist air from the Atlantic Ocean and the Mediterranean Sea—two atmospheric influences that are very frequent in the climatology. In this work, we investigate what characterizes the Atlantic/Mediterranean circulations driving extreme precipitation in the Northern French Alps in comparison to ‘random’ Atlantic/Mediterranean circulations.

We focus on extreme 3-day precipitation over two medium size neighbouring catchments from 1950 to 2017. Atlantic and Mediterranean circulations are identified using an existing weather pattern classification established for Southern France. Every single LSC is characterized using three atmospheric descriptors based on analogy in geopotential shapes at 500 hPa over Western Europe that were introduced in previous works. They are (a) the celerity, characterizing the stationary nature of a geopotential shape, and (b) the singularity and relative singularity, characterizing the resemblance of a geopotential shape to its analogs, in other words the way this geopotential shape is closely reproduced in the climatology. We add to these analogy-based descriptors a new (non-analogy) descriptor accounting for the strength of the low and high-pressure systems. We show that Atlantic/Mediterranean circulations driving extreme 3-day precipitation in the Northern French Alps are the Atlantic/Mediterranean circulations featuring the strongest centres of action as well as the most stationary and the most reproducible geopotential shapes—characteristics that are rare for both atmospheric influences. In the Atlantic case, these characteristics appear to be even more pronounced and rare with regard to the whole climatology, pointing LSC as an important driver of extreme precipitation. In the Mediterranean case, these characteristics appear to be more random with regard to the whole climatology, pointing a more balanced contribution between specific LSC and humidity in driving extreme precipitation.

Keywords
Alps, analog, extreme precipitation, large-scale circulation
1 | INTRODUCTION

Surface weather over Western Europe is influenced by large-scale circulation (LSC) over the North Atlantic and Europe. Therefore, precipitation variability in Europe is often linked to different modes of LSC variability. The North Atlantic Oscillation (NAO) is the first mode of LSC variability over the North Atlantic and the only one remaining the entire year (Barnston and 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 (Schmidli et al., 2002; Bartolini et al., 2009; Durand et al., 2009). The Alpine region acts as a ‘climatic crossroad’ between Oceanic, Mediterranean, Continental, Polar and Saharan influences (Beniston, 2005). The East Atlantic/Western Russia index (EA/WR) appears to better explain winter precipitation variability in the Alps than NAO. The negative phase of the index corresponds to positive pressure anomalies over the East Atlantic and Western Russia and negative pressure anomalies over Europe (Barnston and Livezey, 1987), leading to a northwest flow and positive winter precipitation anomalies over Western Europe and the Alpine range (Bartolini et al., 2009; Lim, 2015).

At finer temporal and spatial scales, the location, the size and the configuration of the Alpine range lead to a wide range of atmospheric influences impacting the different Alpine sub-regions. Horton et al. (2012) point out different atmospheric influences on precipitation variability in the Swiss Alps at two locations 100 km apart. Extreme precipitation in the southern slopes of the French and Italian Alps appears to be mainly impacted by LSC associated with southwesterlies and strong southerly flows (Plaut et al., 2001; Grazzini, 2007; Blanchet et al., 2020), while the Savoy Mont-Blanc region (Northern French Alps) is mainly impacted by pressure anomalies associated with northwesterlies, especially for autumn and winter extreme precipitation (Plaut et al., 2001; Blanchet et al., 2020).

The relation between LSC and regional precipitation can be investigated using weather pattern classifications (Plaut and Simonnet, 2001; Boé and Terray, 2008; Garavaglia et al., 2010). Classifications give useful insights on the influence of different weather patterns on precipitation anomalies and extremes. In the Northern French Alps, the Atlantic and the Mediterranean influences are pointed out as the main weather patterns associated with extreme precipitation through respectively zonal and meridional flows (Garavaglia et al., 2010; Blanchet et al., 2020). However, the discrete nature of classifications leads to a loss of information, since LSC variability within each class is not considered. By somehow considering as much weather patterns as LSCs, the analog method addresses this issue. The method relies on the hypothesis that similar LSCs provide similar local effects. The ‘analog’ term was introduced by Lorenz (1969), who first investigated the relative position of LSCs in relation to each other. The method was applied for the first time by Duband (1981) to produce probabilistic forecast of daily precipitation over South-Eastern France. Since then the method has been widely applied and has been subject to various improvements (Obled et al., 2002; Matulla et al., 2008; Marty et al., 2012; Radanovics et al., 2013; Daoud et al., 2016; Raynaud et al., 2017; Chardon et al., 2018). Unlike weather pattern classifications, the analog method manages to link LSC to regional precipitation in a continuous way, since the link between specific LSCs and the associated precipitation is preserved. However, it does not provide information on the atmospheric influences driving precipitation, unlike classification methods.

The present work combines a weather pattern classification and an analog framework to investigate the characteristics of Atlantic and Mediterranean circulations driving extreme 3-day precipitation in the Northern French Alps, in comparison to ‘random’ Atlantic/Mediterranean circulations. The weather pattern classification of Garavaglia et al. (2010) is used to identify Atlantic and Mediterranean circulations. Atmospheric descriptors based on analogy are then used to characterize every single LSC within those two atmospheric influences. Those descriptors were recently introduced and studied in the literature by Faranda et al. (2017a, 2017b); Messori et al. (2017); Rodrigues et al. (2018) over large regions of the Northern Hemisphere, as well as by Blanchet et al. (2018) and Blanchet and Creutin (2020) for the same region as this article. Here, the celerity, the singularity and the relative singularity of Blanchet and Creutin (2020) are used, considering the 500 hPa geopotential height fields over Western Europe. The celerity gives insights into the stationary nature of a specific geopotential shape, while the singularity and relative singularity indicate the way a geopotential shape is closely reproduced in climatology. We complement the three atmospheric descriptors based on analogy with a new atmospheric descriptor—which is not based on analogy—that accounts for the intensity of low and high-pressure systems. The Isère River catchment downstream Grenoble used in Blanchet and Creutin (2020) is separated into two sub-catchments featuring a different sensibility to large-scale flow, namely the Isère and the Drac River catchments at Grenoble. We first give an overview
of the atmospheric descriptors. We then characterize every Atlantic and Mediterranean circulations, before focusing on the specific Atlantic and Mediterranean circulations associated with extreme 3-day precipitation in each catchment. Finally, the role of LSC in producing extreme 3-day precipitation in the Northern French Alps is discussed by studying the atmospheric humidity associated with extreme 3-day precipitation.

2 | DATA

We use the SPAZM precipitation data set to represent catchment precipitation over the period 1950–2017. SPAZM is a 1 × 1 km² 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). As 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. However, considering catchment precipitation based on station data interpolated with a thin plate spline function does not change the conclusions of this study. We consider the averaged catchment precipitation for two neighbouring catchments of the Northern French Alps, namely the Isère and the Drac River catchments at Grenoble (Figure 1). The Isère River catchment at Grenoble sizes 5,800 km², with altitude ranging from 200 m in Grenoble to more than 3,800 m in the Vanoise National Park. The interannual catchment precipitation reaches 1,370 ± 200 mm-year⁻¹. No clear precipitation seasonality is observed (Figure 2). The Drac River catchment at Grenoble sizes 3,600 km², with altitude ranging from 200 m in Grenoble to 4,100 m in the Ecrins national Park, which is known to be a climatological barrier between the Northern and the Southern French Alps, as shown by the climatological subregions of Auer et al. (2007) (purple dotted line of Figure 1) and by the different moisture sources leading to precipitation in the Alpine region (figure 9 of Sodemann and Zubler, 2010). The interannual precipitation in the Drac catchment reaches 1,308 ± 213 mm-year⁻¹ with more precipitation falling in autumn (Figure 2).

We consider a 3-day time step, which is close to the concentration-time of the catchments and is relevant for flood risk analysis. In order to focus on extreme precipitation, we consider the 1% largest values of 3-day precipitation for each catchment. We keep among them

---

**Figure 1** Left: Map of Western Europe with the analogy window considered for the 500 hPa geopotential height in blue. The region of study and the domain considered for the total column water are represented in red. Right: Altitudinal map of the region (in meters), with the Isère and the Drac River catchments at Grenoble, the main cities and rivers. The purple dotted line represents the border of the climatological barrier of Auer et al. (2007). Coordinates projection is according to the Lambert II extended system.
the independent sequences by performing a temporal declustering: whenever several extreme precipitation sequences (EPS) overlap, we keep only the sequence yielding the largest 3-day accumulation. We end up with 138 independent EPS for the Isère River catchment and 122 independent EPS for the Drac River catchment over the period 1950–2017. The two neighbouring catchments share 54 common EPS. The average EPS precipitation reaches 84 ± 49 mm/C1 3 day–1 for the Isère River catchment and 99 ± 64 mm/C1 3 day–1 for the Drac River catchment, corresponding in both cases to about 7% of the annual catchment precipitation. EPS mostly occurred in winter for the Isère River catchment and in autumn for the Drac River catchment (Figure 2). Furthermore, EPS are quite homogeneously distributed over the period of study for both catchments (Figure 3).

We use the 500 hPa geopotential height fields over a 32° × 16° window covering Western Europe to represent LSC (Figure 1). Geopotential height fields are extracted from the ERA5 reanalysis for the period 1950–2017 (Hersbach et al., 2018), which is the most recent reanalysis. It provides hourly fields of atmospheric variables with 0.25° horizontal resolution. The 500 hPa geopotential height ranges from 4,800 to 6,100 m, giving information about LSC in the middle of the troposphere. This pressure level appears relevant to explain precipitation variability in France and in the Alpine region, especially when combined with the 1,000 hPa geopotential height field (Horton et al., 2012; Marty et al., 2012; Daoud et al., 2016). It was shown to provide better skills than the 1,000 hPa geopotential height field in predicting precipitation accumulation in the Northern French Alps using the same atmospheric descriptors as this study (Blanchet and Creutin, 2020). The size of the geopotential window has not been optimized for this study but it is chosen according to previous optimization works (Raynaud et al., 2017). Absolute geopotential heights values are considered at daily time step, by averaging the
0 a.m., 6 a.m., 12 a.m. and 6 p.m. height fields. Averaging tends to smooth out the resulting field but it has actually little impact on the results of this study (not shown). The choice of the reanalysis has also little impact since using the 500 hPa geopotential height fields from either the ERA20C reanalysis (Poli et al., 2016) or from the first member of the 20CR V2c reanalysis (Compo et al., 2011) led to similar results (not shown).

Finally, the daily total column water (TCW) is also extracted from ERA5 from 1950 to 2017. TCW represents the total available water in an atmospheric column, including water vapour, liquid water, cloud ice, rain and snow. The daily TCW fields are averaged over three consecutive days over a 1.5 × 1.5° domain covering the region of study (Figure 1), to account for the available atmospheric humidity during EPS.

3 | METHOD

3.1 | Atlantic and Mediterranean circulations

We consider the weather pattern classification of Garavaglia et al. (2010) to identify Atlantic and Mediterranean circulations. This classification into eight weather patterns was established to link daily rainfall field shapes over Southern France with synoptic situations. To focus on the main influences, we aggregate the eight weather patterns into four atmospheric influences according to the origin of the airflow reaching the French Alps (see the arrows in Figure 3 of Garavaglia et al., 2010): 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. As the weather patterns of Garavaglia et al. (2010) are established at daily time-step, we define the 3-day atmospheric influences as follows: the 3-day sequences featuring at least two identical atmospheric influences are classified in the dominant atmospheric influence (72%); the 3-day sequences featuring three different atmospheric influences are either classified in the atmospheric influence of the wettest day of the sequence (21%), or in the atmospheric influence of the central day of the sequence for the dry sequences (7%). The Atlantic—the Mediterranean—the Northeast— the Anticyclonic influences respectively account for 44%—26%—8%—22% of 3-day sequences over the period 1950–2017. In this paper, we only focus on the Atlantic and the Mediterranean influences, as they are associated with more than 97% of extreme 3-day precipitation in the region (see also Blanchet et al., 2020). Atlantic circulations are associated with pressure anomalies enhancing the zonality of the flow (Figure 4). Mediterranean circulations are associated with low-pressure anomalies over the East Atlantic inducing a trough over the European west coasts, enhancing the meridional component of the flow over France (Figure 4). Atlantic and Mediterranean circulations share some similarity respectively with the Zonal pattern of Vautard (1990) and the NAO- pattern of Faranda et al. (2017a), although the influences used here are computed on a much smaller region (Garavaglia et al., 2010).

3.2 | Atmospheric descriptors

We define an atmospheric state as a daily 500 hPa geopotential height field and the atmospheric space as the high-dimensional space mapping the atmospheric states. The number of dimension of the atmospheric space is as high as the number of points representing the geopotential height fields, namely 8,385 here. The atmospheric descriptors aim at transforming this high-dimensional space into a much lower dimensional space characterizing each atmospheric state in a continuous way, which differs from classification methods that make classes. Four atmospheric descriptors are used, among which three are based on analogy, that is, they account for the relative position of the atmospheric states with respect to each
others in the atmospheric space. Their definition follows previous developments of Blanchet et al. (2018), Blanchet and Creutin (2020), Faranda et al. (2017a, 2017b) and Messori et al. (2017). They proved to be skilful for predicting precipitation in the region in Blanchet and Creutin (2020). A fourth non-analogy descriptor is added.

3.2.1 | Atmospheric descriptors based on analogy

The analogy in LSC is computed at daily time step using the 500 hPa geopotential height fields over Western Europe (Figure 1). We consider analogy in geopotential shapes using the Teweles-Wobus score (Teweles and Wobus, 1954). The Teweles-Wobus score measures the similarity in shape between geopotential height fields, based on North–South and West–East gradients. Let \( z_{jk} \) denotes the 500 hPa height of grid point \( s_j \) at observation time \( t_k \). The Teweles-Wobus score for days \( t_k \) and \( t_0 \) is given by:

\[
\Delta_{k,k'} = \frac{1}{2} \sum_{(j,f) \in \text{Adj}} \left| \frac{(z_{jk}-z_{j0})-(z_{jk'}-z_{j0})}{\max(z_{jk}-z_{j0},z_{jk'}-z_{j0})} \right|
\]

where \( \text{Adj} \) ranges the set of adjacent grid points in horizontal and vertical directions in the analogy window of geopotential heights. As defined, \( \Delta_{k,k'} \) ranges between 0 and 1. The smaller \( \Delta_{k,k'} \), the more similar the shapes of geopotential height fields of days \( t_k \) and \( t_0 \). The term ‘geopotential shape’—which is widely used in the article—refer to the shapes of geopotential height fields. The analog days of a given day are defined as the 0.5% closest days according to the Teweles-Wobus score computed over all the other days of 1950–2017 (i.e., 124 analog days). The 0.5 percentage appears as a reasonable choice to construct the atmospheric descriptors based on analogy (see below) in order to have a sufficient number of good analogs. However, the precise number of selected analogs does not appear to strongly affect their relevance for precipitation prediction (Figure 4 of Blanchet and Creutin, 2020). The season is not taken into account in the search for analogs because we aim at characterizing LSCs with respect to each others rather than predicting precipitation, so the best analogs are necessary. However, 55% of analog days are selected within a ± 2-month window around the target day (Figure 5a), so the seasonal selection naturally applies without constraining the search. Furthermore, the selection of analog days is only slightly affected by climate instability over the period since analogs of days of the first and second sub-periods (1950–1983 and 1984–2017) are almost equally distributed among the two sub-periods (Figure 5b).

Three atmospheric descriptors based on analogy are used in this study: the celerity, the singularity and the relative singularity. They summarize the way the sequences of pressure fields resemble their neighbours (singularity...
and relative singularity) and how fast they evolve in time (celerity). Blanchet and Creutin (2020) showed their skillfulness for predicting extreme precipitation in the region. The celerity characterizes how fast a given atmospheric state moves in the atmospheric space from one day to another. It is defined for day \( t_k \) as the Teweles-Wobus score between day \( t_k \) and day \( t_k - 1 \):

\[
\text{cel}_k = \Delta_{k-1,k}.
\]  

(2)

The celerity, therefore, represents the change in geopotential shape between two consecutive days. The lower the celerity, the more stationary in shape the geopotential height field.

The singularity and the relative singularity characterize how the atmospheric states cluster in the atmospheric space with their \( Q \) closest states (\( Q = 124 \)). First, the singularity measures the density of atmospheric states around a given atmospheric state. It is defined as the mean Teweles-Wobus score between day \( t_k \) and its \( Q \) closest analog days:

\[
\text{sing}_k = \frac{1}{Q} \sum_{q \in A_k} \Delta_{k,q},
\]  

(3)

where \( A_k \) range the \( Q \) analogs of day \( t_k \). The lower the singularity, the more the target resemble its neighbours (high degree of clustering in the atmospheric space), and so the more closely reproducible it is. The concept of singularity is also used in Jézéquel et al. (2017) and Faranda et al. (2020) to study the temporal evolution of the reproducibility of atmospheric states (using a different metric from the Teweles-Wobus score). Second, the relative singularity is defined as the singularity divided by the Teweles-Wobus score with the \( Q \)th closest analog day of day \( t_k \):

\[
\text{rsing}_k = \frac{\text{sing}_k}{\Delta_{k,(Q)}}.
\]  

(4)

Interpreting the relative singularity is less direct but taking an example helps: for two target days at equal distance to their furthest analog (same denominator in Equation (4)), that with the lowest relative singularity features a lower singularity (numerator in Equation (4)) and hence more analogs are located at close distance to the target day. In brief, the lower the relative singularity, the more the target resemble its close analogs relatively to its farther analogs. The relative singularity is closely related to the local dimension of Faranda et al. (2017a, 2017b) and Messori et al. (2017), although the construction of the local dimension includes further steps (log transformation and Extreme Value Theory). Geometrically speaking, a day with low relative singularity can be seen as a typical point of the ‘attractor’ in the atmospheric space, that is, as featuring a high degree of clustering. Since the singularity and the relative singularity bring complementary information, they will be interpreted jointly. A geopotential shape featuring both a low singularity and a low relative singularity is closely reproduced in the climatology by its analogs (low singularity) but its closest analogs tend to be even more resembling than usual (low relative singularity). Therefore we will say that this geopotential shape is ‘almost similarly reproduced’ in the climatology, or in short that it is ‘reproducible’.

Two final steps are carried out in the construction of these descriptors. First, since 3-day rather than daily sequences are of interest, the descriptor of sequence \( S_k \) ranging from \( t_{k-1} \) to \( t_{k+1} \) is defined as the average descriptor over the 3 days. Second, in order to get a more robust characterization of geopotential shapes, we consider the average descriptor over its \( Q \) closest geopotential shapes, therefore characterizing a ‘region’ of the atmospheric space rather than a point. The new descriptors, hereafter called \( \text{celnei}_k, \text{singnei}_k \) and \( \text{rsingnei}_k \) (\( \text{nei} \) for neighbours), proved to give more robust results when modelling precipitation accumulation over the region (gain of around 0.05 points in CRPSS, not shown). Summing up, the new descriptor \( \text{descrnei}_k \) for sequence \( S_k \) (\( \text{descr} = \text{cel}, \text{sing}, \text{rsing} \)) is defined as:

\[
\text{descrnei}_k = \frac{1}{3Q} \sum_{l=-1}^{1} \sum_{q \in A_{k+l}} \text{descr}_q.
\]  

(5)

3.2.2 | Maximum pressure difference

The analogy-based descriptors previously introduced are based on the Teweles-Wobus score, which considers normalized pressure gradient differences. These descriptors characterize the resemblance and the stationary nature of the geopotential height field shapes, somehow omitting the shape in itself. Yet we know that extreme precipitation systems stem from marked low and high-pressure systems, or in other words from strong centres of action. Thus we complement the above descriptors by a fourth descriptor which is not based on analogy and that characterizes the curvature of a given geopotential height field. We consider the Maximum Pressure Difference (MPD), defined for day \( t_k \) as the range of geopotential heights (in meters) within the same 32° × 16° window (Figure 1):
\[ MPD_k = \max_j (z_{jk}) - \min_j (z_{jk}). \] (6)

The higher \( MPD_k \), the larger the pressure difference between low- and high-pressure systems at day \( t_k \), that is, the more pronounced the centres of action over Western Europe for this day. Note that NAO, although it is also a pressure difference, is actually barely correlated to MPD and it revealed less performing for our region in particular because positive NAO phases can be associated to different storm-track latitudes standing either over Western Europe or being shifted northward. Finally, the MPD for sequence \( S_k \) is defined as the average over the three consecutive days.

### RESULTS AND DISCUSSION

#### 4.1 The atmospheric descriptors

#### 4.1.1 Overview

The 500 hPa geopotential height fields of the 3-day sequences featuring the minimum and maximum celerity, singularity, relative singularity and MPD over the period 1950–2017 are shown in Figure 6. The 60 sequences featuring the largest and the lowest descriptor values have also been mapped and they show similar features to Figure 6 (not shown). The 3-day sequence of minimum celerity...
features high pressure from Northern Africa to Eastern Mediterranean Sea and a trough over the Britannic Islands, inducing a west-to-southwest flow over Western Europe. The position of the low and high-pressure systems is almost stationary, inducing a steady flow direction for 3 days. The 3-day sequence of maximum celerity features on the first day two low-pressure systems in the Eastern Atlantic and Western Mediterranean Sea. These merge with a trough over the Britannic Islands on the second day, which develops into a cold drop over the Mediterranean Sea on the third day. The geopotential shapes and hence the wind direction changes much throughout the sequence in the Western part of the domain, giving high celerity.

Both the 500 hPa geopotential height fields featuring the minimum singularity and the minimum relative singularity show a quite classical flow direction for Western Europe (Figure 6c,e). For the minimum singularity, high and low-pressure systems are respectively located in Northern Africa and in the North Sea with a gradual decrease of pressure at increasing latitude, inducing westerlies over Western Europe (Figure 6c). For the relative singularity, a ridge over the East Atlantic and a pronounced low-pressure system over Scandinavia generate a strong northwest flow over Western Europe (Figure 6e). For both sequences, both the singularity and the relative singularity are among the lowest (the relative singularity associated to the minimum singularity is the 6% lowest; the singularity associated to the minimum relative singularity is the 3% lowest). This means these two geopotential shapes are almost similarly reproduced in the climatology. On the opposite, the 3-day sequence of maximum singularity features a quite flat geopotential shape (small range of geopotential heights) inducing a weak circulation. The 3-day sequence showing the maximum relative singularity features a barometric swamp over Europe. Such shapes are hardly reproducible, making these LSCs singular. This statement does not mean that quite flat geopotentials are rare, but rather that very similar geopotential shapes are not found in the climatology. We deal here with the reproducibility of a specific geopotential shape, not with the frequency of occurrence of a class.

The 500 hPa geopotential height field featuring the minimum MPD feature a flat geopotential with almost no circulation (Figure 6g). The geopotential height field featuring the maximum MPD feature a pronounced ridge over the East Atlantic and a pronounced low pressure system over Northeastern Europe producing a strong northwest flow over the Northern French Alps.

4.1.2 | Climatology

As for the seasonality of the descriptors, Figure 7 shows that Western Europe geopotential shapes tend to be more stationary (lower median celerity) and, to a lesser extent, more closely reproducible (lower median singularity) in summer. However, the most stationary shapes and the most closely reproducible shapes show almost no seasonality (see the 0.1 quantile in Figure 7). The relative singularity reaches a minimum in winter and a maximum in June, which is hard to interpret because it does not follow the seasonality of the singularity. However, one can anticipate from the seasonality of the relative singularity that considering different number of analogs depending on the season, and in particular less analogs in winter, might be an option to consider. The strongest centres of action (largest MPD) tend to occur in winter while the weakest centres of action tend to occur in summer. This was expected since winter is associated with a southward shift of the storm track over Western Europe.

The celerity, singularity and relative singularity of 3-day sequences are plotted against the Maximum Pressure Difference (MPD) in percentile scale in Figure 8. It is important to remind here that the Teweles-Wobus score on which the analogy descriptors are based considers relative—and not absolute—pressure gradient differences. Therefore, it reflects the similarity in geopotential shape regardless the pressure gradient over the region. We anticipate here the benefit of using the MPD together with the analogy descriptors in order to interpret pressure differences associated with geopotential shape characteristics. The points of Figure 8 are coloured with respect to the density of points in the scatterplots, defined as the number of points in the scatterplot at a distance less than half the standard deviation. Note that if the descriptors were uncorrelated, the density of points would be uniform. Figure 8a shows that the celerity descriptor is weakly negatively correlated with the MPD (Spearman rank correlation of −0.45). However, the most stationary geopotential shapes (lowest celerities) tend to be associated with pronounced centres of action (high MPD). Indeed it makes sense that geopotential shapes associated with mild atmospheric circulations (for instance barometric swamp) tend to change more easily than a marked circulation (high MPD) featuring pronounced centres of action (for instance a pronounced westerly). The singularity and especially the relative singularity are more negatively correlated with the MPD, with Spearman rank correlation respectively equal to −0.65 and −0.73. The geopotential shapes that are the most reproducible (the lowest singularities and lowest relative singularities) tend to be associated with pronounced centres of action (high MPD).

4.2 | Characterizing Atlantic and Mediterranean circulations

We use the atmospheric descriptors to characterize the two main atmospheric influences associated with
extreme precipitation in the Northern French Alps, namely the Atlantic and the Mediterranean influences. These two atmospheric influences are stratified by the MPD combined with either analogy descriptor, however to a lesser extent for the celerity (Figure 8). Notably, the stratification of the Atlantic and Mediterranean circulations is mirrored. On the one hand, Atlantic circulations tend to feature pronounced and stationary centres of actions (high MPD and low celerity), with geopotential shapes that are almost similarly reproduced in the climatology (low singularity and relative singularity). On the other hand, the Mediterranean circulations tend to feature flatter and non-stationary geopotential shapes (low MPD and high celerity) that are hardly reproducible (high singularity and relative singularity). Thus the degree of zonality of the flow (i.e., whether the circulation is more Atlantic-like or Mediterranean-like) is strongly related to both the singularity and the relative singularity, while the strength of the flow is more strongly related to the relative singularity due to its large correlation with MPD (Figure 8g). Yet, the singularity was shown to explain usual rainfalls and intermittence in the Northern French Alps in Blanchet and Creutin (2020), while the relative singularity was shown to explain the largest precipitation accumulation in the Northern French Alps in Blanchet and Creutin (2020) and to be related to historical storms over Europe in Faranda et al. (2017a). This suggests that the degree of zonality of the flow influences usual rainfalls and intermittence in the Northern French Alps, while both the degree of zonality and the strength of the flow influence extreme precipitation accumulation.

4.3 | Characterizing the Atlantic and Mediterranean circulations driving extreme precipitation

We now characterize the specific Atlantic and Mediterranean circulations driving EPS (Figure 9). Overall, most of EPS are clustered in the top-left corner of the scatterplots (Figure 9a,d,g), meaning that the associated geopotential shapes share specific characteristics. EPS appear to be associated with quasi-stationary geopotential shapes (low celerity), which was expected since large accumulations over 3 days are related to long-lasting precipitation. This is also consistent with other studies linking quasi-stationary conditions at upper-levels with extreme
precipitation for different Alpine regions. For instance, spring and autumn extreme precipitation over the Po and the Rhone basins appear to be associated with a persistent strong southerly flow during several days (Grazzini, 2007). In Northern Alps, the stationarity of weather systems also appear as a recurring feature associated with historical floods in Switzerland (Stucki et al., 2012). Furthermore, most of EPS are associated with geopotential shapes that are reproducible (low singularity and relative singularity) and that feature pronounced centres of action (high MPD).

We distinguish between EPS associated with Atlantic and Mediterranean circulations. Among 138 EPS in the Isère River catchment, respectively 113 and 21 were associated with Atlantic and Mediterranean circulations, pointing out the Atlantic influence as the main influence driving EPS in the Isère River catchment, as also shown for extreme daily precipitation in Figure 2 of Blanchet et al. (2020). Among 122 EPS in the Drac River catchment, respectively 78 and 42 were associated with Atlantic and Mediterranean circulations, pointing out a more balanced contribution of either influence in producing EPS in the Drac River catchment, again in coherence with Figure 2 of Blanchet et al. (2020). Due to concomitance in EPS, there are 142 distinct EPS associated with Atlantic circulations and 49 distinct EPS associated with Mediterranean circulations (Figure 9). Percentiles of descriptor values associated with EPS are reported in Figure 10 for either influence. The rareness of LSC characteristics is also investigated by comparing in Figure 10 the density of points around the EPS to the density of points around the other sequences in the scatterplots of Figure 9, considering absolute descriptor values.

**FIGURE 8** Scatterplot of every 3-day sequence of the period 1950–2017 for MPD against either the celerity (a,b,c), the singularity (d,e,f) or the relative singularity (g,h,i), all being expressed in percentiles. The points are coloured with respect to the density of points in the scatterplot, defined as the number of points at a distance less than half the standard deviation. Densities are either computed on every 3-day sequences (a,d,g), on 3-day sequences belonging to the Atlantic influence (b,e,h), or on 3-day sequences belonging to the Mediterranean influence (c,f,i). The grey points in the background show all the other sequences. The top-right numbers indicate the range of values actually taken in the corresponding panel.
Most of Atlantic circulations driving extreme 3-day precipitation in the Northern French Alps feature among the most stationary, reproducible and marked geopotential shapes—the stationary feature being less pronounced than the other characteristics. This applies when compared to the other Atlantic circulations (Figure 10a), as well as when compared to all 3-day sequences (clustering in Figure 9, Figure 10c). Those combinations of LSC characteristics are rare in both cases (Figure 10b,d). Mediterranean circulations driving extreme 3-day precipitation in the Northern French Alps also feature among the most stationary, reproducible and marked geopotential shape when compared to the other Mediterranean circulations (Figures 9 and 10a)—characteristics that are rare among Mediterranean circulations (Figure 10b). However, they feature a broader spectrum of characteristics overall (no clustering in Figures 9 and 10c)—characteristics that are not so rare with regard to the whole climatology (Figure 10d).

### 4.4 Atmospheric humidity during EPS

Precipitation results from three-dimensional motions of the atmosphere. Those motions can be seen as a combination of LSC, reflecting air advection in two dimensions, and large-scale convection, reflecting vertical motions. On the one hand, the fact that EPS associated with Atlantic circulations feature among the most stationary, reproducible and marked geopotential shapes with regard to
the whole climatology—characteristics that are rare (Figure 10c,d)—suggests that LSC plays a leading role in producing EPS in the Northern French Alps through Atlantic circulations. On the other hand, the fact that Mediterranean circulations associated with EPS feature a broader range of LSC characteristics (Figure 10c)—in particular less pronounced and stationary centres of action, reflecting a weaker air advection over a given region—possibly points out the strong role played by convection in producing EPS in the Northern French Alps through Mediterranean circulations.

To investigate this, we consider the atmospheric humidity through the TCW over the Northern French Alps (Figure 1). The seasonal cycle of TCW clearly follows the seasonal cycle of air temperature (Figure 11a), and thus of large-scale convection. Although most of EPS associated with Atlantic circulations feature large TCW for their season of occurrence (Figure 11b), they mostly occur between December and March when atmospheric humidity reaches its lowest values (Figure 11a). This confirms that LSC plays a leading role in producing EPS in the Northern French Alps through Atlantic circulations in winter. EPS associated with Mediterranean circulations clearly feature the largest TCW for their season of occurrence (Figure 11b), and mostly occur in autumn when atmospheric humidity remains large after the hot season (Figure 11a). This points out the important role played by the atmospheric humidity in producing EPS under Mediterranean circulations in the Northern French Alps. These EPS probably result from the concomitance of pronounced and stationary Mediterranean circulations combined with a significant convection over the warm Mediterranean Sea.

**FIGURE 10** (a and c) Percentile of the celerity, singularity, relative singularity and MPD of EPS associated with Atlantic circulations (142 sequences, blue boxes) and Mediterranean circulations (49 sequences, beige boxes). (b and d) Percentile of the number of neighbours (density) around the EPS when considering absolute descriptor values rather than percentiles. Percentiles in (a and b) are computed with respect to the 3-day sequences associated to the given atmospheric influence over the period 1950–2017. Percentiles in (c and d) are computed with respect to all 3-day sequences over the period 1950–2017.
FIGURE 11 (a) Seasonality of TCW over the Northern French Alps for the period 1950–2017. The red line represents the interannual median; the grey lines represent the interannual 0.1 and 0.9 quantiles. The TCW of EPS associated with Atlantic and Mediterranean circulations are respectively represented by blue points (142 sequences) and beige points (49 sequences). The dotted lines represent the median TCW of EPS associated with both influences. (b) Percentile of seasonally adjusted TCW for EPS associated with Atlantic and Mediterranean circulations are respectively represented by blue points (142 sequences) and beige points (49 sequences). The dotted lines represent the median; the grey lines represent the interannual 0.1 and 0.9 quantiles. The TCW of EPS associated with Atlantic and Mediterranean circulations are among the most stationary, reproducible and marked geopotential shapes, Atlantic circulations featuring among the most stationary, reproducible and more marked geopotential shapes than Mediterranean circulations (i.e., meridional flows).

5 | CONCLUSION

This article investigated the characteristics of Atlantic and Mediterranean circulations driving extreme 3-day precipitation in the Northern French Alps, in comparison to ‘random’ Atlantic/Mediterranean circulations. We used an existing weather pattern classification to identify Atlantic and Mediterranean circulations. We then characterized every single LSC using three atmospheric descriptors based on analogy in 500 hPa geopotential shapes over Western Europe, combined with a (non analogy) descriptor accounting for the intensity of high- and low-pressure systems.

We showed that the atmospheric descriptors stratify Atlantic and Mediterranean circulations. Atlantic circulations (i.e., zonal flows) feature more stationary, more reproducible and more marked geopotential shapes than Mediterranean circulations (i.e., meridional flows).

Atlantic circulations driving extreme 3-day precipitation in both the Isère and the Drac River catchments are the Atlantic circulations featuring among the most stationary, reproducible and marked geopotential shapes, corresponding to the strongest and the most stationary westerlies over 3 days—LSC characteristics that are rare. Those LSC characteristics are even more pronounced and rare in comparison to the whole climatology, pointing LSC as a leading driver of extreme precipitation in the Northern French Alps through Atlantic circulations.

Mediterranean circulations—LSC characteristics that are also rare. However, they feature a broader spectrum of characteristics that are not so rare in comparison to the whole climatology. Extreme 3-day precipitation associated with Mediterranean circulations mostly occurs in autumn and they are associated with large atmospheric humidity, pointing out a more balanced contribution between LSC and atmospheric humidity brought from the warm Mediterranean Sea.

This work gave insights on the characteristics of extreme precipitation LSC and discussed the role of LSC in producing extreme precipitation in the Northern French Alps through different atmospheric influences. This view opens the door to future studies on the occurrence of such ‘critical’ LSC characteristics in a climate change context—whether they will become more or less frequent—an interesting perspective for climate change studies.

ACKNOWLEDGEMENTS

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). This work is also partly funded by the HYDRO-DEMO project with the support of the European Union via the FEDER-POIA program and thanks to French state funds via the FNADT-CIMA program. 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.

AUTHOR CONTRIBUTIONS
Antoine Blanc: Data curation; formal analysis; investigation; methodology; software; visualization; writing-original draft; writing-review & editing. Juliette Blanchet: Data curation; funding acquisition; methodology; project administration; supervision; validation; writing-review & editing. Jean-Dominique Creutin: Funding acquisition; methodology; project administration; validation.

ORCID
Antoine Blanc https://orcid.org/0000-0003-0935-4502
Juliette Blanchet https://orcid.org/0000-0001-8088-8895

REFERENCES
Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungerstöck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stasny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z. and Niplova, E. (2007) HISTALP—historical instrumental climatological surface time series of the greater alpine region. International Journal of Climatology, 27(1), 17–46. https://doi.org/10.1002/joc.1377.

Barnston, A.G. and Livezey, R.E. (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Review, 115(6), 1083–1126. https://doi.org/10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2.

Bartolini, E., Claps, P. and D’Odorico, P. (2009) Interannual variability of winter precipitation in the European Alps: relations with the North Atlantic Oscillation. Hydrology and Earth System Sciences, 13(1), 17–25. https://doi.org/10.5194/hess-13-17-2009.

Beniston, M. (2005) Mountain climates and climatic change: an overview of processes focusing on the European Alps. Pure and Applied Geophysics, 162(8), 1587–1606. https://doi.org/10.1007/s00024-005-2684-9.

Blanchet, J. and Creutin, J.-D. (2020) Explaining rainfall accumulations over several days in the French Alps using low-dimensional atmospheric predictors based on analogy. Journal of Applied Meteorology and Climatology, 59(2), 237–250. https://doi.org/10.1175/JAMC-D-19-0112.1.

Blanchet, J., Creutin, J.-D. and Blanc, A. (2021) Retreating winter and strengthening autumn Mediterranean influence on extreme precipitation in the southwestern Alps over the last 60 years. Environmental Research Letters, 16, 034056. https://doi.org/10.1088/1748-9326/abb5cd.

Blanchet, J., Stella, S. and Creutin, J.-D. (2018) Analogy of multiday sequences of atmospheric circulation favoring large rainfall accumulation over the French Alps. Atmospheric Science Letters, 19(3), e809. https://doi.org/10.1002/asl.809.

Boë, J. and Terray, L. (2008) A weather-type approach to analyzing winter precipitation in France: twentieth-century trends and the role of anthropogenic forcing. Journal of Climate, 21(13), 3118–3133. https://doi.org/10.1175/2007JCLI1796.1.

Chardon, J., Hingray, B. and Favre, A.-C. (2018) An adaptive two-stage analog/regression model for probabilistic prediction of small-scale precipitation in France. Hydrology and Earth System Sciences, 22(1), 265–286. https://doi.org/10.5194/hess-22-265-2018.

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessoumain, P., Brönnimann, S., Brunet, M., Crouthamel, R.I., Grant, A.N., Groisman, P.Y., Jones, P.D., Kruk, M.C., Kruger, A.C., Marshall, G.J., Maugeri, M., Mok, H.Y., Nordli, O., Ross, T.F., Trigo, R.M., Wang, X.L., Woodruff, S.D. and Worley, S.J. (2011) The twentieth century reanalysis project. Quarterly Journal of the Royal Meteorological Society, 137 (654), 1–28. https://doi.org/10.1002/qj.776.

Daoud, A.B., Sauquet, E., Bontron, G., Obled, C. and Lang, M. (2016) Daily quantitative precipitation forecasts based on the analogue method: Improvements and application to a French large river basin. Atmospheric Research, 169, 147–159. https://doi.org/10.1016/j.atmosres.2015.09.015.

Duband. (1981) Prévision spatiale des hauteurs de précipitations journalières, La Houille Blanche, 67(7-8), 497–512. https://doi.org/10.1051/lhb/1981046.

Durand, Y., Latermer, M., Giraud, G., Etchevers, P., Lesaffre, B. and Méridol, L. (2009) Reanalysis of 44 Yr of climate in the French Alps (1958–2002): methodology, model validation, climatology, and trends for air temperature and precipitation. Journal of Applied Meteorology and Climatology, 48(3), 429–449. https://doi.org/10.1175/2008JAMC1808.1.

Faranda, D., Messori, G., Alvarez-Castro, M.C. and Yiou, P. (2017b) Dynamical properties and extremes of northern hemisphere climate fields over the past 60 years. Nonlinear Processes in Geophysics, 24(4), 713–725. https://doi.org/10.5194/npg-24-713-2017.

Faranda, D., Messori, G. and Yiou, P. (2017a) Dynamical proxies of North Atlantic predictability and extremes. Scientific Reports, 7, 41278. https://doi.org/10.1038/srep41278.

Faranda, D., Vrac, M., Yiou, P., Jézéquel, A. and Thao, S. (2020) Changes in future synoptic circulation patterns: consequences for extreme event attribution. Geophysical Research Letters, 47 (15). https://doi.org/10.1029/2020GL088002.

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

Gottardi, F., Obled, C., Gailhard, J. and Paquet, E. (2012) Statistical reanalysis of precipitation fields based on ground network data and weather patterns: application over French mountains. Journal of Hydrology, 432–433, 154–167. http://www.sciencedirect.com/science/article/pii/S002216941200114X.

Grazzini, F. (2007) Predictability of large-scale flow conducive to extreme precipitation over the Western Alps. Meteorology and Atmospheric Physics, 95, 123–138. https://doi.org/10.1007/s00703-006-0205-8.
Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Rudu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D. and Thépaut, J.-N. (2018). ERA5 hourly data on pressure levels from 1950 to 1978 (preliminary version) and from 1979 to present,. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). [Accessed 20th November 2020]. https://doi.org/10.24381/cds.hd0915c6

Horton, P., Jaboyedoff, M., Metzger, R., Obled, C. and Marty, R. (2012) Spatial relationship between the atmospheric circulation and the precipitation measured in the western Swiss Alps by means of the analogue method. Natural Hazards and Earth System Sciences, 12, 777–784. https://doi.org/10.5194/nhess-12-777-2012.

Hurrell, J.W. (1995) Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science, 269 (5224), 676–679. https://doi.org/10.1126/science.269.5224.676.

Jézéquel, A., Yiou, P., Radanovics, S. and Vautard, R. (2017) Analysis of the exceptionally warm December 2015 in France using flow analogues. Bulletin of the American Meteorological Society, 99, S76–S79. https://doi.org/10.1175/BAMS-D-17-0103.1.

Lim, Y.-K. (2015) The East Atlantic/West Russia (EA/WR) teleconnection in the North Atlantic: climate impact and relation to Rossby wave propagation. Climate Dynamics, 44, 3211–3222. https://doi.org/10.1007/s00382-014-2381-4.

Lorenz, E.N. (1969) Atmospheric predictability as revealed by naturally occurring analogues. Journal of the Atmospheric Sciences, 26, 636–646. https://doi.org/10.1175/1520-0477-26.4.636.

Marty, R., Zin, I., Obled, C., Bontron, G. and Djerboua, A. (2012) Toward real-time daily PQPF by an analog sorting approach: application to flash-flood catchments. Journal of Applied Meteorology and Climatology, 51(3), 505–520. https://doi.org/10.1175/JAMC-D-11-011.1.

Matulla, C., Zhang, X., Wang, X.L., Wang, J., Zorita, E., Wagner, S. and von Storch, H. (2008) Influence of similarity measures on the performance of the analog method for downscaling daily precipitation. Climate Dynamics, 30(2), 133–144. https://doi.org/10.1007/s00382-007-0277-2.

Messori, G., Caballero, R. and Faranda, D. (2017) A dynamical systems approach to studying midlatitude weather extremes. Geophysical Research Letters, 44(7), 3346–3354. https://doi.org/10.1002/2017GL072879.

Obled, C., Bontron, G. and Garçon, R. (2002) Quantitative precipitation forecasts: a statistical adaptation of model outputs through an analogues sorting approach. Atmospheric Research, 63(3), 303–324. https://doi.org/10.1016/S0169-8095(02)00038-8.

Plaut, G., Schuepbach, E. and Marut, D. (2001) Heavy precipitation events over a few alpine sub-regions assessed the links with large-scale circulation, 1971–1995. Climate Research, 17, 285–302.

Poli, P., Hersbach, H., Dee, D.P., Berrisford, P., Simmons, A.J., Vitart, F., Laloyaux, P., Tan, D.G.H., Peubey, C., Thépaut, J.-N., Trémolet, Y., Hólm, E.V., Bonavita, M., Isaksen, L. and Fisher, M. (2016) ERA-20C: an atmospheric reanalysis of the twentieth century. Journal of Climate, 29(11), 4083–4097. https://doi.org/10.1175/JCLI-D-15-0556.1.

Radanovics, S., Vidal, J., Sausquet, E., Ben Daoud, A. and Bontron, G. (2013) Optimising predictor domains for spatially coherent precipitation downscaling. Hydrology and Earth System Sciences, 17, 4189–4208. https://doi.org/10.5194/hess-17-4189-2013.

Raynaud, D., Hingray, B., Zin, I., Anquetin, S., Debionne, S. and Vautard, R. (2017) Atmospheric analogues for physically consistent scenarios of surface weather in Europe and Maghreb. International Journal of Climatology, 37(4), 2160–2176. https://doi.org/10.1002/joc.4844.

Rodrigues, D., Alvarez-Castro, M.C., Messori, G., Yiou, P., Robin, Y. and Faranda, D. (2018) Dynamical properties of the North Atlantic atmospheric circulation in the past 150 years in CMIP5 models and the 20CRv2c reanalysis. Journal of Climate, 31, 6097–6111. https://doi.org/10.1175/JCLI-D-17-0176.1.

Schmidli, J., Schmutz, C., Frei, C., Wanner, H. and Schär, C. (2002) Mesoscale precipitation variability in the region of the European Alps during the 20th century. International Journal of Climatology, 22(9), 1049–1074. https://doi.org/10.1002/joc.769.

Sodemann, H. and Zubler, E. (2010) Seasonal and inter-annual variability of the moisture sources for alpine precipitation during 1995–2002. International Journal of Climatology, 30(7), 947–961. https://doi.org/10.1002/joc.1932.

Stucki, P., Rickli, R., Brönnimann, S., Martius, O., Wanner, H., Grebner, D. and Luterbacher, J. (2012) Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868. Meteorologische Zeitschrift, 21, 531–550. https://doi.org/10.1127/0941-2948/2012/368.

Teweles, S. and Wobus, H.B. (1954) Verification of prognostic flow analogues. Monthly Weather Review, 82(1), 1–16. https://doi.org/10.1175/1520-0477-35.10.455.

Vautard, R. (1990) Multiple weather regimes over the North Atlantic atmospheric circulation in the past 150 years in CMIP5 models and the 20CRv2c reanalysis. Journal of Climate, 29, 4631–4651. https://doi.org/10.1175/JCLI-D-17-0240.1.

How to cite this article: Blanc, A., Blanchet, J., & Creutin, J.-D. (2021). Characterizing large-scale circulations driving extreme precipitation in the Northern French Alps. International Journal of Climatology, 1–16. https://doi.org/10.1002/joc.7254