RESEARCH ARTICLE

Analogy of multiday sequences of atmospheric circulation favoring large rainfall accumulation over the French Alps

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We propose in this article an analogy approach for characterizing the similarity between daily atmospheric state sequences—in our case large-scale geopotential height fields. The similarity is measured using two indices—the persistence and the singularity. The persistence of a sequence is defined through the average distance between its consecutive states. Its singularity is the average distance between its states and their closest analogues. We apply these indices to geopotential heights over Western Europe in view of characterizing the sequences yielding record rainfall accumulations over several days in the Northern French Alps, more specifically in the Isère River catchment at Grenoble. We show that these indices remarkably stratify the heaviness of rainfall sequences in the region. We find that the less singular and the more persistent the atmospheric state sequence, the wetter the rainfall sequence. Although the persistence of atmospheric states leading to extremes was expected, their low singularity might be a feature of the Northern French Alps, which usually experiences roughly westerly winds triggering orographically enhanced precipitation. Relying on some choices that may be improvable, our study opens the door to future research on the characterization of the atmospheric state sequences favoring regional climate extremes based on analogy.

KEYWORDS
analogy, atmospheric circulation, French alps, physical phenomenon, rainfall

1 | INTRODUCTION

The stationarity of the meteorological systems is a factor favoring large rainfall accumulation and consequent flooding situations over watersheds of varied superficies. James, Stohl, Spichtinger, Eckhardt, and Forster (2004) describe the exceptional rainfall event that touched an impressive part of central and southern Europe over a two-week period in August 2002 as related to a quasi-stationary trough in which individual convective systems were readily generated over a period of 2 weeks. Grams, Binder, Pfahl, Piaget, and Wernli (2014) attribute the exceptional rainfall event over mostly the same area in May and June 2013 to a comparable chain of stationary atmospheric features controlled by repeated Rossby wave breakings. Ducrocq, Nuissier, Ricard, Lebeaupin, and Thouvenin (2008) describe more localized exceptional rainfall events that regularly affect much more limited mountainous areas in southern Europe as related to southerly low-level flows that remain persistent over a couple of days and that feed mesoscale convective systems triggered by orography. Looking at extreme rainfall events in the United Kingdom, Hand, Fox, and Collier (2004) confirm the important role of large-scale circulation showing for instance that 80% of the record accumulations under frontal systems are linked to slow moving depressions. In the United States, high amplitude jet stream meanders, when blocked, are also responsible for boreal summer extremes like in 2003 and 2010 in different regions of the Northern Hemisphere (Coumou & Rahmstorf, 2012).

At large scale, the blocking of atmospheric circulation at midlatitudes triggered scientific curiosity since over one century in relation to long-range meteorological forecasting...
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Our study looks if the largest observed rainfall accumulations in an Alpine region in France can be related to some form of atmospheric stationarity, what James et al. (2004) qualify as an “unusually persistent” atmospheric structure. We use an analogy approach to point sequences of daily atmospheric states that remain “unusually” the same from 1 day to the next ones. We investigate the same way whether these unusual sequences are composed of states that are in themselves singular.

The notion of analogy was pioneered by Lorenz (1969) to study how slightly different initial atmospheric conditions may diverge into atmospheric states bearing little resemblance. A central point of his reasoning was to work on differences between states more than on their absolute position in the multidimensional space describing atmospheric physics. Most Lorenz’s followers used analogy between atmospheric states over continental windows making a central assumption: the variables characterizing large-scale atmospheric states—most often pressure fields—govern variables of interest that are observed in situ, at smaller scale, like temperature or precipitation. They used many large- and small-scale variables under many methodological settings—domain sizes, analogy indices, etc. Their main applications are either in forecasting—the in situ observations for the analog days of tomorrow are predictions for tomorrow (Ben Daoud, Sauquet, Bontron, Obled, & Lang, 2016; Paegle, 1974), or in downscaling General Circulation Model outputs—the in situ observations for the analog days of today are plausible alternatives to the observation of today (Raynaud et al., 2017; Zorita & von Storch, 1999). The link between large-scale flow and surface variables may be non-stationary over the long run, in particular for precipitation (Vautard & Yiou, 2009). In summary, most analogy applications are at daily time step and look at similarities between couples of states.

Even though the use of analogy for atmospheric states is now quite mature, its use for sequences of atmospheric states appeared only recently in the literature. Matulla et al. (2008) downscale “ordinary” daily precipitations from pressure fields in California and Austria and find some benefit to take into account sequences of antecedent days to estimate persistent features such as the frequency distribution of dry and wet spells. Zhou and Zhai (2016) use a comparable approach to forecast from pressure and humidity fields “persistent extreme precipitation events” in the Yangtze–Huai River valley in China. Both studies use “weighted” averages of a chosen similarity index over 7 days. The weighting functions applied to the sequence of states are power laws increasing with time, that is, assuming the last day of the sequence is the most important. In both cases, the main motivation for looking at sequences is that the local-scale variable of interest is multidaily. An additional motivation is that the local-scale variable a given day may also result from the atmospheric states of the antecedent days. Yiou et al. (2017) consider a neighborhood of analogues (or “tube” of analogues) of a given monthly circulation sequence to estimate the probability of rainfall accumulation conditional on the atmospheric circulation sequence and use this probability to make conditional extremal rainfall attribution. Yiou (2014) simulates weather by generating new sequences of atmospheric states by “jumping” from one observed sequence to a neighboring one identified by analogy. Finally, Yiou et al. (2013, 2014) consider analogy of sequences of situations to obtain some time continuity in the reconstruction of sea-level pressure, temperature and wind fields above the North Atlantic.

After a description of our case study and the methods we use to define the persistence and the singularity of atmospheric state sequences (section 2), we show how these indices are able to stratify the heaviness of rainfall accumulations (section 3) before to conclude and discuss the results.

2 | MATERIALS AND METHODS

2.1 | Study area and data

We consider large-scale geopotential height fields over Western Europe with view of characterizing the sequences yielding record rainfall accumulations over several days in the Isère River catchment at Grenoble in the Northern French Alps (Figure 1). Altitude of the catchment ranges from about 200 m in the Isère River valley to 3,900 m in the Ecrins national park, with a median altitude of about 1,500 m. This area is characterized by cold winters with precipitations occurring mainly as snow above 1,500 m and warm summers with precipitations under the double influence of air flows originating from the Atlantic and the Mediterranean. In a comparable setting in Switzerland, Scherrer, Begert, Croci-Maspoli, and Appenzeller (2016) show that the influence of large-scale flow on precipitation variability is strongest in winter with Atlantic influence as leading
pattern. It is, however, less obvious than in other settings, as compared to California, for instance, in Matulla et al. (2008).

Since the Isère River catchment has a response time of a few days, we consider in this study 3-day rainfall accumulation at catchment scale. Daily accumulation is obtained by interpolating daily rain gauge data provided by Météo-France on a 1 × 1 km² grid using thin plate spline interpolation. We use 61 stations featuring less than 25% of missing data in the period 1950–2011. Within this period, there is on average 57 measuring stations per day (minimum 36 stations).

We consider geopotential heights at 1,000 and 500 hPa, which are the best predictors found for precipitation in Europe in Raynaud et al. (2017). Geopotential heights are extracted from NOAA-CIRES 20th Century Reanalysis V2c, considering arbitrarily the first member of the reanalyses. Spatial resolution is 2° in longitude and latitude. We use as daily data for a given grid point the daily means of geopotential heights at 0:00 a.m., 6:00 a.m., 12:00 a.m. and 6:00 p.m. Data are available back to 1,851 but we restrict in this study to 1950–2011 to match the rainfall measurement period. The best spatial domain used to compute analogues is expected to be variable- and region-dependent (Chardon et al., 2014). The existing tools to optimize the limits of the spatial analogy (Chardon et al., 2014; Raynaud et al., 2017) are not relevant in our case since there is no simple validation score to use as in the case of Chardon et al. (2014) and Raynaud et al. (2017) aiming prediction. The windows considered for both geopotential heights are centered on 6°E longitude and 44°N latitude (see Figure 1). The spatial domain sizes 32° in longitude and 16° in latitude for the 500 hPa geopotential height and 16° in longitude and 8° in latitude for the 1,000 hPa geopotential. These domains are pretty similar to the optimal windows found in Raynaud et al. (2017) in the region.

### 2.2 Analogy between atmospheric states

The identification of analogues of atmospheric circulation follows previous developments for probabilistic precipitation forecasts in France (Bontron & Obled, 2005; Chardon et al., 2014; Raynaud et al., 2017). For a given target day, a seasonal filter is first applied by considering calendar days within ±30 days around the target day as potential candidates. Then a criterion for similarity between the target day and each candidate day is computed. The chosen criterion is the Teweles–Wobus score (Teweles & Wobus, 1954), which evaluates the similarity in shape of geopotential fields. Let \( z_{jk}^{(i)} \) denote the height at pressure \( p_i \), grid point \( s_j \) and observation time \( t_k \). The Teweles–Wobus score for days \( t_k \) and \( t_k^0 \) at pressure \( p_i \) is

\[
\Delta_{k,k^0}^{(i)} = \frac{\sum_{(j,f) \in A^{(i)}} \left| z_{jk}^{(i)} - z_{jk}^{(i)} \right| - \left| z_{jk}^{(i)} - z_{jk}^{(i)} \right| \right|}{\sum_{(j,f) \in A^{(i)}} \max \left| z_{jk}^{(i)} - z_{jk}^{(i)} \right|},
\]

where \( A^{(i)} \) ranges the set of adjacent grid points in horizontal and vertical directions in the analogy window of geopotential heights at pressure \( p_i \). The final score for days \( t_k \) and \( t_k^0 \) at pressure \( p_i \) is the mean of the scores at 500 and 1,000 hPa:

\[
\Delta_{k,k^0} = \left( \Delta_{k,k^0}^{(1)} + \Delta_{k,k^0}^{(2)} \right) / 2.
\]
2.3 Notions of celerity and singularity of atmospheric state sequences

We move from single states to sequences by suggesting new indices to characterize atmospheric state sequences of $N > 1$ days. As explained in section 1, we assume that two characteristics of the atmospheric state sequences may govern large rainfall accumulations. The first characteristics is that the atmospheric states along the sequence of large rainfall accumulations are in themselves “unusual,” and for this we define a singularity index looking at state analogies from each day of the sequence to its analogues. The singularity of the atmospheric state at day $t_k$, denoted $\tau_k$, is defined as the mean Teweles–Wobus score between $t_k$ and its $D$ most analog days, that is, the mean of the $D$ smallest values of $\Delta_k, 1, \Delta_k, 2, \ldots$, which we denote $\Delta_k, (1), \ldots, \Delta_k, (D)$. In this study, we use $D = 20$ as a compromise between considering quite analog days and having reliable estimates of the mean score. Defined as such, the singularity at day $t_k$ shares great similarity with the local dimension of Faranda, Messori, and Yiou (2016), although by taking $D = 20$ we impose a much greater degree of analogy.

The singularity of an atmospheric state sequence starting at day $t_k$ is defined as the mean singularity of its $N$ days:

$$\tau_k = \frac{1}{ND} \sum_{d=1}^{D} \sum_{n=k}^{k+N-1} \Delta_{n,(d)}. \quad (3)$$

Note that the singularity, as defined, describes the unusualness of the successive states of a sequence, not of a trajectory. It is indeed defined as the mean singularity of the atmospheric states of each day taken individually, omitting their sequentiality. It differs from the analogy from the atmospheric state at day $t_k$, denoted $\tau_k$, is defined as the mean Teweles–Wobus score between $t_k$ and its $D$ most analog days, that is, the mean of the $D$ smallest values of $\Delta_k, 1, \Delta_k, 2, \ldots$, which we denote $\Delta_k, (1), \ldots, \Delta_k, (D)$. In this study, we use $D = 20$ as a compromise between considering quite analog days and having reliable estimates of the mean score. Defined as such, the singularity at day $t_k$ shares great similarity with the local dimension of Faranda, Messori, and Yiou (2016), although by taking $D = 20$ we impose a much greater degree of analogy.

The singularity of an atmospheric state sequence starting at day $t_k$ is defined as the mean singularity of $N$ days:

$$\tau_k = \frac{1}{N} \sum_{n=k}^{k+N-1} \Delta_{n,n+1}. \quad (4)$$

Note that we choose to use a celerity rather than a persistence index for the sake of homogeneity between Expressions (3) and (4) that are both averages of Teweles–Wobus scores. Working on persistence would unnecessarily introduce inverse values.

3 Results

We start studying the link between celerity and singularity of atmospheric state sequences, independently on the rainfall accumulations. Figure 2 shows the scatter plot of celerity and singularity for 3-day sequences between 1950 and 2011. The ellipse-like shape of the points reveals that celerity and singularity are statistically linked, which might be due to the fact that a slow celerity induces a relatively small Teweles–Wobus score between successive days and thus likely a lower singularity. The color of the points in Figure 2 shows the density of sequences in the celerity-singularity plane. It is computed as the number of sequences lying in the circle of radius 0.02 centered on each point $\pi_{\tau_k, \gamma_k}$, that is, the number of points $\pi_{\tau_k}$ such that $(\tau_k - \tau)^2 + (\gamma_k - \gamma)^2 \leq 0.02^2$. The radius 0.02 is arbitrarily chosen in order to consider small circles but containing enough points. We recognize in Figure 2 a Gaussian-like density, with 11% of the sequences featuring celerities and singularities between $\pm 0.02$ their mean values.

In order to link the rainfall accumulation with the celerity and singularity of the corresponding atmospheric sequences, we adopt a “vicinity” approach in the celerity-singularity plane. The idea is to associate to each value of celerity and singularity a statistical distribution of rainfall accumulation. For this, instead of considering the single value of rainfall accumulation for the corresponding sequence of days, we gather the sequences sharing similar values of celerity and singularity, and estimate the

![Figure 2](image-url)
probability density function (PDF) for the corresponding set of rainfall accumulations.

More precisely, let us consider a sequence of days starting at day $t_k$. It has coordinates $\pi_k = (\tau_k, \sigma_k)$ in the celerity-singularity plane. We consider the set of points of the plane lying at less than 0.02 distance from $\pi_k$. This set of points corresponds to the set of sequences sharing similar atmospheric characteristics—in terms of celerity and singularity—to the target sequence. It defines a “vicinity” of the atmospheric state sequence starting at day $t_k$, denoted $\mathcal{V}(\mathcal{S}_k)$.

Now, let us consider the rainfall accumulations corresponding to the sequences in $\mathcal{V}(\mathcal{S}_k)$. The PDF of these values defines the frequency of occurrence of a given rainfall accumulation when the celerity and singularity of the atmospheric state sequence is similar to that of $\mathcal{S}_k$. In other words, it allows to compute quantities such as $p_k(r) = \text{pr}(R > r | S \in \mathcal{V}(\mathcal{S}_k))$, which is the probability that rainfall accumulation exceeds a given level $r$ when the atmospheric state sequence features similar celerity and singularity than that of $\mathcal{S}_k$. Applying this to every sequence between 1950 and 2011 gives a PDF for every sequence $\mathcal{S}_k$.

Since we are mainly interested in large accumulations, let us consider some large quantile associated to $p_k(r)$, for example, the values of $r$ such that $p_k(r) = 1/100$. This represents the accumulation that is exceeded with probability 1% (i.e., the 99%-quantile) when the atmospheric state sequence shares similar celerity and singularity to $\mathcal{S}_k$. To estimate such large quantiles, we consider the 20 largest accumulations in each $\mathcal{V}(\mathcal{S}_k)$ containing at least 20 neighbors. Following extreme value theory (Coles, 2001), we estimate a Generalized Pareto distribution (GPD) based on these 20 values. The $(1 - p)$-quantile is then obtained as

$$r_k(p) = u_k + \frac{\sigma_k}{\xi_k} \left( \frac{\xi_k}{p} \right)^{\frac{1}{\xi_k}} - 1,$$

where $u_k$ is the 20th largest accumulation in $\mathcal{V}(\mathcal{S}_k)$, $\xi_k$ is the proportion of accumulations in $\mathcal{V}(\mathcal{S}_k)$ strictly larger than $u_k$, $\sigma_k > 0$ and $\xi_k \neq 0$ are, respectively, the scale and shape of the estimated GPD. When $\xi_k = 0$, the GPD reduces to the exponential distribution with $(1 - p)$-quantile

$$r_k(p) = u_k + \sigma_k \log(\frac{\xi_k}{p}).$$

Figure 3 depicts the level $r_k(0.01)$ for 3-day accumulations. It shows a remarkable stratification of the 99%-quantiles mainly based on the singularity, with a factor of more than 10 between the smallest and the largest quantiles. The smaller the singularity (i.e., the more common the sequence), the larger the quantile. The celerity has a smaller effect on this ordering. However, the largest quantiles (larger than 100 mm/3 days) are all found for celerities smaller than average. The most extreme quantiles (larger than 150 mm/3 days) are located in the very bottom left corner of the scatter plot, corresponding to very low values of both singularity and celerity. Thus, the largest rainfall accumulations are characterized by both very ordinary (low singularity) and very persistent (low celerity) atmospheric state sequences. Although the persistence of atmospheric states leading to extremes was expected, their usualness might be more surprising at first sight. However, this might be a feature of the Northern French Alps, which usually experiences roughly westerly winds and therefore orographically enhanced precipitation.

Another way of looking at the link between rainfall accumulation and the celerity and singularity of atmospheric sequences is to compute return levels associated to each $\mathcal{V}(\mathcal{S}_k)$. The $T$-year return level corresponds to the level

![Figure 3](image)

**FIGURE 3** Three-day accumulation (mm) that is exceeded with probability 1% when the atmospheric state sequence lies in the vicinity of each $\mathcal{S}_k$, for vicinities containing at least 20 neighbors.
the analogy period to geopotential heights more than on their absolute values, choice of analogy distance, which focuses on the shape of some choices that may be reconsidered. One of these is the rainfall accumulations, we recognize that our study relies on Alps, which usually experiences roughly westerly winds very usualness might be a feature of the Northern French atmospheric states yielding extremes was expected, their wetter the rainfall sequence. Although the persistence of and the more persistent the atmospheric state sequence, the in the Northern French Alps. We find that the less singular and the more persistent the atmospheric state sequence, the singular to \(S_k\). Thus, it differs from Figure 3 in that it corresponds to different probabilities of exceedance, depending on the frequency of occurrence of atmospheric sequences with similar singularity and celerity to \(S_k\).

Figure 4 shows the values of the 30-year return levels for 3-day sequences. It reveals once again that singularity and celerity of atmospheric state sequences remarkably stratify return levels of rainfall accumulation. Large return levels (\(\geq 90 \text{ mm/3 days}\)) are found for singularity lower than its 25% quantile and celerity lower than its median. Extreme return levels (\(\geq 105 \text{ mm/3 days}\)) correspond to singularity between its 0.1 and 8% quantiles and celerity between its 1 and 11% quantiles. Thus, unlike in Figure 3, the largest values are not found in the very bottom left corner due to the rarity of the atmospheric sequences with minimum celerity and singularity.

### 4 | CONCLUSIONS AND DISCUSSION

We proposed in this article a new approach for characterizing analogy between atmospheric state sequences based on their celerity (i.e., nonpersistence) and their singularity. We showed that these indices applied to large-scale geopotential height fields remarkably stratify the heaviness of rainfall accumulations over the Isère River catchment at Grenoble in the Northern French Alps. We find that the less singular and the more persistent the atmospheric state sequence, the the wetter the rainfall sequence. Although the persistence of atmospheric states yielding extremes was expected, their very usualness might be a feature of the Northern French Alps, which usually experiences roughly westerly winds and therefore orographically enhanced precipitation.

Although our new indices reveal to remarkably stratify rainfall accumulations, we recognize that our study relies on some choices that may be reconsidered. One of these is the choice of analogy distance, which focuses on the shape of geopotential heights more than on their absolute values, although this aspect is in part solved by the restriction of the analogy period to \(\pm 30\) days. Moreover, our analogy distance uses geopotential gradients that may be less pertinent than other indices related to potential vorticity and temperature (Hoskins, McIntyre, & Robertson, 1985). Temperature is particularly important in the case of the Isère River catchment because floods usually occur in winter due to the concomitance of large amounts of rainfall and warm wind, which rapidly melts the snowpack.

Another point regards the stationarity of the atmospheric circulation. A short analysis (not shown) revealed that actually the mean celerity increased by about 8% between the 1850s and the 1950s, and decreased afterward but with lesser magnitude. Since record rainfall events respond to low celerity of atmospheric sequences, this recent decrease could imply an increase in the hydroclimatic conditions favoring heavy rainfall. However, the nonstationarity in celerity has to be taken with caution, first because data issues cannot be excluded since the geopotential fields in the beginning of the period are computed from fewer data, and second because this study considers a single reanalysis, while Wyard, Scholzen, Fettweis, Van Campenhout, and François (2017) found contrasting trends in the evolution of the conditions favoring extreme precipitation events in the Belgian Ardennes depending on the considered reanalysis.

Beyond the mere curiosity of characterizing the “unusualness” and “persistence” of situations, our analogy indices may be used as cofactors of extreme rainfall analysis in order (a) to provide more robust rainfall estimates conditional on the atmospheric state sequences and (b) to model possible trends in rainfall consecutive to changes in atmospheric state series. Our approach could also help analyzing long flood chronologies such as, for instance, in Knox (2000) which relates the recurrence of large upper Mississippi floods to an increase in the number of waves and their amplitudes in the middle and upper tropospheric circum-polar westerly circulation. All in all this study opens the door to future research on the characterization of the atmospheric state sequences favoring climate extremes based on analogy. In particular for our case study, next steps would be to analyze more deeply the dynamics of the atmospheric state sequences presenting the lowest values of celerity and singularity in order to better understand the atmospheric circulation favoring the largest rainfall accumulations.

Last but not least, a remaining question regards the generalization of the relation between usualness, persistence and large rainfall accumulation to other catchments. Of particular interest are flatter terrains where analogy might be less efficient according to Chardon et al. (2014), although we consider here analogy of sequences, not states, and our interest is not in prediction. Preliminary results for the Seine River catchment in Paris are encouraging with respect to the strenght of relation usualness–persistence–large rainfall accumulation but this deserves to be validated on deeper analyses.

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