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Abstract

A few types of extreme climate events in the North Atlantic region, such as heatwaves, cold spells or high cumulated precipitation, are connected to the persistence of atmospheric circulation patterns. Understanding or attributing those extreme events requires assessing long-term trends of the atmospheric circulation. This paper presents a set of diagnostics of the intra and interannual recurrence of atmospheric patterns. Those diagnostics are devised to detect trends in the stability of the circulation and the return period of atmospheric patterns. We detect significant emerging trends in the winter circulation, pointing towards a potential increased predictability. No such signal seems to emerge in the summer. We find that the winter trends in the dominating atmospheric patterns and their recurrences do not depend of the patterns themselves.

Introduction

Recent North Atlantic winter and summer extremes have been associated with persistent patterns of atmospheric circulation. Those patterns have been rather contrasted from one year to another. Cold spells of January 2010, December 2010 and February 2012 in Europe resulted from persisting blocking situations over Scandinavia [*Cattiaux et al.*, 2010; *Cohen et al.*, 2010]. Warm winter 2006/2007 [*Cattiaux et al.*, 2009; *Yiou et al.*, 2007] and stormy winter 2013/14 [*Huntingford et al.*, 2014; *van Oldenborgh et al.*, 2015] were dominated by persistent high-pressure systems over the Azores and the Mediterranean sea, respectively. The

low-wind month of December 2016 was dominated by a persisting high pressure center over North-Western Europe [*Vautard et al.*, 2017]. The warm summers of 2003 and 2015 in Europe were associated with either a persisting blocking pattern over Scandinavia or Atlantic low conveying warm air into Europe from North Africa. Therefore it is difficult to claim that a given atmospheric pattern has dominated during recent years to create such climate extremes. However it has been speculated that the amplitude of atmospheric patterns is changing, in particular through a connection between Arctic sea-ice cover and meanders of the jet stream [*Francis and Vavrus*, 2012; *Petoukhov et al.*, 2013]. The statistical significance of such a trend as well as the relevance of the evoked mechanisms has been debated [*Barnes*, 2013; *Screen and Simmonds*, 2013a; b].

The mid-latitude atmospheric variability is characterized by a baroclinic instability of the zonal flow [*Hoskins and James*, 2014]. This instability grows into Rossby waves. It has been argued that the excitation conditions those Rossby waves have increased in the past decades [*Petoukhov et al.*, 2013; *Petoukhov et al.*, 2016].

[*Faranda et al.*, 2016] studied how unstable fixed points of the extra-tropical atmospheric circulation correspond to blocking patterns. [*Faranda et al.*, 2017] investigated the local dimension of North Atlantic atmospheric circulation, and examined the implications for predictability in the winter season.

In this paper, we analyze recently observed trends in the surface North Atlantic circulation in winter and summer. We examine trends in the intra-seasonal recurrence of flow patterns by introducing the notion of recurrence "networks" within a season. The interannual pattern trend is examined by the probability of detecting good analogues of circulation. Those intra and inter annual diagnostics allow to detect emerging properties of the atmospheric circulation.

Data and Methods

We use the reanalysis data of the National Centers for Environmental Prediction (NCEP) [*Kistler et al.*, 2001] between January 1948 and March 2017. We consider the sea-level pressure (SLP) over the North Atlantic (80W-30E; 30-70N). One of the caveats of this reanalysis dataset is the lack of homogeneity of assimilated data, in particular before the satellite era. This can lead to breaks in pressure related variables, although such breaks are mostly detected in the southern hemisphere and the Arctic regions [*Sturaro*, 2003].

The first concept we develop is the intra-seasonal recurrence of atmospheric patterns for the winter and summer seasons (December-January-February (DJF) and June-July-August (JJA)).

The temporal autocorrelation (number of days with an autocorrelation significantly above 0) of SLP around the North Atlantic is close to 5 days on average [*Yiou et al.*, 2012]. If the atmospheric circulation fluctuates around a given state on time scales that are longer than 5 days, this might not be reflected by the sample autocorrelation. Beyond the formal persistence, we are interested in the fact that the atmosphere could come back to a given pattern, after a significant disturbance. This identifies a recurrent --- although unstable --- state of the atmosphere, potentially corresponding to a wave excitation. We adopt two ways of measuring the intra-seasonal recurrence of patterns within a season.

The first one is based on the analysis of weather regimes of the atmospheric circulation. For each season, the SLP anomalies (with respect to the seasonal cycle) are classified onto four weather regimes. The daily seasonal cycle is computed with a smoothing spline of daily averages. We compute the principal components (PCs, [*von Storch and Zwiers*, 2001]) of the NCEP reanalysis SLP data. The weather regimes (WR) are determined by a *k*-means clustering of the first 10 PCs, between 1970 and 2000 [*Michelangeli et al.*, 1995; *Yiou et al.*, 2008]. The WR patterns depend on the season, as well as their effects on surface variables such as precipitation and temperature. For each year and each season (winter and summer), the daily SLP patterns are attributed to the closest WR pattern (in terms of Euclidean distance). The annual frequency of WR is the ratio of the occurrence of the WR to the length of the season. For each year and each season, the *dominant* WR is the one with the highest frequency, and we report the frequency of the dominant weather regime.

The second approach to that concept is based on the similarity of intra-seasonal daily SLP patterns. For each reference day within a season, we determine all the days of the same season that yield a spatial rank correlation that exceeds a threshold r. Here, we take $r = 0.5$, which corresponds to the 60^{th} percentile of all intra-seasonal sample correlation values. Hence, we construct a "network" of resembling days, for each season. The dominating network is the one that yields the largest number of similar patterns. This approach is akin to the dominating WR analysis, but it does not constrain the geographical location of the recurrent weather pattern. The fluctuations of the frequencies of the dominating WR or the "network" sizes help us assess how the persistence of atmospheric patterns varies through time. Those two intra-seasonal quantities (frequency of dominating weather regime and size of dominating network) allow investigating recurrent but potentially unstable patterns of the atmospheric circulation. Those patterns do not need to be visited in spates of consecutive days. Those two approaches are meant to determine the trend of intra-seasonal pattern recurrence. This concept is distinct from the clustering index examined by [*Faranda et al.*, 2017], which focuses on the local

persistence of the system. But the concept is complementary to the analyses of [*Faranda et al.*, 2016] because we identify unstable fixed points (in the phase space of the atmospheric circulation) to which trajectories "try" to come back close to.

The second concept is the interannual recurrence of SLP patterns. The emergence (or disappearance) of patterns is estimated from interannual analogues of circulation [*Yiou et al.*, 2007]. For each day, we determine the best 20 analogues of circulation by minimizing a distance to all days occurring in a different year, but at most 30 calendar days apart. Good analogues have a distance that is smaller than a threshold d_0 corresponding to the 25th percentile of distance, and a spatial correlation that is higher than a threshold $r_0 = 0.5$ corresponding to the 75th percentile of spatial correlations of all 20 best analogues. In practice, the number of good analogues for a given day is always lower than 10 for such data. Therefore retaining more than the 20 best analogues would not change the results. The distributions of correlations for interannual analogues (i.e. picked in another year) and intra-seasonal analogues are different, which explains that the value $r = 0.5$ corresponds to different quantiles in the two cases. The seasonal average number of good analogues is a proxy for the probability of observing a circulation pattern and gives access to the usual character of a season. If this number decreases, then one can conclude that the circulation during that season becomes less typical, leading to the appearance of new patterns with no past analogues.

Results

The frequency of the dominating analogue pattern yields a positive trend in winter (1% of winter days per decade, p-value=0.045) (Figure 1, dashed black lines), and a negative trend in summer (-1% of summer days per decade, p-value=8 10^{-4}) (Figure 2, dashed black lines). The positive winter trend is unstable, due to the upward fluctuation in the 1990s: the trend since 1980 (the use of satellite data in the reanalysis) is close to 0 and not significant, and the trend since 1997 (with the optimal number of assimilated observations) is 1.3% per decade. The summer trend over 1950-2017 is also unstable, with negligible and insignificant trends since 1980 and 1997. The number of days spent in the summer dominating weather regimes (~38 days) or the preferred state (~20 days) is smaller than in the winter (resp. 40 days and 30 days). From a count of the dominant WR frequencies in Figure 1, the zonal weather regime (ZO) has been preferred in the winter between 1948 and 2015. The ZO weather regime dominated 35% of winters (BLO: 29%; NAO- : 19%; AR: 16%). Those weather regimes have

dominated winters roughly equi-probably since 2000. The preferred summer weather regime (Figure 2) has been the Scandinavian blocking (BLO: 40% of summers) (against NAO-: 21%; AR: 21%; AT: 18%). The summer Atlantic Ridge (AR) has dominated only once since 2000 and the other three weather regimes have been rather equi-probable. The AR weather regime is unlikely during warm summers [*Cassou et al.*, 2005]. The period since 2000 has been the longest spell with so few AR occurrences since 1948, although it is difficult to interpret the behavior of the last 15 years in terms of an emerging signal, because of the large decadal variability of the dominating regimes. A similar analysis of the 20CR reanalysis ensemble mean [*Compo et al.*, 2011] provides the same results on the 1948—2012 period (not shown). The period before 1948 does not yield any significant trend, but this could be due to the large ensemble spread whose averaging smears out trends (not shown).

We identify five winters with the largest number of similar days (1969, 1989, 1990, 2010 and 2014). The SLP patterns for those years are shown in Figure 3. The winters that are identified yield zonal (1989, 1990 and 2014) or NAO- (1969 and 2010) weather regimes. We also find that the winters between 1948 and 2014 with more than 35 similar days are in one of those two weather regimes. The extremely persistent winter patterns are the two phases of the North Atlantic Oscillation, that generate either stormy and warm surface conditions (ZO regime), or wet and cold conditions (NAO- regime) over Western Europe.

The five summers for which the recurrence is highest (larger than 25%) are mostly in the Atlantic Ridge regime (4 occurrences) and Scandinavian Blocking (1 occurrence) (Figure 2). By contrast, the five most frequent summer weather regimes (more than 45%) are the Scandinavian Blocking (3 occurrences), Atlantic Ridge (1 occurrence) and Atlantic Low (1 occurrence). This shows that the maximum occurrence of a weather regime within a season is disconnected from its interannual frequency: the summer AR regime is the most recurrent but is not very frequent. Such high recurrence values do not occur after 2000.

The average number of good circulation analogues characterizes the recurrence of the patterns in time. Hence, seasons with few good analogues can be considered as rare, while those with many good analogues are typical. A trend in the number of good analogues indicates a shift in the atmospheric circulation pattern, which might not be detectable in the frequency of weather regimes. Figure 4 shows the time variations of the mean number of good intra-seasonal analogues for the summer and winter. The winter series yields a small but significant positive trend (0.1 analogue day per decade, p-value=$8\ 10^{-3}$, Figure 4a). This means that the daily circulation patterns tend to become more clustered during the last decades, because the circulation analogues become increasingly good.

The summer series yields a significant negative trend (-0.07 analogue day per decade, p-value=8 10^{-3}, Figure 4b). This means that the daily patterns have become individually more exceptional, although not necessarily extreme, from the first part of the period to the second part. The latter JJA decreasing trend does not hold for the last two decades (1990—2016), which yield a slightly positive trend. Therefore, this trend can hardly be interpreted in terms of a climate change signal, because it is likely to be influenced by decadal internal variability.

Discussion

The increasing trend of similar atmospheric patterns in winter started only recently, in the 1970s (Figure 1). This trend means that the patterns become more clustered at the intra-seasonal scale, with a locking to the phases of the North Atlantic Oscillation. Trends in the frequencies of those two weather regimes either bring prolonged episodes of snowfall to Europe (like in 2010, with an NAO- phase), or prolonged stormy episodes and precipitation episodes over northern Europe (like in 2014, with zonal circulation). The concomitant increasing trend of the probability of finding a good winter circulation analogue (Figure 4a) suggests that the return periods of observed winters become shorter, so that winters tend to be similar to already known winters.

The decreasing trend of similar weather patterns in the summer means that slow building extreme events, such as droughts and heatwaves or cold summers, tend to be less frequent in Europe. The concomitant decreasing trend of interannual pattern recurrence suggests that summers become less similar to already known ones, although this trend is very small.

Those results can be interpreted in terms of an increase of predictability of the circulation in the winter because the size of the dominating weather patterns increases. There would be no such trend of predictability in the summer. Therefore, a prediction based on persistence would have an increased skill in the winter.

Our analyses seem to contradict the hypothesis of increased winter mid-latitude atmospheric meandering described by [*Francis and Vavrus*, 2012; *Petoukhov et al.*, 2013], because the winters with the most recurrent weather types we detect have had rather low wave numbers at the surface [*Cattiaux et al.*, 2016] while they were associated to extremely warm and stormy conditions (1989, 1990, 2014) or extremely snowy conditions (1969, 2010) (Figure 3). Arctic sea-ice cover before those winters was either lower or above normal, and the meridional gradient of potential temperature did not show a systematic feature for those five cases, due to the fact that they correspond to opposite phases of the NAO. Yet, our analysis reaches similar

conclusions on the impacts on European surface winter climate, in that more persistent zonal flows increase the probability of observing extra-tropical storms hitting Europe or extreme precipitation amounts in Northern Europe, as in 1999/2000 and 2013/2014. Conversely, prolonged spells of negative phase of the NAO in the winter increases the probability of extreme precipitation (including snow) in Southern Europe, as in 1969 and 2010. Our interpretation is that the atmospheric patterns that dominate during the winter tend to get "trapped" for longer times, although they are not necessarily more stable. We propose a conceptual model for this behavior, with an energy potential model in two dimensions with four wells whose relative depth varies randomly from one year to the next. Daily perturbations can force the system to shift wells, but at the end of the season, the deepest well is the most visited. We find that the deepest well becomes deeper in the winter.

The same analyses (persistence of SLP patterns) were performed for the North Pacific region and the whole Northern hemisphere extra-tropics (not shown). No trend is found on such regions and scales.

Conclusion

In this paper, we have shown significant, albeit small, emerging trends of recurrence properties of the atmosphere over the North Atlantic. Those trends point to increased atmospheric predictability in winter. This is coherent with the small decrease of local dimension reported by [*Faranda et al.*, 2017]. The diagnostics we proposed have an interesting potential to assess the atmospheric temporal variability of climate models, especially for paleoclimates or future scenarios [*Schmidt et al.*, 2014]. Our results can be used to estimate a dynamical contribution in the attribution of extreme events [*National Academies of Sciences and Medicine*, 2016; *Shepherd*, 2016; *Yiou et al.*, 2017], which is considered as a small signal to identify [*Shepherd*, 2016; *Yiou et al.*, 2017]. We have not determined the cause of the winter circulation trends, which could be tied to internal variability [*Cattiaux et al.*, 2016], but this observed emerging trend has an effect on the event attribution process.

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Conflict of interest

The author declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

PY and RV designed the analysis on analogue "networks". PY produced the figures and draft manuscript. All co-authors contributed to the manuscript and figure design.

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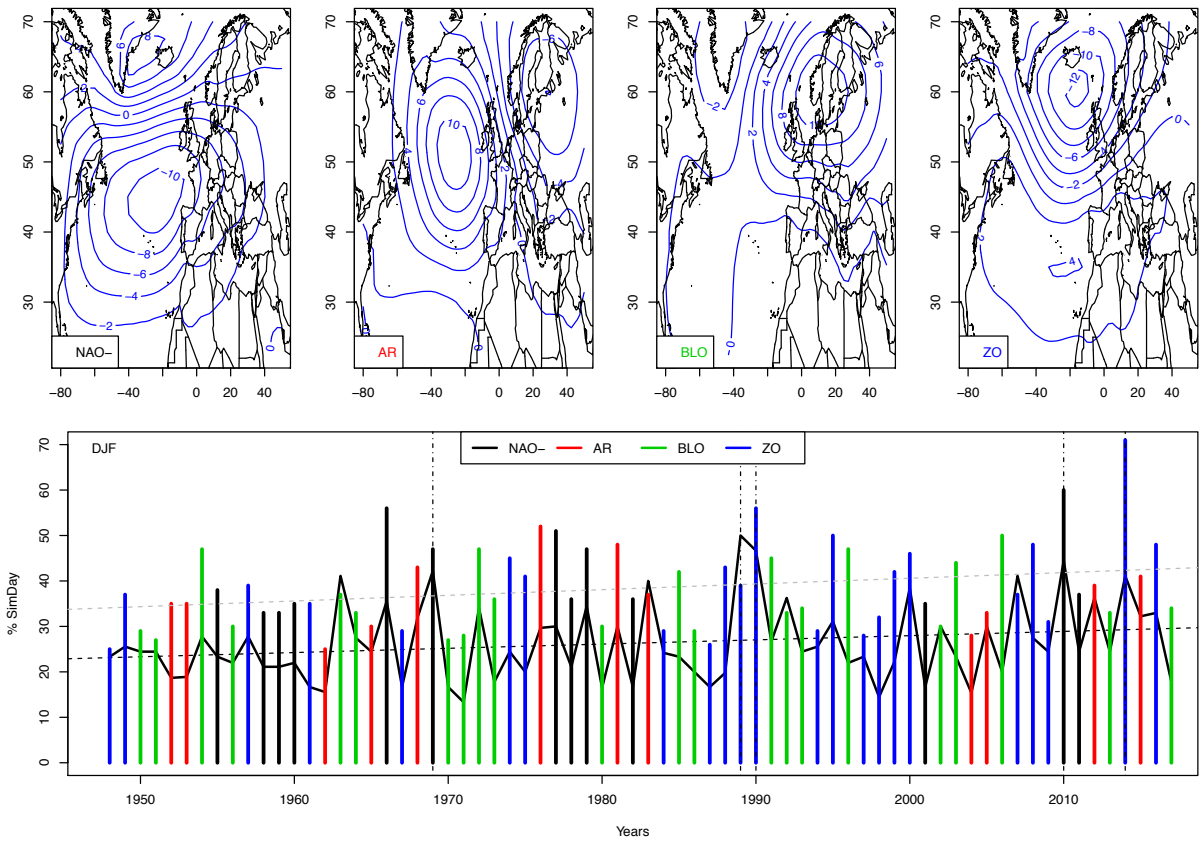


Figure 1: Upper panels: four weather regimes of SLP anomalies in DJF (negative phase of the NAO, Atlantic Ridge, Scandinavian Blocking, zonal flow). The isolines have increments of 2 hPa. Lower panel: Trends in atmospheric persistence for DJF. Vertical colored lines: frequency of dominating weather regime. The color is associated with a weather regime (NAO-: black; AR: red; BLO: green; ZO: blue). Gray dotted lines are for the linear trend of regime frequencies. Continuous black line: maximum percentage of similar days in the winter. Dashed black lines are for the linear trend of similar days. Vertical dash-dotted lines are for the five years with the largest numbers of similar days (1969, 1989, 1990, 2010 and 2014).

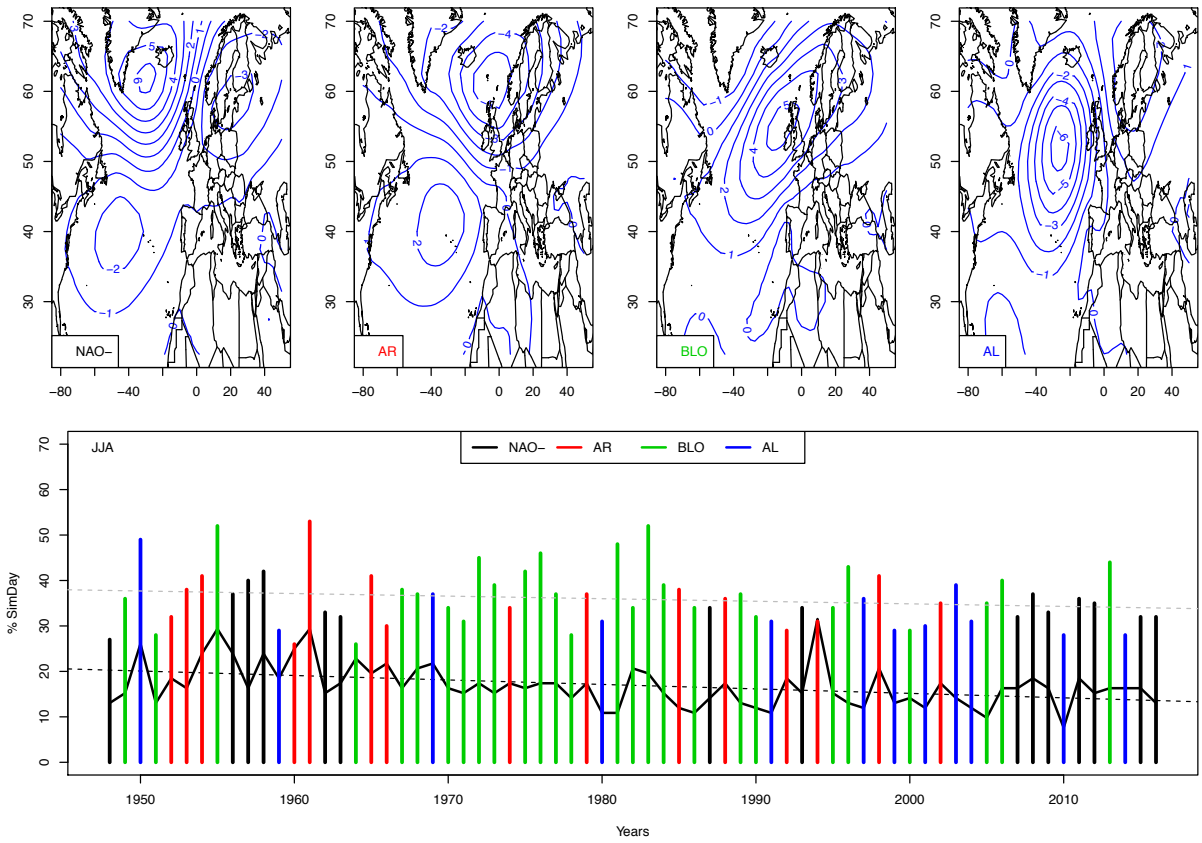
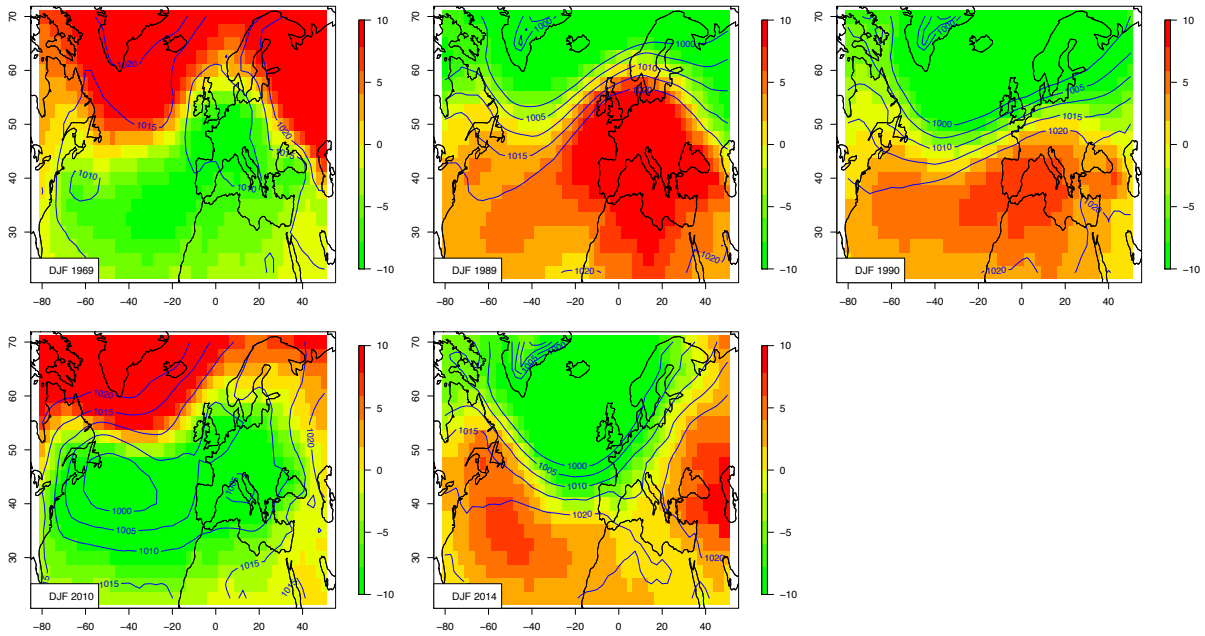


Figure 2: Upper panels: four weather regimes of SLP in JJA (negative phase of the NAO, Atlantic Ridge, Scandinavian Blocking, Atlantic Low). The isolines have increments of 2 hPa. Lower panel: Trends in atmospheric persistence for JJA. Vertical colored lines: frequency of dominating weather regime. The color is associated with a weather regime (NAO-: black; AR: red; BLO: green; AT: blue). Gray dotted lines are for the linear trend of regime frequencies. Continuous black line: maximum percentage of similar days in the winter. Dashed black lines are for the linear trend of similar days.



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312 **Figure 3: Composite of SLP for the clusters of similar winter days for the five years outlined in the text (1969, 1989,**
313 **1990, 2010 and 2014). The isolines represent the SLP with increments of 5hPa. The colors represent anomalies of SLP**
314 **(in hPa) with respect to a mean seasonal cycle computed at each gridcell.**

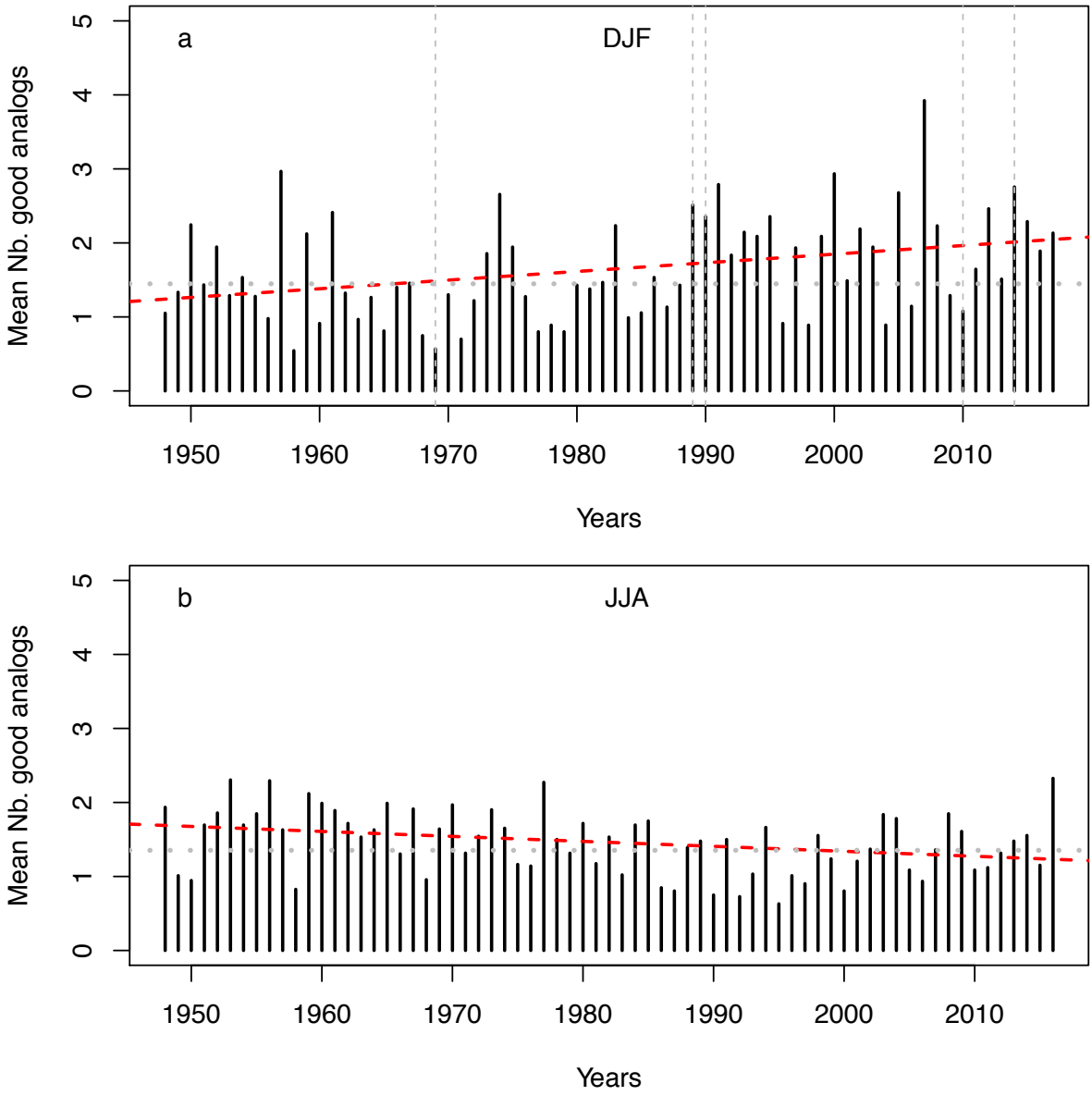

Figure 4: Average daily number of good analogues for the winter (DJF: panel a) and summer (JJA: panel b). The horizontal dotted lines indicate the mean value for all years. The red dashed line is the linear regression of the number of good analogues with time. The vertical dashed lines for panel a indicate the five reference winters (1969, 1989, 1990, 2010 and 2014).