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Extreme climatic events and weather regimes over the North Atlantic: When and where?

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[1] Meteorological events such as severe storms, floods or droughts are often referred to as extreme events. The impact of such events on society is immense and numerous efforts have been devoted to study them. Many proxy indicators in paleoclimate variability reconstructions are sensitive to such extremes, and a careful quantification of their link to environmental parameters is indispensable. In this paper we determine the relationship between typical states of the atmospheric circulation over and around the North Atlantic, on the one hand, and extreme events, on the other. We apply a novel statistical approach to associate extremes and weather regimes. This study enables us to infer the atmospheric conditions that prevailed in the North Atlantic region during key periods of the recent past. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 3220 Mathematical Geophysics: Nonlinear dynamics; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology. **Citation:** Yiou, P., and M. Nogaj (2004), Extreme climatic events and weather regimes over the North Atlantic: When and where?, *Geophys. Res. Lett.*, *31*, L07202, doi:10.1029/2003GL019119.

1. Introduction and Methodology

[2] This paper focusses on the North Atlantic-European region (30–70°N, 80°W–40°E), where the North Atlantic Oscillation (NAO) is most strongly felt [*Hurrell et al.*, 2003]. We consider daily means of the variables over this region, since the events under study last a few days. We examined the extremes of the National Center for Environmental Prediction (NCEP) re-analysis variables of surface conditions: precipitation and temperature from 1958 to 2003. Selected local values of these variables are the ones that have been measured by meteorological stations for a few centuries and it is these variables that affect most directly our society [*Houghton et al.*, 2001]. It must be kept in mind that precipitation values are not *observations*, but result from a state-of-the art model simulation.

[3] We address two types of extreme events. The first type is associated with the events that exceed thresholds of precipitation and temperature, based on the upper 90th and lower 10th quantiles; such events account for the large and instantaneous deviations of the climate variables. A definition of this kind is to be preferred to one based on standard deviation crossing [*Palmer and Räisänen*, 2002], especially when the variable distribution is not Gaussian. This is the case for precipitation, for which a finite standard deviation might not even exist. It must be noted that, based on such a definition, "extremes" do not need to be large values. Using this definition, generalized Pareto distribution models can be fitted to give a fine description of the extremes [*Coles*, 2001; *Zwiers and Kharin*, 1997]. Long intervals without precipitation (more than five days) provide the second type of extremes that we consider, based on duration, which we call drought-like.

[4] Such a distinction between size-based and duration-based extremes is necessary because the physical mechanisms that control storms or droughts are different. Thus we mainly use simple "extreme" indices, keeping in mind that our approach can be applied to more sophisticated ones (e.g., www.cru.uea.ac.uk/cru/projects/stardex/).

[5] The atmospheric circulation variability is estimated by classifying the geopotential height anomalies at 500 hPa (Z500), to obtain the so-called weather regimes over our region if interest [*Barnston and Livezey*, 1987; *Vautard*, 1990]. Before the classification, we performed an empirical orthogonal function (EOF) analysis [*Wilks*, 1995] of the daily winter data (December through February), in order to reduce the number of spatial variables. We kept the first seven EOFs, capturing 80% of the total variance. We applied the *k*-means algorithm [*Michelangeli et al.*, 1995] to the corresponding principal components (PCs).

[6] We obtain the classical four circulation regimes [*Kimoto and Ghil*, 1993; *Michelangeli et al.*, 1995; *Corti et al.*, 1999]: the two phases of the NAO (NAO+, NAO−), the Scandinavian "blocking", and the "Atlantic ridge" (Figure 1). In the sequel, we will only consider episodes within each regime that last more than five consecutive days in order to eliminate transient and ambiguous episodes [*Michelangeli et al.*, 1995].

[7] The connection between the weather regimes and the so-called NAO index can be assessed by computing the number of days per winter spent in each regime, as shown in Figure 2. As expected, the winter NAO index mostly captures the two NAO regimes (panel b), while the other two weather regimes are uncorrelated with this index (panel a). The correlations between the NAO+ and NAO− residence times with the winter NAO index are 0.82 and −0.74. Therefore, although the atmospheric circulation patterns fluctuate on the time scale of a few days, the two NAO regimes do leave their imprint on seasonal time scales during the reanalysis period.

[8] Our strategy is to associate the weather regimes with the extremes of surface variables by checking which regime, if any, is prevailing when an extreme is encountered. Hence we call our approach a regime/extreme attribution (REXA) method: for each gridpoint, when extreme conditions of precipitation or temperature are encountered, we determine

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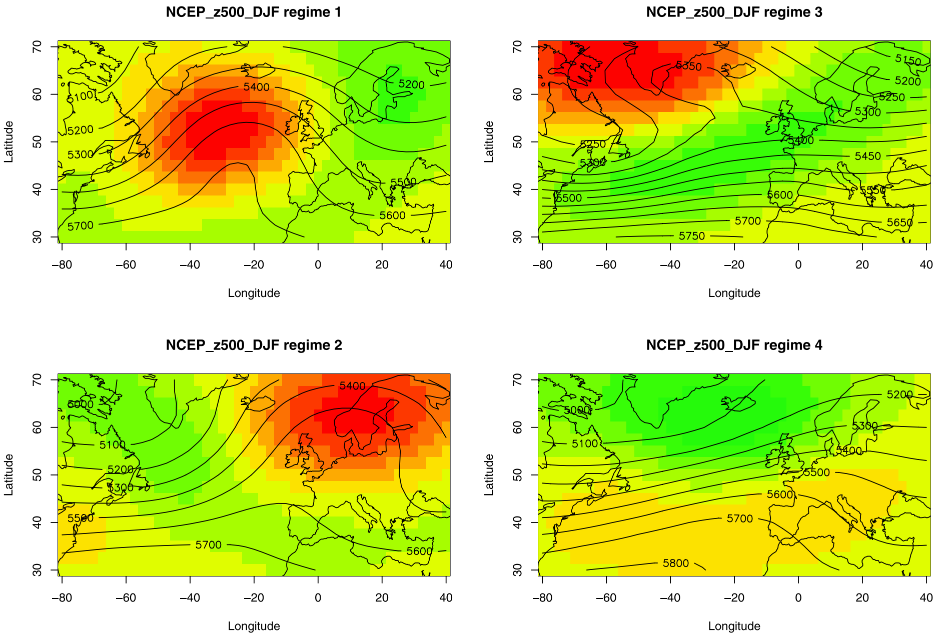


Figure 1. The four regimes of the atmospheric circulation over the North Atlantic, estimated from the 500 mb daily winter (DJF) NCEP re-analysis data set. The colors indicate the regime anomalies and the contour lines indicate the composite geopotential. The isolines are Z500 composites for each regime (1: Atlantic ridge; 2: Blocking; 3: NAO−; 4: NAO+). Contour interval is 100 geopotential meters for Regimes 1, 2 and 4; it is 50 m for Regime 3 (NAO−).

the weather regime that occurs in the majority of cases (we found that the major regimes always "win" with more than 50% of occurrences); recall that only regime episodes that persist for five days or more are counted. With this attribution, we partition the North Atlantic region into zones of influence on extremes for each regime. The outcome of this analysis is based on the amount of the spatial coherence of the partition maps thus obtained, which is crucial with variables with high spatial variability, like precipitation. Our methodology thus differs from the one of [*Plaut et al.*, 2001], who considered weather regimes associated with heavy precipitation events in the southern French Alps, and of [*Robertson and Ghil*, 1999] who used a similar approach for precipitation in the Western United States. The precipitation gauges used in these two analyses correspond to a single gridpoint of the NCEP reanalysis maps at most. Hence our approach is better suited for a global analysis of precipitation extremes. We also used a complementary approach by counting the number of extremes (with ad hoc definitions) for each of the four regimes. The results (not shown) are completely consistent with the REXA maps.

2. Results

[9] The REXA for the maximum winter precipitation reveals the role of the NAO phases on the spatial distribution of the extreme precipitation (Figure 3a). Although the precipitation field exhibits high spatial variability, we find very coherent patterns of regime attribution for the maxima, in the case of three out of four regimes detected. Heavy precipitation is caused by the NAO+ regime (orange) over Northern Europe and the Eastern United States, while the NAO− regime (green) causes it over Southern Europe and the Canadian Arctic. The latter result is consistent with [*Plaut et al.*, 2001], who found that heavy precipitation in the southern French Alps is mostly connected to an NAO− regime. The "blocking" regime (blue) influences mostly on the heavy precipitation over Eastern Greenland and the Mediterranean. The Atlantic ridge regime (red) has generally little impact on precipitation maxima of the North Atlantic–European region.

[10] REXA analysis for the prolonged intervals without precipitation (Figure 3b) reveals that the effect of the NAO phases on drought periods is not at all obtained by a mirror image of the REXA maps for the maximum precipitation rate. The blocking regime controls the drought periods over a large band across the northwestern North Atlantic and Eastern Scandinavia which has a large overlap with the maximum of precipitation due to the NAO+ regime in Figure 3a. This is particularly clear in northwestern Europe, where the flood and drought periods are controlled by the NAO+ and blocking regimes, respectively. In contrast, southern Europe precipitation extremes are controlled by the NAO− (floods, Figure 3a) and NAO+ (droughts, Figure 3b) regimes. The patchy character of the REXA patterns over the Atlantic in Figure 3b may be due to the competition between the Azores and continental high pressure centers to dry the atmosphere.

[11] REXA was then computed on the upper 90% and lower 10% quantiles for surface temperature (Figure 4). The temperature extremes over Northwestern Europe and the Eastern United States are controlled by the two phases of the NAO, as expected from their association with the large-scale flow's intensity [*Hurrell et al.*, 2003], since the atmospheric jet essentially carries warm air across this SW-NE oriented band. The blocking regime affects maximal temperatures over Eastern Greenland, Iceland, and Scandinavia, as well as minimal temperatures over southeastern Europe. Swings between the minimum and maxi-

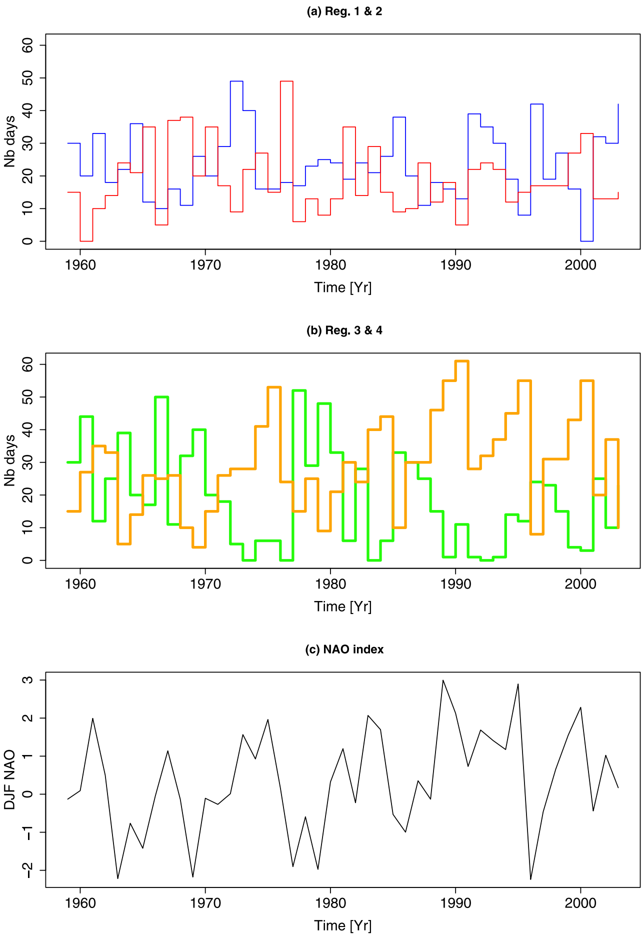


Figure 2. Number of days in each regime for every winter in the NCEP reanalysis. Panel (a): Atlantic ridge (Regime 1: red) and Blocking (Regime 2: blue); panel (b): NAO− (Regimes 3: green) and NAO+ (Regime 4: orange). Panel (c) shows the mean NAO index for the same time interval (from www.cru.uea.ac.uk/cru/data).

mum of temperatures in northern Scandinavia and south-eastern Europe appear to be driven by swings between NAO− and blocking episodes, rather than between the opposite phases of the NAO.

3. Conclusions and Discussion

[12] This paper presents a new synthetic way of mapping the impact of atmospheric regimes on climatic extremes. We based our analysis on daily NCEP reanalysis data, but the method could be applied to other datasets, provided that the regime decomposition of the large-scale atmospheric variability is statistically robust, in terms of a classifiability index [*Michelangeli et al.*, 1995; *Ghil and Robertson*, 2002] suggest that the latter is indeed the case. Our results emphasize the impact of the atmospheric “blocking” regime on precipitation and temperature extremes in much of Southern, as well as high-latitude Northern Europe, although this regime is uncorrelated with the NAO index.

[13] The last decade has witnessed a persistently high NAO index during the winter [*Hurrell et al.*, 2003]. This translates into more frequent NAO+ episodes. The REXA analysis shows that these episodes provoked high winter temperatures in Northern Europe and the Eastern United States, as well as high precipitation rates over these areas. At the same time, Eastern Canada experienced extremely low temperatures. Hence, we were able to give a physical explanation of the extreme climate recurrence when some weather types tend to persist.

[14] The REXA analysis offers a statistical way of reconstructing past atmospheric circulation from records of extreme temperature or precipitation, by attributing the “most probable” weather regime that is consistent with the observed extreme at a given location. To do so, it is necessary to assume that there is a stable physical, or at least statistical, relation between the atmospheric circulation and extremes of precipitation or temperature and that climate change is controlled by changes in the probability distribution of the weather regimes, rather than by changes in the regime themselves [*Ghil and Childress*, 1987, section 6.5; *Corti et al.*, 1999; *Palmer*, 1999].

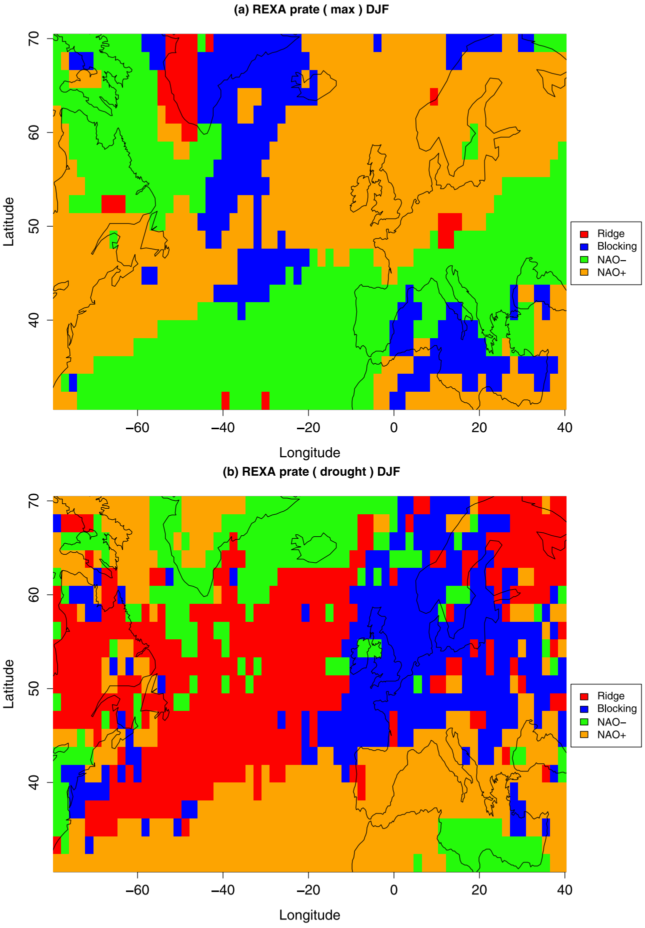
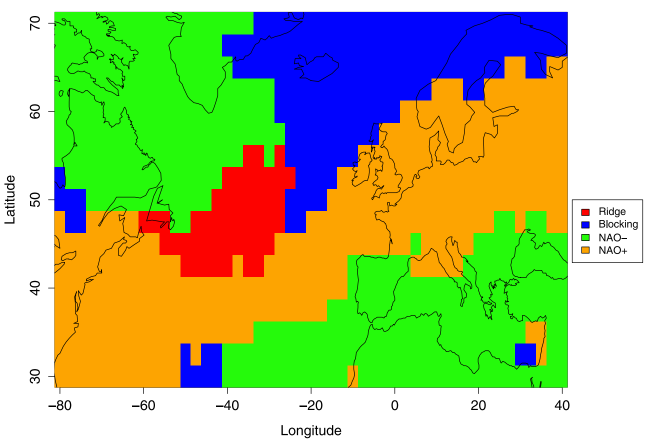


Figure 3. Association between weather regimes and local precipitation: (a) Regime/extreme attribution (REXA) analysis of the effect of weather regimes on precipitation maxima in the winter. (b) Correspondence of weather regimes with persistent episodes (>5 days) without precipitation in the winter. Colors indicate the most probable regime attributed to the extreme event: Atlantic ridge (red), blocking (blue), NAO− (green) and NAO+ (orange).

(a) REXA T air (max) DJF



(b) REXA T air (min) DJF

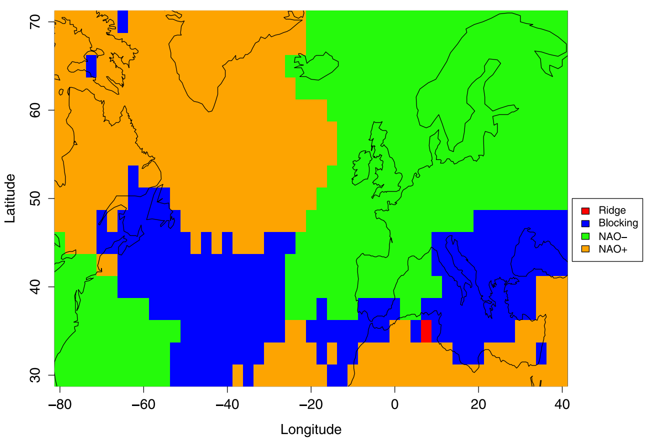


Figure 4. REXA of weather regimes with persistent episodes of (a) high temperature and (b) low temperature in the winter. Same color code as in Figure 3.

[15] The flexibility of this approach suggests the possibility to identify the weather regimes associated with extremes that occur on the following days; the predictive skill of the method remains to be evaluated.

[16] **Acknowledgments.** We thank Michael Ghil and an anonymous reviewer for helping us clarifying this manuscript M. Nogaj acknowledges the support of CEA, région Ile-de-France, and CLIMPACT. It is a pleasure to thank the EMULATE project members for stimulating discussions. This work was also supported by the French PNEDC. The computations were done using the free statistical package R (www.r-project.org).

References

Barnston, A. G., and R. E. Livezey (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, *Mon. Weather Rev.*, *115*, 1083–1126.

Coles, S. (2001), *An Introduction to Statistical Modeling of Extreme Values*, *Springer Ser. Stat.*, Springer-Verlag, New York.

Corti, S., F. Molteni, and T. N. Palmer (1999), Signature of recent climate change in frequencies of natural atmospheric circulation regimes, *Nature*, *398*, 799–802.

Ghil, M., and S. Childress (1987), *Topics in Geophysical Fluid Dynamics: Atmospheric Dynamics, Dynamo Theory and Climate Dynamics*, Springer-Verlag, New York.

Ghil, M., and A. W. Robertson (2002), "Waves" vs. "particles" in the atmosphere's phase space: A pathway to long-range forecasting?, *Proc. Natl. Acad. Sci. U. S. A.*, *99*(suppl. 1), 2493–2500.

Houghton, J. T., et al. (Eds.) (2001), *Climate Change 2001: The Scientific Basis*, Cambridge Univ. Press, New York.

Hurrell, J., Y. Kushnir, G. Ottersen, and M. Visbeck (Eds.) (2003), *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, AGU, Washington, D. C.

Kimoto, M., and M. Ghil (1993), Multiple flow regimes in the Northern Hemisphere winter. Part II: Sectorial regimes and preferred transitions, *J. Atmos. Sci.*, *50*, 2645–2673.

Michelangeli, P. A., R. Vautard, and B. Legras (1995), Weather regimes: Recurrence and quasi stationarity, *J. Atmos. Sci.*, *52*, 1237–1256.

Palmer, T. N. (1999), A nonlinear dynamical perspective on climate prediction, *J. Clim.*, *12*, 575–591.

Palmer, T. N., and J. Räisänen (2002), Quantifying the risk of extreme seasonal precipitation events in a changing climate, *Nature*, *415*, 512–514.

Plaut, G., E. Schuepbach, and M. Doctor (2001), Heavy precipitation events over a few Alpine sub-regions and the link with large-scale circulation, 1971–1995, *Clim. Res.*, *17*, 285–302.

Robertson, A. W., and M. Ghil (1999), Large-scale weather regimes and local climate over the western United States, *J. Clim.*, *12*, 1796–1813.

Vautard, R. (1990), Multiple weather regimes over the North Atlantic: Analysis of precursors and successors, *Mon. Weather Rev.*, *118*, 2056–2081.

Wilks, D. S. (1995), *Statistical Methods in the Atmospheric Sciences: An Indroduction*, Academic, San Diego, Calif.

Zwiers, F. W., and V. V. Kharin (1997), Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling, *J. Clim.*, *11*, 2200–2222.

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