Stability of weather regimes during the last millennium from climate simulations

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[1] The variability of the extra-tropical atmospheric circulation and its potential dependence on external forcings have been debated topics in climate modeling and observation communities. A recent reconstruction of the North Atlantic Oscillation Index has argued that the Medieval Warm Period period yielded a persistent positive phase of this index in contrast with an oscillating mode during the Little Ice Age. This paper tests whether this feature can be obtained, in millennium simulations from three different climate models. We examine the daily atmospheric dynamics that drives the main modes of extra-tropical variability. We find that the transition from a Medieval Warm Period to a Little Ice Age in the North Atlantic does not imply changes in patterns or frequency of weather regimes, although the mean surface temperature change is significant. This implies that the interpretation of proxy records in terms of atmospheric variability should be revised in order to take into account the structure of daily meteorological patterns, and/or climate models are too constrained to infer large changes of atmospheric variability.
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1. Introduction and Motivation

[2] The extra-tropical atmospheric circulation is a strong driver of surface temperature and precipitation [*Vautard and Yiou*, 2009]. Around the North Atlantic sector, its main modes are the two phases of the North Atlantic Oscillation (NAO). The modes also include a Scandinavian blocking, which can generate cold winter spells or summer heatwaves [*Cassou et al.*, 2005] and a North Atlantic Ridge. The pattern, frequency and persistence of those modes have mainly been investigated over the end of the 19th century to the end of the 20th century [*Corti et al.*, 1999; *Michelangeli et al.*, 1995; *Philipp et al.*, 2007]. Those weather regimes act on daily timescales, and have a signature on seasonal timescales through their frequency of occurrence [*Yiou and Nogaj*, 2004]. Investigating the stability of those modes under climate forcing scenarios is crucial to understand past climate variability and predict future changes. We focus here on a paleoclimate perspective over the last millennium, where climate forcings are relatively well documented [*Jansen et al.*, 2007].

[3] Inferences of atmospheric circulation patterns before the 17th century have been obtained from proxy data reconstructions [*Briffa et al.*, 2002; *Luterbacher et al.*, 2002]. For example, the NAO is often represented by an index, which accounts for the difference of pressure between the Azores and Iceland [*Hurrell et al.*, 2003]. Proxy reconstructions of this index provide some information on the NAO mode of atmospheric variability. Those reconstructions are based on heuristic relations between a given proxy and local pressure. Hence their interpretation is often based on hypotheses of stationary connections, and stable atmospheric patterns. A recent study has inferred a surprising shift in circulation during the last millennium [*Trouet et al.*, 2009] from an NAO index reconstruction. The goal of this paper is to investigate the stability of atmospheric patterns and their frequency, during periods of high and low solar activity, in coupled climate models.

[4] We focus on the North Atlantic (NA) climate variability in millennium simulations of three climate models with natural forcings (solar, volcanic, insolation, greenhouse, aerosols). We identify periods of high solar activity during the Medieval Period and low activity. We determine the weather regimes on daily timescale from those periods in order to assess whether significant changes in frequency and patterns can be obtained in such simulations. The multimodel approach gives an idea of the range of the atmospheric dynamic response to a climate forcing.

2. Millennium Simulations

[5] We used three coupled climate model (IPSLCM4v2 [*Servonnat et al.*, 2010], MIROC3.2 [*K-1 Model Developers*, 2004] and CNRM-CM3.3 [*Swingedouw et al.*, 2011]) simulations with comparable horizontal and vertical resolutions. The features of the three models (resolution, forcings) are summarized in the auxiliary material.[1] In all simulations, we used the daily timescale, which is very unusual in most paleoclimate studies but is a prerequisite to pin down the synoptic atmospheric dynamics and its relation with seasonal variability.

[6] The solar activity forcings in the simulations are shown in Figure 1. A high estimate of solar activity was chosen

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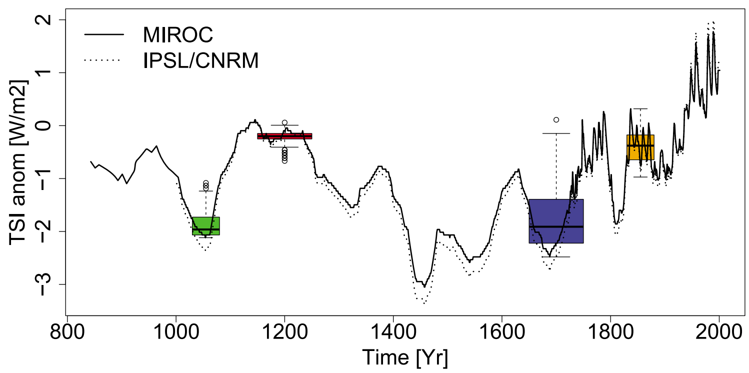

Figure 1. Reconstructed anomalies of Total Solar Irradiance (TSI) used in the model simulations. The IPSL and CNRM simulations use the same solar forcing. The boxplots indicate the variability of the TSI during the Medieval Period (MP: red), Oort Minimum (green), Maunder Minimum (LIA: blue), Late 19th century (blue) we consider.

in the IPSL and CNRM simulations [*Crowley*, 2000]. The MIROC model simulation uses slightly smaller amplitude of solar variability, resulting from combining three datasets to cover the last millennium [*Bard et al.*, 2000; *Crowley*, 2000; *Lean et al.*, 1995]. The CNRM and MIROC simulations also include volcanic eruptions through a parameterization of the variations of optical depth in the lower stratosphere [*Gao et al.*, 2008]. The IPSL and MIROC simulations consider variations of insolation as a response to orbital variations, which have a potential influence on Arctic temperature [*Kaufman et al.*, 2009]. The greenhouse gas forcings are taken from the PMIP3 [*Schmidt et al.*, 2011] and IPCC AR4 [*Jansen et al.*, 2007] databases. Interdecadal variations of the mean temperature in the three simulations lie between the uncertainties of proxy reconstructions [*Servonnat et al.*, 2010].

[7] We chose two century-long periods in those simulations. The first one brackets a period of high solar activity during the Medieval Period (MP: 1150–1250 AD). The second one brackets the Maunder Minimum during the Little Ice Age (LIA: 1650–1750 AD), when solar activity reached a relative minimum. For those two periods, we considered surface air temperature and daily geopotential height at 500mb (z500) to diagnose atmospheric variability and its sensitivity to those two phases of the solar forcing. For verification purposes, we also considered 50-year long periods bracketing the Oort minimum (~1030–1080 AD) and the end of the 19th century (~1830–1880 AD) with high solar activity. Those two 50-year periods were analyzed in the IPSL and CNRM simulations.

[8] We used 100-year excerpts with daily timescale from each of the three stable control simulations in order to make weather regime frequency comparisons. For verification purposes of the stability of the results, we checked that the weather regimes are similar when other excerpts of control simulations are taken (Figures S4 and S5).

3. Methods

[9] The classification of geopotential data into weather regimes is done with a kmeans algorithm [*Michelangeli et al.*, 1995]. We chose to impose four weather regimes, as generally documented in previous studies on contemporary data [*Corti et al.*, 1999; *Michelangeli et al.*, 1995; *Smyth et al.*, 1999], from different statistical approaches. The kmeans algorithm is applied to the first 10 principal components of the z500 data [*von Storch and Zwiers*, 2001] in the winter (December January February). This represents between 80% (with CNRM) and 85% (with IPSL) of the variance. We used the square root of cosine of latitude in order to weigh the variations of grid cell surface in the data so that the simulations can be compared.

[10] We used a Monte Carlo algorithm to stabilize the classification into the most probable weather regimes [*Yiou et al.*, 2008]. The winter weather regime patterns are then sorted by their frequency (number of occurrences/90) order.

[11] The classification is done on Z500 in control simulations. The forced simulations are then projected onto the control weather regimes in order to determine changes in the frequencies of regimes. This procedure is justified by the fact that the weather regimes obtained from each period (independently of the control simulation) are very similar (see Figures S1–S14).

[12] It has been shown that the frequency of the NAO weather regimes is a proxy for the NAO index [*Yiou and Nogaj*, 2004] in reanalysis data. We find that the NAO frequency is more useful because the usual definition of the NAO index depends on fixed locations [*Slonosky and Yiou*, 2002] (e.g., Lisbon and Reykjavik). If the pressure structures are not well located (as happens in the simulations we consider) or if the mean state is modified, the pressure difference might not reflect the nature of the NAO in terms of control of atmospheric flow [*Hurrell et al.*, 2003]. This is similar to using the first principal component of pressure fields (surface pressure or z500) to define this index [*Slonosky and Yiou*, 2002].

4. Results

[13] The winter temperature differences between the MP and LIA periods show similar patterns in the IPSL and MIROC simulations (Figure 2): both models simulate a warming in high latitude regions and cooling zones in the central North Atlantic and Central/Eastern Europe, albeit with differences in amplitudes and location. The CNRM simulation shows a warming in the whole NA region. The pattern of temperature change for IPSL and MIROC is consistent with other simulations of the last millennium [*Mann et al.*, 2009], although in contrast with temperature proxy reconstructions over the ocean. The temperature contrast

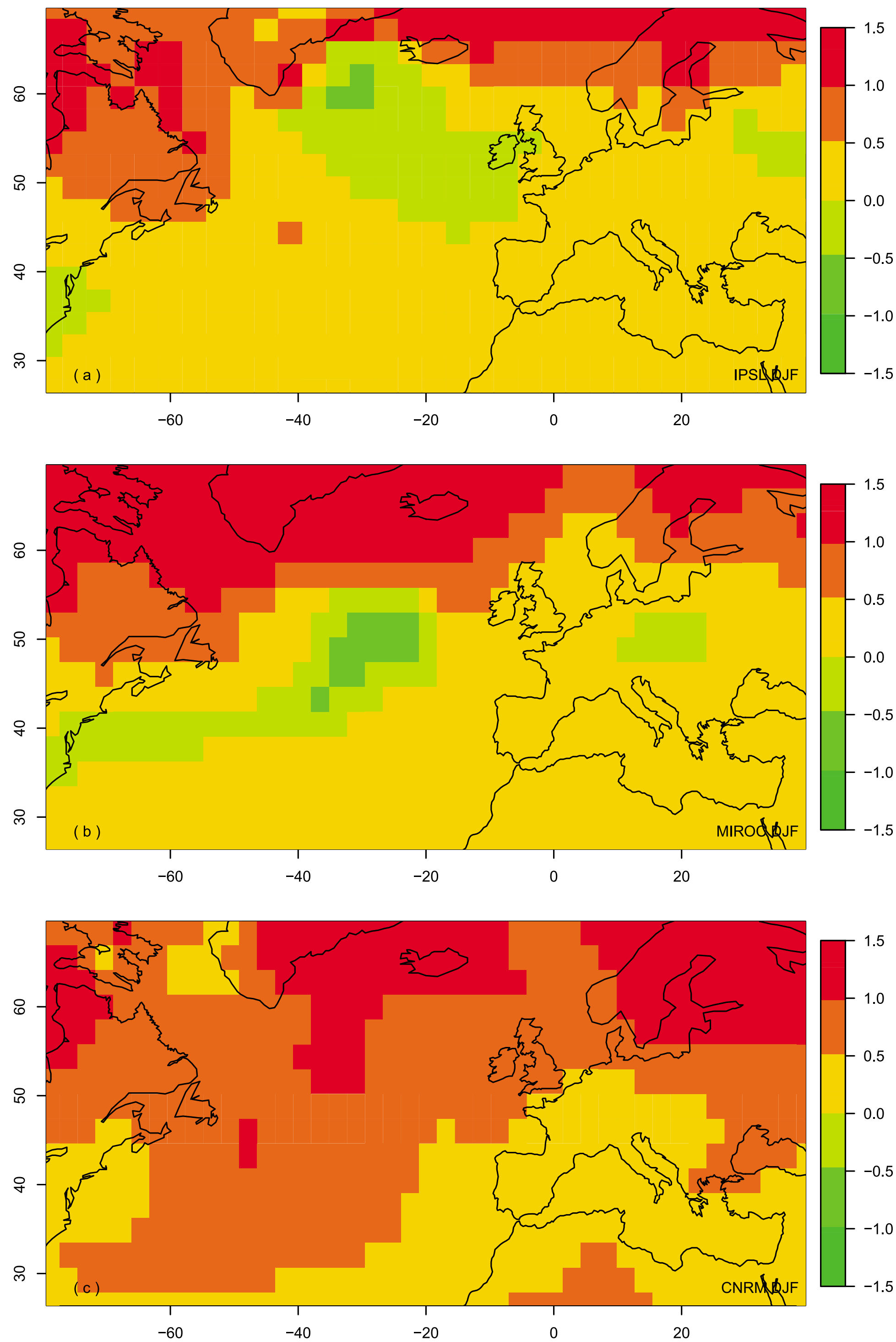

Figure 2. Surface temperature difference (in K) between the MP and LIA periods in the (a) IPSL, (b) MIROC and (c) CNRM simulations during the winter (December January February).

pattern in the CNRM simulation is similar to spatial proxy reconstructions of temperatures [*Mann et al.*, 2009]. Hence this study samples different types of winter temperature response to similar forcings.

[14] We performed a winter (December to February) weather regime decomposition [*Michelangeli et al.*, 1995; *Yiou et al.*, 2008] of the daily z500 in the three control simulations (see Methods). The patterns are consistent among the three simulations (Figure 3). They can be visually associated to those found during the recent period [*Michelangeli et al.*, 1995; *Yiou et al.*, 2008] from reanalysis datasets, although the locations of the centers of action differ, especially for the CNRM model. The weather regime teleconnection patterns with temperature bear visual similarities between models, although they do differ with the NCEP reanalysis [*Kalnay et al.*, 1996] data (Figures S6–S9).

[15] The weather regimes include the two phases of the North Atlantic Oscillation, a Scandinavian Blocking and a

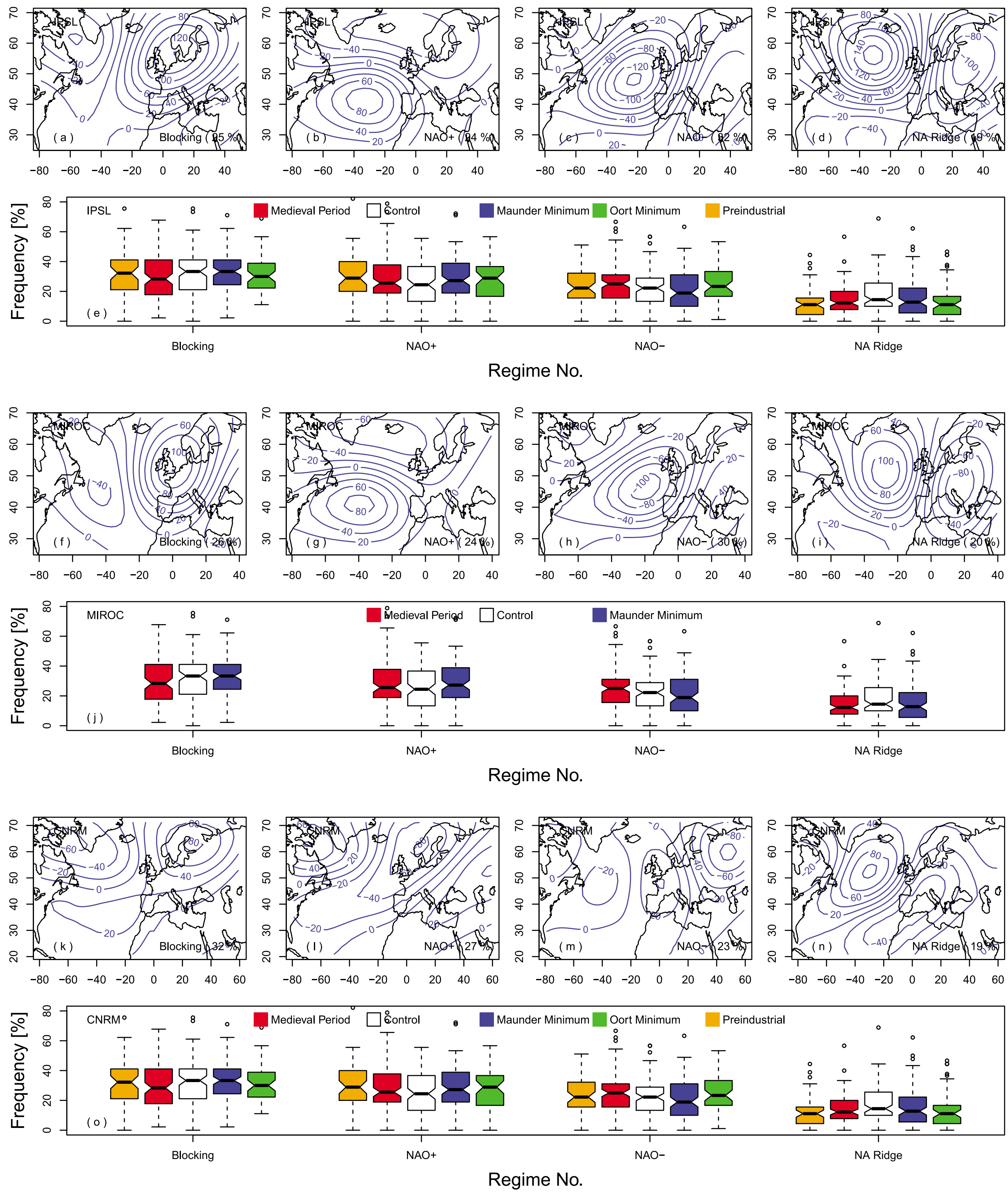

Figure 3. Winter weather regimes in the (a–d) IPSL, (f–i) MIROC and (k–n) CNRM control simulation. Percentages indicate the respective weather regime frequencies. Boxplots of the winter frequencies (as defined in the text) of each weather regimes for the Medieval Period (red), Late 19th century (preind: blue), Control (white), Maunder Minimum (blue) and Oort Minimum (green) for (e) IPSL, (j) MIROC and (o) CNRM models.

North Atlantic Ridge. The Scandinavian blocking is very similar in all simulations and is the second most frequent regime in IPSL (Figure 3a) and MIROC (Figure 3f) control simulations. It is the most frequent regime in the CNRM model (Figure 3k). The NAO structures are rather shifted with respect to their counterparts in reanalyses [*Michelangeli et al.*, 1995] and this is probably due to the resolution of the models [*Doblas-Reyes et al.*, 1998]. The positive phase of the NAO appears with roughly similar frequencies in the three simulations (between 24% in MIROC and 27% in CNRM). It is the second regime in CNRM and third in IPSL and MIROC. We now assess whether the frequencies of NAO+ and Blocking change between the MP and LIA.

[16] The MP and LIA periods were classified onto the weather regimes of the control simulations for each simulation. The frequencies of weather regime for all simulations (as defined in the method section) are shown in Figure 3. In all models we find a marginal (but insignificant) increase of Blocking frequency when moving from MP to LIA. The NAO phases do not yield such systematic shifts (even small) between those two periods. Overall, the frequencies of weather regimes are remarkably stable, in spite of the strong temperature difference between the periods of high vs. low solar activity.

[17] We checked that the interannual regime frequency variability does not exhibit any phase of persisting weather regime (Figures S1–S14). Some winters can be dominated by a given weather regime (with a frequency exceeding 50%) but we find that no weather regime dominates the others (i.e., with a frequency larger than 25%) for periods larger than two years. Hence, a persisting positive phase of the NAO during the MP appears to be very unlikely in those three model simulations. On the other hand, the marginal increase of Blocking frequency during the LIA (with respect to the MP and control simulations) is consistently found in all models.

[18] We checked that the power spectra of the weather regime frequencies did not change (with 95% confidence intervals) between the investigated periods (Figures S10–S14).

5. Discussion and Conclusion

[19] We have analyzed a unique multi-model ensemble of daily atmospheric variability from millennium simulations of global coupled models and focused on the Medieval Warm Period and the Little Ice Age over the North Atlantic region. We find a strong temperature response in the Nordic Seas, while the North Atlantic has a slight cooling in two of the three simulations, which contrasts with existing proxy temperature reconstructions [*Mann et al.*, 2009].

[20] This set of numerical experiments has shown a remarkable stability of weather patterns as a response to solar activity forcing. The analysis of weather regimes during other periods of low solar activity (Oort minimum: ~1030–1080 AD) and high solar activity (~1830–1880 AD) in the IPSL and CNRM simulations (Figures 3e and 3o) does not reveal large shifts. A slight (but barely significant) increase of blocking during the Maunder Minimum is consistently found in two models (CNRM and MIROC). Analyses of other millennium simulations (from other models) would be needed to investigate the potential relevance of this increase. The explanation of this small increase involves mechanisms such as the Atlantic Multidecadal Ocean variability that controls surface temperature gradients [*Häkkinen et al.*, 2011] and stratospheric photochemistry forcing [*Shindell et al.*, 2001], and is beyond the scope of this paper.

[21] If climate models are to be trusted, such a result suggests that the interpretation of proxy reconstructions of the NAO index in terms of atmospheric patterns [*Trouet et al.*, 2009] should be revised (or at least moderated) considering synoptic meteorological processes. This requires a re-examination of the dependence on characteristic time scales of the response of proxies to other climate variables, local and biogenic effects. The alternative interpretation is that climate model simulations are too constrained to obtain different patterns of atmospheric variability or yield large changes in pattern frequencies.

[22] The coming of new high resolution proxies, with intra-annual resolution, presents many scientific challenges at the border between meteorological and climatological scales. Hence our study advocates a more comprehensive use of state of the art meteorological diagnostics to constrain the interpretation of paleoclimate proxy records. The consideration of weather regimes like the Scandinavian blocking in paleoclimate studies would be an important step into that direction. We also argue that the study of daily time scales allows a better insight to extreme events, which have intra-seasonal time scales.

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