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North Atlantic polar lows and weather regimes: do current links persist in a warmer climate?

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Abstract

Polar low development over the North Atlantic under a warmer climate is assessed using simulations of an atmospheric–oceanic coupled general circulation model, specifically with regards to the evolution of large-scale atmospheric variability described by weather regimes, and their links with lower-layer static stability. While a relationship has been identified for the present climate, under a warmer climate, polar low favorable conditions are expected to occur less often, and the large-scale circulation variability appears to have reduced influence on stability, and thus, on polar low occurrence.

Keywords: **polar lows; weather regimes; North Atlantic; climatic projections**

1. Introduction

Polar lows (PLs) are severe meso-cyclones forming during winter at high latitudes over ice-free ocean. They are associated with heavy snow falls, strong surface winds, rough seas and very poor visibility (e.g. Rasmussen and Turner, 2003). The Norwegian and Barents Seas have long been known to be particularly subject to PLs, but with the advent of satellite data, it has been observed that such cyclones form in several regions prone to Cold Air Outbreaks, such as the Labrador Sea. Because of a rather low forecasting ability and their sudden development, PLs pose a significant danger to people and infrastructure in the affected regions (e.g. Rojo *et al.,* 2015). The development and intensification of PLs result from several mechanisms, the two main ones being baroclinic instability and convective development. PLs can be purely baroclinic or purely convective, but most of PLs are hybrids, and convective development dominates over the North Atlantic (Rasmussen and Turner, 2003). Among the environmental variables recognized as 'key variables' associated with PL formation (e.g. Businger, 1985; Noer and Ovhed, 2003), the convective heating driven by surface fluxes appears particularly well suited to distinguish between cyclones that will intensify into PL from non-intensifying systems (c.f. Bracegirdle and Gray, 2008; Yanase *et al.,* 2016), and reveals areas where PL can form (Kolstad, 2011; Mallet *et al.,* 2013). This heating can be successfully estimated from the difference of temperature (sometimes potential temperature) between the sea surface (SST) and the overlying atmosphere at either 700 hPa as in Bracegirdle and Gray (2008) or 500 hPa as in Noer and Ovhed (2003), Claud *et al.* (2007), and Zahn and von Storch (2008a); in this case written as SST-T500.

Because it modifies the spatial and temporal distributions of the above variables, climate change is expected to impact PL occurrence. This kind of impact has already been highlighted for other extreme phenomena, such as heat waves, wind storms, etc. (e.g. Beniston *et al.,* 2007). An assessment of PL occurrence differences due to climate change could be useful coastal region development, offshore exploitation strategy, and polar maritime traffic. However, study of the long-term PL frequencies due to climate change is relatively recent, and only a few articles address this issue using different approaches. Kolstad and Bracegirdle (2008) studied the mean evolution of static stability extreme values in a model ensemble. Zahn and von Storch (2008a, 2008b, 2010) and Romero and Emanuel (2016) applied downscaling methods and a PL detection and tracking method to model ensembles, and concluded that the activity would be somewhat reduced; however, in Zahn and von Storch, 2010, the activity was shifted mainly northward, while in Romero and Emanuel, 2016, northeastward. Finally, Woollings *et al.* (2012) discussed the consequences of a change in the North Atlantic oceanic circulation.

A complementary approach is adopted in this study, which relies on the use of weather regimes (WRs, or regimes, e.g. Cassou *et al.,* 2011). The concept of WRs is based on the representation of the seasonal atmospheric daily to monthly variability as transitions between a limited number of well-defined preferential quasi-stationary states. These states can be determined by statistical classification methods. The application of a cluster analysis to fields representative of the daily wintertime (November to March) tropospheric circulation state (mean sea level pressure or geopotential height at 500 hPa, hereafter respectively MSLP and Z500) over the North Atlantic-Europe domain (20°–80°N/90°W–30°E), provides four regimes, according to the literature: two regimes, whose patterns resemble the positive and negative phases of the North Atlantic Oscillation (NAO), subsequently NAO+ and NAO−, and two regimes corresponding to blocking in the tropospheric meridional flow circulation, Scandinavian Blocking (SB), and Atlantic Ridge (AR). Using several PL inventories, Mallet *et al.* (2013) showed that, depending on geographic location, PLs preferentially develop for specific WRs: over the Norwegian and Barents Seas, a PL formation is close to twice as common in NAO− and AR than in NAO+ and SB. Over the Labrador Sea, most PLs occur during NAO+, while they are almost entirely absent during NAO−. Moreover, WRs for which a maximum versus a minimum of PLs occur appear to correspond to favorable versus less favorable or adverse conditions on key variables for PL development. Also, when PLs form during an adverse regime, the anomalous synoptic circulation pattern weakly projects onto the WR mean pattern, i.e. the regime is then not 'well' defined. This occurs typically when stratospheric intrusions may explain a part of PL development quasi-independently from lower-level conditions, because PL development can be forced by inducing spin-up from a conditional neutral atmosphere (Montgomery and Farrell, 1992), or by enhancing existing surface vorticity (Rasmussen and Turner, 2003).

In the present paper, we study PL development through the evolution of WRs with climate change. To do so, we investigate the differences in the link between WRs and the most relevant key variable for PL development, the SST-T500 for present and future climates. Indeed, because of their typically short life span (1 to 2 days) and small size (typically 100–600 km), the representation of PLs in meteorological reanalysis datasets remains limited. Using respectively a subjective and an objective identification criterion, both Laffineur *et al.* (2014) and Zappa *et al.* (2014) showed that only about 50–55% of observed PLs are represented in ERA-Interim (ERA-I) data, often with a weaker circulation than observed.

2. Data and rationale

Daily mean MSLP fields from the NCEP/NCAR reanalysis are used to investigate the contemporary climate. This reanalysis covers the period 1948 to today, on a global grid of 2.5° in latitude per 2.5° in longitude, and with 17 vertical pressure levels from 1000 to 10 hPa (Kalnay *et al.,* 1996).

To investigate future climate change due to anthropogenic greenhouse gas concentration increases, we use the ECHAM5/MPI-OM (European Center Hamburg Version 5/Max-Planck-Institute – Ocean Model) general circulation model (Marsland *et al.,* 2003; Roeckner *et al.,* 2003). This model has the advantage of being an atmospheric-oceanic coupled model, and has a relatively high spatial resolution: T63 L31 for the atmospheric model, corresponding to a 1.875° horizontal resolution and 31 vertical levels; and GR1.5 L40 for the ocean/sea-ice model, i.e. 1.5° horizontal resolution and 40 vertical levels. The simulation of future climate is for the most extreme greenhouse gas emission scenario, named A2, (Houghton *et al.,* 2001), and the selected outputs MSLP, SST (or skin temperature over sea ice), T500 and sea-ice cover.

We consider two 30-year periods. The period 1970–99 is selected for the present-day climate and future climate considers the 2070–99 period. WRs are calculated for present-day climate winter months (November–March) on the NCEP/NCAR daily MSLP maps.

To obtain the closest representation of the WRs in the ECHAM5/MPI-OM simulation, the daily anomaly maps of simulated MSLP are directly compared with the centroids of the NCEP/NCAR regimes, as in Goubanova *et al.* (2010). Each day of the simulation is classified into the WR whose centroid has the highest similarity with the daily MSLP anomaly, according to a spatial correlation measurement. To increase the representation accuracy of WRs, transition days between regimes are not considered, and only those WRs with a persistence of at least 3 days are retained (as in Sanchez-Gomez and Terray, 2005).

Figure 1 presents the four WR centroids for the present climate using reanalyses (top), from the contemporary simulations (middle), and for the future climate simulations (bottom). Unsurprisingly, there is no large difference between WR centroid patterns determined from the reanalysis and the simulation. The main differences are in the intensity of patterns, and the importance of the Greenland influence, which is particularly pronounced in ECHAM5/MPI-OM, probably due the different representations of orography in the model versus the reanalysis.

3. Changes under warmer climate

In this section, we determine how the evolution of large-scale atmospheric variability, as represented by the WRs, impacts the convective tropospheric heating due to surface fluxes during wintertime.

Figure 2 shows the difference of SST-T500 in the simulations between future and present climate. The SST-T500 mean values decrease practically everywhere of present-days' PL occurrence area, making it on average less favorable for PL development. Negative values are found over the central part of the North Atlantic Ocean, and maximum values to the south of Greenland and Iceland, and over the Labrador Sea, with differences around −2.5 to −3 K. The situation is different over the Nordic Seas. The Norwegian Sea has a moderate decrease, near −1.5 K, while the Barents and

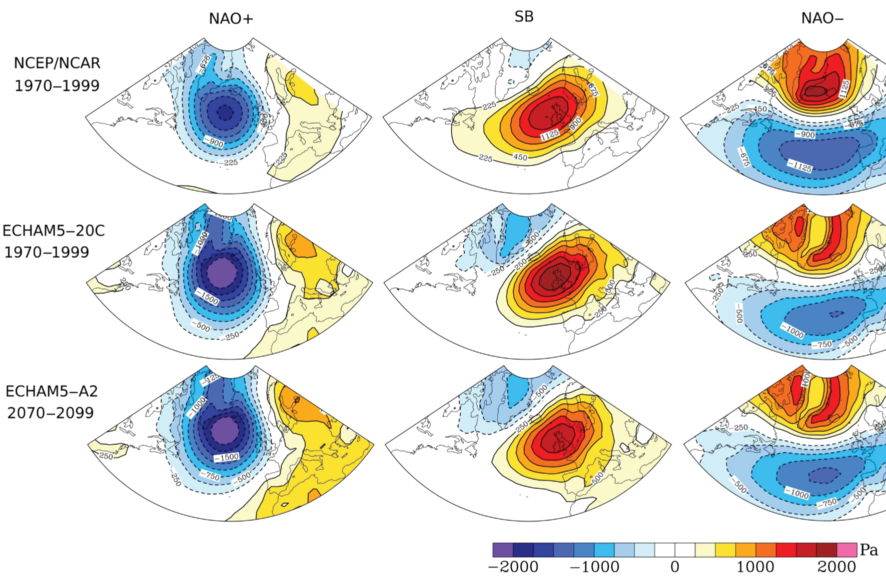

Figure 1. The four wintertime (NDJFM) MSLP weather regime (WR) centroids over the North Atlantic/Europe region for (top) NCEP/NCAR reanalysis over 1970–1999; (middle) ECHAM5 simulation, run 20C over 1970–1999, obtained by projection of MSLP daily anomalies onto NCEP/NCAR centroids; (bottom) and ECHAM5 simulation, scenario A2 for 2070–2099, obtained by projection of MSLP daily anomalies onto NCEP/NCAR centroids.

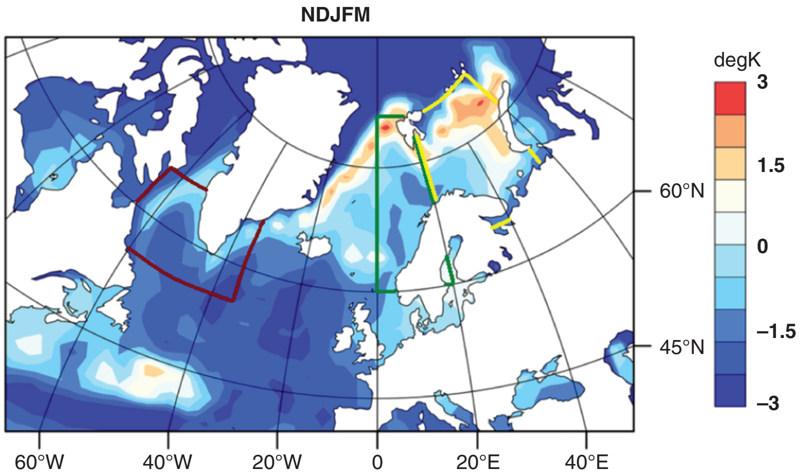

Figure 2. SST-T500 wintertime (NDJFM) difference between future and contemporary climates in ECHAM5. Considered areas are represented in red (Labrador Sea), green (Norwegian Sea), and yellow (Barents Sea).

Greenland seas show near zero or positive differences. Note that some areas – mainly the eastern and northern Barents Sea, and a part of the sea-ice edge along the eastern Greenland coast – marked by particularly strong increases of SST-T500 on Figure 2, correspond to ice-covered areas in the present-day winter season transitioned to ice-free in the future.

Statistical downscaling is a method used to estimate a local variable from its statistical relation to a large-scale field, i.e. from a global climate model (see Wilby *et al.,* 2004 for more considerations). Over the Nordic and Labrador seas, the statistical relationship between WRs and PL occurrence, as well as SST-T500, have been rather well established (Mallet *et al.,* 2013). It would therefore be possible to assess the change of PL occurrence under warmer climate by determining WRs. Such climate change would manifest itself as differences in the occurrence of atmospheric circulation regimes (e.g. Corti *et al.*, 1999; Palmer, 1999). However, to be correct, the statistical downscaling assumes that the link between large-scale and local conditions is still valid under modified climate. Thus, the WRs/SST-T500 link is investigated. To assess which part of the total change in mean SST-T500 can be expressed as a difference in WR occurrence, and which one is due to a change in the link between local SST-T500 values and WRs, we use the linear decomposition proposed by Boé *et al.* (2006):

$$\Delta X = X^F - X^P = \sum \left(f_k^F x_k^F - f_k^P x_k^P\right) + \left(f_0^F Y^F - f_0^P Y^P\right)$$

where the total mean change ΔX of the local property, SST-T500, between the present climate (X^P) and the future climate (X^F) is written according to the frequency of occurrence f_k^P (f_k^F) for each k regime in the simulation of present (respectively, future) climate, the mean value of the property x_k^P (x_k^F) of each k regime in the simulation

Table 1. Weather regime occurrence (%) in the present and future climate simulations of ECHAM5.

	NAO+	SB	NAO−	AR
20C (1970–1999)	9	9	19	10
A2 (2070–2099)	10	10	19	10

Table 2. Influence of the different terms in the mean SST-T500 change between 1970–1999 and 2070–2099 periods for three North Atlantic regions.

	Labrador Sea	Barents Sea	Norwegian Sea
Inter-type	−0.063	−0.08	−0.063
Intra-type	−2.203	−0.14	−1.318
Mixed term	0.008	0.006	0.005
Total	−2.258	−0.214	−1.376

in present (respectively, future) climate, the frequency of occurrence of transition days between regimes f_0^P (f_0^F) in the simulation in present (respectively future) climate, and the mean value of the property Y^F (Y^P) for transition days in the simulation in present (respectively future) climate.

ΔXcan be rewritten as the sum of three terms:

$$\Delta X = \left\{ \sum_{k=1}^{4} \left[f_k^P \left(x_k^F - x_k^P \right) \right] + \left[f_0^P (Y^F - Y^P \right] \right\}$$
$$+ \left\{ \sum_{k=1}^{4} \left[x_k^P \left(f_k^F - f_k^P \right) \right] + \left[Y^P (f_0^F - f_0^P \right] \right\}$$
$$+ \left\{ \sum_{k=1}^{4} \left(x_k^F - x_k^P \right) \left(f_k^F - f_k^P \right) + \left(Y^F - Y^P \right) \left(f_0^F - f_0^P \right) \right\}$$

The first term, above, which corresponds to the total change due to changes within regimes, i.e. of the WRs/local variable relationships, is called 'intra-type'; the second term corresponds to the total change due to WR occurrence changes or 'inter-type'. The last, or mixing, term depends on both the occurrence differences and internal changes.

We have found no significant difference of WR occurrence frequencies in the future (Table 1). The linear decomposition of the SST-T500 mean change has been applied separately to the three areas where a statistical association between WRs and PL occurrence was confirmed from the analysis of extensive PLs observations in Mallet *et al.* (2013): the Norwegian Sea, the Barents Sea, and the Labrador Sea (respectively in green, yellow, and red on Figure 2). Table 2 shows that a strong signal is only found for the intra-type. Thus, we conclude that the total change in SST-T500 is dominated by a change in the link between local climate conditions and large-scale variability, rather than a change in the occurrence frequency of WRs. To better understand this result, conditions specific to each WR are now studied.

Figure 3 compares the SST-T500 winter mean values for days belonging to each WR for the present climate (left side) and for the future (right side). Over the Labrador Sea, the mean decrease of close to −2 K depends on the regime, but not in a statistically significant way. Notwithstanding, we note that the difference appears more important for NAO+ than for other WRs, up to near 4 K in the southern area. There, the WR approach is not determinant to consider the change in SST-T500 under warmer climate. Over the Norwegian and Barents Seas, the change is better distinguished according to WRs. There is practically no SST-T500 difference during SB, a weak one during NAO+, but a large decrease (1–2 K) during NAO− and AR. Figure 4 compares how much difference the WRs make to SST-T500 for the two periods. The WR-related SST-T500 departure from the mean decreases in future climate in almost all presented cases, which indicates that the large-scale variability has a reduced influence on local SST-T500. The same analysis repeated with standardized anomalies, i.e. by dividing deviation from the mean by local variability during the time slice in question, presents smaller differences between present and future climate anomalies (not shown). Thus, future climate reduced WR influence on SST-T500 seems due, at least in part, to a reduced variability, which is likely associated with sea-ice retreat (e.g. Borodina *et al.,* 2017).

The distribution of SST-T500 values for the Norwegian (right side) and Barents (left side) seas by WR days for the present and future climates is shown in Figure 5. We preferentially consider the highest values because PL development depends on strong thermodynamic fluxes from the sea to the atmosphere. For the Norwegian Sea, a decrease is observed for all WRs, but it is weak for SB (close to 0 K for the 95th centile, 0.4 for the 75th, and 0.7 for the mean), while it is notably strong for AR (around 1.5 K). For the Barents Sea, NAO+ shows a very weak decrease (close to 0.5 K for the 95th centile, near zero for the 75th and the mean), NAO− and AR show a mean decrease of 0.5 to 1 K, while an increase of between 0.3–0.5 K is observed for SB. Thus, it appears that the most favorable WRs for PL development in the contemporary period show the greater decrease in the highest SST-T500 values in the future.

4. Summary and conclusions

Because an association between PL occurrence and the large-scale variability of WRs has been statistically established for the present climate over the Nordic and Labrador Seas, we investigate change in PL frequency occurrence under warmer climate through the evolution of WRs, and their links with the SST-T500 proxy. This one indicates convective heating by thermodynamic surface fluxes, which is critical for most of PL developments. Evolution of the larger environmental conditions is assessed using ECHAM5/MPI-OM atmospheric/ocean coupled model in a warmer climate scenario (2070–2099) relative to the present climate run (1970–1999). We found a SST-T500 decrease over the largest part of the North Atlantic area, and

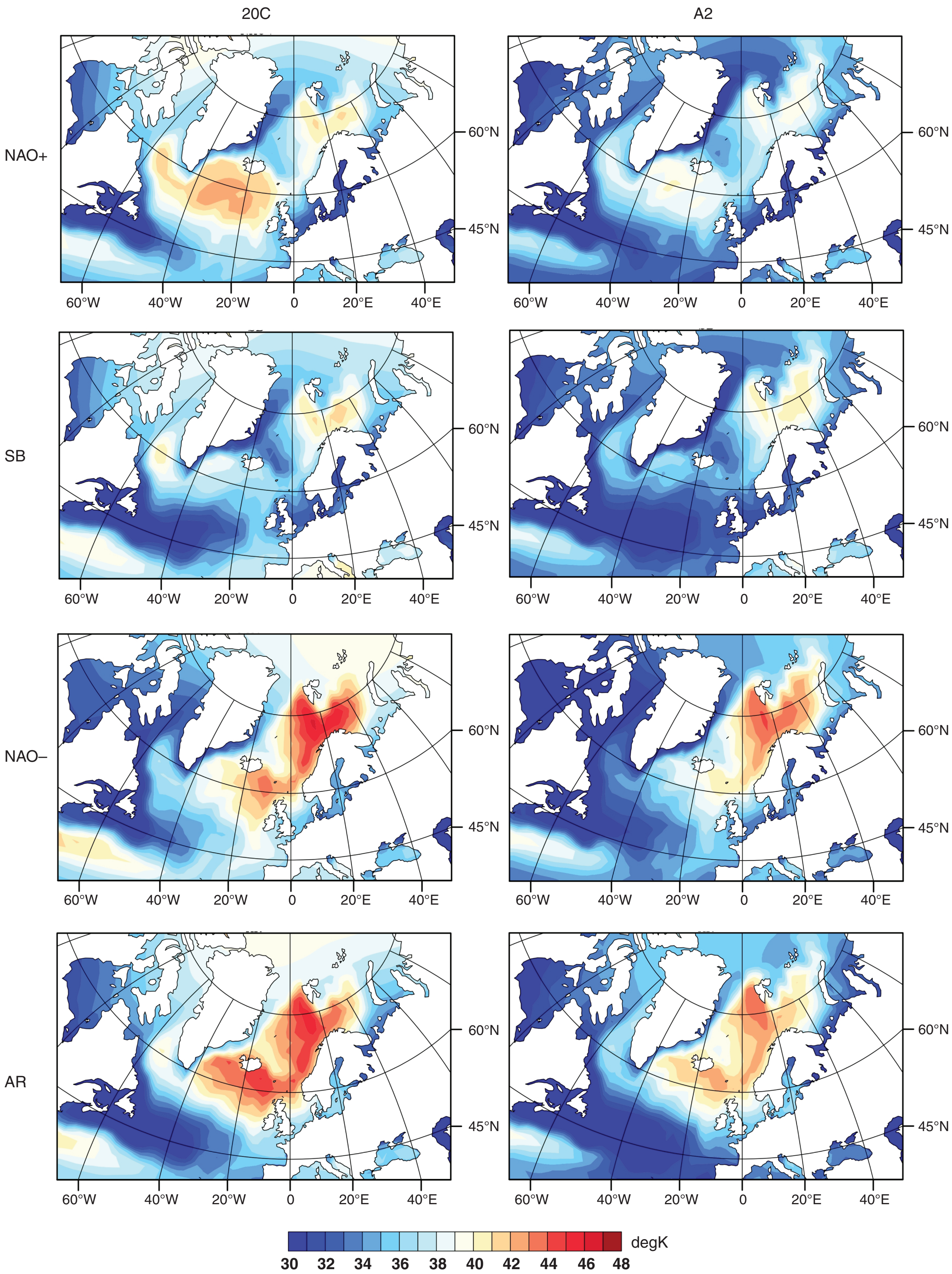

Figure 3. Comparison between wintertime (NDJFM) simulated SST-T500 mean values according to associated WRs for present-day climate (1970–1999, left) and future climate (2070–2099, right).

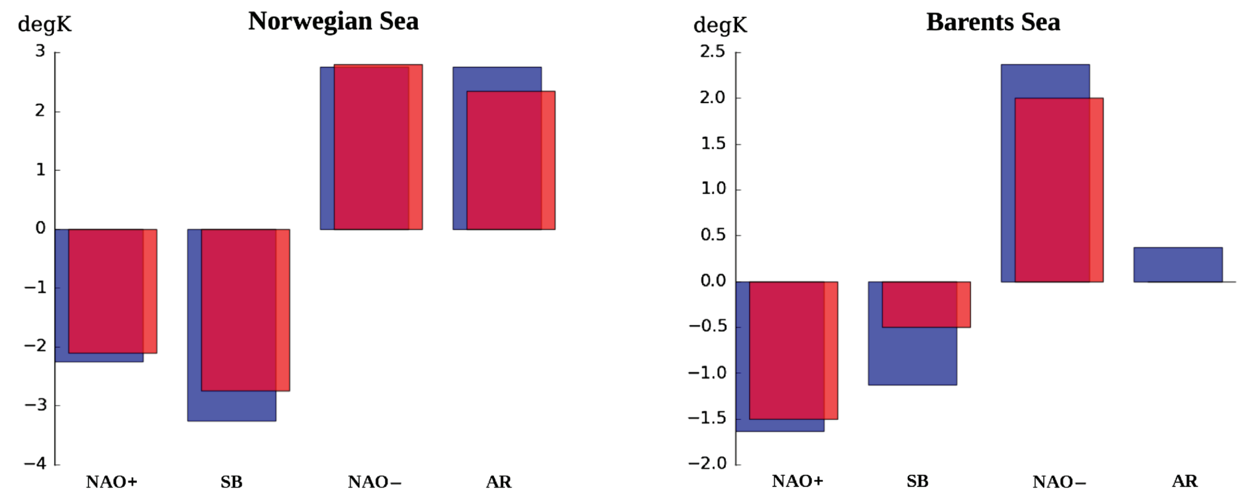

Figure 4. Comparison between WR-related SST-T500 anomalies for present-day climate (1970–1999, blue) and future climate (2070–2099, red).

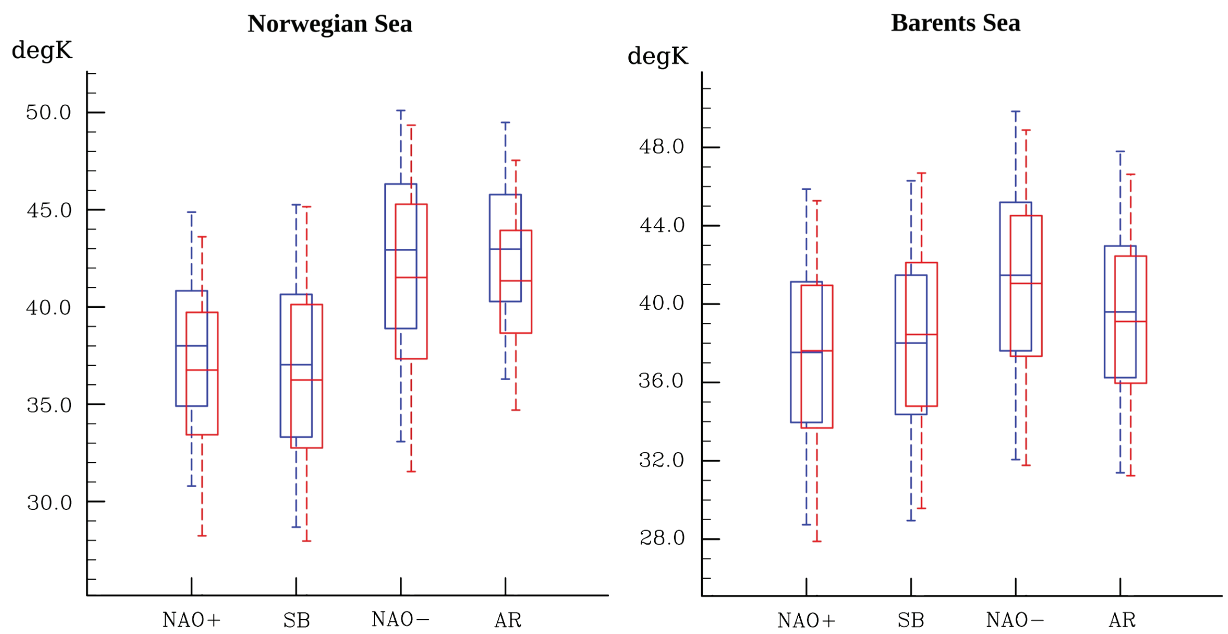

Figure 5. Comparison between wintertime (NDJFM) SST-T500 daily value distributions over the Norwegian (left) and Barents (right) seas according to associated WRs for the present-day climate (1970–1999, blue) and for future climate (2070–2099, red). The horizontal line within the box corresponds to the mean; bottom and top box bounds show the 25th and 75th percentiles, respectively; bottom and top whisker bounds indicate the 5th and 95th percentiles, respectively.

a more contrasted situation over the Nordic Seas, in good agreement with literature. The occurrence of WRs is not significantly modified. However, the statistical link between WRs and local SST-T500 values changes. The basic hypothesis of statistical downscaling is thus not valid in this case. Moreover, WRs present a reduced influence on stability, which is due to reduced variability associated with sea-ice retreat (e.g. Borodina *et al.,* 2017). WRs corresponding in contemporary climate to the highest SST-T500 values present the greater decrease in future climate. This is the case for NAO− and AR over the Nordic Seas, and for NAO+ over the southern Labrador Sea. Conversely, WRs corresponding in present-day climate to lowest SST-T500 values show a weaker decrease, and sometimes an increase. This is the case for NAO+, and mostly for SB over the Nordic Seas, and to a smaller extent for AR over the Labrador Sea. We confirm previous findings that episodes of high vertical instability occur less often. We conclude that the large-scale patterns of variability have a reduced influence on vertical stability, an indicator of the convective activity which is necessary for the development of most of PLs. In order to improve the robustness of our results and complete and refine our diagnostic, similar procedures should be applied to other models and on the other key conditions for PL development, as baroclinicity and upper level cold trough occurrence.

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