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Key Points:
- Mean temperature does not change over Europe
- More cold extremes over Europe
- Larger temperature variability over Europe

Supporting Information:
- Readme
- Supplementary Figures S1–S5

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Influence of the western North Atlantic and the Barents Sea on European winter climate

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Abstract Despite global warming, Europe experienced several unusually cold winters in recent years. Reduced sea ice concentration in the Arctic and increased sea surface temperatures (SSTs) in the Atlantic are independently hypothesized as possible triggers for such cold winters. We investigate the individual and combined influence of Barents Sea and Atlantic sea ice and SST conditions on European winter temperatures. In our simulations cold extremes become more frequent, but the imposed sea ice and/or SST anomalies only weakly affect European winter mean temperatures. We argue that a forced cooling of European mean temperatures would have to include additional mechanisms, but the variability of European winter temperatures is large, and cold winters could just be the result of internal variability.

1. Introduction

Over the last decade the Northern Hemisphere winters experienced a cooling trend while the other seasons showed a warming [*Cohen et al.*, 2012]. Cooling over Europe in winter, however, does not necessarily contradict global warming, and several mechanisms could produce the observed cooling. A negative North Atlantic Oscillation (NAO) [e.g., *Cattiaux et al.*, 2010], blocking systems [e.g., *Croci-Maspoli and Davies*, 2009; *Sillmann and Croci-Maspoli*, 2009], changes in the jet position and in storm track activity (STA) [e.g., *Degirmendzic and Wibig*, 2007; *Mahlstein et al.*, 2012], increased northerly advection, and a weak polar vortex [e.g., *Kolstad et al.*, 2010] are all expected to favor low temperatures over Europe. These atmospheric phenomena have been linked to sea ice concentration in the Arctic [e.g., *Petoukhov and Semenov*, 2010; *Tang et al.*, 2013], sea surface temperature (SST) anomalies in the Atlantic [e.g., *Drevillon et al.*, 2001; *Croci-Maspoli and Davies*, 2009], and changes in other components, such as stratospheric conditions [*Scaife and Knight*, 2008] or snow cover over Eurasia [e.g., *Cohen and Entekhabi*, 1999]. All of these components are altered by global warming and can therefore affect European winter climate. Both sea ice reduction and SST increase in the North Atlantic were independently presented as possible triggers for the unusually cold winter 2005/2006 [*Croci-Maspoli and Davies*, 2009; *Petoukhov and Semenov*, 2010]. However, as both anomalies prevailed during winter 2005/2006, the combination of both may be needed for a cold winter to develop. To better understand possible mechanisms causing cold European winters, we investigate how sea ice and/or SST anomalies in the Atlantic and the Barents Sea individually, or in combination, can change the temperature over Europe. While previous studies mainly focus on the mean response, we additionally investigate cold extremes.

2. Model and Experimental Setup

For this study we use the Community Climate System Model, version 4 (CCSM4) from the National Center for Atmospheric Research (NCAR) [*Gent et al.*, 2011]. The horizontal resolution of the finite-volume grid of the atmosphere is 0.9°×1.25° with 26 vertical hybrid layers.

Four simulations with prescribed ocean and sea ice components are performed. The control run (CTRL) uses climatological SSTs and sea ice cover. The ATL experiment includes a SST anomaly in the western North Atlantic of +3°C in the region between 30°W–60°W and 40°N–60°N (see region indicated in Figure 2a). The spatial extent and the magnitude of the anomaly are similar to the anomalies observed from December 2005 to February 2006 relative to the 40 year winter mean of the European Center of Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) data. In the BAR experiment sea ice is set to zero between 25°E–55°E and 75°N–80°N, and in addition SSTs are increased by +3°C analogous to ATL (see region indicated in Figure 2a). The Barents Sea area is chosen because according to the literature it probably has the largest impact on European climate [e.g., *Honda et al.*, 2009; *Petoukhov and Semenov*, 2010]. Finally,

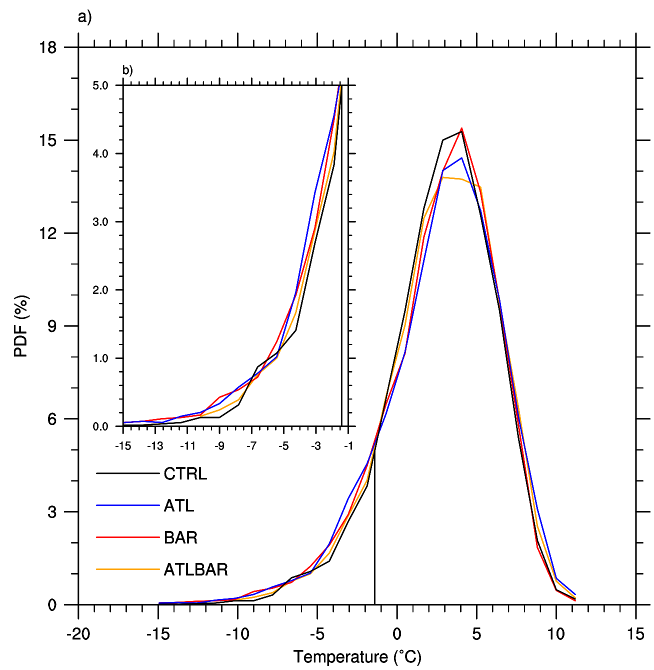

Figure 1. (a) Probability density function (PDF) of 60 year daily DJF European mean temperature. (b) Inset showing the lower tail of the PDF. Black: CTRL, blue: ATL, red: BAR, orange: ATLBAR. The vertical black line marks the 10% quantile of CTRL (−1.4°C). The 10% quantiles of ATL (−2.0°C), BAR (−2.0°C), and ATLBAR (−1.6°C) are not marked.

the ATLBAR experiment is a combination of ATL and BAR with both anomalies acting simultaneously, as observed in winter 2005/2006. In all experiments the anomalies are imposed from October to April. All simulations are run for 90 years with a repeating annual cycle of SSTs and sea ice. The first 30 years are regarded as spin-up and are not used for the analysis.

Additionally, ERA-Interim and NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) daily surface temperature fields (1979–2013) are evaluated. Correlation maps of temperature show similar sensitivity to the anomalies in the ATL and BAR regions in our model and in the reanalysis (see Figure S5 in the supporting information).

The focus of our analysis lies on winter temperatures over Europe. The analysis is performed on the 60 year December to February (DJF) mean (hereafter DJF_{AVG}) and on cold-days composites (hereafter CDE_{10}). These are defined as the mean of the 10% coldest days over Europe in DJF for each simulation. Europe is defined as the average over land between 0°E–20°E and 43.8°N–55.1°N (see region indicated in Figure 2a).

3. Results and Discussion

3.1. Surface Air Temperature

Changes in winter mean temperatures (DJF_{AVG}) over Europe due to the sea ice and/or SST anomalies are small and nonsignificant. This can be seen in the probability density function (PDF) of the 60 year mean of daily temperatures over Europe in Figure 1a as well as in Figures 2a–2c, which shows the DJF_{AVG} temperature anomalies compared to CTRL for all experiments. Significant warming is observed over the imposed anomalies and in ATL and ATLBAR over the Central Arctic and Siberia. While no significant signal in mean temperatures is observed over large parts of the Northern Hemisphere, extreme temperatures over Europe are more frequent in the experiments, along with a significant increase in the variance of the temperature distribution (p values of a one-sided F test, ATL: 7.8×10^{-15}, BAR: 5.7×10^{-8}, ATLBAR: 8.6×10^{-3}).

Therefore, we investigate the changes in cold extremes, i.e., the lower tail of the PDF, shown in Figure 1b. The number of days colder than the 10% quantile of CTRL over Europe (−1.4°C, vertical black lines in Figure 1) increases in all experiments compared to CTRL. The coldest days over Europe are getting colder when the anomalies are in place (Figures 3a–3c). Negative temperature anomalies for CDE_{10} (i.e., the 10% coldest days over Europe) are observed also over the northeastern U.S. and Canada and over Asia south of 45°N. Positive

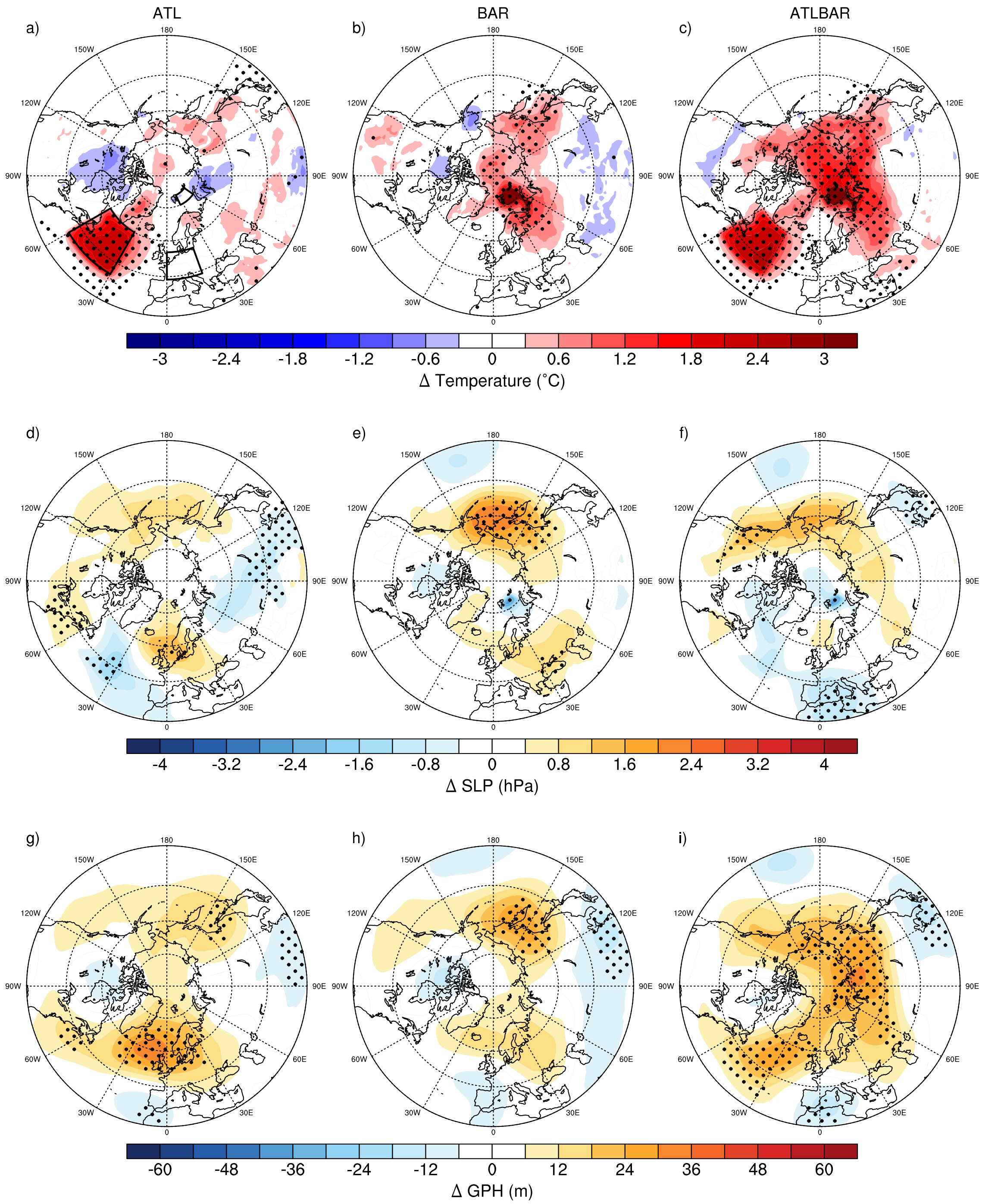

Figure 2. Sixty year DJF_{AVG} anomalies relative to CTRL for the three experiments (left) ATL, (middle) BAR, and (right) ATLBAR. (a–c) Surface temperature anomalies (°C), (d–f) SLP anomalies (hPa), and (g–i) GPH anomalies (m) at 300 hPa. Stippling denotes regions where the anomalies are significant at 90% confidence using a Student's *t* test. The boxes in Figure 3a mark the regions where the sea ice and/or SST anomalies are imposed and the area of Europe which is used (only grid points over land) to calculate European mean values.

temperature anomalies compared to CTRL for CDE_{10} are observed in the same regions where significant warming is observed for DJF_{AVG} and additionally over the northwestern U.S. and Canada. Furthermore, a warm Mediterranean region is present in ATL and ATLBAR.

Significance is tested for all anomalies. For DJF_{AVG} a Student's *t* test at 90% confidence is performed. For CDE_{10}, stippling marks anomalies significant at 90% confidence using a Mann-Whitney test (corrected for autocorrelation; see section S1.1).

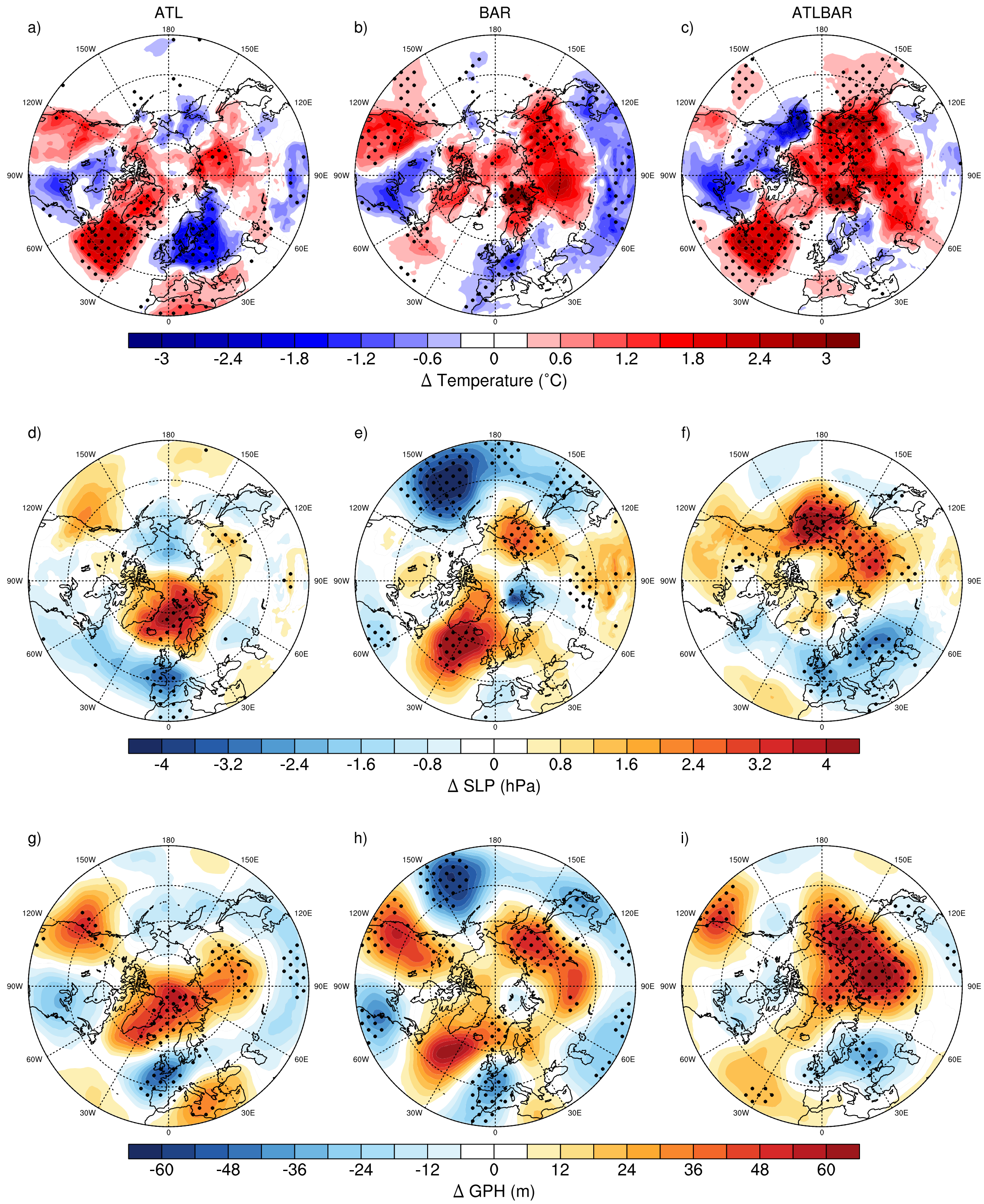

Figure 3. Sixty year anomalies of the 10% coldest days over Europe (CDE_{10}) compared to CTRL for the three experiments (left) ATL, (middle) BAR, and (right) ATLBAR. (a–c) Surface temperature anomalies (°C), (d–f) SLP anomalies (hPa), and (g–i) GPH anomalies (m) at 300 hPa. Stippling denotes regions where the anomalies are significant at 90% confidence using a Mann-Whitney test (using only days which are at least 5 days apart to avoid issues with autocorrelation).

3.2. Atmospheric Mean Response

As discussed above and shown in Figures 2a–2c, the mean temperatures over Europe are not significantly affected by the imposed sea ice and/or SST anomalies. In our experiments the NAO (not shown), blocking frequency (see section S1.2 and Figure S1) and jet position (defined as in *Mahlstein et al.* [2012], not shown) show only small changes over the eastern Atlantic. Still, some significant impacts on sea level pressure (SLP) and geopotential height (GPH) are observed (Figures 2d–2i). The main direction of advection over Europe is from southeast and thus associated with warm air advection (evident as a positive anomaly in the meridional wind component, see Figure S2). On the other hand, the storm track activity (STA, a measure of the strength and frequency of storms, see section S1.3 and Figure S3) over the North Atlantic and Europe decreases, which is expected to favor cold anomalies in Europe, as weaker and less frequent storms bring less energy from the warm ocean toward the continent [*Mahlstein et al.*, 2012]. The temperature effects of the meridional wind component and STA are of opposite sign, and thus, the combined impact on temperatures over Europe in winter is small.

3.3. Mechanisms Causing European Cold Extremes

The same compensating effects of a decrease in STA (see Figure S3) and an increase in southerly advection (see Figure S2) are visible for the 10% coldest days over Europe (CDE_{10}). Changes in the blocking frequency are too small to explain the cold anomalies over Europe (except for BAR, where an increase over Scandinavia might contribute to the anomalous easterly advection; see Figure S1). The jet position, however, shows some differences (not shown). Compared to the DJF_{AVG}, where the dominating jet position is between 44°N and 53°N, the northern and southern jet (north of 53°N and south of 44°N, respectively) are dominant for CDE_{10}. In ATL a shift to a more southerly jet is observed, while in BAR the jet shifts to the north, and in ATLBAR the jet is squeezed to a central position, compared to CTRL. The NAO index is significantly more negative for CDE_{10} in ATL compared to CTRL and might be important for the temperature anomalies over Europe (see below). The SLP and GPH anomalies compared to CTRL show that temperature anomalies for CDE_{10} are strongly influenced by anomalous easterly to north easterly advection (Figures 3d–3i). However, different mechanisms are responsible for the negative temperature anomalies over Europe, depending on the acting sea ice and/or SST anomaly.

The heating over the SST anomaly in the western North Atlantic is shallow, i.e., up to approximately 800 hPa in the mean response. A low-pressure anomaly over the eastern edge of the SST anomaly and a high-pressure anomaly over the European continent are visible in the SLP field (Figure 2d). Combined with another low-pressure anomaly over western Russia, they form a stationary wave train [*Hoskins and Karoly*, 1981]. The negative temperature anomaly over Canada and the positive temperature anomaly over the western North Atlantic (Figure 2a) form a temperature gradient in the direction of the flow, resulting in weak zonal advection. At upper levels a positive GPH anomaly exists over the northern Euro-Atlantic region (Figure 2g). This response is in agreement with the results by *Hoskins and Karoly* [1981]. However, the heating over the SST anomaly in ATL occasionally becomes deep (i.e., up to approximately 500 hPa; see Figure S4), likely due to upward eddy heat fluxes caused by transient eddies of many scales [*Hoskins and Karoly*, 1981]. In ATL deep heating is more frequent for cold days over Europe than for warm days. Deep heating might be the reason significant negative temperature anomalies are observed over Europe for CDE_{10}, as the atmospheric response is different for deep and shallow heating [*Hoskins and Karoly*, 1981]. In contrast to shallow heating, deep heating is mainly balanced by meridional advection. Consistent with that, the negative SLP anomaly in CDE_{10} develops further downstream of the SST anomaly compared to shallow heating, inducing northerly advection over the SST anomaly (Figures 2d and 3d). Furthermore, the downstream low-pressure anomaly in CDE_{10} likely pushes the high-pressure anomaly, which is located over the European continent in DJF_{AVG}, to the north. The resulting SLP pattern for CDE_{10} resembles the negative phase of the NAO, which is in agreement with anomalous easterly advection and associated with low temperatures over Central and Northern Europe and a warm Mediterranean area.

Over the Barents Sea, a low-level inversion is present in the observed climatology in winter [e.g., *Serreze et al.*, 1992]. This inversion is also present in our model simulations in CTRL and ATL. However, in the Barents Sea anomaly experiment it is eliminated. The absence of the inversion induces a negative SLP anomaly over the Barents Sea (Figures 2e, 2f, 3e, and 3f). This low-pressure anomaly generally does not penetrate to upper levels (Figures 2h and 2i), resulting in a shallow anomaly in the mean state. The low-pressure anomaly is, however, sometimes strong enough to penetrate to upper levels. According to *Bhatt et al.* [2008] this is mainly due to transient eddy vorticity fluxes. Still, a barotropic low-pressure anomaly over the Barents Sea does not necessarily cause negative temperature anomalies over Europe. However, the low-pressure anomaly over the Barents Sea induces northerly flow. Combined with a secondary barotropic high-pressure anomaly over the Atlantic and a low-pressure anomaly to the south of Spain, which drive an easterly flow, an S-shaped flow establishes and advects cold Arctic and Siberian air toward Europe. This situation is visible for CDE_{10} in BAR (Figures 3e and 3h) and is most likely responsible for the negative temperature anomalies over Europe. A slight increase in blocking frequency over Scandinavia for CDE_{10} may further reinforce the cold anomalies (see Figure S1).

The temperature response in the combined experiment (ATLBAR) is the weakest of the three cases (Figure 3c). The two anomalies in the western North Atlantic and the Barents Sea do not interact linearly, and the Atlantic anomaly dominates. A reason for this imbalance is likely that the SST anomaly in the Atlantic is located in the region where European weather is "generated" and may thus directly affect it. Furthermore, the spatial extent of the SST anomaly in the Atlantic is several times larger than the one in the Barents Sea. Still, the low-pressure anomaly developing over the Barents Sea anomaly is able to disturb the high-pressure anomaly over the Arctic Ocean, which develops in ATL (Figures 3d and 3f). This high-pressure anomaly does not reach as far south as when the anomaly in the Atlantic is imposed alone. Thus, the NAO does not change significantly, and advection from the east is weak. Moreover, the low-pressure anomaly over the Barents Sea does not become barotropic (Figure 3i), as it is likely dampened at upper levels due to anomalous warm air advection from the SST anomaly in the Atlantic. Still, a weak easterly cold air advection is responsible for the slight cooling over Europe for CDE_{10}.

4. Conclusion

Here we present results from a climate model in which winter mean temperatures over Europe do not change significantly as a result of reduced sea ice and/or increased SSTs. Nevertheless, we do observe an increase in cold extremes. For the 10% coldest days over Europe with the imposed anomaly in the western North Atlantic a negative NAO establishes. The anomaly in the Barents Sea produces a barotropic low-pressure anomaly over the sea ice and SST anomaly, and a secondary high-pressure anomaly over the Atlantic develops. Both responses result in anomalous easterly to northeasterly advection toward Europe. The response is weakest when both anomalies are combined. The two anomalies do not interact linearly, and the two mechanisms in combination cancel most of the temperature responses produced by the single forcings. Still, the overall circulation change is a weak easterly advection in the combined experiment.

These results are different from earlier studies, which provide possible links between European winter mean temperatures and sea ice or SST conditions. One reason our simulations do not show the mechanisms proposed by *Croci-Maspoli and Davies* [2009] and *Petoukhov and Semenov* [2010] could be the use of different oceanic conditions. However, the lack of a temperature response over Europe to SST and sea ice anomalies has been documented before [*Jung et al.*, 2010].

The occurrence of several cold winters in recent years has frequently been linked to climate change in the popular media. The ERA-Interim time series of DJF average temperatures show that recent winters were not exceptionally cold even though temperatures were below the long-term positive trend. According to the correlation maps the interactions between the western North Atlantic and Barents Sea temperature and European temperatures are small (see Figure S5).

Based on our model results and ERA-Interim data we argue that the low mean temperatures of the recent winters, if they are in fact forced, need to be explained by other factors besides SST and sea ice anomalies, while the short cold spells might be triggered by these two anomalies. Therefore, the mechanisms proposed in earlier studies to cause low mean winter temperatures should be interpreted carefully, and results may be model or method dependent.

Aware of the characteristics of the model, we argue that the increases in cold extremes and the mechanisms proposed are just possible explanations. Reanalysis data for winter 2012 shows a similar pattern as our BAR experiment. However, 1 single year is not representative and can not provide a causal link to any mechanisms. An alternative explanation for recent cold winters is that they are simply a particular realization of natural variability.

In summary, we argue that recent anomalously cold winters may not be triggered by sea ice or SST anomalies alone. Hence, a negative temperature trend in winter over Europe may not be a consequence of sea ice decline, and SST increase due to anthropogenic global warming and may thus not continue in the future.

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References

Bhatt, U. S., M. A. Alexander, C. Deser, J. E. Walsh, J. S. Miller, M. S. Timlin, J. Scott, and R. A. Tomas (2008), The atmospheric response to realistic reduced summer Arctic sea ice anomalies, in *Arctic Sea Ice Decline: Observations, Projections, Mechanisms and Implications, Geophys. Monogr. Ser.,* vol. 180, edited by T. DeWeaver, C. M. Bitz, and L.-B. Tremblay, pp. 91–110, AGU, Washington, D. C., doi:10.1029/180GM08.

Cattiaux, J., R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, and F. Codron (2010), Winter 2010 in Europe: A cold extreme in a warming climate, *Geophys. Res. Lett.*, *37*, L20704, doi:10.1029/2010GL044613.

Cohen, J., and D. Entekhabi (1999), Eurasian snow cover variability and Northern Hemisphere climate predictability, *Geophys. Res. Lett.*, *26*(3), 345–348, doi:10.1029/1998GL900321.

Cohen, J. L., J. C. Furtado, M. Barlow, V. A. Alexeev, and J. E. Cherry (2012), Asymmetric seasonal temperature trends, *Geophys. Res. Lett.*, *39*, L04705, doi:10.1029/2011GL050582.

Croci-Maspoli, M., and H. C. Davies (2009), Key dynamical features of the 2005/06 European winter, *Mon. Weather Rev.*, *137*(2), 664–678, doi:10.1175/2008MWR2533.1.

Degirmendzic, J., and J. Wibig (2007), Jet stream patterns over Europe in the period 1950–2001—Classification and basic statistical properties, *Theor. Appl. Climatol.*, *88*(3-4), 149–167, doi:10.1007/s00704-006-0237-5.

Drevillon, M., L. Terray, P. Rogel, and C. Cassou (2001), Mid latitude Atlantic SST influence on European winter climate variability in the NCEP reanalysis, *Clim. Dyn.*, *18*(3-4), 331–344, doi:10.1007/s003820100178.

Gent, P. R., et al. (2011), The Community Climate System Model version 4, *J. Clim.*, *24*(19), 4973–4991, doi:10.1175/2011JCLI4083.1.

Honda, M., J. Inoue, and S. Yamane (2009), Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters, *Geophys. Res. Lett.*, *36*, L08707, doi:10.1029/2008GL037079.

Hoskins, B. J., and D. J. Karoly (1981), The steady linear response of a spherical atmosphere to thermal and orographic forcing, *J. Atmos. Sci.*, *38*, 1179–1196, doi:10.1175/1520-0469(1981)038<1179:TSLROA>2.0.CO;2.

Jung, T., T. N. Palmer, M. J. Rodwell, and S. Serrar (2010), Understanding the anomalously cold European winter of 2005/06 using relaxation experiments, *Mon. Weather Rev.*, *138*(8), 3157–3174, doi:10.1175/2010MWR3258.1.

Kolstad, E. W., T. Breiteig, and A. A. Scaife (2010), The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, *Q. J. R. Meteorolog. Soc.*, *136*(649), 886–893, doi:10.1002/qj.620.

Mahlstein, I., O. Martius, C. Chevalier, and D. Ginsbourger (2012), Changes in the odds of extreme events in the Atlantic basin depending on the position of the extratropical jet, *Geophys. Res. Lett.*, *39*, L22805, doi:10.1029/2012GL053993.

Petoukhov, V., and V. A. Semenov (2010), A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents, *J. Geophys. Res.*, *115*, D21111, doi:10.1029/2009JD013568.

Scaife, A. A., and J. R. Knight (2008), Ensemble simulations of the cold European winter of 2005–2006, *Q. J. R. Meteorolog. Soc.*, *134*(636), 1647–1659, doi:10.1002/qj.312.

Serreze, M. C., J. D. Kahl, and R. C. Schnell (1992), Low-level temperature inversion of the Eurasian Arctic and comparisons with Soviet drifting station data, *J. Clim.*, *5*(6), 615–629, doi:10.1175/1520-0442(1992)005<0615:LLTIOT>2.0.CO;2.

Sillmann, J., and M. Croci-Maspoli (2009), Present and future atmospheric blocking and its impact on European mean and extreme climate, *Geophys. Res. Lett.*, *36*(10), L10702, doi:10.1029/2009GL038259.

Tang, Q., X. Zhang, X. Yang, and J. A. Francis (2013), Cold winter extremes in northern continents linked to Arctic sea ice loss, *Environ. Res. Lett.*, *8*(1), 014,036, doi:10.1088/1748-9326/8/1/014036.