

## RESEARCH LETTER

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## Key Points:

- CAOs are identified relative to the climatology of each period in contrast to previous work
- CAOs become less severe in response to sea ice loss, but their frequency and duration do not change
- The response of midlatitude CAOs to sea ice loss is largely governed by thermodynamical processes

## Supporting Information:

- Supporting Information S1

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## Future Arctic sea ice loss reduces severity of cold air outbreaks in midlatitudes

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**Abstract** The effects of Arctic sea ice loss on cold air outbreaks (CAOs) in midlatitudes remain unclear. Previous studies have defined CAOs relative to the present-day climate, but changes in CAOs, defined in such a way, may reflect changes in mean climate and not in weather variability, and society is more sensitive to the latter. Here we revisit this topic but applying changing temperature thresholds relating to climate conditions of the time. CAOs do not change in frequency or duration in response to projected sea ice loss. However, they become less severe, mainly due to advection of warmed polar air, since the dynamics associated with the occurrence of CAOs are largely not affected. CAOs weaken even in midlatitude regions where the winter mean temperature decreases in response to Arctic sea ice loss. These results are robustly simulated by two atmospheric models prescribed with differing future sea ice states and in transient runs where external forcings are included.

### 1. Introduction

Cold air outbreaks (CAOs) are persistent events of intrusions of cold air into warmer regions. In the Northern Hemisphere (NH), they are often linked to the occurrence of blocking highs (BHs) [e.g., Walsh *et al.*, 2001] with frequently dramatic effects on society, agriculture, and economy of the affected areas. In the last decade, in spite of the global warming trend, a high number of CAOs have occurred in NH midlatitudes, and several studies have cited the rapid warming of the Arctic in recent decades as a potential cause [e.g., Petoukhov and Semenov, 2010; Francis and Vavrus, 2012].

Arctic amplification (AA) refers to the stronger warming over the Arctic than over lower latitudes, leading to a reduction in the meridional temperature gradient [Cohen *et al.*, 2014]. The main driver of near-surface AA is the loss of Arctic sea ice due to increased greenhouse gas (GHG) concentrations [Screen and Simmonds, 2010; Screen *et al.*, 2012]. Its effects are also reinforced by other factors such as local radiative feedbacks owing to the stable Arctic lower atmosphere [Bintanja *et al.*, 2011; Pithan and Mauritsen, 2014] and changes in water vapor content [Screen and Simmonds, 2010].

Several studies have hypothesized that extreme weather events in midlatitudes may increase in likelihood as a result of the weakening of the near-surface meridional temperature gradient. The proposed mechanism involves the slowdown of upper level zonal winds and a subsequent increased meandering of the jet stream, which may favor the occurrence of more persistent weather patterns and thus, more extreme weather events [Francis and Vavrus, 2012, 2015]. However, this causal chain remains largely unproven and highly uncertain [Barnes and Screen, 2015]. For instance, Barnes [2013] and Screen and Simmonds [2013] found that assessments of the change in the amplitude of planetary waves and in the frequency of BHs depend strongly on the metric used and that observed trends are well within the range of natural variability.

While the aforementioned dynamical mechanism could cause an increase in CAOs, there are thermodynamical reasons to expect the opposite: a decrease, or reduction in severity, of CAOs. Screen [2014] proposed that a weakened meridional temperature gradient leads to a decrease in subseasonal temperature variability, related to fewer (or less severe) cold days together with a smaller increase in the frequency (or severity) of warm days. Screen *et al.* [2015a, hereinafter S15a] performed model experiments with projections of reduced Arctic sea ice cover and identified a future decrease in the frequency of cold days over high latitudes and, to a lesser extent, over central and eastern U.S. The response of cold extremes over other midlatitude regions, in particular the highly populated western U.S., European, and East Asian regions, remains unclear and is explored further in this study.

It has been argued that detected changes in cold extremes in S15a may only reflect time mean atmospheric warming, rather than less extreme weather per se [Francis, 2015]. This is because S15a (and to our knowledge,

all previous studies on this topic) identified extreme cold events based on a threshold derived from the climatological temperature of the present-day climate. Arguably, society will become accustomed to the warmer climate of the future, and the discomfort of a cold spell may be perceived relative to the new (warmer) average temperature. Indeed, there is evidence that the effects of a given cold temperature on human mortality vary temporally based on how unusual it is for that time [Lee *et al.*, 2014]. Motivated by this, here we revisit the topic about possible future changes in cold extremes and the contribution of the projected sea ice retreat, but for the first time, we identify extreme events relative to the future climatological state.

Furthermore, it has been suggested that while the frequency (or severity) of cold days may decrease in response to Arctic sea ice loss (S15a), longer duration cold events may increase if weather patterns become more persistent [Francis, 2015]. For this reason we focus here on CAOs lasting 5 or more days, expanding on S15a that focused on daily extremes.

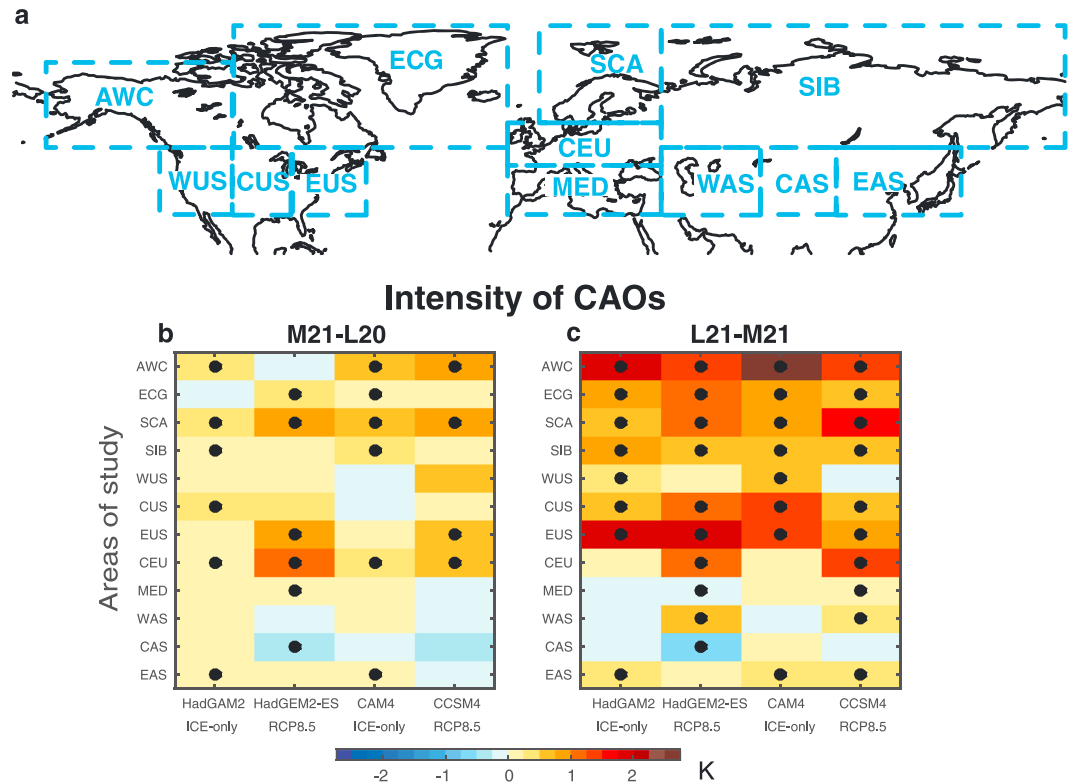
## 2. Data and Methodology

Time-slice simulations with prescribed sea surface temperatures (SSTs) and sea ice concentrations (SICs) representative of different periods are used in this study. The simulations are run for 260 years using two independent atmospheric models: the Hadley Centre Global Atmospheric Model version 2 (HadGAM2) [Collins *et al.*, 2011] and the Community Atmosphere Model version 4 (CAM4) [Gent *et al.*, 2011]. The version of HadGAM2 used here has a horizontal resolution of  $1.875^\circ$  longitude by  $1.25^\circ$  latitude and 38 vertical levels. CAM4 has a horizontal resolution of  $1.25^\circ$  longitude by  $0.9^\circ$  latitude and 26 vertical levels. The top of both models is located at 10 hPa. The prescribed SSTs and SICs include an annual cycle and are taken from transient simulations with the coupled version of the models (HadGEM2-ES and CCSM4, respectively) averaged across different 20 year periods and all available ensemble members (see Table S1 in the supporting information). For the reference simulation, SSTs and SICs come from the Coupled Model Intercomparison Project Phase 5 (CMIP5) “historical” simulations averaged in the period 1980–1999 (late twentieth century; L20). In the case of the sensitivity runs, they include projections of SICs representative of mid-21st century (M21) and late 21st century (L21) conditions taken from the CMIP5 Representative Concentration Pathway 8.5 (RCP8.5) simulations averaged over the periods 2030–2049 and 2080–2099, respectively. In both simulations, SSTs remain the same as in the L20 simulation except for the grid points where the ice has disappeared in the future, where SST values are taken from RCP8.5 simulations of the corresponding periods. The prescribed differences in sea ice concentrations are shown in Figure S1 in the supporting information. We note that over the period 1980–1999 the CCSM4 simulations bear close resemblance to observations, whereas HadGEM2-ES simulates too little ice in autumn and too much ice in the other seasons (Figure S1).

The mentioned CMIP5 historical and RCP8.5 transient simulations of the coupled models HadGEM2-ES and CCSM4 are also analyzed in the study to assess the full future change in CAOs in response to increasing GHG concentrations. The contribution of sea ice loss to this total change is inferred by contrasting the sea ice sensitivity runs to the transient climate change simulations.

Cold air outbreaks are studied in different areas of the NH (see Figure 1a), consistent with S15a and based upon those used in the Intergovernmental Panel on Climate Change Fifth Assessment Report [Intergovernmental Panel on Climate Change, 2013]. A CAO is identified if the 1.5 m air temperature ( $T$ ) over land, averaged over each area, drops below the 10th percentile of the climatological distribution for a given day for at least five consecutive days starting or ending in December, January, or February. The daily climatology of  $T$  is smoothed by a 10 day running mean to ensure the robustness of the  $T$  threshold for CAOs and is computed for each simulation; i.e., the  $T$  threshold is different for each model and sea ice/climate condition. In each run, the first January and February and the last December of the simulation are removed in order to compute the climatologies over 259 complete winters. The minimum duration of 5 days is chosen because it is the same as that usually imposed for blocking highs and CAOs are often linked to the occurrence of those phenomena. Apart from the frequency, two characteristics of CAOs are analyzed: intensity and duration. The duration of CAOs is defined as the number of consecutive days during which the area-averaged  $T$  is below the 10th percentile of its daily climatological value. The intensity of a CAO is computed as the mean anomalous area-averaged  $T$  during the duration of the event.

The statistical significance of changes in CAOs due to sea ice loss, or an increase in GHG concentrations, is computed by applying two-sample Student's  $t$  test where the null hypothesis is the equality of means of the samples.



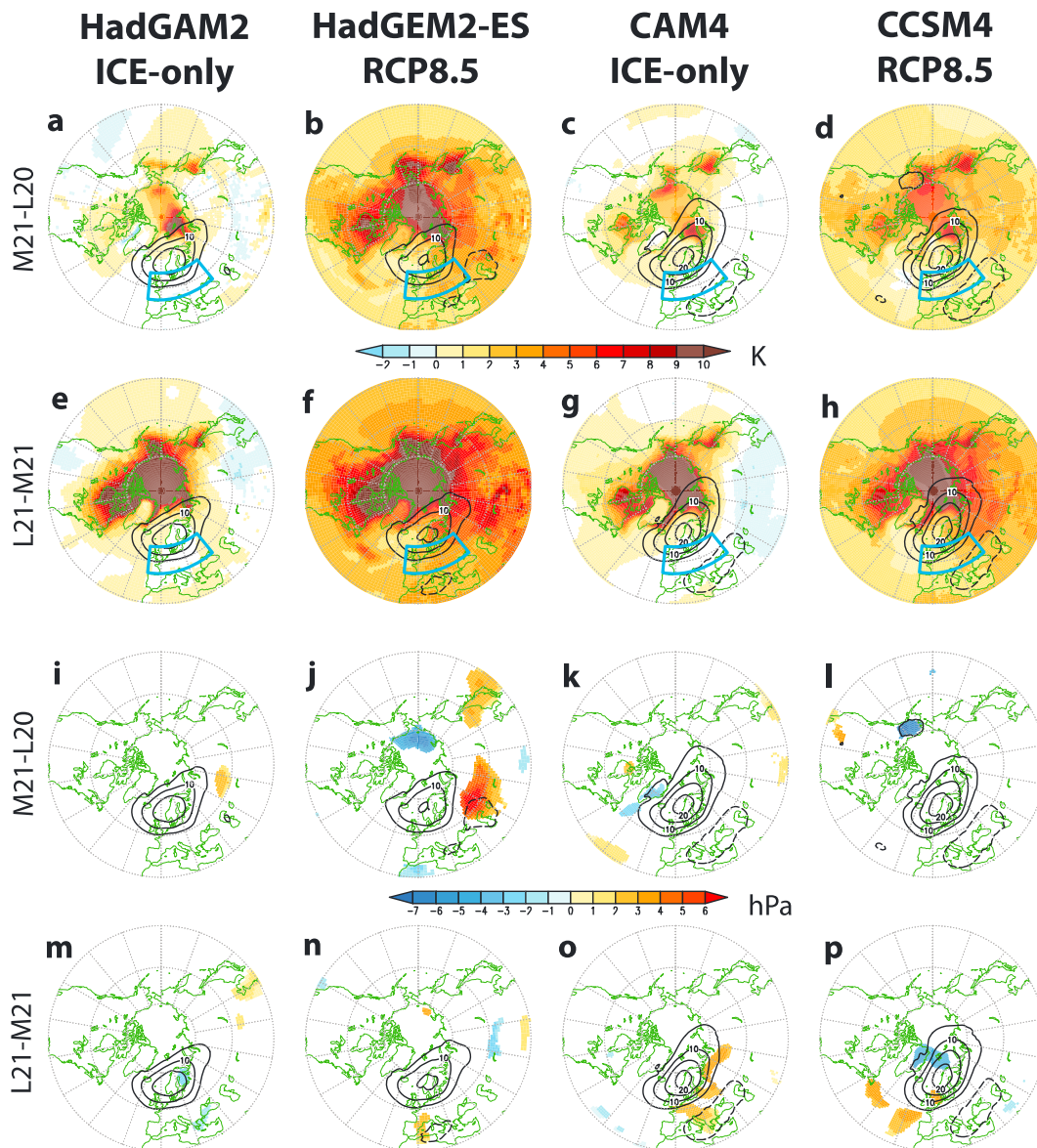
**Figure 1.** (a) Areas of study of CAOs. (b) Changes in the intensity of CAOs in each region of Figure 1a due to projected GHG-induced sea ice loss in time-slice simulations of HadGAM2 and CAM4 and to projected GHG increase according to RCP8.5 scenario in transient runs of HadGEM2-ES and CCSM4 from mid-21st century (M21) with respect to late twentieth century (L20) period. (c) Same as Figure 1b but for the change from late 21st century (L21) with respect to mid-21st century (M21) period. Dots in Figures 1b and 1c denote statistically significant change at a 95% confidence level.

### 3. Results

The frequency and duration of CAOs do not show any robust change in the future, either in response to solely Arctic sea ice loss or in response to increasing GHG concentrations, in either model, or in either the M21 or L21 (Figure S2 in the supporting information). However, statistically significant changes in the intensity of CAOs are identified in the future (Figures 1b and 1c). As expected, the regions closest to the Arctic (Alaska and western Canada (AWC), eastern Canada and Greenland (ECG), Scandinavia (SCA), and Siberia (SIB)) show the clearest signal, and all of these regions show a significant CAO weakening in response to sea ice loss. CAOs also appear strongly affected by sea ice loss in several midlatitude regions, and we will focus our attention on these. Sea ice loss in the first half of the century causes significantly warmer CAOs in both models across central Europe and East Asia (Figure 1b). Projected sea ice loss in the second half of the century leads to warmer CAOs in both models in western, central, and eastern U.S., and East Asia (Figure 1c). In these regions the projected changes due to sea ice loss represent a sizeable fraction of the overall simulated change to increasing GHG. There is no evidence for sea ice loss affecting the intensity of CAOs over the Mediterranean, western, or central Asia. In the rest of our analysis we focus on three midlatitude areas in different continents (central Europe, western U.S., and eastern Asia) which warrant more detailed analysis due to their high population and noteworthy aspects of the simulated changes.

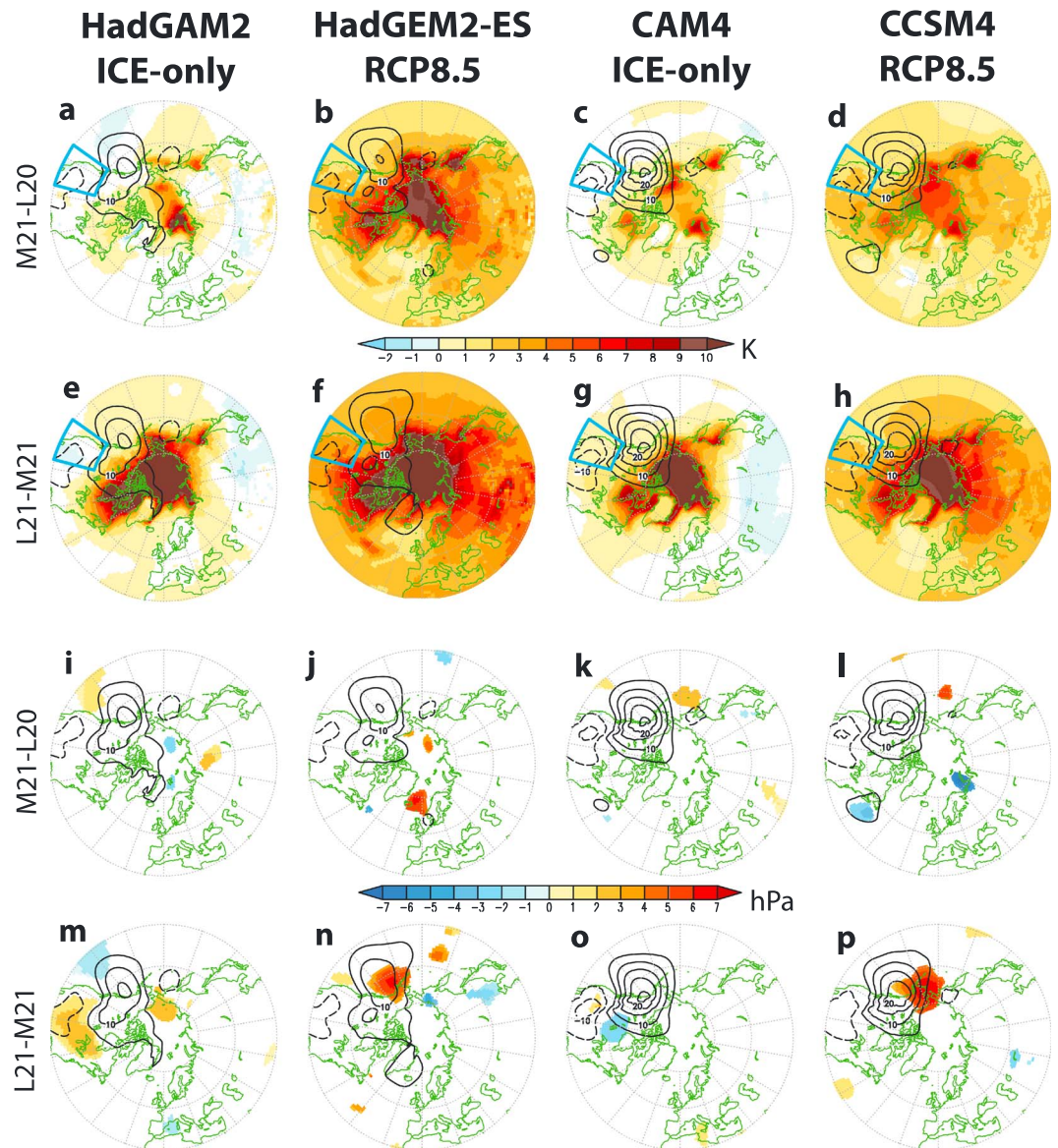
#### 3.1. CAOs Over Central Europe

CAOs over central Europe weaken in the future due to GHG-induced climate change (Figures 1b and 1c). The contribution of Arctic sea ice loss is significant in the first part of the 21st century but not in the second part. The circulation (sea level pressure) pattern associated with the occurrence of these events corresponds to an anomalous anticyclone west of Scandinavia and resembles the negative phase of the North Atlantic



**Figure 2.** Analysis for central Europe (blue box). (a–d) Composite of SLP anomalies for the first day of all L20 CAOs (contoured every 5 hPa) and differences in mean winter (December–January–February) 1.5 m temperature between M21 and L20 (shaded) in the four models. Only statistically significant differences at the 95% confidence level are shaded. (e–h) Same as Figures 2a–2d but with composite SLP anomalies for M21 (contours) and temperature differences between L21 and M21 (shaded). (i–l) Composite SLP anomalies for the first day of all L20 CAOs (contours; repeated from Figures 2a–2d) and statistically significant differences in composite SLP anomalies for M21–L20 (shaded). (m–p) Same as Figures 2i–2l but with composite SLP anomalies for M21 (contours; repeated from Figures 2e–2h) and SLP differences for L21–M21 (shaded).

Oscillation, although it is shifted northeastward in the case of CAM/CCSM (Figure 2, contours). This circulation pattern is associated with cold anomalous easterly winds over central Europe and is not significantly altered due to GHG increases or Arctic sea ice loss (Figures 2i–2p, shading). However, sea ice loss causes warming upstream (Figures 2a–2h, shading), and hence, it is the advection of warmer air into central Europe that dominates the change in intensity of CAOs. The advected air initially comes from the Barents and Kara seas (deduced from contours in Figures 2a–2h), where the loss of sea ice, and thus, the associated atmospheric warming is larger in the first half of the 21st century than in the second (Figure S3 in the supporting information). This provides an explanation for the diminishing influence of Arctic sea ice loss on central European CAOs through the century. Other reasons such as a possible nonlinearity of the temperature response to sea ice loss, as explained by *Semenov and Latif* [2015], might also help explain this diminishing influence.

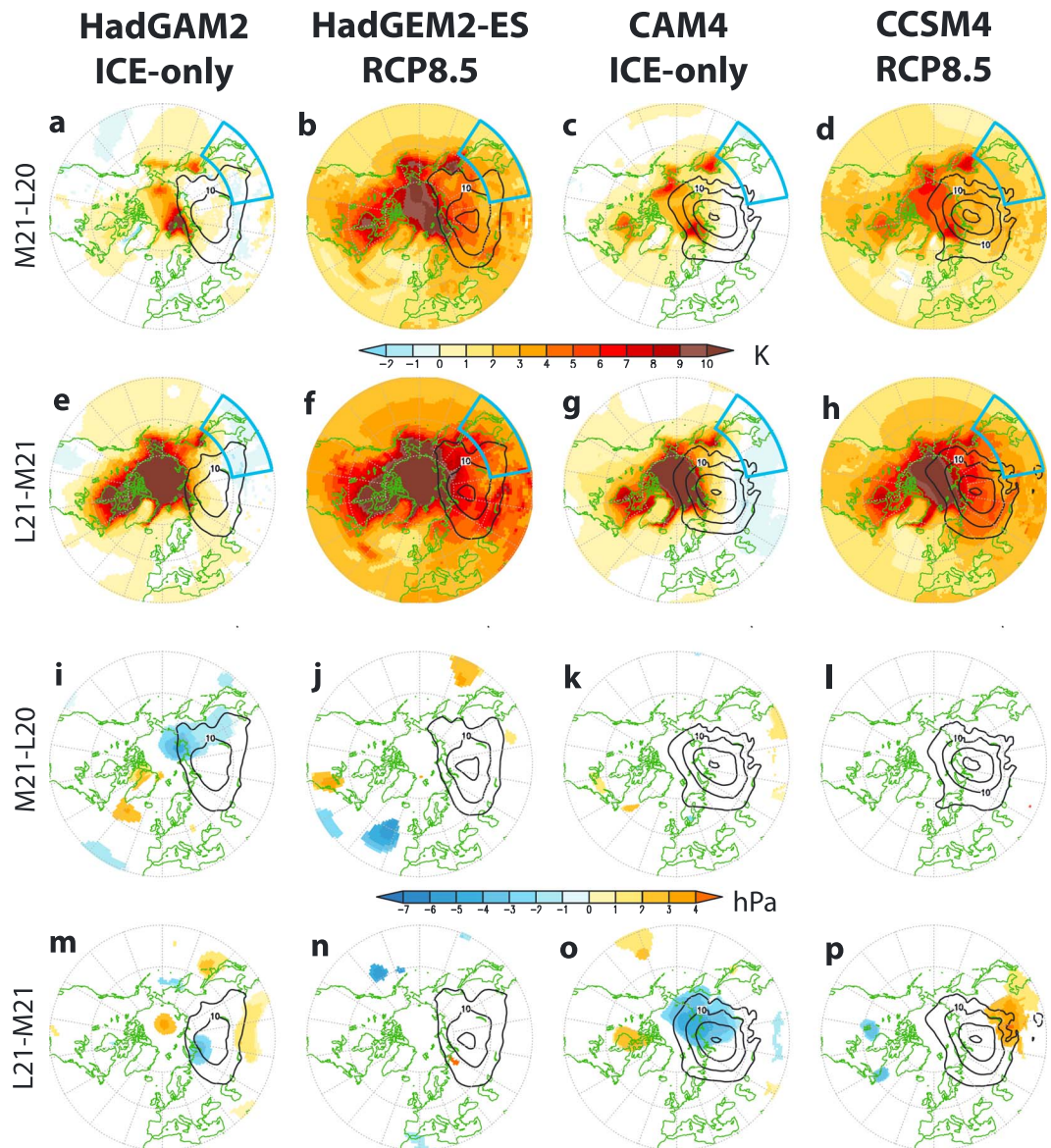


**Figure 3.** Same as Figure 2 but for the western U.S.

### 3.2. CAOs Over Western United States

All three areas of the U.S. show a weakening of CAOs in the second half of the 21st century due to the sea ice loss (Figure 1c). The following analysis focuses on the western U.S., as changes over the central and eastern U.S. were discussed in detail in *Screen et al.* [2015b]. The circulation pattern during CAOs over the western U.S., with an anomalous anticyclone over the eastern North Pacific drawing down cold air from Arctic Canada (Figure 3, contours), shows little change in response to sea ice loss (Figures 3i–3p, shading). However, atmospheric warming over Arctic Canada, driven by sea ice loss, results in warmer air being advected across the western U.S. during CAOs (Figures 3a–3h, shading). Thus, just as for central Europe, the intensity reduction of western U.S. CAOs appears to be primarily driven by thermodynamics rather than dynamics. Sea ice loss and associated warming in Arctic Canada is larger during the second half of the century, and hence, the influence of sea ice loss on CAOs in the western U.S. also increases through time.

In central and eastern U.S. the overall effect of GHG increases is also to weaken CAOs (Figure 1c). However, over the western U.S. there is no significant change in response to GHG increases, despite a significant weakening of CAOs in response to sea ice loss. This implies that additional GHG-induced changes, unrelated to sea



**Figure 4.** Same as Figure 2 but for the East Asia.

ice loss, offset the sea ice-induced changes. Comparing the sea level pressure anomalies between L21 and M21 reveals that the anomalous anticyclone west of Canada associated with CAOs strengthens in response to increased GHG (Figures 3m–3p). This acts to intensify CAOs (a dynamical effect) while the upstream warming acts to weaken CAOs (a thermodynamic effect), leading to a small and insignificant overall change in CAO intensity. This highlights that even when the effects of sea ice loss are significant in isolation, competing factors may lead to no, or even an opposite-signed, change when all forcing factors are considered together. The transient runs also show a climatological increase in SLP in the same area (not shown), which may be related to a future enhancement in the frequency of BHs as shown by *Masato et al.* [2013].

### 3.3. CAOs Over Eastern Asia (EAS)

CAOs over eastern Asia are weakened in response to sea ice loss in both the first and second parts of the 21st century. CAOs in this region are linked to a strengthened Siberian High and anomalous northerly advection of polar air into midlatitudes. Once more, thermodynamics seems to play a predominant role in the change of CAOs, since no robust change in the SLP pattern is detected under changing sea ice loss conditions among the different models (Figures 4i–4p), but significant warming is simulated upstream. Nevertheless, dynamical

changes might also have an important contribution to the weakening of CAOs in this area. For instance, in the first half of the century in HadGAM2 and in the second half in CAM4, there is a weakening of the anomalous anticyclone at its eastern edge. In both cases this might contribute to the weakening of CAOs.

The warming of CAOs over eastern Asia in response to sea ice loss is in contrast to the winter mean cooling. Our simulations exhibit wintertime cooling over eastern Asia (Figures 4a and 4c) due to an intensification of the Siberian high, consistent with previous studies [Vihma, 2014, and references therein]. This cooling has often been assumed (implicitly) to increase the intensity of cold extremes. However, our simulations do not support this and instead show that CAOs in East Asia become significantly warmer due to sea ice loss. This highlights that changes in (cold) extremes may not simply follow changes in the mean temperature and can occur even in the absence of change in mean climate. In fact, in all three regions considered in detail here (central Europe, western U.S., and East Asia), the changes in the intensity of CAOs are more robust (significant in both models) than are changes in the winter mean temperature.

#### 4. Discussion

The projected decrease in CAO intensity over the U.S., Europe, and East Asia arising from continued sea ice loss is a robust response in two independent models, despite the models being prescribed with different sea ice conditions and different rates of future sea ice retreat (Figure S1 in the supporting information). This suggests that our results are not highly sensitive to model uncertainty in the projected sea ice trends due to GHG forcing or to the differences in the mean state that may lead to a different nonlinear response of temperature to sea ice loss as indicated by Yang and Christensen [2012] and Semenov and Latif [2015]. The strong model agreement is further suggestive of a predominant role of the thermodynamics (i.e., the advection of warmer polar air to midlatitudes during CAOs) over dynamics, as thermodynamical changes tend to be more robust between models than are dynamical changes. Finally, a similar reduction in the severity of CAOs is found in transient runs with the coupled version of models, which reinforces the conclusions derived from the sea ice experiments, and highlights the key role of sea ice loss to the total changes of CAOs under GHG-induced warming.

CAOs in our study do not increase in occurrence or their persistence in response to sea ice loss, contrary to suggestions by several studies such as Francis and Vavrus [2012, 2015] or Cohen *et al.* [2014]. We point out that these studies have focused on short-term trends observed over the recent past whereas we have considered longer-term trends projected for the future. It is plausible that the dominant factors leading to changes in CAOs differ on these very different time scales. However, we can at least say that according to our simulations, there is no evidence that CAOs will increase in frequency, duration, or intensity in the long term. Instead, our simulations suggest that there are robust thermodynamical reasons to expect the intensity of CAOs to decrease.

CAOs at high latitudes in our study do not decrease in the frequency or duration either as suggested by S15a. This discrepancy is important to highlight because S15a used the same sea ice experiments as we have. However, the thresholds used in S15a for the identification of the cold extreme events were based on the late twentieth century climatology, whereas here we have used the future climatologies. The discrepancy implies that the reduction of cold extremes at high latitudes, as shown by S15a, is largely a result of mean high-latitude warming and not reduced temperature variability. Conversely, in this study we have identified significant changes in midlatitude regions that are not apparent in S15a: western U.S., central Europe, and East Asia. Over these regions, sea ice loss induces (weak) wintertime mean cooling in one or both models, leading to no significant, or nonrobust, changes in cold extremes in S15a. However, when this mean cooling is removed (by defining cold extremes relative to the future climatology) a significant decrease in CAO intensity is found. This implies that while sea ice loss may induce weak wintertime cooling over these midlatitude regions, the severity of CAOs decreases owing to warming of polar air masses that are advected into midlatitudes during CAOs. Thus, our study highlights the dependence of the results concerning sea ice-induced changes in cold extreme events on the technique for the identification of events. Nevertheless, our results agree with previous work such as Screen [2014] and S15a in that the response of midlatitude cold extremes to Arctic sea ice loss is largely governed by thermodynamical processes (advection of warmed air).

Finally, we would like to highlight that we have restricted our analysis to the troposphere and not discussed and/or analyzed the contributions of other parts of the climate system with a potential effect on the connection between sea ice variability and CAOs. For instance, some authors have suggested an important role of

the stratosphere in the link between the AA and the occurrence of midlatitude extreme weather events [Jaiser et al., 2013; Kim et al., 2014]. However, our conclusion about the unchanged dynamics associated with CAOs seems to contradict this idea. Nevertheless, the current study has been carried out with the output of simulations of low-top models. A comparative analysis involving also high-top models might be a next step in this research topic.

## 5. Conclusions

We have revisited the topic of changes in NH CAOs in the future due to projected GHG-induced sea ice retreat. We have applied a different methodology for the identification of CAOs in comparison with previous literature on this topic, as we have selected the events relative to the mean climate of each epoch, rather than relative to the past or present day. Our main conclusions are the following:

1. The frequency of CAOs and their duration in high and middle latitudes of the NH do not significantly change in the future.
2. Future CAOs at high latitudes and in the highly populated midlatitudes become weaker, i.e., warmer, than in the present-day climate in response to projected sea ice loss.
3. A weakening of CAOs is also detected in transient runs where all natural variability and other external forcings are included. Sea ice loss contributes significantly to this overall trend and is, depending on region, reinforced or partly counteracted by the effects of other forcings.
4. Most of the circulation structures associated with the occurrence of CAOs do not seem to be affected by the sea ice retreat. It is the local advection of warmer polar air to the midlatitudes that dominates the change in CAOs intensity.
5. The change in the intensity of CAOs at midlatitudes is, in some regions, opposite in sign to the mean winter temperature response to Arctic sea ice loss. For instance, the winter temperature response over central Europe, Western United States, and East Asia shows either a nonsignificant change, a dissimilar signal between the two models, or even a robust cooling, respectively. In contrast, CAOs robustly weaken in each of these regions in response to sea ice loss.

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