Atmospheric response in summer linked to recent Arctic sea ice loss

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Since 2007 a large decline in Arctic sea ice has been observed. The large-scale atmospheric circulation response to this decline is investigated in ERA-Interim reanalyses and HadGEM3 climate model experiments. In winter, post-2007 observed circulation anomalies over the Arctic, North Atlantic and Eurasia are small compared to interannual variability. In summer, the post-2007 observed circulation is dominated by an anticyclonic anomaly over Greenland which has a large signal-to-noise ratio. Climate model experiments driven by observed SST and sea ice anomalies are able to capture the summertime pattern of observed circulation anomalies, although the magnitude is a third of that observed. The experiments suggest high SSTs and reduced sea ice in the Labrador Sea lead to positive temperature anomalies in the lower troposphere which weaken the westerlies over North America through thermal wind balance. The experiments also capture cyclonic anomalies over Northwest Europe, which are consistent with downstream Rossby wave propagation.

Key Words: Arctic sea ice loss; summertime atmospheric circulation; Labrador sea ice

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1. Introduction

Changes observed in the Arctic such as the long-term decline in sea ice cover and the increase in surface air temperature (SAT) are tangible indicators of a changing climate. Arctic Amplification is a phenomenon where the SAT in the Arctic is expected to increase at a rate almost twice that of the global mean temperature increase (e.g. IPCC, 2007). The reduction of Arctic sea ice is an important contributory factor to Arctic Amplification through the ice-albedo feedback effect (Serreze *et al.*, 2009).

Arctic sea ice extent has been in decline since at least 1979 with a reduction of $\sim -4.0\%$ per decade between 1978 and 2010 increasing to a rate of $\sim -8.3\%$ per decade between 1996 and 2010 (Comiso, 2012). Sea ice is a physical barrier between the ocean and atmosphere regulating the exchanges of heat, moisture and momentum. The recent observed decline in Arctic sea ice may therefore change the surface energy budget in the Arctic (Porter *et al.*, 2012) and has the potential to impact the large-scale atmospheric circulation. Whilst this is a two-way process where the atmospheric (and oceanic) circulation can also influence the sea ice cover (e.g. Wang *et al.*, 2009; Ogi and Wallace, 2012), this article will only be addressing the question of the impact of Arctic sea ice loss on the atmospheric circulation. The focus of this article is the summertime response to recent declines in Arctic sea ice, although the winter response is also discussed.

A number of observational and modelling studies have investigated the potential impact of Arctic sea ice loss on the atmospheric circulation. In winter the atmospheric circulation response is investigated with respect to low Arctic sea ice conditions in the preceding autumn. Recent studies of reanalysis data such as Francis *et al.* (2009), Jaiser *et al.* (2012) and Liu *et al.* (2012) have suggested that anomalously low ice conditions in autumn lead to negative North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) patterns in the following winter. Similar results can be found in some modelling studies (many of which look at projected Arctic sea ice decline in the twenty-first century) such as Deser *et al.* (2010). Despite a number of articles indicating that the winter atmospheric response to low autumn Arctic sea ice projects onto a negative NAO/AO pattern, the evidence is not conclusive. For example, Singarayer *et al.* (2006) suggest a positive AO response to anomalously low Arctic sea ice cover in the preceding autumn. Screen *et al.* (2013a, 2013b) suggest that the winter response may be so weak that it is dominated by interannual variability. The impact of Arctic sea ice decline on the summer circulation has received less attention. Recent observational studies such as Wu *et al.* (2013) and Tang *et al.* (2014) have investigated potential links between Arctic sea ice and summer circulation. Wu *et al.* (2013) suggested that winter sea ice conditions to the west of Greenland and associated sea surface temperature (SST) anomalies over the North Atlantic (which persist into spring) are precursors to anomalous summer circulation patterns over northern Eurasia. Tang *et al.* (2014) suggested the loss of Arctic sea ice (combined with the reduction in Northern Hemisphere snow cover) weakens the upper-level zonal winds and induces a higher-amplitude, poleward-shifted jet stream, increasing the likelihood of extreme summer weather over the northern midlatitudes. The modelling study of Balmaseda *et al.* (2010) suggested that the loss of Arctic sea ice may be associated with the negative phase of the summer NAO (SNAO; Folland *et al.*, 2009), and Screen (2013) suggests a link between the reduction in Arctic sea ice and increased summer rainfall over northern Europe.

The aim of this study is to improve our understanding of the impact that the reduction in Arctic sea ice may have on the large-scale atmospheric circulation in summer and winter. This is achieved by analysing the European Centre for Medium-range Weather Forecasting reanalysis product ERA-Interim (ERA-I; Dee *et al.*, 2011) to identify recent circulation changes. Atmosphere-only climate modelling experiments are then performed to estimate the impact of Arctic sea ice reduction on atmospheric circulation. The results of the observational analysis and the model experiments are compared to better understand the atmospheric response to the reduction in Arctic sea ice and used to identify potential mechanisms for the atmospheric response.

2. Data and experimental design

The ERA-I data were used to identify circulation changes in the period 2007–2011. Differences (relative to a reference period) which have a signal-to-noise ratio greater than 1.0 indicate that the differences are reasonably large compared with natural variability. The signal-to-noise ratio is defined as the ratio of a difference divided by one standard deviation of the seasonal mean. The period 2007–2011 is considered a 'low-ice' period as it captures the low Arctic sea ice coverage of recent years (Comiso, 2012). The climate model experiments were atmosphere-only experiments thus requiring the sea ice concentration (SIC) and SST data to be prescribed. These were obtained from the Hadley Centre Global Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner *et al.*, 2003) which has a 1° latitude–longitude resolution. The monthly means of these data were averaged over the low-ice period and a reference period. (Adjusted monthly means were used such that the true monthly mean is recovered after interpolation to daily data; Sheng and Zwiers, 1998). The reference period was chosen to be 1996–2005 so that it is after the anomalous warming in the North Atlantic in the early 1990s (e.g. Sarafanov *et al.*, 2008) therefore anomalously high SSTs in this region are minimised in the prescribed SSTs. While this is a relatively short reference period, the experimental results are not sensitive to this choice. This is due to the fact that the SST differences for the low-ice period are insensitive to the choice of reference period except in the North Atlantic. Notably, the circulation differences identified in the reanalysis data for the chosen low-ice period are also insensitive to the choice of reference period (Figure S1, File S1).

Three atmosphere-only runs were performed using the UK Met Office's Hadley Centre Global Environmental Model version 3 (HadGEM3) at N96L85 resolution (Hewitt *et al.*, 2011). Annually repeating cycles of SIC and SST were prescribed as the boundary conditions and the model was integrated for 30 years, resulting in a 30-member ensemble for each experiment. All other forcings, e.g. greenhouse gases (GHGs) are annually repeating cycles of the mean of the reference period. The three model integrations performed are summarised in Table 1. The CTRL experiment uses SICs and SSTs from the reference period, the SST+ICE experiment uses SICs and SSTs from the low-ice period while the ICE experiment uses SICs from the low-ice period and SSTs from the reference period. The ICE experiment has grid points where the ice has retreated in the low-ice period relative to the reference period and no SST data are available. Where this occurred, SSTs were set to −1.8 °C following e.g. Deser *et al.* (2010). However, without consideration of the local SST changes associated with the loss of sea ice, the surface fluxes in these regions may be underestimated and consequently the circulation response may also be underestimated. By prescribing annually repeating cycles of SSTs and SICs, the mean response of the model to the imposed boundary conditions can be analysed without consideration of interannual variability. The model experiments consider only the recent low-ice period, therefore the forcing from the reduced Arctic sea ice is weaker than other studies that consider the potential effects of Arctic sea ice reduction over this century with increasing GHGs (e.g. Magnusdottir *et al.*, 2004; Seierstad and Bader, 2009; Deser *et al.*, 2010).

Table 1. Summary of boundary condition forcings. The reference period is 1996–2005, the low-ice period is 2007–2011 and each experiment is a 30-member ensemble.

Experiment	Sea ice forcing period	SST forcing period
CTRL	Reference	Reference
SST+ICE	Low ice	Low ice
ICE	Low ice	Reference

This experimental design considers changes in both SSTs and SICs. The difference between SST+ICE and ICE gives an indication of the relative contribution of the SST and SIC changes to the model response; coupled atmosphere–ocean and nonlinear processes are not accounted for in this experimental design. This design allows for a comparison between the model responses and the differences in the ERA-I data, however this is subject to the following caveats:

(i) inherent model deficiencies: e.g. model resolution, sensitivity to the boundary conditions, parametrizations, etc.;
(ii) factors not considered in the experimental design: e.g. coupled or nonlinear processes or changes due to GHGs; and
(iii) the ERA-I data include components that may be due to natural internal variability, or forced by GHGs.

Informed comparisons between the model responses and the observations can be made provided these caveats are considered. In addition, the results from the model experiments are subject to the model's ability to simulate the atmospheric circulation. The mean of the model CTRL run was compared to the mean of the ERA-I data over the reference period and is shown in Figure S2, File S1. It shows that the model is able to reproduce the basic states of mean sea-level pressure (MSLP) and geopotential height (GPH) well, with differences representing only ∼ 1% of the magnitude of the basic state. Walters *et al.* (2011) give further details on this model.

The SIC and SST boundary conditions are shown in Figures 1 and 2 respectively as differences between the low-ice and reference periods, i.e. showing the effective boundary forcings for the perturbation experiments. Between these two periods there is a decline in SIC in the Barents and Kara Seas and small increases in SIC in the Greenland Sea and Denmark Strait in all seasons. The most notable differences are in summer and autumn where there is a marked decrease in SIC in all the marginal seas surrounding the central Arctic. In general the SST differences between these two periods are small in the Atlantic. There are positive anomalies in the Barents and Kara Seas in all seasons and positive SST anomalies in the Labrador Sea in summer associated with the loss of sea ice. The largest SST differences are negative differences in the tropical Pacific which are most pronounced in autumn; this resembles a negative Pacific Decadal Oscillation (PDO) pattern.

3. The surface temperature response to the reduction of Arctic sea ice

In this section the SAT over the Arctic and Northern Hemisphere midlatitudes are considered in the ERA-I data and the model experiments.

Figure 3 shows the ERA-I SAT differences between the low-ice and reference periods and the model SAT responses. Over the central Arctic in summer, the ERA-I temperature differences are small. In summer available energy is used to melt the sea ice and warm the upper ocean (e.g. Serreze and Barry, 2011); since the heat flux is from atmosphere to ocean there is little SAT warming observed in the central Arctic. In autumn when the ice begins to reform, heat is released back to the atmosphere

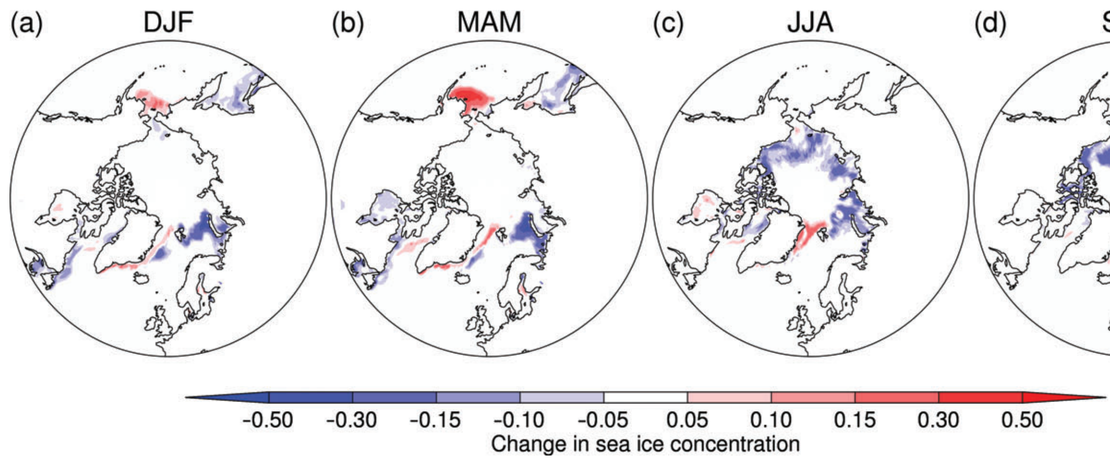

Figure 1. Difference in sea ice concentration between the low-ice period (2007–2011) and the reference period (1996–2005) for (a) December–February, (b) March–May, (c) June–August, and (d) September–November from the HadISST data.

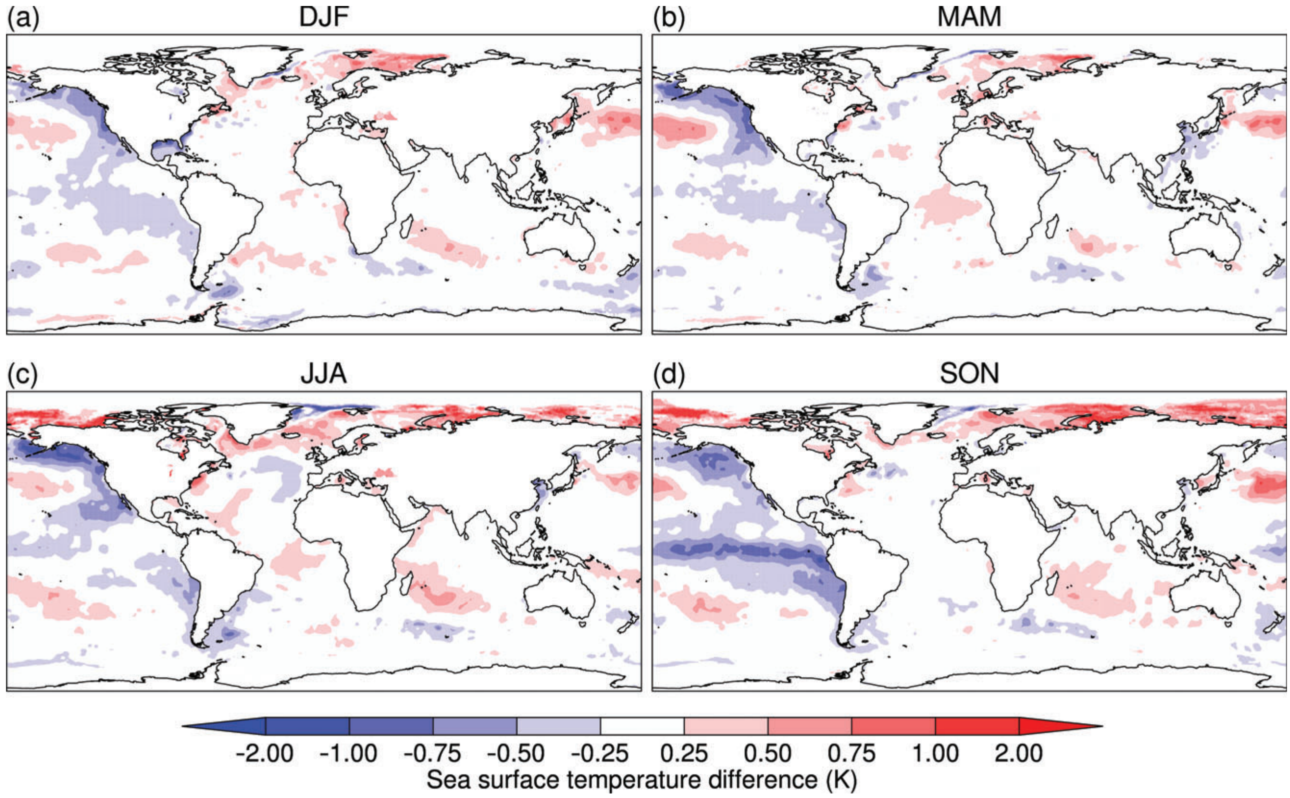

Figure 2. As Figure 1, but showing difference in sea surface temperature.

and the ERA-I data show positive SAT differences over the Arctic region that have a signal-to-noise ratio greater than 1.0, indicating that the differences are reasonably large compared with natural variability, consistent with Serreze *et al.* (2009). Winter and spring also show positive temperature differences at high latitudes in the ERA-I data that are reasonably large compared with natural variability. In winter there are negative temperature differences over the continental midlatitudes which have a signal-to-noise ratio greater than 1.0. This is consistent with the warm Arctic and cold continents (WACC) pattern described by Overland *et al.* (2011). The model responses at high latitudes are consistent with the ERA-I data showing positive SAT responses co-located with regions of ice loss and changes in SST. This indicates that the model is responding to the loss of sea ice in a thermodynamically consistent manner. In winter the model does not show any statistically significant continental cooling which would be consistent with the WACC distribution of temperature anomalies. Nor do the positive SAT responses seen in the model capture the full magnitude or spatial extent of the positive SAT differences seen in the ERA-I data. These differences are a consequence of the fact that the model does not simulate the observed winter circulation as a response to the prescribed changes in SIC and SST. These circulation responses are discussed in the next section.

4. The Northern Hemisphere atmospheric circulation response to reduced Arctic sea ice

In this section the MSLP and GPH from ERA-I are analysed and compared with the modelling results to try to understand the the impact of changes in Arctic SIC and SSTs on the large-scale atmospheric circulation.

4.1. *Mean sea level pressure (MSLP)*

The ERA-I winter and summer MSLP differences between the low-ice period (2007–2011) and the reference period (1996–2005) are shown in Figure 4(a, b).

In winter (Figure 4(a)) there is an anticyclonic difference which has a signal-to-noise ratio greater than 1.0 over the North Pacific

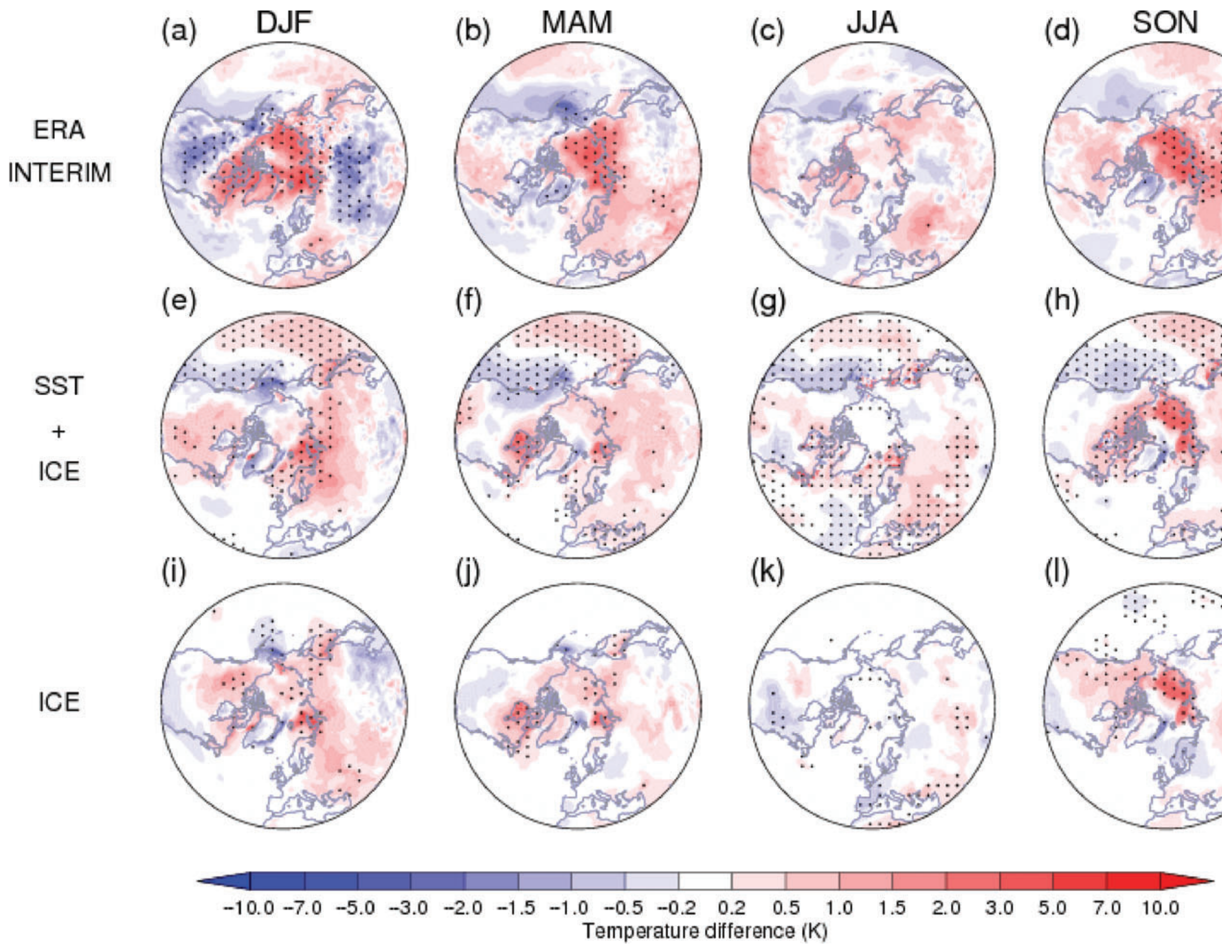

Figure 3. SAT differences from 30 to 90°N in ERA-I between the low-ice and reference periods for (a) December–February, (b) March–May, (c) June–August, and (d) September–November. (e)–(h) and (i)–(l) shows the corresponding model responses (relative to CTRL) for SST+ICE and ICE, respectively. Stippled regions in the ERA-I data indicate where the signal-to-noise ratio is greater than 1.0, and in the model data where the significance of Student's t-test is greater than 95%.

indicating a weakening of the Aleutian Low which is reasonably large compared with natural variability. This pattern is consistent with a negative PDO pattern forced by anomalously low tropical SSTs (e.g. Dawson *et al.*, 2011). The MSLP differences over the Arctic, North Atlantic and northern Eurasia are within the range of natural variability. The differences are largely dominated by the anomalously large negative AO winter of 2009/2010 (e.g. Santos *et al.*, 2013). In this study there are only a few low-ice years, and it may be that a larger number of low-ice years would be required to find a detectable signal.

In summer (Figure 4(b)) there is an anticyclonic MSLP difference over Greenland and cyclonic differences over North America and Eurasia which have large signal-to-noise ratios and therefore are reasonably large compared with natural variability. This pattern shares some of the structure of the Arctic Dipole (Overland and Wang, 2010; Overland *et al.*, 2012). The ERA-I MSLP cyclonic difference over Northwest Europe with a large signal-to-noise ratio has been associated with a number of wet summers in this region during the low-ice period (Screen, 2013). Since the analysis of the ERA-I data contains only a small number of years, it is important to consider if the signal of summer circulation difference is distinctive over a longer time period.

To achieve this a Greenland–UK (G-UK) dipole is defined as the difference in integrated MSLPs over Greenland (70–15°W, 60–85°N) and a region centred on the UK (15°W–15°E, 50–60°N). This is an approximation of the SNAO index (Folland *et al.*, 2009). When the dipole is positive, Northwest Europe experiences low pressure (relative to Greenland). The variations in the G-UK dipole are considered in the Hadley Centre's MSLP dataset (HadSLP2; Allan and Ansell, 2006). HadSLP2 has a $5 \times 5°$ resolution but has data available back to 1870. Figure 5 shows the dipole amplitude from 1900 to 2012. The time series shows that the dipole has predominantly negative amplitudes with a mean value of −2.5 hPa over the whole period. In stark contrast, the mean value of the dipole between 2007 and 2012 is 0.78 hPa, a difference which is over 98% significant using a boot-strapping method. Therefore it is concluded that the anticyclonic anomaly over Greenland and the cyclonic anomaly over Northwest Europe in the period 2007–2012 is distinctive in the long-term observational record.

The SST+ICE and ICE winter and summer responses are shown in Figure 4(c–f). In SST+ICE in winter, the model response is a statistically significant pattern that projects onto the AO. In ICE there are no statistically significant responses. A low pressure response over the Barents and Kara Seas is seen in both ICE and SST+ICE (which is significant at the 90% level in ICE). The low pressure response is co-located with the warm SAT response, it is consistent with the pressure signature of a thermal low (Screen *et al.*, 2013a) and also projects onto the AO. This feature aside, the ICE response is not consistent with the SST+ICE response, therefore it is concluded that the winter response in SST+ICE is mostly driven by the imposed SSTs. It is likely that the significant weakening of the Aleutian low present in SST+ICE in winter is a response to the prescribed SSTs (cf. Figures 4(c) and 4(e)), in particular to the anomalously low tropical Pacific SSTs (Figure 2; Dawson *et al.*, 2011) and not to changes in sea ice conditions. In this study it is concluded that the imposed sea ice loss in this experiment does not have a significant impact on the winter circulation.

In SST+ICE in summer (other than the significant weakening of the Aleutian low) there are weak but statistically significant low pressure responses over the western North Atlantic and Northwest Europe which are also present in ICE. In ICE they are generally weaker and smaller in spatial extent; this is consistent with Balmaseda *et al.* (2010) which suggests that the summer circulation anomalies are driven by changes in both SST and SIC.

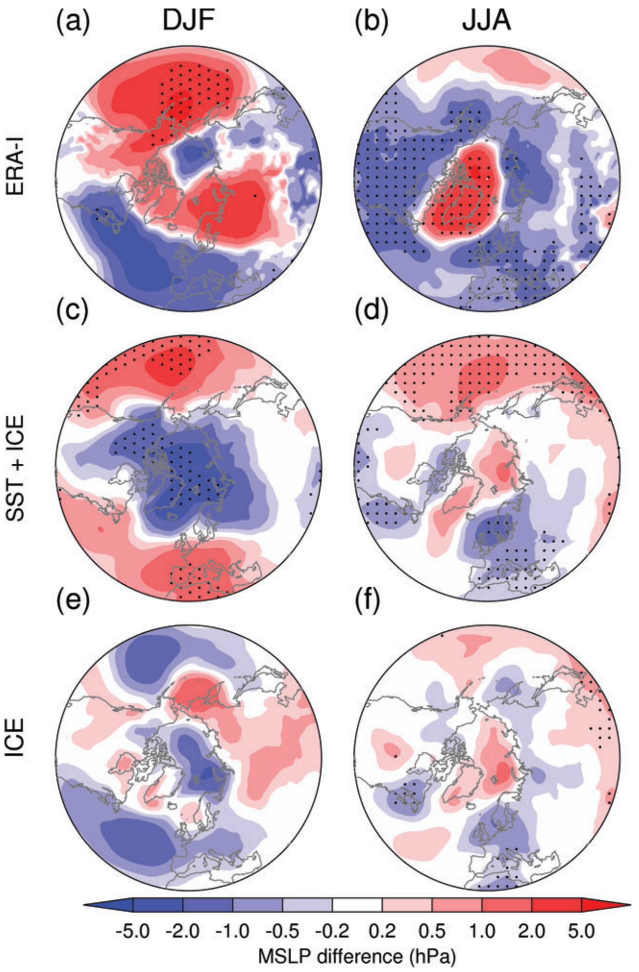

Figure 4. (a, c, e) winter and (b, d, f) summer MSLP differences from 30 to 90°N. (a, b) show the difference in MSLP for ERA-I between the low-ice (2007–2011) and reference (1996–2005) period, with stippled regions indicating where differences have a signal-to-noise ratio greater than 1.0. (c, d) and (e, f) are the model responses relative to CTRL for SST+ICE and ICE respectively, with stippled regions indicating where the significance of Student's *t*-test is greater than 95%.

The model responses in the Euro-Atlantic sector are consistent with the ERA-I differences although they are weaker and smaller in spatial extent. The average MSLPs differences over western Europe (15°W–15°E, 50–60°N) for ERA-I, SST+ICE and ICE are −3.4, −2.1, and −1.4 hPa respectively, indicating that up to approximately one third of the observed low pressure difference in this region in ERA-I may be a response to Arctic sea ice loss (from the ratio ICE/ERA-I). (This conclusion is subject to the caveats listed in section 2). Screen (2013) finds a similar anomalous pattern in MSLP in the Euro-Atlantic sector and a similar proportion in summer rainfall trends over Northwest Europe which may be related to the decline in Arctic sea ice.

4.2. *Summertime circulation and its response to Arctic sea ice loss*

In summer the ERA-I data showed that the circulation differences have a signal-to-noise ratio greater than 1.0 and the HadSLP2 data show that in the Euro-Atlantic sector the anomalous circulation in this region is distinctive in the historical observational record. The large signal-to-noise ratios may appear in summer rather than in winter (when differences are larger in magnitude) since in summer the range of natural variability is smaller than in winter. Although the model MSLP responses in the Euro-Atlantic and North American region in summer are smaller in magnitude than in winter, they are statistically significant and the spatial distribution of the circulation responses in SST+ICE and ICE are partially consistent with the ERA-I data. Therefore in this section only the summertime circulation is considered in more detail.

Figure 6(a) shows the difference between the low-ice and reference period summer ERA-I 500 hPa GPH. Figure 6(c, e) show 500 hPa GPH model responses relative to CTRL for the summer SST+ICE and ICE, respectively. The vertical structure of the GPH anomalies for ERA-I, SST+ICE and ICE are equivalent barotropic since the 500 hPa GPHs show a similar spatial pattern to the MSLP anomalies (cf. Figure 4). On the Pacific side, there is little consistency between the model responses and ERA-I. On the Atlantic side, the SST+ICE and ICE responses are similar to (although weaker than) the differences seen in ERA-I. The consistent pattern comprises a cyclonic anomaly in the western North Atlantic, an anticyclonic anomaly over Greenland and a cyclonic anomaly over Northwest Europe. By averaging over the regions of circulation anomalies, the model experiments indicate that up to approximately one third of the circulation differences seen in ERA-I may be a response to changes in SIC and SSTs. Therefore it is necessary to consider how changes in SIC and SSTs may affect the large-scale circulation.

The summer 850 to 500 hPa (lower free troposphere) vertically averaged temperature differences for ERA-I and the SST+ICE and ICE model responses are shown in Figure 6(b, d, f) respectively. The green dotted line is the 5700 m isopleth at 500 hPa and is indicative of the position of the summer jet stream. The ERA-I data (Figure 6(b)) show positive anomalies in the lower free troposphere over the Labrador Sea and Baffin Bay region that have a signal-to-noise ratio greater than 1.0 and are co-located with regions of sea ice loss and anomalously positive SSTs (Figures 1(c) and 2(c)). The boundary-layer inversion over the Labrador Sea in summer is much weaker than the inversion in the high Arctic, partly due to the jet stream reaching higher latitudes over the North American continent in summer. The positive temperature anomaly over the Labrador Sea and Baffin Bay region lies on the poleward flank of the summer jet stream. Over Newfoundland the prevailing westerlies are weakened, consistent with thermal wind balance. Downstream of the positive temperature anomaly there is a cyclonic anomaly over Western Europe indicative of an eastward shift in the ridge/trough pattern over the North Atlantic which would be consistent with downstream Rossby wave propagation (e.g. Hoskins and Karoly, 1981). Kvamstø *et al.* (2004) show a similar circulation response in wintertime to changes in sea ice conditions in the Labrador Sea. This result supports the suggestions of Screen (2013) and Wu *et al.* (2013) that sea ice conditions in the Labrador Sea are important in summer circulation anomalies. This is consistent with Kidston *et al.* (2011), which suggests it is the latitude of sea ice change that is an important factor in its ability to interact with the jet stream and therefore affect the large-scale circulation. In SST+ICE and ICE there are also positive temperature anomalies in the Labrador Sea and Baffin Bay region, however they are much smaller in magnitude than in ERA-I. Consequently through thermal wind balance the weakening of the westerlies over Newfoundland is less pronounced than in ERA-I, and weaker cyclonic anomalies over western Europe are seen in SST+ICE and ICE. The model results suggest that the loss of Arctic sea ice and changes in SSTs (consistent with Balmaseda *et al.*, 2010), particularly in the Labrador Sea and Baffin Bay region, are contributory factors to the summer circulation anomalies in the Euro-Atlantic sector between 2007 and 2011. However neither SST+ICE or ICE capture the full magnitude of the anomalies, so it is likely that other factors such as internal variability, coupled or nonlinear processes also play important roles in driving the summer circulation anomaly. For example, it has been suggested that the Atlantic Multidecadal Oscillation (AMO) may play a role in forcing the summer circulation anomalies between 2007 and 2011 in the Euro-Atlantic sector (Sutton and Dong, 2012).

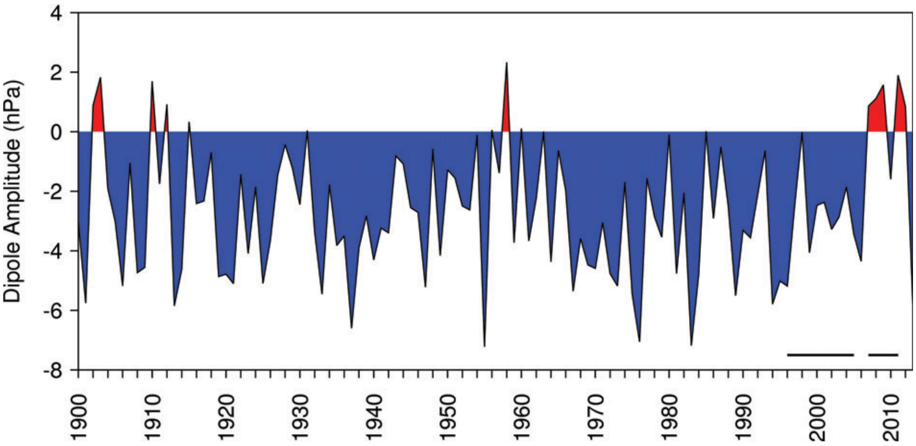

Figure 5. The Greenland–UK dipole calculated from HadSLP2 data from 1900 to 2012. The black bars denote the reference and low-ice periods.

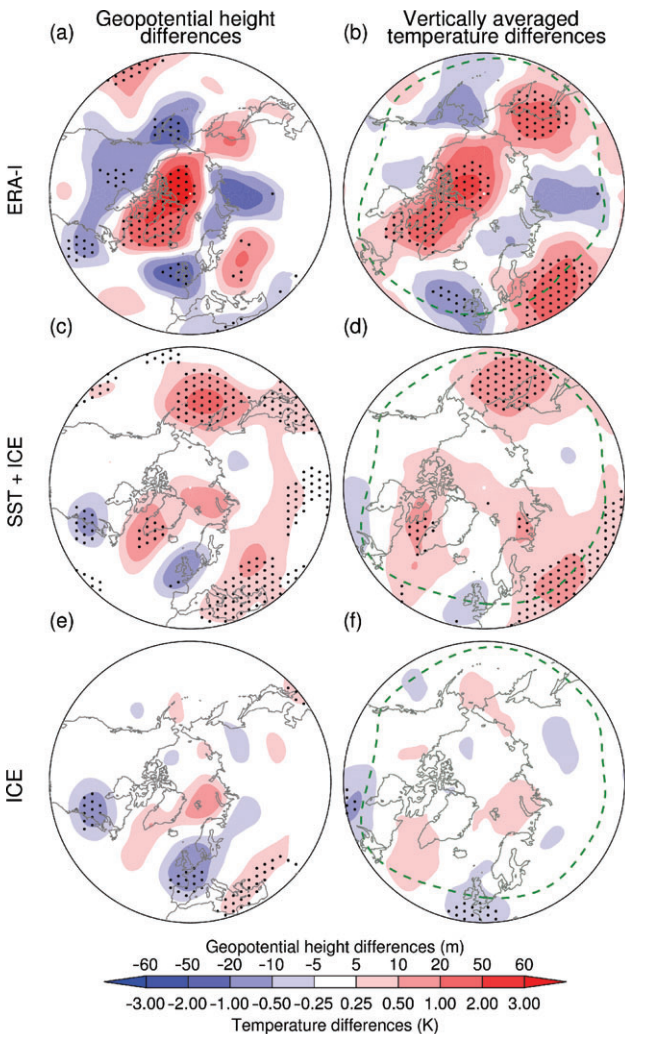

Figure 6. (a, c, e) show summer 500 hPa geopotential height differences from 30 to 90°N for (a) ERA-I, (c) SST+ICE and (e) ICE. (b, d, f) show the corresponding 850–500 hPa vertically averaged temperature differences. The green dotted line is the 5700 m isopleth at 500 hPa. Stippling is as in Figure 4.

5. Discussion and conclusions

The ERA-Interim data have been analysed to detect circulation changes in the recent low-ice period (2007–2011) relative to the reference period (1996–2005). Atmosphere-only climate modelling experiments were performed with realistic ('present-day') declines in Arctic sea ice as the boundary conditions to investigate how observed changes in circulation may have been forced by the declining Arctic sea ice. In this article the modelling experiments were performed on only one general circulation model (GCM), therefore the conclusions drawn here are based on only one model's response to the boundary forcings described in section 2.

In winter over the North Pacific there is a weakening of the Aleutian Low which the ERA-I data show is reasonably large compared with natural variability; it is statistically significant in SST+ICE but not in ICE. A weakening of the Aleutian Low is consistent with a negative PDO pattern forced by relatively low SSTs in the tropical Pacific (Dawson *et al.*, 2011). In SST+ICE the model is forced with relatively low SSTs in the tropical Pacific and therefore the weakening of the Aleutian Low is a likely a response to SSTs rather than reductions in Arctic sea ice.

The main conclusions of this article are:

- In ERA-I, differences in the winter atmospheric circulation (except over the North Pacific) between 2007–2011 and 1996–2005 are small compared with natural variability.
- In ERA-I, the summer atmospheric circulation differences between 2007–2011 and 1996–2005 have a signal-to-noise ratio greater than 1.0, indicating they are reasonably large compared with natural variability. The persistent anticyclonic anomaly over Greenland and the cyclonic anomaly over Northwest Europe between 2007 and 2011 are exceptional in the historical record since 1900. HadGEM3 model experiments suggest changes in sea ice may have contributed up to one third of the magnitude of the observed anomalies, with an additional role for changes in SSTs.
- In summer the positive temperature anomaly in the lower troposphere over the Labrador Sea and Baffin Bay region (which has a signal-to-noise ratio greater than 1.0 in the ERA-I data and is associated with changes in sea ice and SSTs) acts to weaken the prevailing westerlies over North America. Consistent with downstream Rossby wave propagation in response to the positive temperature anomaly, there is a cyclonic anomaly over Northwest Europe.

The cyclonic anomaly over Northwest Europe is of particular importance as it has been associated with a number of unusually wet summers in this region between 2007 and 2011. It is interesting to note that in 2013 the sea ice area in the Labrador Sea and Baffin Bay region was approximately 5% above the 1980–2010 summer average, there was not a pronounced warm anomaly in the lower free troposphere in this region, and Northwest Europe did not experience a cyclonic anomaly. Given the model responses in summer are weaker than the differences seen in the reanalysis data, it is unlikely that the loss of Arctic sea ice and changes in the SSTs are the sole drivers of the summer circulation anomaly. Other factors such as natural variability, atmosphere–ocean interactions, tropical–extratropical connections, nonlinear processes and the decline of the Northern Hemisphere snow cover may also be important in the development of the large-scale summer circulation anomaly.

Future work will investigate the hypothesis that the cyclonic anomaly over Western Europe in summer is a downstream response to a positive temperature anomaly on the poleward flank of the jet over the Labrador Sea and Baffin Bay region. Coupled climate model simulations (which may change and potentially increase the significance of the responses) will investigate the importance of atmosphere–ocean interactions in the circulation response to declining Arctic sea ice cover.

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Supporting information

The following supporting information is available as part of the online article:
File S1. Atmospheric response in summer linked to recent Arctic sea ice loss.

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