Consistency and discrepancy in the atmospheric response to Arctic sea ice loss across climate models

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Abstract

The decline of Arctic sea ice is an integral part of anthropogenic climate change. Sea ice loss is already having a significant impact on Arctic communities and ecosystems. Its role as a cause of climate changes outside the Arctic has also attracted much scientific interest. Evidence is mounting that Arctic sea ice loss can affect weather and climate throughout the Northern Hemisphere. The remote impacts of Arctic sea ice loss can only be properly represented using models that simulate interactions among the ocean, sea ice, land and atmosphere. A synthesis of six such experiments with different models shows consistent hemispheric-wide atmospheric warming, strongest in the mid-to-high latitude lower troposphere; an intensification of the wintertime Aleutian Low and, in most cases, the Siberian High; a weakening of the Icelandic Low; and a reduction in strength and southward shift of the midlatitude westerly winds in winter. The atmospheric circulation response seems to be sensitive to the magnitude and geographic pattern of sea ice loss and, in some cases, to

the background climate state. However, it is unclear whether current-generation climate models respond too weakly to sea ice change. We advocate for coordinated experiments that use different models and observational constraints to quantify the climate response to Arctic sea ice loss.

Main

Sea ice covers only 7% of the Earth's surface but plays a central role in the climate system, affecting its energy balance, water cycle and dynamics. In the Northern Hemisphere, sea ice reaches the low point of its seasonal cycle in September and since the late 1970s, September Arctic sea ice cover has halved[1]. The decline of Arctic sea ice is an integral part of anthropogenic climate change and is projected to continue as greenhouse gas concentrations rise[2,3]. Arctic sea ice loss is already having a significant impact on Arctic communities and ecosystems[4,5]. Meanwhile, there is also intensive scientific interest in considering its role as a cause, in its own right, of changes outside the Arctic. The interest is driven in part by mounting evidence that Arctic sea ice loss affects weather and climate throughout the Northern Hemisphere, and in part by scientific uncertainty regarding the strength, pattern and physical mechanisms involved in these remote impacts[6-13].

Arctic sea ice loss and associated warming can influence lower latitude weather and climate in a number of ways[6-14]. The simplest mechanism is that air warmed by underlying sea ice loss is then advected to lower latitudes by atmospheric motion (i.e. winds), even in the absence of changes in the circulation. The southward migration of the warming signal is mediated by feedbacks between the atmosphere and ocean[15]. More complex are the potential influences of Arctic sea ice loss on the atmospheric circulation. In observational records there exists a correlation between sea ice loss and the negative phase of the Arctic Oscillation (AO)[6-8], which is characterised by weaker and more southerly-located midlatitude westerly winds. However, correlation can be misleading[16] and determining causality from observations is an intractable problem. Climate models are a useful tool for assessing causality, as the effects of sea ice loss can be studied in the absence of other confounding factors. However, atmospheric circulation changes in response to Arctic sea ice loss vary considerably across model simulations[6-8,10]. Such divergence between models, and between models and observations, precludes confident assessment of the distant effects of Arctic sea ice loss. To make progress, it is useful to identify the aspects of the atmospheric response to Arctic sea ice loss that are consistent across climate models and, where discrepancies exist, to better understand the physical reasons for them.

In 2014, Cohen and colleagues[6] provided a review on linkages between Arctic warming and midlatitude weather and climate in *Nature Geoscience*. Since then, research in this nascent scientific field has moved on significantly, warranting an update. Here, we highlight key results that have emerged or gained support in the intervening years. Our goal is not to provide a thorough review of the burgeoning literature on this topic, but instead to focus on scientific advances that have emerged from a raft of new and innovative modelling experiments. More specifically, we consider the role of the ocean in the climate response to sea ice loss, the robustness of the response, its detectability, and the "tug of war" between the influences of Arctic and tropical warming. We finish by making the case for coordinated model experiments and the use of observational constraints to better quantify the response to Arctic sea ice loss.

Role of the ocean

Recent research has pointed out the limitations of using earth system models that lack an interactive ocean component (hereafter termed atmosphere-only models, although they are coupled to land surface models) to isolate the effects of Arctic sea ice loss. It appears that to fully capture the global impacts of Arctic sea ice loss, coupled ocean-atmosphere models that simulate interactions among the ocean, sea ice, land and atmosphere are required. In the context of connections between the Arctic and lower latitudes, the ocean may provide additional pathways of influence (e.g., via altered ocean currents[14]) and/or modify atmospheric pathways through ocean-atmosphere interaction. To explicitly isolate the importance of ocean-atmosphere coupling, Deser and coauthors[15] compared a sea ice perturbation experiment in an atmosphere-only model with prescribed sea surface temperatures (SSTs) to an experiment in which a dynamical ocean component was switched on and the ocean could adjust to the altered sea ice. This comparison revealed several differences, including that Arctic warming extended to lower latitudes and higher altitudes with ocean coupling than without, and a 50% increase in the amplitude of the associated weakening of the midlatitude westerly winds in winter. In addition, ocean feedbacks produced greater warming over the northern hemisphere landmasses and a larger precipitation increase over western North America.

The overall effects of sea ice loss can be partitioned into a direct component, largely governed by thermodynamic/radiative (i.e., temperature-related) adjustment, and an indirect component related to changes in dynamics (i.e., circulation); and these components may oppose one another. A good example of this is the oft-discussed Eurasian winter cooling response[17-19], which is understood to be dynamically driven by a strengthened Siberian High or negative phase of the AO, but may be partially compensated by advection of warmed Arctic air by the climatological flow. Ocean coupling appears to enhance both components, but unequally. Despite a stronger dynamical response with an interactive dynamical ocean, the Eurasian cooling response may be weaker than without ocean coupling, owing to a greater enhancement of the thermodynamic effect[20]. The presence of Eurasian cooling in some studies[17] and not others[18,19] may reflect this balance of processes, with a large dynamical response needed to overcome the basic warming effect of sea ice loss[21].

The ocean may provide a pathway for Arctic sea ice loss to influence climate as far away as the tropics. Deser and colleagues[15] invoke the notion of a “mini global warming” response to sea ice loss, referring to the fact that the zonal-mean tropospheric temperature response to Arctic sea ice loss (with ocean coupling) shows the same broad features as the response to increased greenhouse gas concentrations: these being lower tropospheric warming in polar regions and upper tropospheric warming in the tropics. Fuller diagnosis of the tropical upper tropospheric warming suggests a critical role for ocean heat transport changes[15,22]. In these experiments, freshening of the subpolar Arctic due to sea ice melt reduces the strength of the Atlantic Meridional Overturning Circulation (AMOC) and associated northward ocean heat transport, causing a build-up of heat in the tropical oceans. The resulting increase in tropical SSTs enhances atmospheric deep convection and associated latent heat release, leading to tropical upper tropospheric warming. A "mini global warming" response to Arctic sea ice loss has been found in several different coupled models (Fig. 1), but only when a full-depth dynamical ocean model is used and allowed to freely evolve with the atmosphere. Suppression of a deep ocean response, by constraining ocean temperature and salinity below 200 metres[16], appears to inhibit warming of the tropical upper troposphere (Fig. 1f). A critical and largely unresolved question is the timescale of the ocean heat transport response, which has been diagnosed from long equilibrated model simulations. This calls for closer examination of the transient oceanic response to sea ice loss, including the mechanisms responsible for warming the tropical Pacific ocean. Preliminary results from work which is currently underway suggest that it takes approximately 20-30 years for tropical Pacific SSTs to reach their equilibrium response to an abrupt loss of Arctic sea ice via ocean circulation changes.

Consistent atmospheric circulation response

Systematic comparison of the atmospheric circulation response to Arctic sea ice loss in a coupled ocean-atmosphere framework is now possible due to the recent availability of multiple distinct experiments[15,16,23-26], motivating a synthesis here. The apparently robust features revealed by these new experiments have advanced our understanding of the large-scale atmospheric response to Arctic sea ice loss. In particular, the wintertime sea level pressure response is remarkably similar across six distinct model experiments (Fig. 2), despite using different models and/or methodologies (Box 1). The six coupled ocean-atmosphere experiments, each comprised of hundreds of years of simulation (to minimise sampling error) show a common tendency for Arctic sea ice loss to intensify both the wintertime Aleutian Low and the Siberian High, to weaken the Icelandic Low, and for reduced pressure over North America and/or the North Atlantic (Fig. 2). The sea level pressure responses are also of similar magnitude, when scaled by the amount of sea ice loss in each case. The physical mechanisms driving the sea level pressure response to Arctic sea ice loss are not fully understood, but likely include changes in baroclinicity and storm tracks[27], planetary wave activity[16], and both equatorward- and poleward-propagating Rossby waves (e.g., the Aleutian Low may deepen partly in response to tropical heating induced by sea ice loss[20]). The spatial patterns of the sea level pressure responses depicted by the models closely resemble the negative phase of the so-called Arctic Rapid change Pattern[28] as seen in observations, and which has been linked to accelerated sea ice loss.

This similarity across the six different coupled model experiments is not restricted to the surface: the wintertime zonal-mean westerly wind responses also look alike throughout the depth of the troposphere (Fig. 3). Weakening on the poleward side of the climatological maximum westerly wind and strengthening on its equatorward side characterise each, implying an equatorward shift of the midlatitude westerly wind belt. In most experiments, the weakening on the poleward flank is larger in magnitude and latitudinal extent than is the strengthening on the equatorward flank, implying an overall slowdown of the westerly winds. The possible exceptions to this are the experiments from Ref 25 (Fig. 3d) and Ref 26 (Fig. 3e), which show greater strengthening of the subtropical jet compared to the others. The experiments from Ref 25 and 26 included sea ice loss in both hemispheres. We speculate that Antarctic sea ice loss drives additional tropical upper tropospheric warming in the northern hemisphere (Fig. 1), leading to a greater strengthening of the northern hemisphere subtropical jet. Observational evidence suggests the midlatitude westerlies have weakened in winter during the recent era of rapid sea ice decline[29]. It has been hypothesised that the weaker westerly flow is associated with a wavier jet stream[29]; however, there is little evidence for increased planetary wave amplitude in response to sea ice loss in models[23,25].

The consistency of the atmospheric circulation response in these six coupled ocean-atmosphere model experiments (Fig. 1-3) is encouraging, but simulations with a greater diversity of coupled models are needed to confirm the robustness of the circulation response to projected Arctic sea ice loss. Nevertheless, this consistency contrasts with results from previous studies using atmosphere-only models, which exhibited a high level of divergence and lack of robustness. For example, atmosphere-only studies disagree on the character of the winter sea level pressure response to sea ice loss over the North Atlantic, with some showing a tendency for the negative phase of the North Atlantic Oscillation (NAO)[30,31], others for the positive NAO phase[32,33], and others still finding a pattern of change that bears little resemblance to the NAO[34,35]. On the face of it, it appears that the atmospheric circulation response is more consistent across the coupled ocean-atmosphere experiments than in atmosphere-only experiments. However, it would be premature to draw this conclusion with any confidence as there could be alternative explanations. For one, all the coupled experiments discussed have examined the response to a large sea ice perturbation, reflecting projected future sea ice loss by the middle to end of the century. In contrast, many of the atmosphere-only experiments have examined the response observed anomalies or trends, which are smaller in magnitude than projected future ice loss. Although the atmospheric response may not scale linearly with sea ice loss[36-40], one might expect to find a more robust response in the case of a larger sea ice perturbation. In atmosphere-only experiments prescribed with future sea ice loss, the patterns of wintertime circulation change are broadly consistent with the coupled model results shown in Figures 2 and 3, but with reduced magnitude[15,20]. An open question is whether coupled models would yield a robust response to observed sea ice loss. This calls for novel coupled ocean-atmosphere model experiments mimicking the observed sea ice trend in order to attribute past climate change to sea ice loss.

Although our focus here is the atmospheric circulation response to sea ice loss, it is worth briefly mentioning the ocean circulation response and in particular, that of the AMOC. The AMOC is of special interest because of the possible role of Arctic sea ice loss on the recent observed AMOC slow-down[41-43] and on model predicted future AMOC weakening[44]. Those studies that have explicitly examined the AMOC have found that it weakens in response to Arctic sea ice loss[14,22,23-25], but with widely varying magnitude, from a 10% reduction[25] to a 50% reduction[14]. Also, in two studies[14,23], the AMOC weakens gradually over 100 years after the sea ice is reduced and then stabilises, whereas in another study[25], the AMOC decreases over 30 years before recovering to its original strength after 400 years.

Sensitivities

Progress is being made in understanding the many factors that influence if and how Northern Hemisphere weather and climate are affected by Arctic sea ice loss. The distant effects are dependent on the magnitude[39] and geographic pattern of sea ice loss[45-48]. Sun and coauthors[45] compared atmosphere-only model experiments in which sea ice was reduced in the Atlantic and Pacific sectors separately and in combination. Whilst both pan-Arctic and Atlantic sea ice loss induced an equatorward shift of the tropospheric westerly winds, sea ice loss in the Pacific sector had little effect on the zonal-mean tropospheric circulation. This implies that sea ice loss in the Atlantic sector is critical for the equatorward wind shift response seen in Figure 3, a result corroborated by other studies that have emphasised the importance of Barents-Kara Sea ice loss[47,48]. It remains unclear the extent to which divergence in the modelled responses to sea ice loss (Box 2) can be explained by differences in the magnitude and spatial pattern of sea ice loss. This question can only be fully addressed through coordinated experimentation by specifying identical sea ice loss in different models. We call for a collaborative approach to future model experiments.

The atmospheric response to sea ice loss may also depend on the background state. Sensitivity studies have identified appreciably different atmospheric responses depending on the prescribed sea surface temperatures[49], the phase of multi-decadal climate variability[50,51] and biases in the models' mean state[16]. However, McCusker and coauthors[24] found a robust atmospheric response to sea ice loss across two different climate states, one representing a pre-industrial climate and the other a warmer climate with doubled atmospheric CO_2 concentration. Further work is required to understand why the response to sea ice loss appears sensitive to certain mean state differences and not to others. We conjecture that the spatial pattern of the mean state differences might be critical.

Sensitivity of the large-scale atmospheric circulation response to both the location of sea ice loss and the background state can partly be explained by wave-mean flow interaction. One mechanism for triggering a change in the AO or NAO is through modifying the propagation of planetary wave activity into the stratosphere[37,45,48,52-54]. The concept of linear interference[55,56] states that if the forced response has a similar wave pattern to the climatological planetary waves, termed constructive interference, there is increased vertical wave propagation. Conversely, vertical wave propagation is suppressed if the forced response and climatological waves have opposite phase, termed destructive interference. Whether the forced response interferes constructively or destructively depends on the location of forcing and the phase of the background planetary waves. Sea ice loss in the Barents-Kara Sea appears conducive to constructive interference, which helps explain why ice loss in this region is especially effective in forcing a negative AO/NAO response[45,47,48]. It is possible however, for sea ice loss to trigger a negative AO/NAO response through a solely tropospheric pathway when stratospheric processes are suppressed[53] or even if vertical wave activity is reduced[16] and therefore, linear interference cannot fully explain the varying character of the dynamical responses in different experiments.

Detectability

Advances in computing power have meant that long simulations and/or large ensembles are now routine. This has aided the separation of the forced response to sea ice loss from internal variability in models. Typically, however, several tens and possibly hundreds of simulated years are required to obtain a statistically significant large-scale atmospheric circulation response, depending on the magnitude of the sea ice perturbation (the response to observed sea ice loss is harder to detect than that due to the larger projected sea ice loss by the late twenty-first century), suggesting low detectability[17,24,25,32,39,57]. One interpretation of this low signal-to-noise ratio is that the circulation response to sea ice loss is small compared to atmospheric internal variability. This could be true, especially in the case of the response to observed sea ice; but is open to debate. An on-going concern is whether the current breed of climate models has the correct signal-to-noise ratio. Some models appear to respond too weakly to forcing in the case of seasonal-to-decadal predictions of the NAO[58]. These forecasts exhibit high levels of skill in predicting the winter NAO up to a year in advance[59,60], but the predictable component (i.e., the forced signal) is lower in the models than that estimated from observations[58]. Since Arctic sea ice is one potential source of NAO predictability[59-62], the low signal-to-noise could imply that models respond too weakly to sea ice. Whether this is indeed the case and if so, whether this is a systematic problem in current-generation climate models, is a critical point to address, as it could mean that the dynamical response to sea ice loss is larger than originally thought. Coordinated experiments using different models are required to assess this potential flaw. The detectability of the response to Arctic sea ice loss in the real world also depends on its relative magnitude compared to other aspects of climate change, which may overwhelm it.

The “tug-of-war” paradigm

Arctic sea ice loss is only one component of greenhouse-gas-induced climate change. A paradigm that has gained traction in recent years is that the climate response to sea ice loss may partly counteract other aspects of the response to increased greenhouse gases. Since two dominant characteristics of greenhouse-gas-induced climate change are pronounced warming in the tropical upper troposphere and in the Arctic lower troposphere, this has been conceptualised as a "tug-of-war" between the Arctic and tropics. A case in point is the projected response of the winter Atlantic jet stream. It is understood that sea ice loss will act to shift the jet stream equatorwards whilst tropical warming will act to shift the jet poleward, leading to a small net response[15,23,24,26]. This decomposition only makes sense if the responses to greenhouse-gas-induced sea ice loss (in the absence of increased greenhouse gases) and to increased greenhouse gases (in the absence of sea ice loss) are separable and linearly additive, which they appear to be, at least in winter[24]. The tug-of-war has been used to reconcile model uncertainty in the Intergovernmental Panel on Climate Change projections for the winter Atlantic storm track, with models that simulate more Arctic warming tending to be those that also simulate more equatorward (or less poleward) shifts of the storm track and jet stream[63-67]. Since society does not feel the influence of sea ice loss in isolation from other aspects of climate variability and change, it is important to further consider whether this balance of effects is fairly constant in time, or whether for some periods one influence may exceed that of the other. The tug-of-war is a useful perspective for the Atlantic winter jet stream since the processes driving Arctic warming are arguably distinct from those contributing to tropical warming. However, this concept cannot be generalised, as the regional responses to tropical warming and sea ice loss may reinforce each other in other locations. The westerly wind response to Arctic sea ice loss enhances the response to tropical warming over the Pacific sector in winter, for example[23,24].

Observational constraints

Despite progress in understanding the modelled response to sea ice loss, an uncertain and arguably most critical question of all is, what is the response to sea ice loss in reality as opposed to in models? Model divergence (Box 2), which is often viewed as a hindrance, may actually be useful in constraining the real world response. In other aspects of climate science the concept of emergent constraints has been exploited to narrow projections of future climate change. The basic idea of an emergent constraint is that inter-model spread in future projections can be related to a characteristic of the modelled current climate[2,68-71]. For example, future projections of Arctic sea ice depend on past conditions, with models that simulate less ice in the recent past simulating smaller trends in the future, and vice versa[2,72]. Such relationships, which describe the inter-model diversity, can be used together with known past conditions to observationally constrain future trends. The first such application of this approach in the context of the response to sea ice loss is by Smith and coauthors[16] who suggested uncertainty in the Atlantic jet stream response to sea ice loss was related to the climatological-mean planetary wave refractive index. This result suggests the potential exists to use observations to constrain the response to sea ice loss, but it must be viewed with caution as it was based on only three model experiments. To make further progress, coordinated experiments are needed with as many different models as possible. The planned Polar Amplification Model Intercomparison Project (https://www.agci.org/sites/default/files/pdfs/lib/main/PA_MIP_Junl2017.pdf) will provide the largest set of coordinated model simulations on this topic to date and will seek to provide the first observationally constrained estimates of the climate response to Arctic sea ice loss.

A growing list of societally impactful phenomena across the Northern Hemisphere are being linked to diminished Arctic sea ice, arguably quite speculatively: from extreme pollution haze in China[73], to poor crop yields in the United States[74], to the unusual track of Hurricane Sandy[75], the second-costliest hurricane in U.S. history. The need has never been greater for carefully designed model simulations and novel observational analyses[76] to infer which connections are causal and which are purely coincidental.

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Methods. The data used to construct Figures 1-3 are taken from previously published papers (Refs 15, 23, 24, 25, 26 and 16 for panels a-f, respectively), in which full details of the experiments can be found. Briefly, in each case, the atmospheric response to Arctic sea ice loss is estimated by contrasting the long-term average in a baseline simulation with that in a simulation with reduced Arctic sea ice. The procedure to induce sea ice loss in a coupled ocean-atmosphere model differs between studies, as discussed in Box 1. Since the amount of induced sea ice loss also differs between these experiments, we have scaled the wintertime atmospheric responses by the reduction in Arctic sea ice extent in each case, to yield a change per million square kilometres of ice loss. The scaling uses an average of the months September to February. The rationale for including the autumn months in the scaling is that sea ice loss in preceding months can affect the wintertime atmosphere. For example, autumn SST anomalies induced by sea ice loss may persist into winter and influence the wintertime atmosphere. Also, some of the mechanisms involved in the response to sea ice loss appear to operate over multiple seasons. For example, sea ice loss in autumn can lead to a wintertime tropospheric circulation response via a stratospheric pathway[45,52-54]. Two of the perturbation experiments included sea ice loss in both hemispheres (Refs 25 and 26). In Fig 1-3 we show data only for the Northern Hemisphere and boreal winter, in which the effects of Antarctic sea ice loss are assumed to be weak compared that of Arctic sea ice loss. This assumption is validated by the close agreement in the northern hemisphere atmospheric responses between studies that include Antarctic sea ice and those that do not (Fig. 1-3).

Boxes

Box 1. Modelling protocols

Several approaches have been utilised to perturb the sea ice component of a coupled ocean-atmosphere model. Although in each case the ultimate goal is to introduce a change in the sea ice, the precise approach differs, which may have implications for how the results are interpreted.

Albedo reduction. By reducing the albedo of sea ice, absorbed solar radiation is increased thereby reducing the sea ice[25,26]. A lower albedo is maintained throughout the simulation to prevent sea ice recovery. Energy and water are conserved but the albedo may be unphysical. This approach yields an amplified seasonal cycle, as the sea ice reduction is disproportionately in the sunlit portion of the year.

Ghost forcing. An additional surface heat flux is added to the sea ice throughout the simulation[15,20,22]. "Ghost forcing" refers to the fact that it is not seen by other climate model components except indirectly through changes in sea ice. The flux is dependent on the ice state, only being applied if sea ice is present. Melt water enters the ocean, conserving water, but energy is not conserved. Energy imbalance could lead to unintended responses, irrespective of sea ice loss.

Flux adjustment. Similar to ghost forcing, except an additional surface heat flux is applied to the ocean model[23]. The flux is independent of the sea ice state, being added irrespective of whether ice is present or not; however, it is applied only in locations where sea ice loss is desired. The forcing is seen by the ocean first and then communicated to the ice and atmosphere components. Applying forcing to the ocean model could lead to responses irrespective of sea ice loss. Water is conserved but energy imbalance may drive unintended responses.

Nudging. Sea ice is constrained to a target value, which can be done in subtly different ways. In Ref 16, the nudging method calculates the difference between the existing sea ice state and the target state at regular time intervals, and applies an adjustment. In this nudging approach sea ice is simply added or taken away (rather than through freezing or melting) and therefore, neither water or energy is conserved. Continual nudging increments could lead to unintended effects and to partially circumvent this, the deep ocean was constrained; however, this prevents any legitimate dynamical deep ocean response to sea ice loss. In Ref 24, the nudging method calculates the heat flux required to grow or melt ice to reach the target state, and applies this additional flux to the sea ice. In this nudging approach water is conserved but energy is not. In both cases, the nudging is not seen by other model components, except indirectly through changes in sea ice.

Initial condition. The initial sea ice thickness is reduced, leading to enhanced summer melt[77,78]. Energy and water are conserved. Sea ice recovers to unperturbed values within a few years, making this approach unsuitable for examining the long-term effects of sea ice loss.

No freezing. Allowing seawater to cool below freezing point inhibits sea ice formation[79]. Energy and water are conserved, but the prevention of freezing is unphysical. To date this approach has only been applied in a shallow "slab" ocean model, which may yield an unrealistic response due to the lack of deep ocean circulation[22].

Box 2. Sources of disagreement in model experiments

A major impediment to better understanding the atmospheric response to Arctic sea ice loss is the lack of consistency in modelling studies; both in terms of their experimental design and the responses identified. Known sources of divergence between model results include:

1. Magnitude and spatial pattern of sea ice loss. Studies have examined the response to observed sea ice trends, sea ice anomalies from specific years, and projected future trends – which all differ considerably in magnitude. Additionally, some studies have imposed sea ice changes in specific geographical regions rather than Arctic-wide. Studies also differ in whether they prescribe monthly-mean or daily-mean sea ice fields, which may result in small but non-negligible differences in the atmospheric responses[80].

2. Ice thickness. Some atmosphere-only studies include changes in sea ice thickness whereas others maintain a fixed ice thickness. In cases where the thickness is fixed, this is typically a pragmatic choice either due to the absence of suitable thickness data or inability to prescribe variable thickness in the model code. Sea ice thinning leads to Arctic warming and, particularly in winter, can yield a large-scale atmospheric response of the same order of magnitude as changes in sea ice cover[81]. One recent study estimated a 37% increase in Arctic amplification for the period 1982-2013 in a simulation that included historical thinning compared to a simulation with constant thickness[82]. This is not an issue in coupled ocean-atmosphere simulations.

3. Treatment of new open water. Reduced sea ice cover leads to new areas of open water. Atmosphere-only modelling studies differ in their treatment of the SSTs in these regions. A common approach is to set the SSTs in these regions to -1.8 °C, the freezing point of seawater. This is unrealistic however, with observations suggesting that SSTs can reach 5 °C in summer where sea ice is lost[83]. Alternative approaches are to prescribe SSTs that increase with sea ice loss[84] or use projected SSTs taken from other model simulations[85]. This is not an issue in coupled ocean-atmosphere simulations.

4. Stratospheric representation. Models differ in their representation of stratospheric processes and troposphere-stratosphere coupling. Sun and coauthors[45] found a stronger negative AO response in a high-top model with a well-resolved stratosphere compared to a low-top version of the same model. Other studies have also emphasised the importance of the stratospheric pathway in amplifying the winter negative AO response[48,52-54].

5. Ocean. As discussed in the main text, the atmospheric response is enhanced in magnitude and latitudinal reach by ocean-atmosphere coupling and oceanic processes[15,20]. Differences amongst coupled ocean-atmosphere modelling experiments may arise due to the varying ways sea ice loss is achieved (**Box 1**) and differences in the ocean model physics.

6. Background state. Different models and/or experimental setups have different background ocean-atmosphere states, which may affect the response to sea ice loss[16,49-51]. For example, Osborne and coauthors[51] found that the prescribed climatological SST determined the character of the atmospheric response over North America, and Smith and colleagues[16] found that sign of the NAO response depended on the models' mean state.

7. Model physics. The response to sea ice loss can be sensitive to the atmospheric model used, even when the imposed sea ice and SST changes are identical[32,84]. Such differences must arise due to different model physics and parameterisations, such as atmospheric boundary layer processes and cloud microphysics.

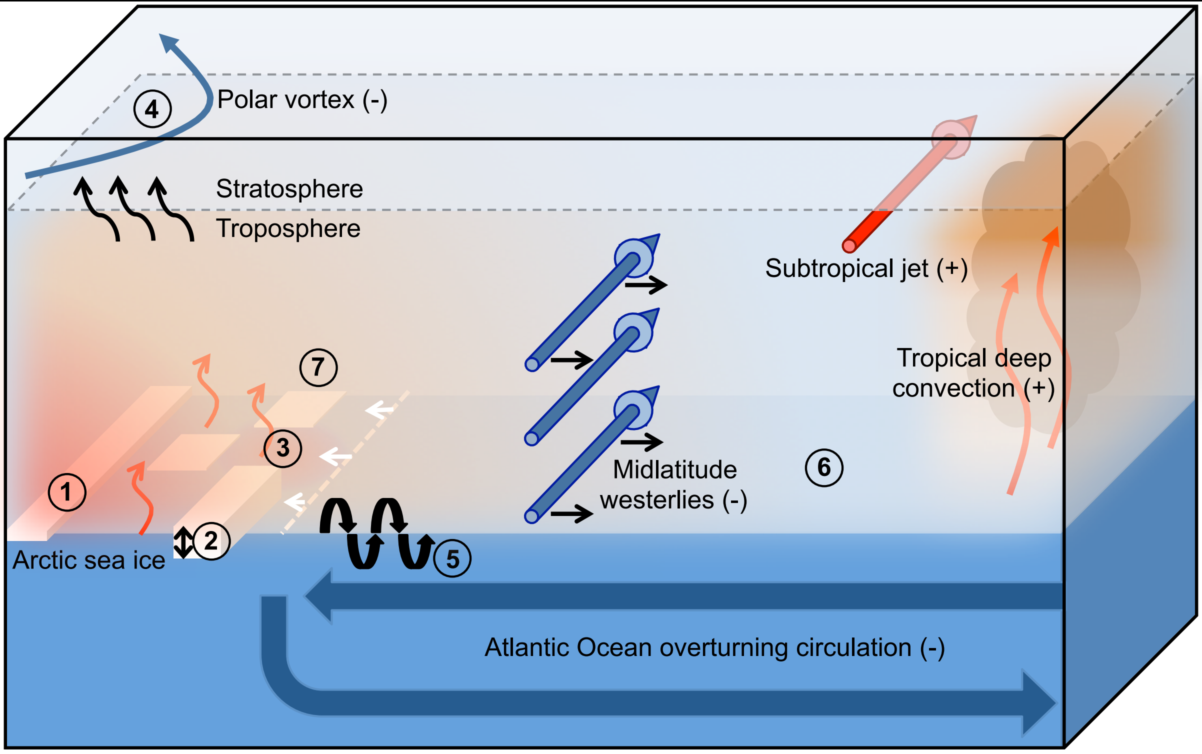

Figure B2. Schematic representation of the potential climate response to Arctic sea ice loss. An illustrative cross-section from the North Pole to Equator. Major atmospheric and oceanic circulation features that are weakened by Arctic sea ice loss are shown by blue arrows and labelled with minus signs, and those that are strengthened by Arctic sea ice loss are shown by red arrows and labelled with plus signs. Red and orange shading indicates regions of greatest warming in response to sea ice loss. Circled numbers indicate sources of disagreement in model experiments and are referred to in the boxed text. Not drawn to scale.

Figures

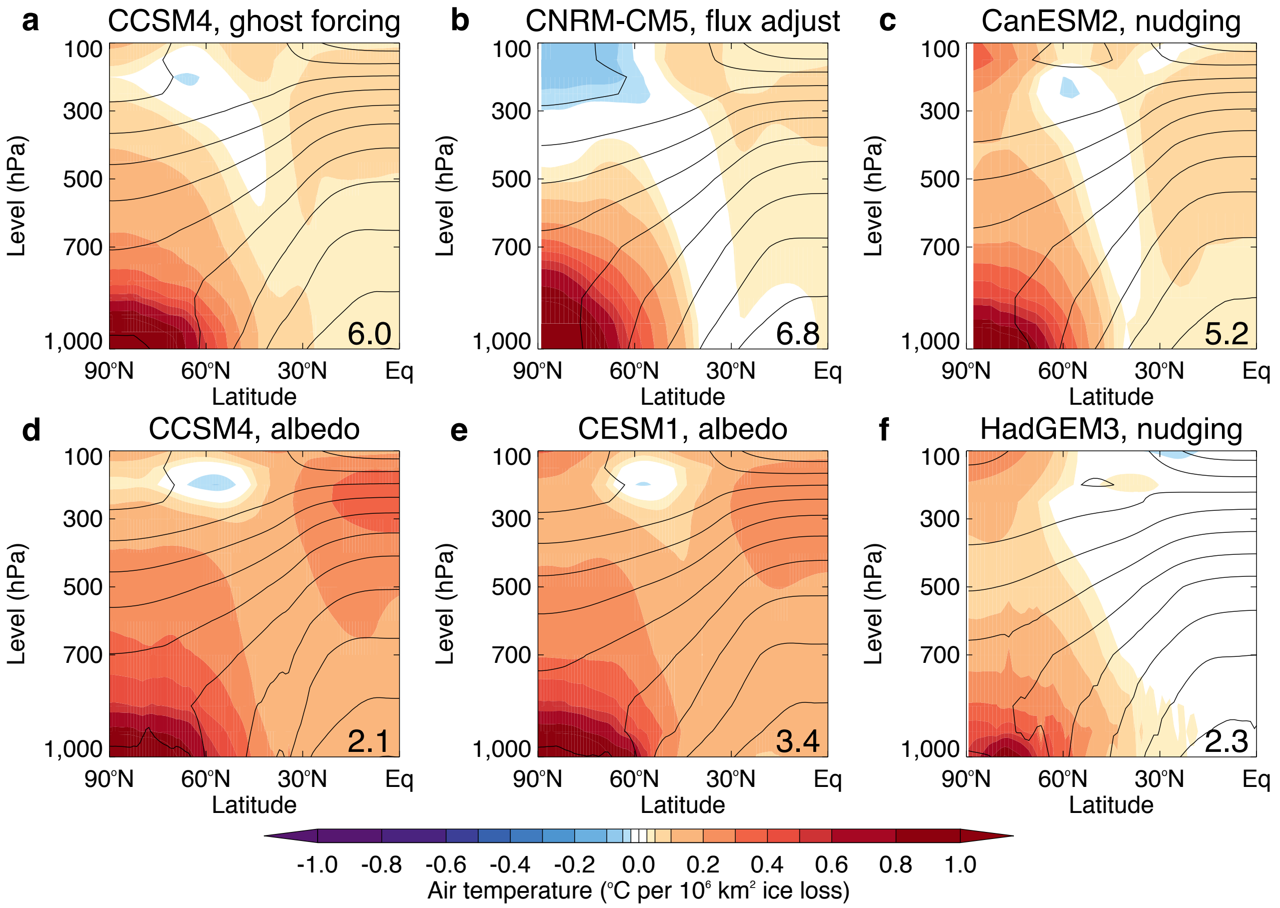

Figure 1. Effects of Arctic sea ice loss on winter air temperature. Boreal winter (December-January-February) zonal-mean air temperature response (coloured shading; note the nonlinear colour scale) to Arctic sea ice loss in six unique sets of coupled ocean-atmosphere model simulations. The responses have been scaled by the reduction in sea ice extent in each case (provided in the lower right corner of each panel in million square kilometres; see Methods). The black contours indicate the baseline climatology (contour interval of 10 °C). The simulations presented in **a-f** are described in Refs 15, 23, 24, 25, 26 and 16, respectively. The panel titles provide the model and protocol (refer to Box 1 for more details) used.

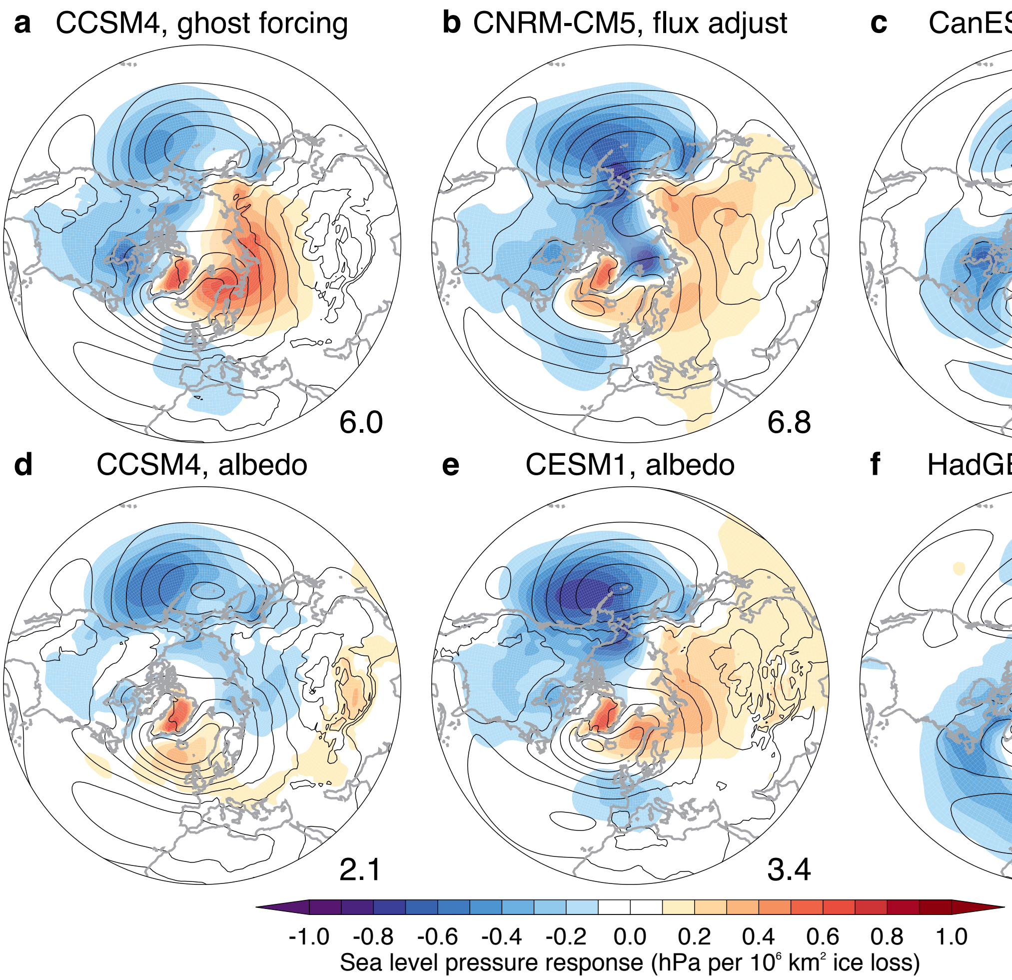

Figure 2. Effects of Arctic sea ice loss on winter sea level pressure. Boreal winter (December-January-February) mean sea level pressure response (coloured shading) to Arctic sea ice loss in six unique sets of coupled ocean-atmosphere model simulations. The responses have been scaled by the reduction in sea ice extent in each case (provided in the lower right corner of each panel in million square kilometres; see Methods). The black contours indicate the baseline climatology (contour interval of 5 hPa). The simulations presented in **a-f** are described in Refs 15, 23, 24, 25, 26 and 16, respectively. The panel titles provide the model and protocol (refer to Box 1 for more details) used. Continental outlines are shown in grey.

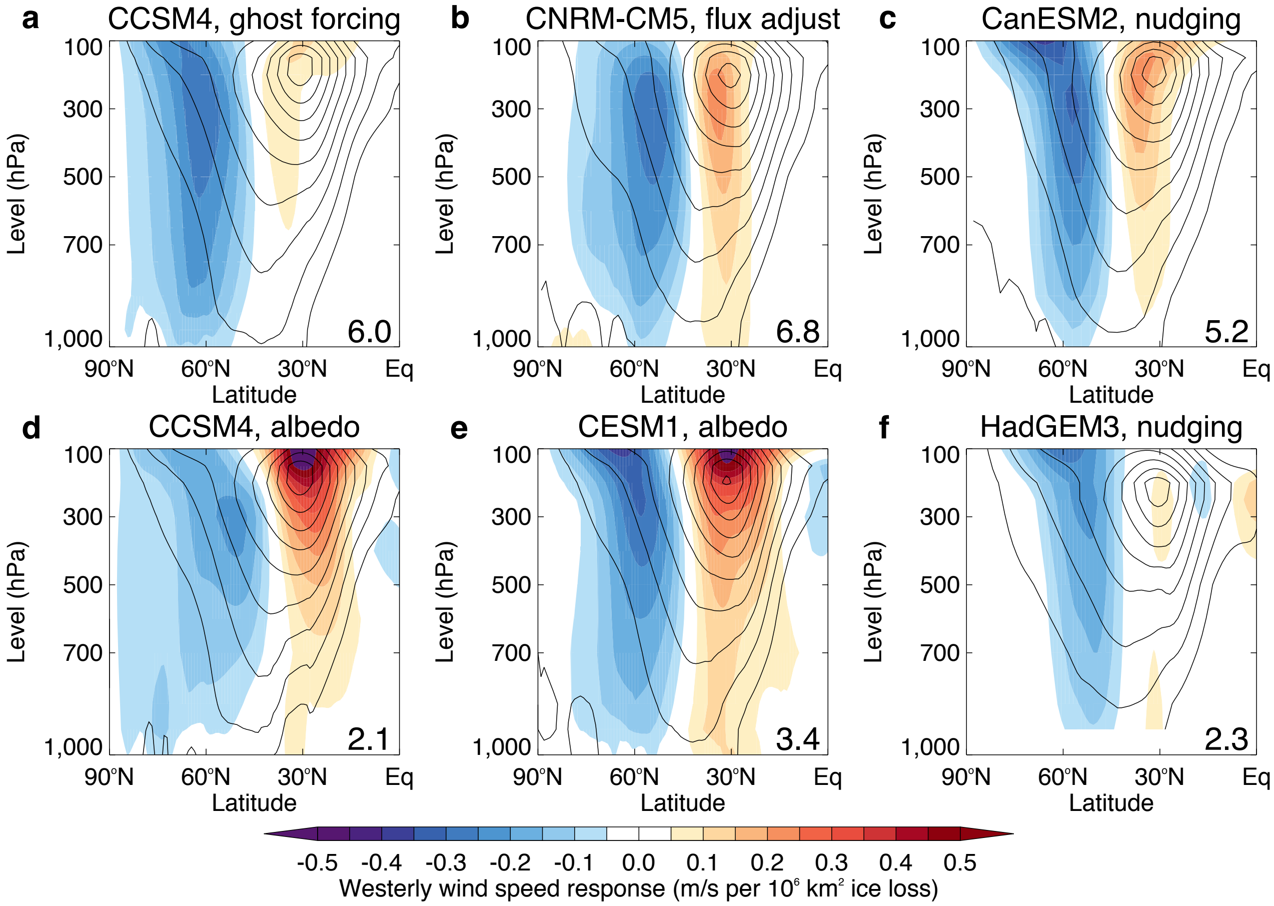

Figure 3. Effects of Arctic sea ice loss on winter atmospheric circulation. Boreal winter (December-January-February) zonal-mean westerly wind response (coloured shading) to Arctic sea ice loss in six unique sets of coupled ocean-atmosphere model simulations. The responses have been scaled by the reduction in sea ice extent in each case (provided in the lower right corner of each panel in million square kilometres; see Methods). The black contours indicate the baseline climatology (contour interval of 5 m/s). The simulations presented in **a-f** are described in Refs 15, 23, 24, 25, 26 and 16, respectively. The panel titles provide the model and protocol (refer to Box 1 for more details) used.