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Key Points:
- Atmospheric processes drive the Arctic climate response to European aerosol emission changes
- Changes in ocean heat transport play a smaller role and buffer the response
- Accurate simulation of sea ice changes is critical for predicting the Arctic response to midlatitude aerosol changes

Supporting Information:
- Supporting Information S1
- Data Set S1

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The Roles of the Atmosphere and Ocean in Driving Arctic Warming Due to European Aerosol Reductions

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Abstract Clean air policies can have significant impacts on climate in remote regions. Previous modeling studies have shown that the temperature response to European sulfate aerosol reductions is largest in the Arctic. Here we investigate the atmospheric and ocean roles in driving this enhanced Arctic warming using a set of *fully coupled* and *slab-ocean* simulations (specified ocean heat convergence fluxes) with the Norwegian Earth system model (NorESM), under scenarios with high and low European aerosol emissions relative to year 2000. We show that atmospheric processes drive most of the Arctic response. The ocean pathway plays a secondary role inducing small temperature changes mostly in the opposite direction of the atmospheric response. Important modulators of the temperature response patterns are changes in sea ice extent and subsequent turbulent heat flux exchange, suggesting that a proper representation of Arctic sea ice and turbulent changes is key to predicting the Arctic response to midlatitude aerosol forcing.

Plain Language Summary Aerosols are liquid or solid particles suspended in air, which may have adverse air quality and health impacts. Sulfate aerosols also have a cooling influence on climate and can mask some of the greenhouse gas-induced global warming. While aerosol emissions are variable in space and time, their impacts are not limited to where they are emitted. In fact, studies using global climate models have shown that changing sulfur dioxide emissions in Europe can have significant impacts on Arctic climate. Here we investigate the roles of changes in atmospheric and ocean heat transport in driving these changes in the Arctic by conducting a series of climate model simulations with specified anthropogenic sulfur dioxide emissions and different ocean heat transport fluxes. We find that changes through the atmosphere play a primary role in affecting the Arctic climate. These changes are modulated by changes in sea ice extent and the energy exchange between ocean and atmosphere in the sub-Arctic. Aerosol-driven changes in ocean heat transport play a smaller, secondary role in the Arctic and tend to reduce the impacts. Our results show that the proper representation of Arctic sea ice is crucial for accurately modeling the Arctic response to changes in midlatitude aerosol forcing.

1. Introduction

Arctic amplification of global temperature trends has been a consistent feature found in observations and model simulations over the past century (Pithan & Mauritsen, 2014; Screen & Simmonds, 2010; Serreze & Barry, 2011; Winton, 2006). Potential reasons for this amplification include the sea ice albedo feedback (Manabe & Stouffer, 1980), heat flux exchange between Arctic ocean and overlying atmosphere (Screen & Simmonds, 2010; Serreze et al., 2009), changes in atmosphere and ocean heat transport (Chylek et al., 2009; Graversen et al., 2008; Yang et al., 2010), and changes in cloud cover and water vapor content affecting long-wave radiation (Francis & Hunter, 2006). Greater ice loss and warmer Arctic temperatures can cause local vegetation changes (Bhatt et al., 2010; Hinzman et al., 2013) and increased permafrost melt in the Arctic that further accelerate high-latitude warming (Anthony et al., 2016; Foley et al., 1994; Lawrence et al., 2008; Levis et al., 2000). Sea ice changes can also affect atmospheric circulation patterns with local (Bengtsson et al., 2004) and remote consequences (Overland & Wang, 2010; Seierstad & Bader, 2008). While the increase of atmospheric CO_2 concentrations has been the main driver of global warming and the Arctic amplification over the industrial era, changes in anthropogenic aerosol emissions can also affect Arctic climate (e.g., Acosta Navarro et al., 2016; Westervelt et al., 2020).

Aerosols affect climate by scattering or absorbing solar radiation and modifying cloud properties, but their contribution to the overall forcing is still highly uncertain (Boucher et al., 2013). In contrast to greenhouse gases, their distribution and associated radiative forcing is spatially heterogenous. However, they can influence remote atmospheric circulation and rainfall patterns (Westervelt et al., 2017; Wilcox et al., 2019). Over the past 40 years, two distinct patterns of global anthropogenic aerosol emission changes are the reduction in emissions from Europe and North America and the increase in emissions from East and South Asia (Lamarque et al., 2010). Emissions from these regions can have remote and global climate impacts (Lewinschal et al., 2013; Persad & Caldeira, 2018; Samset et al., 2018; Sand et al., 2016; Shindell & Faluvegi, 2009; Stjern et al., 2019; Westervelt et al., 2018). Aerosol emissions from Europe and North America can impact the Arctic through long-range transport and deposition (Hansen & Nazarenko, 2004), but it is unclear whether there has been a significant change in aerosol concentrations in the Arctic (Tunved et al., 2013). More generally, the removal of European and North American aerosols have been shown to increase regional warming (Westervelt et al., 2015) and reduce Arctic sea ice (Gagné et al., 2016). An enhanced Arctic response was found in modeling studies using the Norwegian Earth System Model (NorESM), which evaluated the impact of drawdown of European sulfate aerosols since the 1980s (Acosta Navarro et al., 2016) and for idealized changes in anthropogenic emissions of sulfur dioxide (SO_2) separately over Europe, North America, South Asia, and East Asia (Lewinschal et al., 2019). Robust Arctic responses were also observed for SO_2 reduction from different regions in three other models, NOAA GFDL-CM3, NCAR-CESM1, and NASA GISS-E2 (Westervelt et al., 2020). However, the mechanistic reasons for this remote response have not been fully explored.

A potential driver of the enhanced Arctic response to anthropogenic aerosol forcing is through changes in ocean heat transport and overturning circulation. Delworth and Dixon (2006) suggested that an aerosol-driven cooling of the subpolar gyre masked the greenhouse gas-driven warming and freshening in their model. Cowan and Cai (2013) showed that a reduction of non-Asian aerosols had a large impact on meridional overturning by changing the pattern of global atmosphere-ocean heat flux exchange. Iwi et al. (2012) found that sulfate aerosol increases from volcanic eruptions could drive an increase in the strength of the Atlantic Meridional Overturning Circulation and meridional heat transport. For simulations with modified European SO_2 emissions, Acosta Navarro et al. (2016) suggested that changes in meridional ocean heat convergence near the Arctic might have played an important role in setting the high-latitude response.

Modification of high-latitude feedbacks or changes in atmospheric energy and moisture fluxes to the Arctic can also drive the Arctic response to midlatitude forcing (Screen et al., 2012; Serreze & Barry, 2011). High-latitude feedbacks include snow and ice albedo feedback (Manabe & Stouffer, 1980; Manabe & Wetherald, 1975), lapse-rate feedbacks (Pithan & Mauritsen, 2014), or processes affecting terrestrial long-wave radiation (Graversen & Wang, 2009; Winton, 2006). Remote changes in sea surface temperature and energy and moisture fluxes into the Arctic have been implicated as important contributors to Arctic amplification (Screen et al., 2012; Yoshimori et al., 2017). The role of remote energy transport versus high-latitude feedbacks has typically been distinguished by the nature and timing of Arctic warming. Changes in remote heat and energy transport from the lower latitudes cause a warming response aloft in the midtroposphere (Alexeev et al., 2005; Chung & Räisänen, 2011; Yang et al., 2010), while changes in ice and local feedbacks warm the lowest atmosphere, typically during autumn and early winter (Deser et al., 2010; Serreze et al., 2009). It is likely that the relative importance of these mechanisms depends on the nature of forcing (Alexeev & Jackson, 2013), although an evaluation by Stjern et al. (2019) comparing the Arctic response to CO_2, solar forcing, SO_4, and CH_4 suggested that the mechanism may be similar between these drivers. Crucially, these studies highlight the important role of atmospheric changes in determining Arctic amplification.

While these studies show that aerosol forcing in the midlatitudes affect Arctic climate, the relative contributions of the atmosphere and ocean are poorly understood. Here we improve this understanding by isolating the role of ocean circulation and meridional ocean heat transport in driving the remote polar response to midlatitude changes in sulfate aerosol forcing. NorESM is used to perform a pair of fully coupled atmosphere-ocean simulations with low-aerosol (F-LOEM) and high-aerosol (F-HIEM) emissions from Europe. The ocean heat convergence fluxes (OHFC) from these simulations are used to drive NorESM in slab-ocean mode, with the atmospheric model (with interactive sea ice) driven with low and high SO_2

emission scenarios. The resulting four NorESM slab-ocean simulations are used to isolate the role of meridional ocean heat transport and atmospheric-driven changes in driving the different feedback processes that determine the Arctic response.

2. Materials and Methods

NorESM (version 1; Bentsen et al., 2013) is based on the Community Climate System Model 4.0 (CCSM4.0) with a modified interactive aerosol module (CAM4-Oslo; Kirkevåg et al., 2013), the Bergen version of the Miami Isopycnic Coordinate Ocean Model (MICOM), the Community Land model version 4 (CLM4), and the Community Ice CodE (CICE4). The atmospheric model has a finite volume grid with a resolution of 1.9° × 2.5°. The aerosol components considered are sulfate, black carbon, organic matter, sea salt, and mineral dust. Aerosol emissions are treated as either primary particles or secondary particles through aqueous- and gas-phase conversions.

For our analysis, we use output from fully coupled NorESM simulations presented in Lewinschal et al. (2019). These simulations span 200 years, and the means from the last 100 years are taken for analysis. To identify the roles of atmospheric and ocean pathways separately and together in driving the Arctic response to midlatitude aerosol forcing, equilibrium simulations are performed with NorESM in a slab-ocean configuration. These simulations span 80 years, and means from the last 50 years are used for analysis. Year 2000 is chosen as the reference year, and aerosol emissions, precursor emissions, trace gas concentrations, and land use representation are prescribed from the Coupled Model Intercomparison Project Phase 5 (CMIP5) historical data set (Lamarque et al., 2010). The emission region of Europe is defined according to the definitions of the Task Force of Hemispheric Transport of Air Pollution (HTAP). In the perturbed simulations, anthropogenic SO_2 emissions from Europe (~13.3 $Tgyr^{-1}$) are increased by a factor of 7, following Lewinschal et al. (2019), resulting in a global emission rate of ~220 $Tgyr^{-1}$ as compared with ~140 $Tgyr^{-1}$ for year 2000.

In the slab-ocean simulations, the spatial distribution of ocean heat fluxes (Q_{flx}) are prescribed from the integration of the last 50 years of the fully coupled full-depth ocean and atmospheric simulations for both low-aerosol (“warm”) and high-aerosol (“cold”) emission simulations in Lewinschal et al. (2019), and only vertical exchange of heat with the atmosphere is permitted. Q_{flx} is obtained from the monthly mean fields using

$$Q_{flx} = \rho_0 c_p h \frac{\delta SST}{\delta t} - F_{net} \tag{1}$$

where ρ_0 is the density of sea water, c_p is the ocean heat capacity, h is the ocean mixed layer depth, $\frac{\delta SST}{\delta t}$ is the mean climatology of temperatures from the fully coupled simulations, and F_{net} is the net ocean surface energy budget (Bitz et al., 2012).

The experiments are labeled as (experiment type)-(atmosphere SO_2 emission level)-(OHFC source), where experiment type describes whether the model is fully coupled (F) or slab ocean (S). The atmosphere SO_2 emission level describes whether emission values are set to year 2000 (“LOEM”) or 7 times the anthropogenic emissions from year 2000 (“HIEM”). The OHFC source describes whether the OHFC fluxes are taken from the fully coupled simulation with low emissions (“LOOF”) or high emissions (“HIOF”). Four slab-ocean experiments are performed (Table 1). Results are presented as the difference between the control simulation (S-LOEM-LOOF) and perturbed simulation, to represent the impact of reducing European sulfate aerosol emissions. To evaluate the Arctic response through the atmospheric only pathway, we compare S-HIEM-LOOF, where ocean heat fluxes do not respond to modified aerosol forcing, to S-LOEM-LOOF (the comparison is referred to as “modified atmosphere”). To evaluate the Arctic response to ocean heat transport changes due to modified aerosol forcing, we compare S-LOEM-HIOF, where meridional ocean heat transport is taken from the high-aerosol emission fully coupled simulations (F-HIEM), to S-LOEM-LOOF (referred to as “modified ocean”). In order to evaluate the total response through the atmospheric pathway and prescribed ocean heat fluxes, we compare S-HIEM-HIOF with S-LOEM-LOOF (referred to as “modified atmosphere-ocean”). To highlight the impact of a full-coupling between the atmosphere and deep ocean, we also compare the “modified atmosphere-ocean” with the fully coupled comparison (F-HIEM-HIOF – F-LOEM-LOEF).

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Table 1
List of Simulations Used in This Study With the Experiment Type, Atmospheric SO_2 Emission Levels, and Ocean Heat Convergence Fluxes (OHCF) Used

Simulation	Experiment type	Atmosphere SO_2 emission level	OHCF level
F-LOEM	Fully coupled	Year 2000	-
F-HIEM	Fully coupled	7×EU	-
S-LOEM-LOOF	Slab	Year 2000	Year 2000
S-HIEM-LOOF	Slab	7×EU	Year 2000
S-LOEM-HIOF	Slab	Year 2000	7×EU
S-HIEM-HIOF	Slab	7×EU	7×EU

Note. The fully coupled simulations are obtained from Lewinschal et al. (2019).

3. Results

Results are presented as the difference between the low-aerosol and the high-aerosol scenario to mimic the response of reducing European sulfate aerosol emissions. The fully coupled simulations show that a decrease in European SO_2 emissions (F-LOEM vs. F-HIEM) causes significant warming over the Northern Hemisphere with a 1–2 °C temperature change over Northern Europe, Northern Canada, and the high Arctic (Figure 1a). The largest temperature responses are observed near Greenland (4–5 °C) and the Barents Sea (3–4 °C). Smaller yet significant changes occur over most of the northern tropics and subtropics. Changes in the Southern Hemisphere are not significant.

For the "modified atmosphere" comparison, the Arctic response is similar but larger than the fully coupled comparison (Figure 1b vs. 1a). Significant warming of 3–5 °C is observed throughout the northern midlatitudes and over Europe, with the largest increase of 5–7 °C observed over the Arctic and Siberia. For "modified ocean" (Figure 1c), cooling is seen over most northern latitudes (although much of this change is not significant). The response in the "modified atmosphere-ocean" comparison is similar to that of the "modified atmosphere" but with smaller magnitude changes of warming over Europe of 1–3 °C and Arctic warming of 3–5 °C, showing the buffering role of the ocean (Figure 1d). The zonal mean surface temperature differences for the control simulation (S-LOEM-LOOF for the slab-ocean simulations and F-LOEM for the fully coupled simulation) versus the different slab simulations are shown in Figure 1e. An overall Northern Hemisphere warming is found for the "modified atmosphere" and "modified atmosphere-ocean" simulations, with a maximum warming of ~5 and ~4 °C at ~70°N, respectively. In the

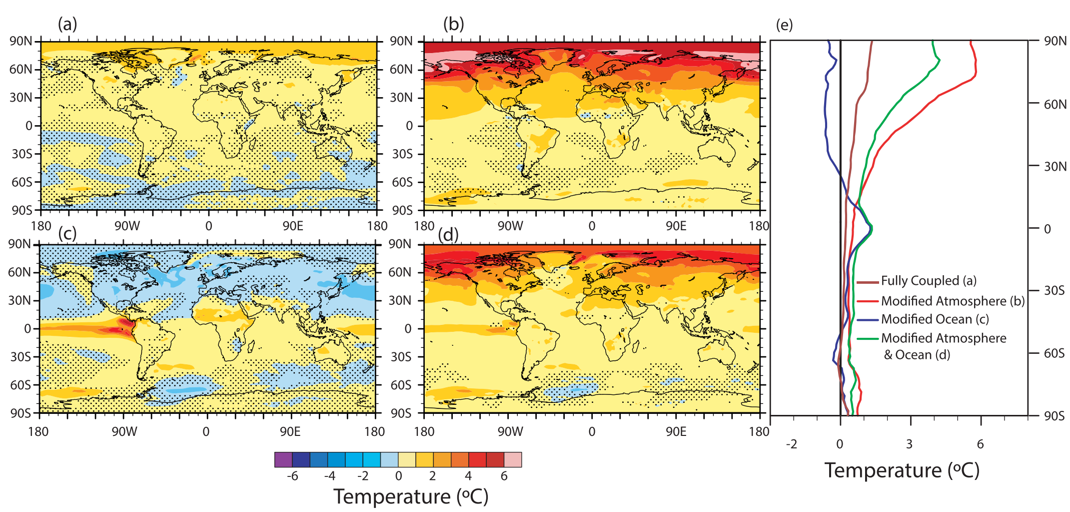

Figure 1. Spatial changes in surface temperature for (a) fully coupled, (b) modified atmosphere, (c) modified ocean, (d) modified atmosphere-ocean, and (e) zonal differences in surface temperature. Nonstippled regions are significant. Nonstippling indicates statistical significance at 95% for annual mean changes between the perturbed and the control simulations using a Student's t test.

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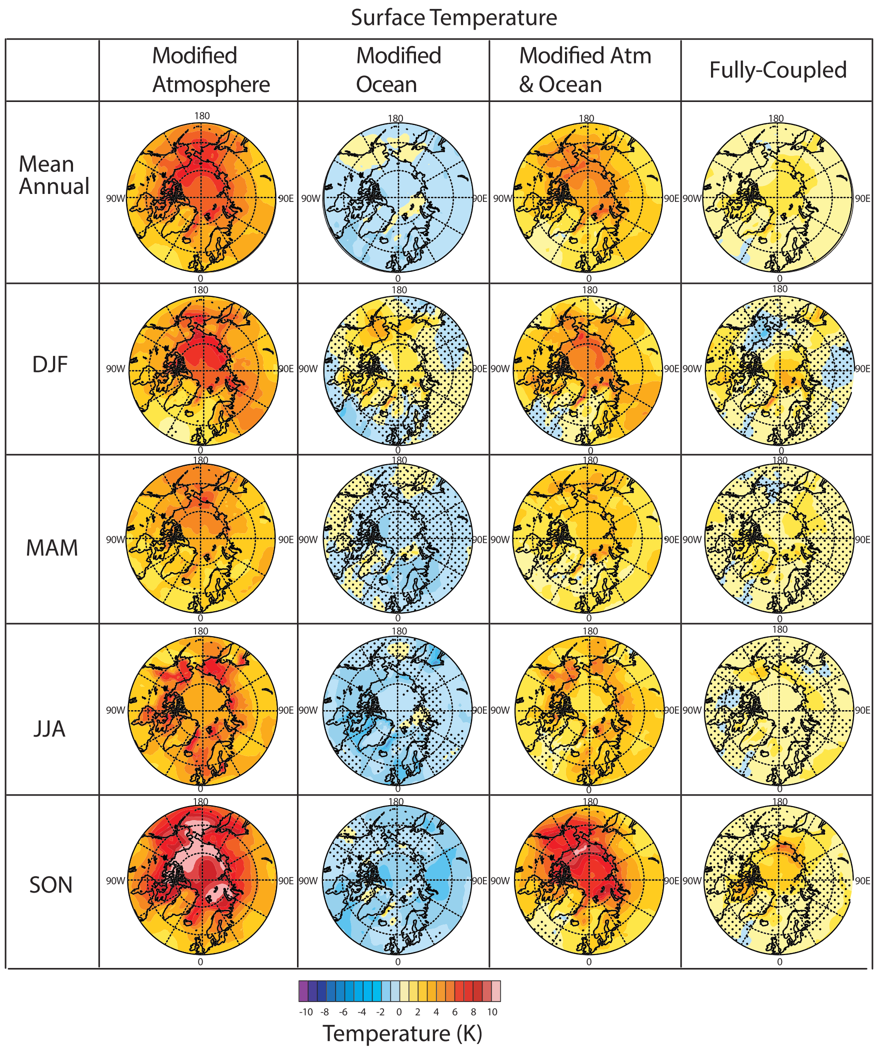

Figure 2. Mean annual and seasonal changes in surface temperature for "modified atmosphere," "modified ocean," "modified atmosphere-ocean," and fully coupled simulations. Nonstippling indicates statistical significance at 95% between the perturbed and the control simulations using a Student's *t* test.

"modified ocean" and "modified atmosphere-ocean" cases, ~2 °C warming is found between ~5°N and ~5°S. As this warming is absent in the "modified atmosphere" simulation, it must be related to changes in the meridional ocean heat convergence. The temperature patterns in these simulations show an amplified Arctic response to midlatitude aerosol forcing in all cases where the atmosphere is able to respond to the forcing.

The timing of simulated warming can indicate the mechanisms that drive Arctic amplification (Figure 2). The largest Arctic responses are found during September–November (SON; by ~10 °C) and December–February (DJF; ~6 °C) in the "modified atmosphere," "modified atmosphere and ocean," and fully coupled simulations, with the smallest responses during March–May (MAM). This corresponds to the annual coverage of Arctic sea ice extent which is lowest during September and highest during April (supporting information Figures S1 and S2). The timing of these changes suggests that changes in Arctic sea ice related feedbacks, such as delayed sea ice formation, are likely driving surface temperature warming during autumn and early winter, while changes in atmospheric energy transport and the vertical temperature profile intensify winter warming (Screen et al., 2012). However, the mechanisms are not independent of each other. Laîné et al. (2016) evaluated the Arctic amplification over the ocean surface for CMIP5 models using the radiative kernel technique and suggested that greater ocean heat uptake during the summer leads to greater heat exchange from the ocean to the atmosphere in the winter, increasing the winter amplification. For simulations with a "modified atmosphere," the autumnal warming suggests that sea ice-related feedback

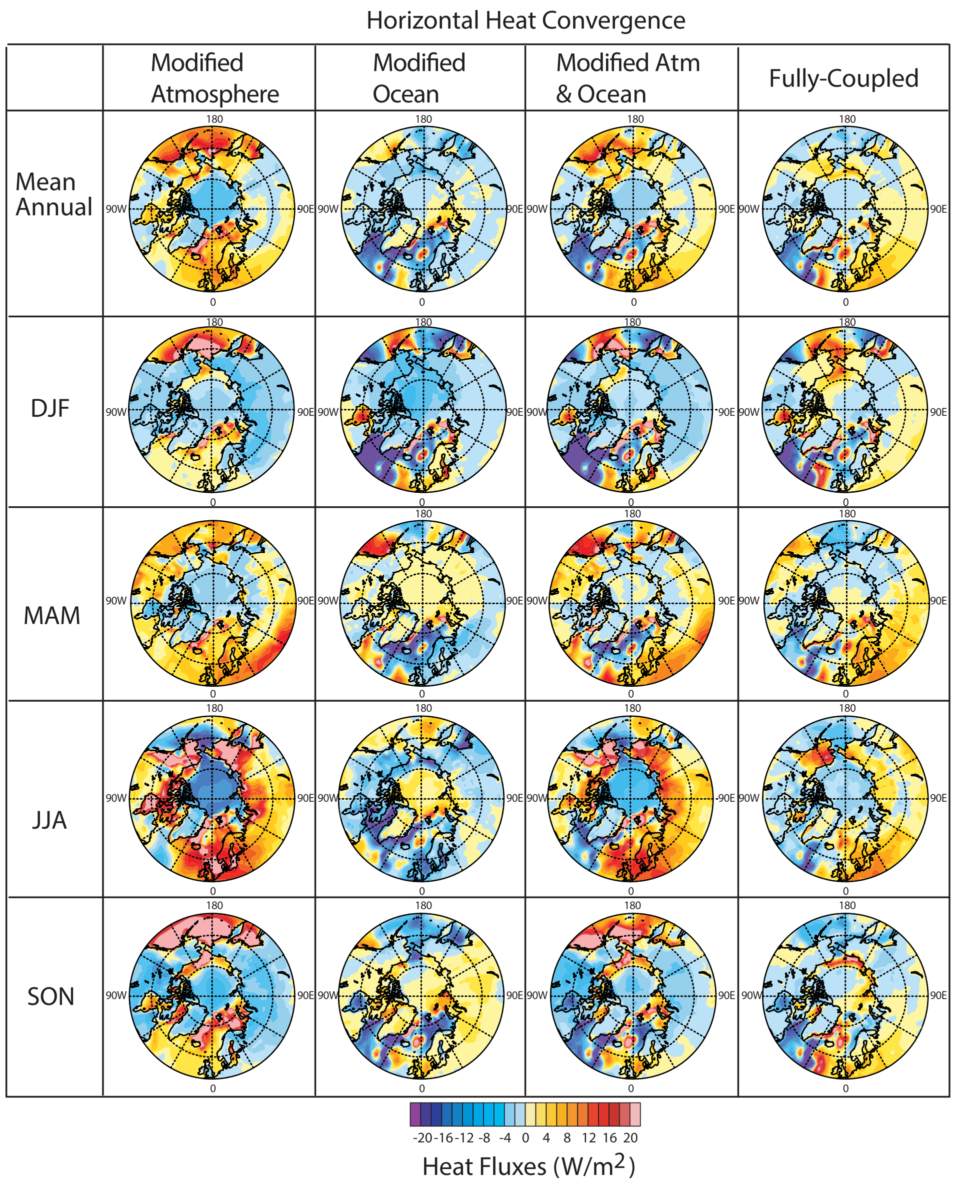

Figure 3. Mean annual and seasonal changes in horizontal heat convergence fluxes for "modified atmosphere," "modified ocean," "modified atmosphere-ocean," and fully coupled simulation.

mechanisms play an important role. However, winter warming means we cannot rule out the role of atmospheric energy transport and heat and energy release from the oceans. For the "modified ocean" simulation, the largest response is observed during June–August (JJA) and SON, but these changes are not significant over the Arctic Ocean. The ocean heat flux changes likely play a smaller role, for example, in delaying and reducing sea ice formation in certain areas, such as the high Arctic during winter, which would affect the ocean-atmosphere heat exchange, but further analysis of the sea ice response with more significant changes due to the ocean heat fluxes is needed to draw more firm conclusions. Our results show that Arctic amplification is mainly driven through atmospheric changes, rather than through changes in the meridional ocean heat fluxes.

To further elucidate the role of atmospheric heat transport in amplifying Arctic warming, we calculate changes in the atmospheric horizontal heat convergence (HHC; Figure 3) and its correlation with changes in surface temperature within the Arctic (Table S1). HHC is estimated as the mean of net (positive -> down) surface energy fluxes minus net top-of-atmosphere energy fluxes. For slab-ocean simulations, this correlation is strongest in winter (0.43, 0.53, and 0.40 for modified atmosphere, modified ocean, and modified atmosphere-ocean, respectively) and weakest in autumn (0.15, 0.14, and 0.20 for modified atmosphere, modified ocean, and modified atmosphere and ocean, respectively). For the "modified atmosphere" and "modified atmosphere-ocean" cases, the largest HHC changes are found over NW Europe and on the Arctic sea ice edges during JJA (Figure 3). During MAM, there is an increase in HHC over land, especially over Europe, with smaller changes in the Pacific Ocean. In SON, large changes are seen in the Pacific Ocean, near Greenland, and in the Barents Sea. During DJF, there is a decrease in HHC over land and a smaller change on both the Atlantic and Pacific oceans. The magnitude of HHC changes in the Arctic for the "modified ocean" case is not statistically significant. While we do not expect a 1:1 correlation between HHC and surface temperature (due to monthly mean averages), correlations between the two variables suggest that changes in HHC partially explain the pattern of temperature response.

The largest contribution to HHC changes is through changes in turbulent fluxes (latent and sensible heat: Figure S3). The location and timing of these changes suggest that they are related to sea ice changes (Figure S1). There seems to be a 3-month lag between the maximum changes in turbulent fluxes (July) and sea ice fraction (September). While this suggests a connection between changes in ocean-heat flux exchanges and timing of sea ice formation, we are limited in investigating this further due to the use of monthly mean model output. For the slab-ocean simulations, the largest change in ice fraction is observed for the "modified atmosphere" simulations (Figure S2), at the ice edge (50–70°N) during JJA and SON. These changes are mirrored in "modified atmosphere-ocean," although the magnitude of ice fraction changes is smaller, consistent with the ocean moderation of surface temperature (Figure 1).

4. Discussion

4.1. Slab-Ocean Simulations

Our simulations with NorESM in slab ocean mode show that the largest (warming) Arctic response to reductions in European sulfate aerosol is when only the atmosphere is allowed to respond and the smallest (cooling) response is when only the ocean heat transport is allowed to change. This shows that the high-latitude response to European sulfate reductions in NorESM is primarily driven through the atmospheric pathway. Ocean heat transport-driven changes play a secondary role, even if it influences sea ice formation. The nature of the small cooling response in "modified ocean" is consistent with results presented by Delworth and Dixon (2006), and Iwi et al. (2012). The Arctic response is strongly linked to changes in sea ice-covered area, especially near the edges of the ice (between 50°N and 70°N; Figures 1 and S4). When only the atmosphere responds, a significant loss in sea ice coverage occurs during JJA and SON near the Greenland coast, Barents Sea, and the Bering Sea. Less ice coverage and more open-ocean areas in the summer coupled to an ocean with fixed meridional heat transport leads to warming of the upper ocean mixed layer and a positive feedback which further enhances sea ice reduction and increased heat flux exchange from the ocean to the atmosphere. This acts as a local high-latitude source of heat that warms the lower atmosphere. The nature of our simulations precludes us from investigating the initial trigger for sea ice change in the first 30 years. But it is clear that high-latitude feedbacks mediated by sea ice changes play the most important role in determining the Arctic response.

Our aerosol-driven high-latitude temperature responses can be compared with those from greenhouse gas doubling experiments conducted with the Community Earth System Model v1.1 (CESM1) in the slab-ocean mode (Singh et al., 2017). In the Northern Hemisphere, they identified a poleward shift of the OHFC, with an increase in turbulent flux exchanges, sea ice retreat, and high-latitude warming. These changes in turbulent fluxes and sea ice extent are mirrored in this study. However, the source region of emission changes for the two studies are different. While CO_2 changes in Singh et al. (2017) were global in nature, here we constrain the regional emission changes only in Europe. In both cases, while ocean dynamics and heat convergence play a role in setting the Arctic response, this role is secondary and opposite compared to the atmosphere. The feedback analysis conducted by Singh et al. (2017) suggests that the lapse rate feedback, associated with surface warming and cooling aloft (related to midlatitude surface cooling), played the biggest role in setting the Arctic response. Here we note similar changes for the modified atmosphere simulations, where the surface temperature changes in the Arctic are larger than changes observed aloft (Figure S4). A change in the vertical temperature profile with colder temperatures aloft leads to a reduced heat loss at the top of the atmosphere and greater surface warming.

4.2. Fully Coupled Simulations

The slab ocean simulations with the modified atmosphere and ocean show larger remote responses than that with a fully coupled interactive ocean (Figures 1a and 1d). This difference is most likely driven by the low sea ice fraction change in the coupled simulation (Figure S2). Shu et al. (2015) noted that NorESM showed very low rates of monthly changes in sea ice extent compared to other CMIP5 models—the intermediate resolution version NorESM1-M (and NorESM1-ME which includes a prognostic biogeochemical cycle, in particular, carbon cycling) shows linear trends that are 45% and 53% (4% and 5% for NorESM1-ME) of the observed and multimodel ensemble mean changes, respectively. Therefore, it is possible that the fully coupled model underestimates the remote response to European sulfate reductions due to the tendency in NorESM to maintain Arctic sea ice. In the slab-ocean simulations, OHFCs are fixed and do not respond to changes in ocean-atmospheric heat flux exchange. Therefore, reduced summer ice will lead to a positive feedback due to warmer mixed-layer ocean temperatures that persist into the autumn and lead to a greater reduction in ice formation. This suggests a secondary but important role played by ocean heat transport in damping and redistributing heat in the Arctic. This damping explains the smaller response of the slab simulation with “modified atmosphere-ocean” than the “modified atmosphere” case. The addition of a fully coupled full-depth ocean where excess heat can be transported away from the Arctic further indicates the importance of a fully coupled ocean in damping Arctic changes (also suggested in other studies such as Marshall et al., 2015).

Caveats in this study include the fact that results presented here are changes in one Earth system model—NorESM-1 (in fully coupled and in slab-ocean modes)—and not a multimodel evaluation. Further, treating the oceanic response as a forcing for slab-ocean simulations ignores the dynamic coupling between the atmosphere, sea ice, and oceans and can lead to spurious conclusions regarding the individual roles. Finally, the use of unrealistically large SO_2 emission values is useful to increase the signal-to-noise ratio of the response, but the magnitude of the response to smaller emission changes need not scale linearly to the changes observed in this study (Lewinschal et al., 2019). Despite these caveats, it is clear that regional changes in European sulfate aerosol forcing drive a relatively large Arctic response.

5. Conclusion

Fully coupled and slab ocean experiments were performed with NorESM to identify the mechanism by which reductions in European SO_2 emissions contribute to amplified Arctic warming. We compare the climate response in experiments that vary which parameter is allowed to respond to aerosol changes: 1) atmosphere alone; 2) ocean alone; and 3) both atmosphere and ocean. Our results show that the atmosphere plays the primary role in driving Arctic warming in response to European aerosol reductions. Comparisons of the response to aerosol changes in experiments where the atmosphere alone, ocean alone, and both the atmosphere and ocean show that the atmosphere plays the primary role in driving Arctic warming in response to European aerosol reductions. Warming driven by that atmospheric pathway is partially offset by a cooling resulting from changes in ocean heat flux convergence. In both cases, a key mediator of the temperature response is changes in sea ice extent, through modifications of turbulent flux exchanges and surface temperature. The Arctic temperature response is smaller in the fully coupled experiments than the slab ocean experiments, due to the tendency in the fully coupled model to maintain Arctic sea ice and transport excess heat away from the Arctic. This suggests that a good representation of Arctic sea ice is vital for confident projections of future Arctic climate change, even for remote midlatitude forcing changes.

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