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Key Points:

- A large amount of solar dimming of 13% is required to save the sea ice
- Compensating changes in local and remote energy fluxes are important
- Meridional overturning circulation would be still reduced

Supporting Information:

- Readme
- Supplemental Figure S1 and Table S1

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Can regional climate engineering save the summer Arctic sea ice?

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Abstract Rapid declines in summer Arctic sea ice extent are projected under high-forcing future climate scenarios. Regional Arctic climate engineering has been suggested as an emergency strategy to save the sea ice. Model simulations of idealized regional dimming experiments compared to a business-as-usual greenhouse gas emission simulation demonstrate the importance of both local and remote feedback mechanisms to the surface energy budget in high latitudes. With increasing artificial reduction in incoming shortwave radiation, the positive surface albedo feedback from Arctic sea ice loss is reduced. However, changes in Arctic clouds and the strongly increasing northward heat transport both counteract the direct dimming effects. A 4 times stronger local reduction in solar radiation compared to a global experiment is required to preserve summer Arctic sea ice area. Even with regional Arctic dimming, a reduction in the strength of the oceanic meridional overturning circulation and a shut down of Labrador Sea deep convection are possible.

1. Introduction

Sea ice is an important climate component in the Earth system [*Solomon et al.*, 2007]. Considerable reductions in Arctic sea ice extent have been observed in the past years, due in part to increasing greenhouse gas concentrations [*Stroeve et al.*, 2007; *Serreze et al.*, 2007a; *Kay et al.*, 2011; *Holland*, 2012]. The most important drivers for Arctic amplification are the positive surface albedo feedback associated with reduced sea ice cover and land snow and net cloud feedback [*Budyko*, 1969; *Hall*, 2004; *Serreze et al.*, 2007b]. Nevertheless, sea ice cover is tightly coupled to the global temperature increase, mainly due to the reduction in atmospheric heat convergence [*Winton*, 2008; *Tietsche et al.*, 2011; *Kay et al.*, 2012]. Along with sea ice reduction with increasing greenhouse gas concentrations, models predict a reduction of the strength of the oceanic meridional overturning circulation (MOC) by the end of the 21st century [*Weaver et al.*, 2012; *Meehl et al.*, 2012]. This is partly due to the impact of melting sea ice on Arctic freshwater export and the stratification in the deep convection regions of the North Atlantic [*Jahn and Holland*, 2013]. Large uncertainties exist in a potential acceleration of climate change due to enhanced outgassing of climate gases, CO_2 and CH_4, that are stored in the cryosphere and permafrost [*Zimov et al.*, 2006; *Schuur et al.*, 2009; *McGuire*, 2010], which could lead to abrupt climate change.

If sufficient greenhouse gas emission reduction measures are not put into place early enough, climate engineering strategies may be considered to cool the climate and, for instance, to serve as an emergency plan to cool the Arctic and retain summer sea ice cover. The artificial global reduction of incoming shortwave (SW) radiation in climate models was shown to reduce global temperatures back to control conditions [*Kravitz et al.*, 2013]. However, various unintended side effects are likely to occur [e.g., *Robock*, 2008]. Other climate engineering strategies have been explored, like the reduction of SW radiation in only one hemisphere [*Haywood et al.*, 2013], resulting in large impacts on regional precipitation patterns. Regional climate engineering performed over high northern latitudes may be less intrusive, and the most effective location to induce temperature changes, as suggested by *MacCracken et al.* [2013]. Model studies show that this option would require a much larger amount of local solar dimming than global interventions.

Here we discuss the processes that control the Arctic energy budget for a number of regional solar dimming experiments, and one global dimming experiment, using a fully coupled global climate model. This includes an assessment of changes in the surface heat balance, the northward heat transport (NHT) of the atmosphere and ocean, and associated changes in ocean circulation. The effectiveness of idealized regional solar dimming over the Arctic is explored for a business-as-usual case, with the aim of maintaining a summer

Arctic sea ice pack close to present-day conditions and assessing the possible impact on the regional to global climate.

The paper is structured as follows. The model simulations are described in section 2. The evolution in summer sea ice area for different experiments is summarized in section 3.1. In section 3.2, we outline changes in both local surface fluxes and remote heat fluxes. The impact of regional climate engineering on the meridional overturning circulation is discussed in section 3.3. Section 4 discusses and concludes the findings of the paper.

2. Experimental Design

A transient 21st century model experiment with a large radiative forcing scenario (RCP8.5) is analyzed [*Meehl et al.*, 2012]. The simulations are performed with a fully coupled state-of-the-art global climate model (Community Climate System Model version 4) [*Gent et al.*, 2011], using $0.9 \times 1.25^\circ$ horizontal resolution for the atmosphere and approximately 1° resolution in the ocean and ice models. A global dimming experiment, denoted "1xGlobal" is performed starting in 2020 through 2099. The global solar constant is increasingly reduced between 2020 and 2099 to achieve a balanced top of the atmosphere radiative flux, reaching up to 3.3% ($\approx$ 45 W/m^2) of the total solar irradiance (TSI) by the end of the century. Additional regional solar dimming experiments are performed where reductions in the solar constant are applied to latitudes poleward of 60°N or 70°N. The Arctic dimming experiments for latitudes $>$ 60°N use solar reductions times 1 to 4 of the global solar dimming amount (Table S1 in the supporting information). One regional experiment for latitudes $>$ 70°N is performed using 4 times the global dimming amount. Only one simulation per experiment is investigated. We focus our analysis on changes between averages for 2080–2099 and control conditions (2005–2024). Control conditions are defined here as the average between years 2005 and 2024 in the RCP8.5 simulation.

3. Results

3.1. Changes in Summer Sea Ice Area

Increasing greenhouse gases in the RCP8.5 experiment result in an ice-free Arctic Ocean in September by the end of the 21st century [*Vavrus et al.*, 2012; *Jahn and Holland*, 2013]. In the regional solar dimming experiments, the area of retained summer sea ice is strongly correlated with the amount of solar dimming (Figure 1). A local dimming poleward of 60°N of 1 or 2 times the amount of the global insolation reduction saves less than half of the present-day sea ice area. Four times the amount of the global insolation reduction is required, reaching 180 W/m^2 (approximately 13% of TSI) by the end of the century, to save 82% of the summer ice, a figure similar to the 1xGlobal experiment (Figure 1). In this case, the summer sea ice volume is still reduced by 34% compared to the control, and the summer snow volume on the sea ice is increased by half (Table S1 in the supporting information) due to enhanced moisture transport from lower latitudes, as discussed below. Changes in the 4x70N experiment are comparable to the 3x60N experiment, resulting in a summer Arctic sea ice area that is 64% of the control.

3.2. Changes in Heat Fluxes

Both local radiative changes and adjustments in the northward heat transport (NHT) by the atmosphere and ocean are important drivers of the Arctic energy budget. Our simulations show that, with growing regional solar insolation reduction, both local feedback processes and NHT counteract the initial decrease in surface energy flux and therefore require a much larger amount of solar dimming locally than for global interventions.

In summer, changes in the net SW radiation are largely controlled by local feedback, which lead to a net increase in the absorbed SW radiation and cooling of the atmosphere (supporting information, section 1, and Figure 1). In fall and winter, changes in sensible and latent heat fluxes from the surface to the atmosphere are the dominant forces in the surface energy budget, resulting in intensified heat exchange from the ocean surface to the atmosphere. Poleward of 60°N, the change in net downward surface energy flux in RCP8.5 is about 10 W/m^2 in early summer (June) and -10 W/m^2 in October/November (Figure 2). This results in the seasonality of surface air temperature and the largest warming in autumn and winter [*Manabe and Stouffer*, 1980].

The artificial reduction in incoming SW radiation on top of the atmosphere in regional Arctic dimming experiments leads to a reduction in the downwelling surface SW energy flux mostly in summer (Figure 2,

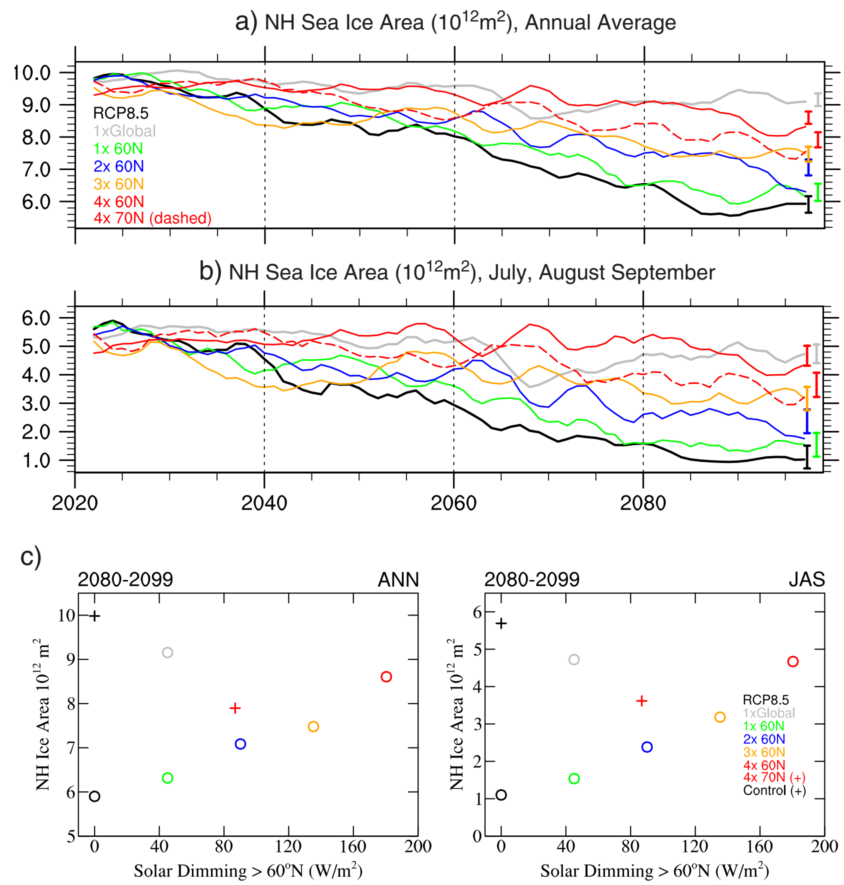

Figure 1. Sea ice area for different model experiments. Evolution of Northern Hemisphere (a) annual average and (b) summer average sea ice area between 2020 and 2100 for different experiments (see legend); a 5 year running mean is applied. The standard deviations of changes with regard to the 5 year running mean are shown on the right of each line, marking the average value derived for the last 20 years of each of the simulations. (c) Scatterplot of NH Ice Area and the downward SW clear sky forcing north of 60°N, for different experiments between 2080 and 2099, (left) annual average and (right) summer average. The forcing of the 4x70N experiment is averaged over 60–90°N.

bottom). However, continuous loss of sea ice in spring and early summer induces a positive surface albedo feedback, especially for the experiments with a smaller amount of dimming. For regional dimming experiments where temperatures are closer to being stabilized (3x60N and 4x60N), more summer Arctic sea ice is retained. With increasing regional dimming, changes of clouds and turbulent fluxes counteract the artificial insolation reduction (Figure 2, bottom), requiring additional dimming to sufficiently maintain summer sea ice area close to control conditions.

In winter, when SW radiation is mostly irrelevant to the local energy budget, a reduction of net longwave fluxes in the strongest dimming experiments (due in part to changes in moisture transport, as discussed below) contribute to the warming of the atmosphere of 4–6 K in high latitudes (Figure 2). Winter warming reduces ice growth rates, leading to a continuous reduction of Arctic ice volume. Changes of surface energy fluxes for the 1xGlobal experiment are smaller than regional interventions but still lead to modest high-latitude warming in winter and a reduction of Arctic ice volume.

A net downward surface SW flux change of −20 W/m^2 in summer high latitudes is required for the regional dimming experiments to balance changes in the horizontal atmospheric and oceanic NHT (Figure 3). In response to increased greenhouse gas concentrations, the atmospheric latent NHT increases proportionally to the global temperature change. In contrast, the sensible NHT decreases with a magnitude related to a reduction in the temperature gradient between high and low latitudes [*Hwang et al.*, 2011]. Despite the high-latitude temperature reduction in the Arctic dimming experiments, the warming equatorward of 60°N (and hence globally) is similar to RCP8.5. Latent NHT into the Arctic is therefore similar or even slightly increased for 4x60N in comparison to the RCP8.5 case (Figure 3). In contrast, an increased meridional

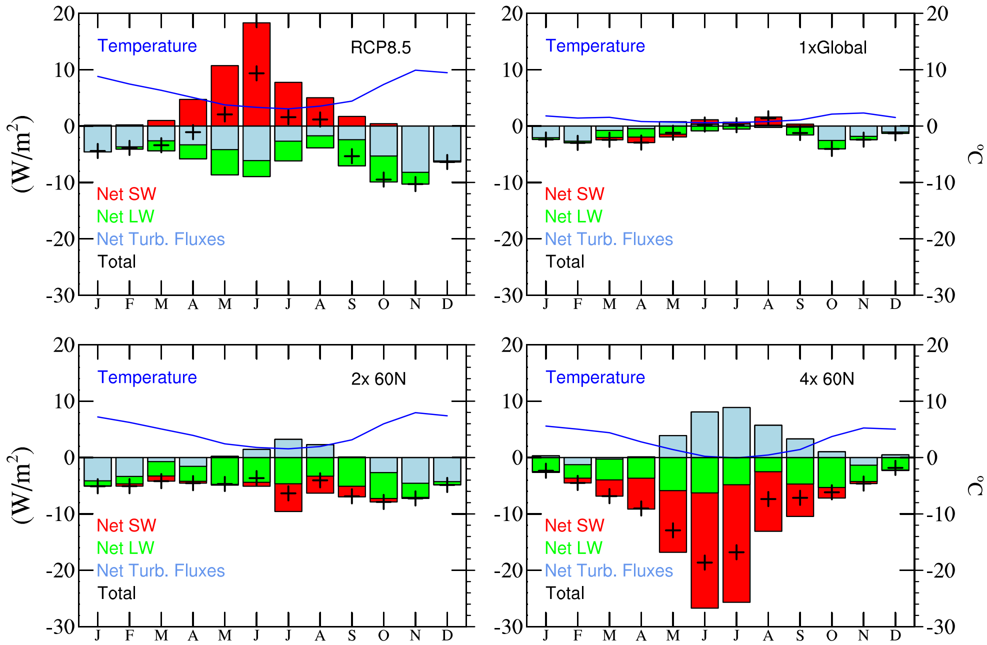

Figure 2. Surface energy budget for different experiments. Seasonal cycle of the Arctic surface heat budget change relative to the control for net shortwave (SW), net long wave (LW), net turbulent (colored bars), total fluxes (black plus signs), and temperature changes relative to the control (blue line), averaged between 60 and 90°N for different experiments (different panels). Flux changes are positive downward.

temperature gradient in the regional dimming experiments, due to the relative cooling of high latitudes, leads to a smaller reduction of the sensible NHT compared to RCP8.5. Indeed, in the 4x60N experiment, sensible NHT actually increases relative to the control (Figure 3). Therefore, the total atmospheric NHT increases strongly in the regional dimming experiments compared to RCP8.5 and control conditions.

High-latitude ocean heat transport also changes with rising greenhouse gases. In the RCP8.5 simulation, the ocean transports less heat poleward as the meridional overturning circulation weakens over the 21st century [*Winton*, 2008]. In both the global and regional dimming experiments, the reduction in ocean NHT in RCP8.5 is mitigated by a smaller MOC response; in fact, in 4x60N (Figure 3), there is an increase in ocean NHT compared to the control. For the 4x70N experiment, more than half of the Arctic sea ice area is retained compared to RCP8.5, while the ocean NHT decreases much more than in all the other regional dimming experiments (Figure 3). This is due to a large increase in net precipitation in the 4x70N experiment (Table S1 in the supporting information), resulting in a stronger MOC response than the other dimming experiments.

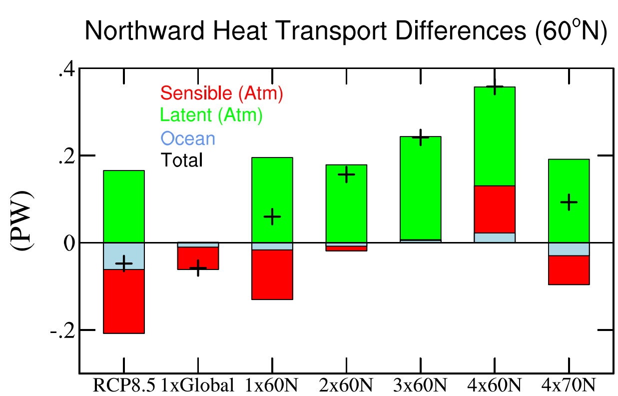

Figure 3. Northward heat transport (NHT) change in Pettawatts at 60°N, relative to the control, for sensible NHT, latent NHT, ocean NHT (colored bars), and total NHT (black plus signs) and for different experiments.

3.3. Impact on the Meridional Overturning Circulation

Relative to the control, all the regional dimming experiments show a freshening of the northern North Atlantic and consequent reductions in Labrador Sea convection, with the largest changes in the weaker dimming experiments (Table S1 in the supporting information). This weakens the MOC. These changes are smaller than for RCP8.5, due to the reduced melting of sea ice and a cooling in the Labrador Sea region, but are still considerable. In addition to sea ice melting, the enhanced hydrological cycle in a warmer global climate leads to increased river input from midlatitudes into the Arctic Ocean and increased net precipitation over the Arctic Ocean. Together with the sea ice melt, this in turn leads to increased liquid Arctic freshwater export through the Fram Strait and enhanced stratification in the Labrador Sea. The runoff is even larger in the regional dimming experiments than in RCP8.5, due to the increased temperature gradient and the resulting increased northward atmospheric latent heat and moisture fluxes.

4. Discussion and Conclusions

In order to constrain the summer Arctic sea ice area close to present-day conditions comparable to a global intervention, our experiments suggest that a large amount of regional solar dimming (180 W/m^2 or 13% of TSI) is required by the end of the century. Regional reduction of solar radiation in this scale would be very difficult to achieve based on limits of the achievable reduction in radiative forcing, as derived in recent studies on proposed global climate engineering approaches [*Lenton and Vaughan*, 2009; *Niemeier et al.*, 2010; *English et al.*, 2012]. If an albedo increase of 13% could somehow be achieved, for instance, by placing sunshades into space or applying combined methods [*MacCracken et al.*, 2013], the sea ice volume and the MOC would still be reduced with a likely continuation of sea ice reduction. Regional dimming would result in some cooling in midlatitudes but would also change global scale precipitation [*Frierson and Hwang*, 2012; *MacCracken et al.*, 2013]. Changes in incoming solar radiation are also likely to significantly affect Arctic ecosystems [*Caldeira and Wood*, 2008]. If stratospheric aerosol particles were used to increase the Arctic albedo, a large reduction of stratospheric ozone and increase in surface UV is possible due to the increase of heterogeneous reactions and therefore chlorine activation [*Tilmes et al.*, 2008]. In addition, the artificially defined dimming region north of 60°N would not be achievable, due to the transport of aerosol particles into lower latitudes between spring and fall [*Robock et al.*, 2008; *Haywood et al.*, 2013].

This idealized model study contributes to the understanding of the processes that lead to the requirement of an unrealistically large amount of Arctic dimming to preserve Arctic sea ice under global warming. Quantitatively, uncertainties exist due to shortcomings in the model performance, for example, with regard to clouds in high northern latitudes [*Kay et al.*, 2012]. The required reduction may also vary depending on the strength of polar amplifications in different models. Arctic regional dimming does therefore not provide a possible solution for containing Arctic sea ice for a business-as-usual greenhouse gas emission scenario.

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