Auxiliary Material: Can regional climate engineering save the summer Arctic Sea-Ice?

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The auxiliary material includes a summery of changes in the shortwave heat flux, and a table summarizing Arctic sea-ice and snow diagnostics, as well as diagnostics for freshwater and the meridional overturning circulation for different experiments.

1. Changes in shortwave heat fluxes

Changes in the Arctic surface shortwave (SW) energy budget in different experiments, RCP8.5, 1xGlobal, 2x60N, and 4x60N (see main paper), relative to the control, are shown (Fig 1). Changes in SW radiation are most important in summer due to the largest intensity of sunlight. In RCP8.5, the upwelling SW energy flux (direction downward) is

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increased. Less SW radiation is reflected back to space relative to the control, mainly because of the loss in sea-ice. The downwelling clear sky energy flux in RCP8.5 is reduced globally, due to increases in gases like water vapor and methane, reflecting more SW radiation in the atmosphere. Further, the SW cloud component over the Arctic is reduced in part as a result of the increase in the ice-free area of the Arctic ocean. In the global dimming experiment (1xGlobal), sea-ice is largely contained close to levels of the control experiment and changes in the SW upwelling component are only slightly positive. The SW downwelling clear-sky energy flux changes balance the changes in clouds and SW upwelling component, with a net SW radiation change to be around zero.

In the 2x60N regional Arctic dimming experiment, the increase in the SW upwelling component of the energy flux is balanced by the artificial reduction of incoming SW solar radiation, resulting in almost no change in the net surface energy flux compared to the control. However, since the Arctic energy balance is not controlled by the local surface energy flux alone, as discussed in the main paper, more solar dimming is needed to control surface temperatures and therefore summer Arctic sea-ice. The required SW solar reduction of 13%, as the case in the 4x60N experiment, results in a reduced increase in the upwelling SW component compared to the control due to the contained sea-ice area. However, between June and September, changes in clouds result in an increase of the SW downwelling energy flux, which counteract the reduction of the net SW radiation achieved by the artificial regional dimming.

2. Table

Table 1. Changes in solar dimming in W/m^2 by the end of the century, July/August/September mean Arctic sea ice area, sea ice volume, snow volume, the MOC index, Labrador Sea deep convection, Fram Strait liquid and solid freshwater export, river runoff into the Arctic Ocean, and net precipitation (precipitation − evaporation) over the Arctic Ocean, for years 2080-2099 in the dimming experiments, compared to the 2005-2024 average from the control simulation (values shown in the first column, changes shown in % of that value). Freshwater fluxes are calculated relative to a reference salinity of 34.8 PSU.

	Control	RCP8.5	1xGlobal	1x60N	2x60N	3x60N	4x60N	4x70N
Amount Dimming (W/m^2)	0	0	45	45	90	135	180	60N equiv. 87
Sea Ice Area	5.69 1012m^2	19%	83%	27%	42%	56%	82%	64%
Sea Ice Vol.	1.60 1013m^3	10%	60%	15%	25%	38%	66%	45%
Snow Vol.	0.43 1013m^3	5%	70%	9%	21%	54%	151%	76%
MOC index	23.94 Sv	77%	101%	86%	86%	93%	94%	84%
Labrador Sea deep convection max depth FMA[a]	977m	23%	108%	63%	50%	50%	55%	30%
Fram Strait LFWE[b]	1798 km^3/yr	229%	116%	184%	195%	199%	162%	206%
Fram Strait SFWE[c]	2419 km^3/yr	33%	79%	36%	47%	67%	96%	65%
River runoff	6881 km^3/yr	119%	103%	123%	122%	128%	126%	123%
Net precip. over the Arctic Ocean	2901 km^3/yr	117%	100%	121%	117%	126%	126%	127%

[a] February/March/April

[b] liquid freshwater export

[c] solid freshwater export

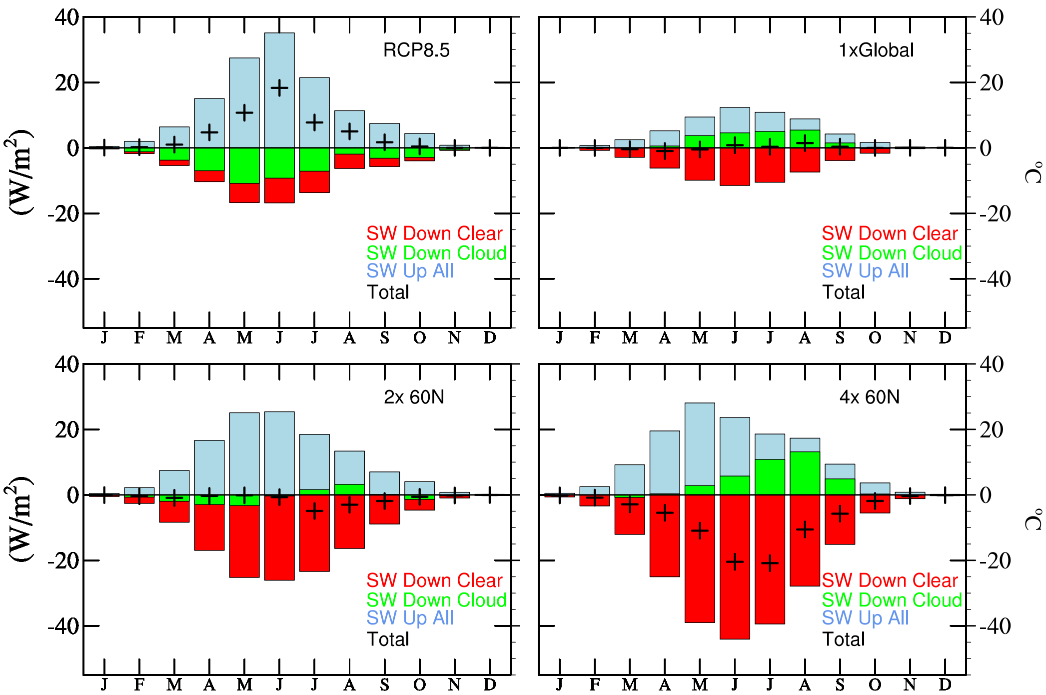

Figure 1. Shortwave (SW) surface energy budget for different experiments. Seasonal cycle of the Arctic SW surface heat budget change relative to the control for SW downwelling clear sky (red), SW downwelling cloudly sky (green), SW upwelling (blue), and total fluxes (black plus signs), averaged between 60 and 90^{o}N for different experiments (different panels). Flux changes are positive downward.