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Climate response and efficacy of snow albedo forcing in the HadGEM2-AML climate model

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The presence of black carbon in lying snow can reduce the albedo of the snow surface (Warren and Wiscombe, 1980) and cause a perturbation to the Earth's radiation budget (Clarke and Noone, 1985) by enhancing the absorption of shortwave radiation at snow surfaces. The induced warming is likely to increase the rate of snow melt, which can expose the less reflective underlying surface and decrease the surface albedo further. Here, we present the results of an idealised experiment using the HadGEM2-AML climate model where land snow albedo has been decreased by 0.05. The resulting radiative forcing at the top of the atmosphere is +0.28 Wm^{-2} and global near-surface temperature warms by 0.72 K. Compared to a doubling of CO_2 concentration, this perturbation to snow albedo has a climate efficacy of 2.6. This large value stems from the large efficiency of snow albedo forcing to warm high latitudes, with a relatively larger impact on sea-ice area and snowpack as compared to the CO_2 forcing. These results provide some support to the idea that emission reduction of black carbon can bring some benefits to mitigate climate change in Arctic and snow regions.

1. Experiments

The Hadley Centre general circulation model HadGEM2 can be configured to couple an atmosphere model (Martin *et al.*, 2006) with a 50-m thermodynamic mixed-layer ocean and sea-ice model (Johns *et al.*, 2006). This configuration is used here for a control and two experiment simulations. The control simulation uses trace gas and aerosol concentrations for 1860. The control CO_2 concentration is 286.2 ppmv. That value is doubled in a first experiment, labelled DCO2, to 572.4 ppmv. The albedo of snow-covered land surfaces is prescribed by default at 0.8. That value is decreased to 0.75 in a second experiment, labelled SNOW. In reality, such a large decrease in albedo would only correspond to the largest concentrations of black carbon in snow. The albedo of snow-covered sea ice is left unchanged.

Each simulation consists of running the model for 30 years after a common starting point obtained by a calibration simulation for 1860 conditions. The 20-year calibration simulation determines the heat-flux distribution needed for maintaining sea-surface temperatures close to climatological values in a mixed-layer ocean which cannot simulate ocean currents. DCO2 and SNOW experiments take about 10 simulated years to reach an equilibrium beyond which the global-averaged 1.5-m temperature, sea-ice fraction and depth, and net radiative fluxes at the top of the atmosphere do not vary significantly. In the following, averages over the last 20 years of each simulation are used. Although the experiments are used to determine the response to their associated forcing, they cannot provide an estimate of the forcings themselves as the model evolution is affected by feedbacks. We quantify the forcing in an additional 5-year atmosphere-only simulation where the model evolution is made independent of the imposed forcing by calling the radiation code twice, first with the forcing mechanism included, then with the control configuration. This last state is used for advancing the model into its next time step.

2. Forcing

Decreasing the albedo of snow exerts a radiative forcing that is purely in the shortwave with a global average of +0.28 Wm^{-2}. This global average is relatively small, considering the large change in snow albedo. Locally, the magnitude of the forcing depends on the duration of snow cover and the amount of solar radiation. In consequence, this radiative forcing displays a strong seasonality, being maximum during summer over polar regions and during spring over northern continents, and virtually zero during polar winter.

Doubling the CO_2 concentration exerts a forcing of -0.19 Wm^{-2} in the shortwave and +4.02 Wm^{-2} in the longwave, for a net forcing of +3.83 Wm^{-2} measured at the tropopause. The CO_2 radiative forcing has a maximum in the Tropics and is zonally symmetric.

3. Climate response

Decreasing snow albedo induces a warming of +0.72 K, and +3.85 K for a doubled CO_2 concentration. North Hemisphere warming is stronger in winter than in summer in both experiments. Figure 1 shows the zonal mean temperature change normalised by the globally averaged forcing for both experiments. The normalised warning in SNOW is significantly stronger than in DCO2. Both show an enhancement of the warming at high latitudes. In addition to the surface albedo feedback discussed below, it is hypothesised that changes in the poleward atmospheric heat transport also contribute to the enhancement. In DCO2, heat is transported from tropical to high-latitude regions. In SNOW, heat remains confined at high-latitudes although the Tropics also warm as poleward heat transport is reduced (Shindell and Faluvegi, 2009).

Table 1 gives the global change with respect to the control simulation in 1.5-m temperature, sea-ice area, and precipitation rate, normalised by the imposed forcing. The climate sensitivity is 2.57 K/(Wm^{-2}) for SNOW and 1.01 K/(Wm^{-2}) for DCO2. The ratio of these two numbers, equal to 2.6, is the efficacy of decreasing snow albedo in HadGEM2-AML. This value is at the lower end of the range of 2.5-4.1 estimated for black carbon deposition on snow by Flanner *et al.* (2007) and consistent with Koch *et al.* (2009) and references therein. This large climate sensitivity is likely to be due to the feedback between climate and surface albedo which is excited stronger by this forcing: the reduction in sea-ice area per unit forcing is 4.1 times larger in SNOW than DCO2 (Table 1). Retreating sea ice exposes the darker ocean surface, leading to more warming. Interestingly, in SNOW sea ice reacts to a remote forcing, as the albedo of snow-covered sea-ice surfaces was not modified.

The water cycle is also affected by warmer temperatures. Both SNOW and DCO2 show an increase in precipitation as warmer conditions increase the surface latent heat flux. With an increase in precipitation rate that is 2.8 times larger, the response in SNOW is again larger than in DCO2. The limit between rain and snow moves toward higher latitudes, although snowfall rates are increased north of that line. Snow melt is also affected by warming. Figure 2 shows seasonal distributions of change in snowmelt rates in SNOW and DCO2. Magnitudes are comparable in both experiments, hinting at a larger efficiency at melting snow per unit forcing in SNOW as the snow albedo forcing is located where it matters most to melt snow, directly on snow surfaces. In northern continents, snow melt first increases in winter and even more strongly in spring, before decreasing in summer and autumn as snow has already melted earlier in the year. Snow melts rapidly at the edges of Greenland during summer.

4. Conclusion

Two radiative forcing mechanisms have been compared in the Hadley Centre atmosphere/mixed-layer ocean climate model. Reducing the albedo of snow-covered land surfaces by 5% and doubling the CO_2 concentration yield a positive response in near-surface temperature, enhanced at high latitudes. The snow albedo mechanism is more efficient at warming the Earth's climate, with an efficacy of 2.6. This large value is due to the snow albedo forcing being applied in precisely the regions where the strong surface albedo feedback operates. It is thus more efficient at reducing sea-ice and land-snow areas. The hydrological cycle is also more affected by reducing snow albedo than doubling CO_2, with a disproportionate effect on snow melt.

Mitigating the causes of a reduction in snow albedo, such as deposition of black carbon on snow, would only address a small component of the radiative forcing of the Earth's climate but is likely to suppress a significant warming in high-latitude regions.

5. References

Clarke A.D. and Noone, K.J. Soot in the Arctic snowpack: a cause for perturbations in radiative transfer. *Atmos. Env.*, 19, 2045-2053, 1985.

Flanner, M.G., Zender, C.S., Randerson, J.T., and Rasch, P. Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res.*, 112, D11202, doi:10.1029/2006JD008003, 2007.

Johns T.C. *et al.*, The new Hadley Centre climate model (HadGEM1): Evaluation of coupled simulations. *J. Clim.*, 19, 1327-1353, 2006.

Koch *et al.*, Distinguishing aerosol impacts on climate over the past century. *J. Clim.*, 2659-2677, doi:10.1175/2008JCLI2573.1, 2009

Martin G.M. *et al.*, The physical properties of the atmosphere in the new Hadley Centre Global Environment Model (HadGEM1). Part I: Model description and global climatology. *J. Clim.*, 19, 1274-1301, 2006

Shindell D. and Faluvegi, G. Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience*, 2, 294-300, doi:10.1038/ngeo473, 2009.

Warren S.G. and Wiscombe, W.J. A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols. *J. Atmos. Sci.*, 37, 2734-2745, 1980

Table 1. Global annual-mean responses normalised by global annual-mean forcing for at 5% decrease in land snow albedo (SNOW) and doubling of CO_2 concentration (DCO2)

Normalised response	**SNOW**	**DCO2**
1.5-m temperature (K/Wm^{-2})	+2.57	+1.01
Sea-ice area (10^6 km^2/Wm^{-2})	-13.9	-3.4
Precipitation rate (10^{-2} mm day^{-1}/Wm^{-2})	+14.0	+5.0

Figure 1. Temperature response normalised by global-mean radiative forcing (K/(Wm^{-2})) for a 0.05 absolute decrease in land snow albedo (solid) and a doubling of CO_2 concentration (dashed).

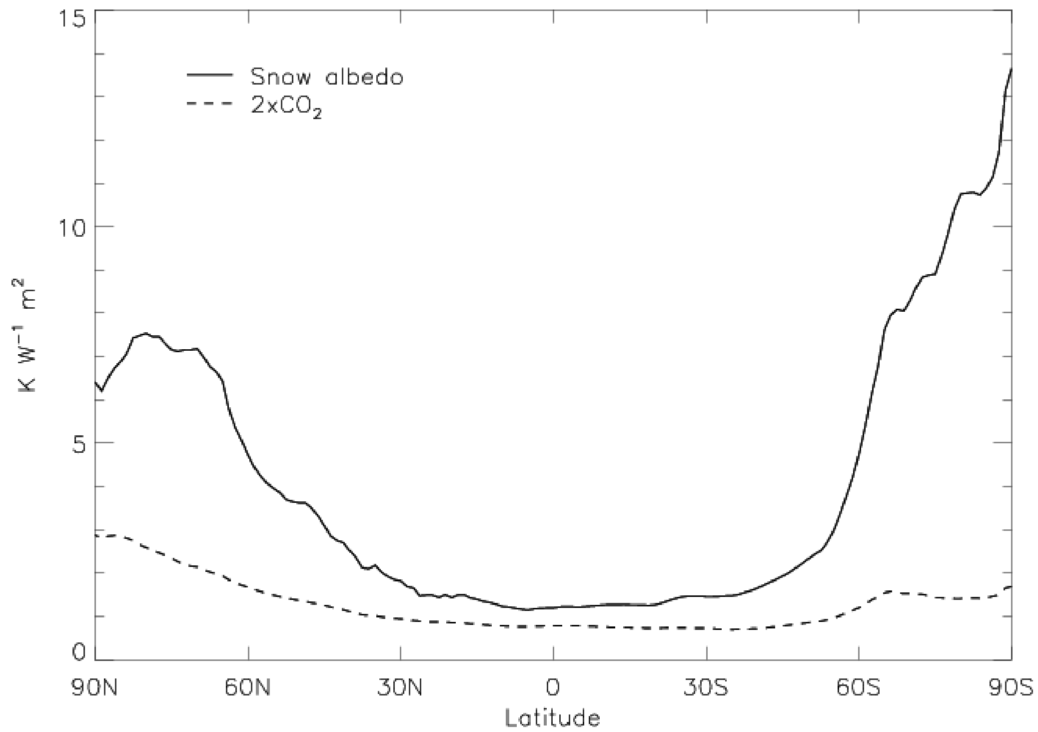
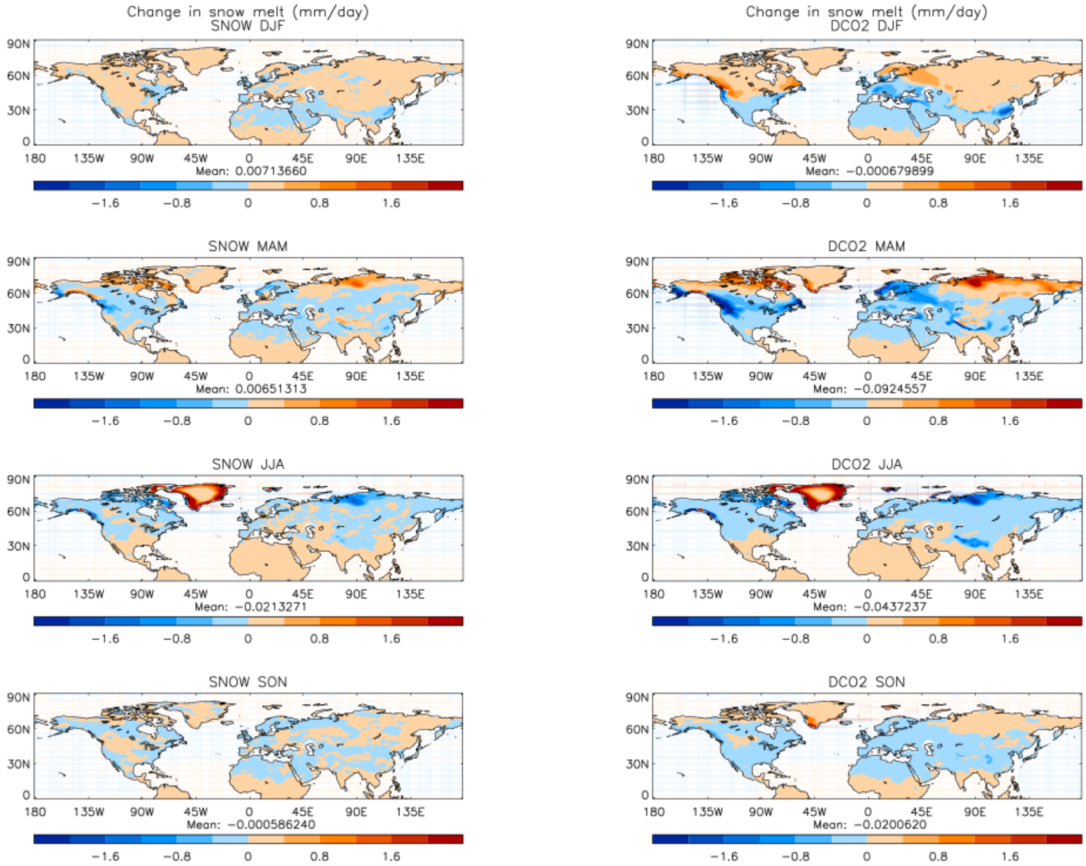


Figure 2. Seasonal change in snow melt rate (mm/day) for a 0.05 absolute decrease in land snow albedo (left) and doubling of CO_2 concentration (right).



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