CRAICC Deliverable 6: Quantification of the current direct radiative and indirect forcing of SLCFs in the Arctic

1. Background and objective

Climate change is proceeding fastest at the high latitudes of the Arctic, with its near-surface warming being about twice the global average during the recent decades. Simultaneously with warming, the Arctic cryosphere has experienced notable changes: the Arctic sea-ice area has been decreasing in all seasons, and precipitation and river discharges into the Arctic Ocean have been increasing. These changes have dramatic impacts on the ecology and societies of the Arctic, underlining the urgent need for a better understanding of the processes leading to climate change.

There is still no consensus on the reasons why climate changes so fast in the Arctic, and whether the amplified Arctic warming will continue in the future. It is clear, however, that the Arctic surface radiation balance regulates the melting and freezing of the pack ice, which in turn is a key climate regulator. Model simulations of Arctic clouds are particularly deficient, impeding correctly simulated radiative fluxes, vital for the snow/ice-albedo feedback. Important, yet poorly-quantified players in this context are short-lived climate forcers (SLCF), including natural and anthropogenic aerosols, ozone and methane.

In this deliverable report we outline the recent advances taken by the researchers in CRAICC to accurately quantify the current effects of SLCFs on the Arctic radiative balance. The reader is directed elsewhere for comprehensive reviews on the international efforts in the Arctic (see e.g. AMAP reports at www.amap.no) and the climate effects of Black Carbon (BC) aerosols (Bond et al., 2013).

2. Direct radiative forcing

Myhre et al. (2013) present a comprehensive overview summarizing results on direct aerosol effect in the industrial period based on simulations with 16 different global aerosol models within the AeroCom initiative. The models include those run within CRAICC. All the models simulated anthropogenic sulfate, BC, OA from fossil fuel, biofuel and biomass burning. Some models also simulated the effects of nitrate and anthropogenically-influenced SOA. The reported mean global all-sky radiative forcing of direct aerosol effect for present vs. pre-industrial times (2000 or 2006 vs. 1850, depending on the model simulations) was -0.27 W m^{-2}, and for the period of 1750 to 2010 with updated aerosol emissions -0.35 W m^{-2}.

For latitudes > 70 ºN, all-sky direct radiative forcing values in Myhre et al. (2013) range from about -0.3 to about 1.2 W m^{-2}, and clear-sky direct radiative forcing values from about -0.4 to about 1.3 W m^{-2}. All models turn over into a positive net radiative forcing at high northern latitudes, due to higher surface and cloud albedo in the Arctic.

Myhre et al. (2013) investigated the direct aerosol effect separately for the different aerosol components. Here we will summarize the findings for the Arctic (here defined as latitudes > 70 ºN), as obtained from the figures presented by Myhre et al. (2013). According to these results, sulphate causes a small negative forcing: about -0.5 to about 0.1 W m^{-2}, with a model mean about -0.1 W m^{-2} at the > 70 ºN latitudes. Black Carbon, on the other hand, causes a positive forcing from <0.02 to about 0.7 W m^{-2} (model mean around 0.3 W m^{-2}) at the high latitudes – but there is about an order of magnitude difference between models with the largest and smallest prediction, probably due to different absorptive properties of BC. BC is particularly important for the Arctic, it's effect increases with latitude (see Sect. 4 for a brief focused discussion on BC effects in the Arctic radiative balance).

The models used in Myhre et al. (2013) show a relatively weak sensitivity of direct radiative forcing to organic aerosols (OA) from fossil fuels in the Arctic, with values ranging from -0.01 to 0.04 W m^{-2} (model mean about 0 W m^{-2}). This result can be easily understood due to the low hygroscopicity of the OA components, along with their low burdens in the Arctic. Secondary organic aerosol has is not predicted to be a very important component for the direct forcing either: its radiative forcing is predicted to range from -0.06 to 0.02 W m^{-2} (model mean about 0.1 W m^{-2}). The models that simulated nitrate estimate its contribution to the direct effect to be between -0.05 and 0.15 W m^{-2}, with a model mean of about 0 W m^{-2}.

Besides the anthropogenic aerosols discussed above, sea salt aerosol emissions represent the most important natural aerosol component in the Arctic. Struthers et al. (2011, 2013) investigated specifically the feedback between sea salt aerosol emissions, sea ice, and the Arctic climate. They find that sea salt aerosol emissions are likely to be strongly linked to the sea ice loss, with a feedback through their impcats on climate. They investigated the radiative impacts of changes in sea salt aerosol emissions induced by prescribed changes in sea ice extent for present day conditions vs. year 2100, and found that the natural component of direct forcing over the Arctic polar cap for this period is probably between between -0.2 and -0.4 W m^{-2}.

3. Indirect radiatinve forcing

Alterskjær et al. (2010) conducted simulations CAM-Oslo, one of the main atmospheric models utilized within CRAICC, to investigate the radiative effects of aerosol-cloud interactions in the Arctic climate. They considered the effect of sulfate, organic, and BC aerosols increased from pre-industrial to present day (year 2000) conditions, and considered the impact of these emission increases on the liquid phase clouds. They found that the long-wave component of the indirect aerosol effect between preindustrial times and the year 2000 was 0.1-0.85 W m^{-2} (annual average north of 71ºN), with an average of 0.55 W m^{-2}, while the short-wave indirect effect could explain -1.29-0.12 W m^{-2} (annual average north of 71ºN), with an average of -0.85 W m^{-2}. Due to the long-wave dominance in winter time there was an on average positive change (-0.16-0.29 W m^{-2}) in the net (including both long-wave and short-wave effects) cloud forcing between October and May, while the corresponding change for the summer months was negative (from -2.63 to -0.23 W m^{-2}, depending on the model setup). The annual average change in the net cloud forcing was found to be -0.98-0.12 W m^{-2}, with a model average of -0.3 W m^{-2}.

The values reported by Alterskjær et al. (2010) are somewhat lower than the corresponding values from experimental studies: for instance Lubin and Vogelmann, (2006) suggest that the longwave component of the first indirect effect could be as high as 3.4 W m^{-2}. Based on 6-year data set of observations on the cloud transmissin and its link to CN concentrations, the same authors (Lubin and Vogelmann, 2010) estimate first indirect effect in the high Arctic to yield a transition from surface warming of 3 W m^{-2} during March to a cooling of –11 W m^{-2} during May – thus indicating a strong seasonal dependence like Alterskjær et al. (2010) found. Sporre et al. (2012) present further experimental evidence on the impact of aerosols on the cloud properties. Their study reports a connection between cloud optical thickness, depth and droplet number concentrations with aerosol loadings.

The reasons for the quantitative discrepancies between the model simulations and the experimental data have not been fully resolved, but the explanation could be related to the fact that the observational data being representative of a specific place and time, while the model simulations are large-scale averages over the Artic and several years.

4. Radiative forcing of Black Carbon (BC) emissions

Since black carbon aerosols are one of the major SLCFs of interest at the moment, there has been significant effort within CRAICC to nail down its impacts on the Arctic climate. Here we will summarize these efforts.

As outlined above, Myhre et al. (2013) report that BC causes a positive direct forcing from <0.02 to about 0.7 W m^{-2} (model mean around 0.3 W m^{-2}) at the latitudes > 70 ºN. In their recent paper also Sand et al. (2013) investigated the effect of BC emissions from Artic or mid-latitudes on Arctic surface temperature with fully coupled Nor-ESM, including a snow model SNICAR to include the effect of BC deposition on snow. Direct, as well as the first and second indirect effects were simulated, although the indirect effects include only those associated with liquid phase clouds. The BC emissions used by Sand et al. (2013) were obtained from the project ECLIPSE, other emissions through IPCC for year 2008. In this study, Arctic was defined as everything north of 60ºN. Sand et al. (2013) conducted six different model simulations: a control run (CTRL), ARCem – where BC emissions were scaled up north of 60 ºN, MIDem – where BC emissions were scaled up in the mid-latitudes, and runs that were otherwise the same as the previous two runs but without the effect of BC deposition on snow and ice. To investigate the effects of BC emissions within the Arctic additional dimulation termed gridARC was also conducted – in which all gridcells in the Arctic had the same emissions.

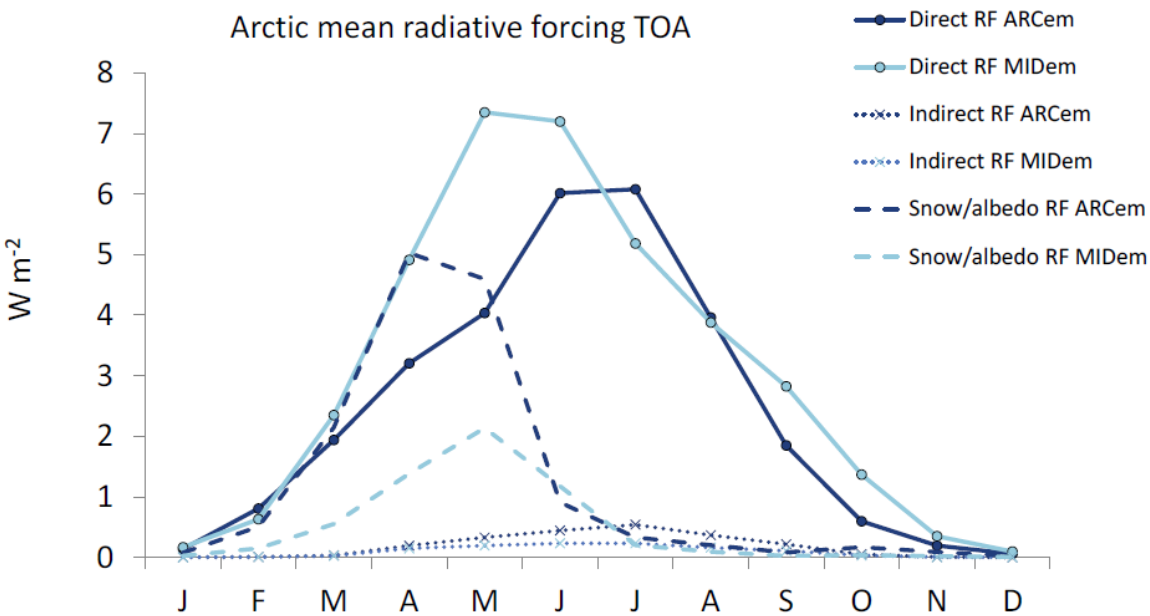

Figure 1. Arctic monthly mean (60-90°N) direct, indirect and snow/albedo (from BC on snow 526 on land) top-of-the-atmosphere radiative forcing for ARCem-CTRL and MIDem-CTRL. Units in W m^{-2}. Adopted from Sand et al. (2013). The scaling factors for the perturbation runs have been chosen to yield statistical significance without sacrificing the linearity of the sensitivity of the results (see Sand et al., 2013 for details).

Sand et al. (2013) found that the Arctic radiative forcing is particularly sensitive to BC during winter, and that BC emissions within the Arctic have 5 times larger effect on the surface temperature per unit emitted mass than those emitted at the mid-latitudes. Direct forcing was found to dominate the BC effects, with deposition on snow and ice as major contributors, particularly during the winter time (see Fig. 1). Direct effect of shortwave radiation due to increased BC absoroption is the main driver of the positive radiative forcing, and for Arctic emissions particularly, also the increases also snow/albedo effect were found to be important (see Fig. 2). The normalized BC radiative forcing according to Sand et al. (2013) was 0.38 W m^{-2} (Tg yr^{-1})$^{-1}$ for emissions within the Arctic, and 0.17 W m^{-2} (Tg yr^{-1})$^{-1}$ for emissions at the mid-latitudes.

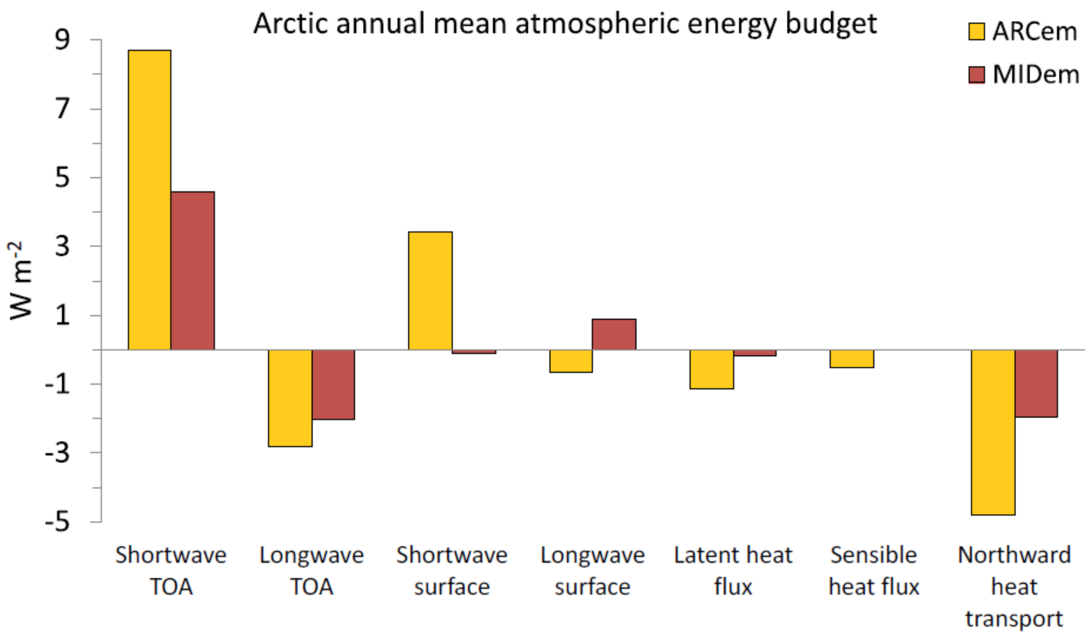

Figure 2. Change in Arctic annual mean (60-90ºN) atmospheric energy nudget for ARCem-CTRL (yellow) and MIDem-CTRL (red). The northward heat transport is calculated as a residual of the top-of-the-atmosphere and surface enery budget. All top-of-the-atmosphere (surface energy budget terms are defined positive when the atmosphere (surface) gains energy. Units in W m^{-2}. Adopted from Sand et al. (2013).

Laaksonen et al. (2013) did a study specific to Finnish emissions using ECHAM5-HAM global aerosol climate model. They investigated the impacts of BC emissions from Finland on the Arctic climate, using AeroCom (see Myhre et al., 2013) emissions updated with estimates from SYKE and IIASA.The effect of BC on snow albedo was not accounted for. They found that the effect of removing Finnish BC emissions on the Arctic climate was relatively small, with some local effects predicted, of the order of in maximum ±0.2 W m^{-2}. However, along the lines of Sand et al. (2013), Laaksonen et al. (2013) recommended BC emission reductions in Finland, particularly in the winter time.

References

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