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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies" *by* P. K. Quinn et al.

P. K. Quinn et al.

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Response to Referee #1

Note that the comments of the Referee are in brackets followed by our responses.

[Quinn et al. present a summary of short-lived climatically important pollutants in the Arctic and their seasonally averaged forcing values. These forcing values are based on earlier published simulations made with several different models. However, as far as I understand, the seasonally averaged data presented in Table 1/Figure 2 of this manuscript have not been published before.

The manuscript addresses an important current topic (near-term opportunities to slow down the Arctic warming), is written clearly and uses scientifically sound methodology. However, it presents fairly little new unpublished data/calculations, and does not dis-

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cuss the uncertainties related to the forcing/temperature response estimates or compare the estimates with results from other published model studies. I am therefore not quite sure whether the authors have intended this work to be a summary of what is known of the short-lived Arctic pollutants (as the abstract suggests; however, the manuscript does not review the existing literature very thoroughly), or a report of new scientific results (despite the missing uncertainty estimates etc., or the fact that the abstract does not mention any of the calculated values).]

Based on comments made by the referee and editor, we think we may not have stated the goals of the paper clearly enough. The goal is not to provide a comprehensive review or definitive answers concerning forcing and response estimates. Rather, the goals are to focus attention on the impact and mitigation of climate impacts of short-lived pollutants in the Arctic, provide a first attempt at quantifying seasonally averaged forcing and response estimates specific to the Arctic, and provide potential mitigation strategies based on current knowledge. To clarify the intent of the paper, we have added the following text to the introduction:

The large uncertainties associated with parameterizing the forcing and temperature response due to these pollutants prevent us from providing definitive answers regarding impacts and mitigation strategies. We can, however, focus attention on the issues involved, provide a state of the art; review, and make initial estimates of the forcing and response due to each pollutant. The forcing agents included in this discussion are methane, tropospheric ozone, and tropospheric aerosols. In this article we describe the mechanisms by which these short-lived pollutants impact Arctic climate (Figure 1) and present the first seasonally averaged forcing and temperature response estimates for the Arctic. In addition, we outline near-term climate mitigation opportunities for the Arctic and suggest areas of future research.

Finally, we have added a sentence to the abstract summarizing the results of the forcing/response analysis. We hesitate to make the discussion in the abstract quantitative because of the uncertainties in the calculations. Instead, the goal is to identify those

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pollutants that should be targeted for mitigation strategies to be most effective. The text added to the abstract reads as follows:

The calculations indicate that the forcings due to black carbon, methane, and tropospheric ozone lead to a positive surface temperature response indicating the need to reduce emissions of these species within and outside the Arctic. Additional aerosol species may also lead to surface warming if the aerosol is coincident with thin, low lying clouds.

[I therefore recommend this work to be published in ACP only if the authors provide a much more detailed discussion of the following points:

- uncertainties related to their estimates due to the models used (e.g. Koch and Hansen (2005) underpredict the BC concentrations in the Arctic)]

We have added a new section (Section 3.3) that describes uncertainties in the models used for the forcing calculations. In this section, we summarize relevant results from the AeroCom initiative of which the NASA GISS model was a part, the comparison reported by Koch et al. (2007) between measured and modeled BC concentrations in the Arctic, and the discussion presented in Flanner et al. (2007) concerning uncertainties associated with the SNICAR-CAM3 estimates of the BC-snow forcing. In addition, we report the climate sensitivity of the GISS and NCAR models used here and compare those to the range in current state-of-the-art GCMs. The text in this section is as follows:

3.3 Model Performance and Uncertainties

As these are the first Arctic estimates of seasonally averaged forcing for the short-lived pollutants, it is difficult to assess model performance by comparing to values calculated using other models. It is possible, however, to compare geographical distributions of aerosol species and forcing estimates averaged over annual and global scales. The NASA GISS model used in the calculation of the aerosol direct and indirect forcings was

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thoroughly compared to other global aerosol models as part of the AeroCom initiative. A comparison of black carbon mass in the polar regions that included sixteen models found that two models had greater than 7% of their BC mass in the Arctic, 5 had 6 to 7% of their BC in the Arctic, and nine had less than 6% of their BC in the Arctic (Textor et al., 2006). Falling within this range of variability, the GISS model had 7% of the BC in the Arctic. Hence, the GISS model was at the higher end of the range but was not an outlier.

Also as part of the AeroCom initiative, Schulz et al. (2006) compared annually averaged total direct aerosol forcing from nine global aerosol models. The GISS model and one other (UIO_GCM) had the most positive values of aerosol direct forcing within the Arctic (0.02 to 0.05 W m-2 vs. 0.0 to 0.2 W m-2) due to a larger load of BC transported to the region. However, a comparison of modeled BC concentrations from the GISS model to those measured at Spitsbergen and two Alaskan sites did not reveal systematically high biases within the GISS model (Koch et al., 2007). The ratio of modeled to observed concentrations was found to be between 0.5 and 0.67 at Spitsbergen (i.e., model values were lower than observed) and between 0.67 to 1.5 at the two sites in Alaska.

Uncertainties in model calculations of the BC-snow forcing arise from emissions, effects of snow aging and meltwater scavenging, black carbon optical properties, and snow cover fraction with the contribution to uncertainty following the order listed. Based on uncertainties in these five factors, the potential range in black carbon-snow forcing is -87% to +240% relative to the central estimates given here. This large range is indicative of the current state of understanding of this forcing mechanism. On a global, annually averaged basis, the model used in this study produced a forcing estimate for fossil fuel and bio-fuel black carbon of +0.04 W m-2 which is slightly smaller than those reported by Hansen et al. (2005) (+0.05 W m-2) and Jacobson (2004) (+0.06 W m-2).

Global, annual average radiative forcing due to tropospheric ozone increases from the preindustrial to the present have been calculated in a number of models, though ob-

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servational evidence to constrain these calculations is minimal. The time-evolving tropospheric ozone used in the GISS climate simulations discussed here was taken from Shindell et al. (2003). The adjusted global annual average radiative forcing due to preindustrial to present-day tropospheric ozone change in that study, 0.30 to0.33 W m-2 depending on emissions, is near the center of the 0.25 to 0.45 W m-2 range (with a mean of 0.34 W m-2 and a standard deviation of 0.07 W m-2) seen in the most recent IPCC assessment (IPCC, 2007). Additional uncertainties in the forcing due to tropospheric ozone come from lack of knowledge about preindustrial emissions of ozone precursors. Uncertainty in the global mean annual average radiative forcing due to methane increases from the preindustrial to the present is very small, at only 10% of the total forcing of 0.48 W m-2 (IPCC, 2007).

The sensitivity of the Arctic to either local or remote forcing has not been quantified across a number of models. Therefore, it is not possible to compare the responses reported here with other studies. It is possible to consider climate sensitivities, however, where the climate sensitivity is defined as the change in equilibrium global surface-air temperature due to a doubling of carbon dioxide. Climate sensitivity of the GISS and NCAR models used here are both 2.7°C which is in the middle of the range seen in current state-of-the-art global climate models (2 to 4.5°C) (Kiehl et al., 2006; Kiehl, 2007).

Finally, in Section 6, we acknowledge these uncertainties and differences in model output and state that they are a motivating factor for future work aimed at improving our understanding of the impact of short-lived pollutants in the Arctic. We have added the following statement:

This lack of understanding is evident in the large range of potential forcing values calculated by single and multiple models as discussed in Section 3. This paper presents the first seasonally averaged forcing and temperature response estimates focused solely on the Arctic for a broad range of chemical species. Being a first attempt, there is much work left to be done to more accurately quantify the impacts of each pollutant and to

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identify the most effective mitigation strategies.

[- a comparison of their forcing/response estimates with other estimates available in the literature]

This comment is related to the previous one. Please see the above response concerning the comparison of forcing estimates based on the models used in this paper to estimates from other models.

[- how comparable are the forcing/response estimates for different pollutants as they are not from the same model]

The atmospheric forcing and response estimates for tropospheric aerosols, ozone, and methane are all from the GISS model. The only exception for the atmospheric forcings is the longwave emissivity that results from the interaction of aerosols and low lying, thin clouds during the Arctic winter. Because of the small spatial scale of the clouds involved, this mechanism can not accurately be modeled by GCMs. The BC-snow forcing and response is from the coupled SNICAR-CAM3 model. As stated above, we now provide several comparisons of these forcings from different models so that the reader can assess the robustness of the model calculations.

[- based on the results in this manuscript and earlier studies as well as the technology available, which ones of the listed mitigation opportunities (which could be more specific especially for methane and ozone) have the greatest realistic potential to slow down the Arctic warming]

We have added more discussion on the mitigation opportunities and their potential effect on Arctic climate in Section 5. The following text was added:

Methane. Reducing methane emissions will require targeting major controllable anthropogenic sources. Because of the relatively long lifetime of methane, reductions that benefit the Arctic can occur globally. The U.S. EPA has examined major methane sources and identified the following areas where considerable mitigation potential ex-

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ists. These include worldwide coal mine desgasification and mine ventilation air capture, identification and repair of natural gas leaks, and better handling of municipal solid wastes including using landfill methane as a source of energy. On a global basis, coal mine methane accounts for 8% of total methane emissions due to anthropogenic activities (U.S. EPA, 2006). Methane is removed from active mines with large ventilation systems and from both active and abandoned mines with degasification or gas drainage systems. Coal mine methane can be captured and used for power production, heating, and in manufacturing and industrial applications.

Ozone and black carbon: targeting source regions. Ozone and black carbon are not globally well mixed due to their relatively short lifetimes. Hence, specific source regions must be targeted to lessen their impacts in the Arctic. On timescales of days to weeks, northern Eurasia is the strongest source region for Arctic air pollution, especially in the lower troposphere (Barrie, 1986; Klonecki et al., 2003; Stohl, 2006). Therefore, to decrease concentrations of ozone precursors and black carbon in the lower atmosphere, emissions in this region should be reduced. The source regions of short-lived pollutants in the upper Arctic atmosphere include northern Eurasia and also areas in North America and Asia (Klonecki et al., 2003; Koch and Hansen, 2005; Stohl, 2006). Therefore, a substantial reduction of ozone and BC in the upper troposphere will require more widespread emission reductions throughout the northern hemisphere. The correspondence between surface temperature response in the Arctic and global and Northern Hemisphere extratropical forcings due to ozone emphasizes the need to reduce ozone on a northern hemisphere and global basis to reduce climate response in the Arctic. Finally, emissions of ozone precursors and BC within the Arctic should be kept at a minimum as these will have a disproportionately large impact on within-Arctic concentrations.

Ozone and black carbon: targeting sources. Reducing methane emissions as outlined above will decrease ozone production. Reductions in NOx also will contribute but, at the same time, will decrease OH which is the major sink for methane. Hence, an ozone

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reduction strategy using NOx controls that benefits climate will also include methane, NMVOCs, and/or carbon monoxide reductions. Carbon monoxide forms when carbon in fuel does not burn completely. The main source of carbon monoxide is gasoline-powered vehicles. Abatement options include catalysts, routine inspection and maintenance, and addition of oxygen-containing compounds to gasoline (U.S. EPA, 1993). The majority of anthropogenic NMVOCs released into the atmosphere are from transportation sources and industrial processes utilizing solvents such as surface coating (paints), printing (inks), and petrochemical processing. The choice of NMVOC control measure is compound specific. Options include installation of control devices such as an incinerator, a solvent recovery system, limits on the amount of solvent used in products, and product stabilization (U.S. EPA, 1999). In addition to targeting transportation and industrial sources, reducing or eliminating agricultural fires in eastern Europe and northern Asia would effectively reduce CO, NMVOC, and ozone concentrations in the Arctic.

Reducing black carbon concentrations will require targeting sources that emit aerosols with a high absorptivity and relatively low reflectance (e.g., diesel combustion and residential stoves). Reducing within-Arctic emissions of black carbon (e.g., generators) and implementing emission controls on marine vessels operating within Arctic waters (particularly in light of the likely increase in shipping activity as the snow/ice pack decreases) will also be required. Additional strategies include reducing prescribed agricultural burns in eastern Europe so that black carbon emission and deposition does not occur in spring as radiation is increasing and the area of snow/ice pack is large. Reducing ozone and black carbon emissions has the added benefit of improving air quality and decreasing associated health hazards.

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