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# *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 the Editor

Note that the comments made by the Editor are in brackets followed by our responses.

[This is a useful review of short term effects on Arctic climate. However, it would be much more useful to the community if some improvements could be made.]

We thank the editor for appreciating the worth of the paper. 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.

[Firstly, the review section of the paper, although well written, requires substantially more references. Many statements are made with no literature support. I would estimate that at least 30 more references are required in this section.]

We thank the editor for this suggestion. We have substantiated statements made in the introduction with the addition of 30+ references.

In Section 2.2, we have added more information about the impact of boreal fires on Arctic ozone concentrations. The additional text is as follows:

Fires emit large quantities of CO and non-methane volatile organic carbon (NMVOC) compounds which may combine with anthropogenic emissions in the same region to produce large amounts of ozone. Generoso et al. (2007) showed that CO emissions from boreal fires in the spring and summer of 2003 made a substantial impact on concentrations in the Arctic. Agricultural fires may be particularly important sources to the Arctic, especially in eastern Europe and northern Asia as these are regions with very high fire frequency (Korontzi et al., 2006).



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In Section 2.3 we have added more information about the impact of boreal forest fires on tropospheric BC. The added text reads as follows:

In years of intense burning, boreal forest fires can be an important source of BC throughout the Arctic. Stohl et al. (2006) found Pan-Arctic enhancements of aerosol light absorption during the summer of 2004, a year with strong burning in Canada and Alaska, and a coincident decrease in snow albedo at Summit, Greenland. Measurements of BC in snow at Summit confirm the deposition of BC to the snow surface. The summer of 2004 stands out as having the highest BC concentrations in snow in recent years (Hagler et al., 2007) yet the range of concentrations (1.0 to 1.4 ng g-1) was far too low to significantly affect snow albedo if the BC were uniformly distributed in the upper snow layers (Warren and Wiscombe, 1985, Figure 2). A thin layer of BC on the top surface might reduce albedo until it is covered with new snow. However, even if the snow albedo at Summit is usually unaffected by BC, this does not rule out a significant effect at lower-elevation locations in the Arctic, where average BC concentrations are usually much larger. Boreal forest fires in Siberia may have a larger impact than those in North America because of the larger burn area (Stohl, 2006). The fires occurring in Siberia in 2003 have been estimated to account for 16 to 33% of the observed aerosol optical thickness and 40 to 56% of the mass of BC deposited north of 75°N in spring and summer (Generoso et al., 2007).

[Secondly, please briefly describe the issues associated with calculating surface temperature response from forcings. What are the uncertainties here?]

We are not exactly sure what the intent of this question is. We did not directly calculate responses from the forcings (e.g., by applying an efficacy factor). Instead, the climate responses were calculated as part of the GCM experiments. Hence, there is no issue of uncertainty from the process of estimating responses from forcings. However, there is uncertainty in the GCM approach in knowing what the climate sensitivity is of a particular forcing. As a result, uncertainty comes from different climate models giving different sensitivities. We feel that a discussion of the uncertainties in modeling



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climate change when there are forcings is beyond the scope of this paper. We certainly agree with the editor and the referee, however, that we should place the calculations presented here in a larger context. Therefore, we have addressed this comment (and several others made by both the editor and the referee) by adding comparisons of the forcings and climate sensitivites from the models used in this analysis to those from other models. Please see the newly added Section 3.3 for the complete discussion.

[Thirdly, Section 5 should include an estimate of the change in surface warming that can be achieved by the various mitigation strategies.]

The inclusion of estimates of changes in surface warming that could be achieved by the suggested mitigation strategies is beyond the scope of this paper. Proper estimates will require modeling studies that consider simultaneous reduction of all species from a given source. We have added a description of this next step in modeling to Section 6 where Directions for Future Research are presented. The added text reads as follows:

Mitigation. Modeling studies are required to determine the effectiveness of individual mitigation strategies on Arctic climate and, in particular, the surface temperature response. The choice of mitigation strategies is complicated as each pollutant source includes multiple chemical species (e.g., forest fires emit black carbon, organic carbon, and ozone). Accurate estimates of the climate impacts due to a specific mitigation strategy must take into account the simultaneous reduction of all species from a given source.

[Also, some comment should be made, backed up by references, about what we already know about source regions. Reductions in, say, EC emissions in some regions will presumably have very little effect on Arctic climate.]

We have added information to Section 5 about source regions for ozone and black carbon that impact both the lower and upper troposphere in the Arctic. The additional text reads as follows:



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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.

[Fourthly, Section 6 is too brief. For example, for EC, clearly we need to understand sources, transport and sinks, but what are the major challenges here? Why have previous studies not quantified these terms? What is the relative importance of uncertainties in sources and sinks? Similar questions arise for the other forcing agents.]

We have expanded the discussion in Section 6. It now includes more information about the major challenges in assessing the impact of BC on Arctic climate and provides strategies for overcoming those challenges. In addition, we have expanded the sections on surface warming due to non-BC aerosol species and feedbacks and climate responses. Finally, we have added a section on modeling mitigation strategies. The text of Section 6 now reads as follows:

Many of the impacts of short-lived pollutants on Arctic climate are not well understood



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or quantified. 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 identify the most effective mitigation strategies. Specific scientific issues and areas of uncertainty in need of future research are discussed below.

Methane. Wetland and permafrost methane emissions within the Arctic and sub-Arctic that result from rising surface temperatures are highly uncertain. Quantifying these emissions and how they might be expected to change in the coming years in response to rising temperatures is critical to understanding the impact of methane on Arctic climate.

Ozone. The effectiveness of controlling near-Arctic or within-Arctic NOx emissions to reduce tropospheric ozone within the Arctic is unknown. Local NOx emissions are likely to become significant if Arctic shipping activity increases as predicted. Research is needed to improve our understanding of reactive nitrogen chemistry and the oxidation capacity of the Arctic atmosphere.

Black carbon. Our understanding of deposition of black carbon-containing aerosol and trends in atmospheric concentrations of black carbon is constrained by limited measurements. Questions concerning responsible source regions, transport, and atmospheric processing of the aerosol persist. Simultaneous pan-Arctic measurements of atmospheric and deposited BC combined with modeling studies are needed to identify sources, particularly those that impact the timing and rate of snow/ice melt, and to gain a better understanding of transport pathways and deposition processes. Recent measurements of BC and tracer species in a Greenland ice core demonstrated the power of this method for identifying source regions of BC at one site in the Arctic over the last 200 years (McConnell et al., 2007). Similar measurements at other Arctic sites would help to identify differences in source regions of BC across the Arctic. This infor-



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mation can be used to assess the emission inventories used in global aerosol models. A comparison of 16 global aerosol models revealed that harmonizing aerosol sources has only a small impact on differences in calculated global aerosol burdens (Textor et al., 2007). Rather, the amount of BC estimated to be in the Arctic is dependent on model-specific treatment of vertical mixing, meridional transport, and aerosol removal (Textor et al., 2006; 2007). Measurements of atmospheric BC (or aerosol light absorption) are required across the Arctic and in the vertical to assess modeled transport and aerosol removal processes. Satellite observations of aerosol vertical and horizontal distributions also will help in model validation.

Other tropospheric aerosols: surface warming. The enhancement of longwave emissivity from thin liquid-phase Arctic clouds due to interactions with anthropogenic aerosols may lead to significant surface temperature increases. These increases occur in phase with sea ice melt, potentially leading to a resonant amplification. As for black carbon, combined measurement and modeling studies are required to determine the source regions, chemical composition, and climate impact of different aerosol types. Measurements at sites with radiation instrumentation are particularly key so that information about aerosol and cloud properties, the impact of aerosols on cloud properties, and the resulting impacts on the radiation budget can be assessed. In addition, further research is required to evaluate the role of aerosols in ice formation in low level mixed-phase clouds.

Other tropospheric aerosols: surface cooling. Reflective aerosols in atmospheric layers prevent incoming solar radiation from reaching the ground and yield a cooling at the surface. Hence, reductions in aerosol concentrations within the Arctic and in distant source regions may contribute to Arctic warming (Shindell, 2007). Assessing the overall impact of tropospheric aerosols in the Arctic (direct and indirect effects) is required to determine how reductions in aerosol concentrations will affect Arctic climate.

Feedbacks and Climate Responses. The feedback mechanisms that come into play due to the combination of forcings from all pollutants and the complexity of the Arc-



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tic environment are highly uncertain. Models are the only tool available to assess the climate response of individual and combined forcings and feedback mechanisms. In addition, models are required for predictions of climate impacts of the short-lived pollutants over the coming decades. The measurements described above will serve to constrain models thereby improving our predictive capability and our understanding of climate sensitivites to forcings. Modeling efforts required for a better understanding of feedbacks and climate responses include improved parameterizations of snow albedo and interactions between aerosol and mixed-phase clouds, studies that allow for the discrimination between forcings and feedbacks within the climate system, and multi-model comparisons aimed directly at emissions, transport, and atmospheric processes that impact the Arctic.

Mitigation. Modeling studies are required to determine the effectiveness of individual mitigation strategies on Arctic climate and, in particular, the surface temperature response. The choice of mitigation strategies is complicated as each pollutant source includes multiple chemical species (e.g., forest fires emit black carbon, organic carbon, and ozone). Accurate estimates of the climate impacts due to a specific mitigation strategy must take into account the simultaneous reduction of all species from give source.

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Interactive Comment