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The climate impact of
short-lived pollutants
in the Arctic

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Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies

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Abstract

Several short-lived pollutants known to impact Arctic climate may be contributing to the accelerated rates of warming observed in this region relative to the global annually averaged temperature increase. Here, we present a summary of the short-lived pollutants that impact Arctic climate including methane, tropospheric ozone, and tropospheric aerosols. For each pollutant, we provide a description of the major sources, the mechanism of forcing, seasonally averaged forcing values for the Arctic, and the corresponding surface temperature response. We suggest strategies for reducing the warming based on current knowledge and discuss directions for future research to address remaining uncertainties.

1 Introduction

Arctic temperatures have increased at almost twice the global average rate over the past 100 years (IPCC, 2007). Warming in the Arctic has been accompanied by an earlier onset of spring melt, a lengthening of the melt season, and changes in the mass balance of the Greenland ice sheet (Stroeve et al., 2006; Zwally et al., 2002). In addition, Arctic sea ice extent has decreased from 1979 to 2006 in every month (Serreze et al., 2007). During the 2007 melt season, Arctic sea ice dropped to the lowest levels observed since satellite measurements began in 1979 resulting in the first recorded complete opening of the Northwest Passage (NSIDC, 2007). Impacts of ice loss include reduction of the Earth's albedo, a positive feedback which leads to further warming. The earlier onset of spring melt is of particular concern as this is the season of maximum snow-albedo feedback (e.g., Hall and Qu, 2006). Timescales for a collapse of the Greenland ice sheet and a transition to a seasonally ice-free Arctic are highly uncertain as are the regional and global impacts. However, clear ecological signals of significant and rapid response to these changes within the Arctic are already present. For example, paleolimnological data from across the Arctic have recorded striking changes

in diatoms and other bioindicators corresponding to conditions of decreased ice cover and warming (Smol et al. 2005). Circumpolar vegetation also is showing signs of rapid change including an expansion of shrub and tree coverage (Chapin et al., 2005).

Arctic warming is primarily a manifestation of global warming such that reducing global-average warming will reduce Arctic warming and the rate of melting. Reductions in the atmospheric burden of CO_2 are the backbone of any meaningful effort to mitigate climate forcing. But, even if swift and deep reductions were made, given the long lifetime of CO_2 in the atmosphere, the reductions may not be achieved in time to delay a rapid melting of the Arctic. Hence, the goal of constraining the length of the melt season and, in particular, delaying the onset of spring melt, may best be achieved by targeting shorter-lived climate forcing agents, especially those that impose a surface forcing that may trigger regional scale climate feedbacks pertaining to sea ice melting. Addressing these species has the advantage that emission reductions will be felt immediately. The forcing agents included in this discussion are methane, tropospheric ozone, and tropospheric aerosols. The goals of this article are to describe the mechanisms by which these short-lived pollutants impact Arctic climate (Fig. 1), summarize the seasonally averaged forcing and surface temperature response due to each pollutant (Table 1 and Fig. 2), outline near-term climate mitigation opportunities for the Arctic, and suggest areas of future research.

2 Short-lived pollutants that impact Arctic climate

2.1 Methane

Since the industrial revolution, rapid increases in human activity have led to more than a doubling of atmospheric methane concentrations (Wuebbles and Hayhoe, 2002). A combination of ice core records and atmospheric measurements has revealed that methane levels, at ~1770 ppbv, are higher now than at any time in the past 650 kyr (Petit et al., 1999; Spahni et al., 2005). Growth rates have slowed over the last few

decades with current observations indicating that methane levels are either leveling off or starting to increase after a brief decline in the early 1990s (Dlugokencky et al., 2003). At the same time, growth rates are becoming more variable. Reasons for the change in growth rates are not well understood beyond the acknowledgement of a change in the balance between sources and sinks (IPCC, 2001).

Anthropogenic sources, which account for about two thirds of emitted methane, include coal and gas production and use, rice cultivation, agriculture and waste disposal, biomass burning, landfills, and animals in the form of solid waste and enteric fermentation. The largest single source of methane is natural wetlands (IPCC, 2001) with those north of 60° N responsible for about 13% of the global natural methane flux (Cao et al., 1998). Measurements in the sub-Arctic and Arctic over the past decade have indicated that methane emissions from these regions are increasing due to increasing temperatures and the resulting disappearance of permafrost and wetter soil conditions. For example, permafrost and vegetation changes in one region in sub-Arctic Sweden have led to 20 to 70% increases in local methane emissions between 1970 and 2000 (Christensen et al., 2004). In Arctic regions of continuous permafrost, warming has resulted in a degradation of permafrost and an increase in the size and number of thaw lakes. It has been estimated that this increase in lake area has led to a 58% increase in methane emissions (Walter et al., 2006). Further warming in Siberia could result in thousands of teragrams of methane being emitted from the 500 gigatons of labile C that is currently stored in regional permafrost (By comparison, the atmosphere now contains 9000 teragrams of methane.).

With a lifetime of about 10 years, methane is much shorter lived than CO_2 but still is globally well-mixed. Methane has contributed the second largest anthropogenic radiative forcing since the pre-industrial after CO_2 and, on a per molecule basis, is a more effective Greenhouse Gas (GHG) (IPCC, 2001). Radiative forcing by methane results directly from the absorption of longwave radiation and indirectly through chemical reactions that lead to the formation of other radiatively important gases. The latter is dominated by the formation of tropospheric ozone, also a short-lived GHG, through the

oxidation of methane by the hydroxyl radical (OH) in the presence of nitrogen oxides (NO_x).

2.2 Tropospheric ozone

Both observations and modeling studies provide evidence that tropospheric ozone concentrations, which are controlled primarily by photochemical production and loss processes within the troposphere, have increased since pre-industrial times due to increases in emissions of anthropogenic ozone precursors (Oltmans et al., 1998). The rapid increase in ozone concentrations during the latter half of the 20th century has been attributed to increases in economic development at middle and low latitudes (Shindell et al., 2006). Ozone precursors include NO_x, carbon monoxide, methane, and non-methane volatile organic compounds (NMVOC). Anthropogenic sources of these precursor gases include fossil fuel combustion and production, biofuel combustion, industrial processes, and anthropogenic biomass burning. Natural sources include wildfires, biogenic emissions from soils and vegetation, and lightning. In polluted air masses, ozone is formed primarily from rapid photochemical oxidation of NMVOCs in the presence of NO_x. In contrast, methane, being globally well-mixed, contributes to increases in background tropospheric ozone levels (Crutzen, 1973; Fiore et al., 2002; Dentener et al., 2005).

Changes in local tropospheric ozone affect Arctic climate by altering local radiation fluxes, while changes in both local and distant ozone amounts can modulate the transport of heat to the polar region. The lifetime of ozone decreases during the summer in the extratropics since photochemical destruction rates increase with increasing insolation. Hence, ozone that is produced in the northern hemisphere mid-latitudes is most efficiently transported to the Arctic in the non-summer months. Little is known about the contribution of local production of ozone and its precursors within the Arctic relative to extrapolar sources. Local sources include marine vessel emissions. Shipping emissions in the Arctic have the potential to increase Arctic ozone levels by a factor of 2 to 3 relative to present day, bringing them to the same level as in the middle latitudes

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(Granier et al., 2006).

Sub-Arctic and Arctic ozone precursor emissions may be increasing as boreal regions warm and forest fire frequency increases (Kasischke et al., 2005). Record high concentrations of ozone were measured at the Zeppelin research station in Spitsbergen (79° N) in April and May of 2006 (Stohl et al., 2007). This severe air pollution episode was a result of the combination of unusually high temperatures in the European Arctic and large emissions from agricultural fires in Belarus, Ukraine, and Russia. The high temperatures in the Arctic reduced the temperature gradient between the source and receptor regions, making low-level transport of pollution into the Arctic possible. Should the warming of the Arctic continue to proceed more quickly than that of the middle latitudes, transport from highly polluted source regions may become more frequent in the future, resulting in increased tropospheric ozone concentrations and a further increase in surface temperatures.

2.3 Tropospheric aerosols

Tropospheric aerosol concentrations in the Arctic are marked by a large increase each year in late winter and early spring (e.g., Shaw, 1995; Sirois and Barrie, 1999). The combination of intense isentropic transport from the mid-latitudes to the Arctic and strong surface-based temperature inversions that inhibit turbulent transfer (and, therefore, aerosol removal via deposition) results in this recurring phenomenon known as Arctic Haze. In addition, the dryness of the Arctic troposphere results in very little wet deposition during this time of year. The dominant source regions for the haze include northern Europe and Asia with emissions of sulfate aerosol from fossil fuel combustion, nitrate from combustion of diesel and gasoline, and organic carbon and soot (black carbon) from fossil fuel, bio-fuel, and biomass combustion. Long-term, ground-based measurements of sulfate and light scattering by aerosols show that, since the late 1970s, the highest recorded levels of Arctic Haze occurred in the 1980s and early 1990s. Levels then decreased through the end of the 1990s primarily due to reductions in industrial emissions in the early years of the new Eurasian republics and, to a lesser

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extent, to more stringent power plant emission laws in the United States and Europe. More recent measurements indicate that levels of light scattering and black carbon may be increasing once again (e.g., Quinn et al., 2007). From 1980 to the present, nitrate concentrations have increased, suggesting that while power-plant sulfur emissions have decreased in the source regions to the Arctic, emissions from diesel and gasoline engines have increased. The same agricultural fire event reported by Stohl et al. (2007) that resulted in anomalously high ozone also led to record high levels of aerosol optical depth and black carbon, indicating the potential impact of natural and prescribed episodic fires.

Tropospheric aerosols in the Arctic can perturb the radiation balance of the earth-atmosphere system in a number of ways. Direct aerosol forcing occurs through absorption or scattering of solar (shortwave) radiation by aerosols. For example, a scattering aerosol over a low albedo surface will reflect incoming solar radiation, resulting in a cooling of the surface as well as the surface-atmosphere-aerosol column. An absorbing aerosol, such as one containing soot, over a highly reflective surface will result in a warming at altitudes above and within the haze layer and, instantaneously, a reduction of solar energy at the surface. The added atmospheric heating will subsequently increase the downward longwave radiation to the surface, warming the surface. With the highly reflective surfaces typical of the Arctic springtime, even a moderately absorbing aerosol can lead to a heating of the surface-atmosphere-aerosol column. The Airborne Arctic Stratospheric Expedition (AASE) II flights in the winter of 1992 observed soot-containing aerosols at an altitude of 1.5 km. Pueschel and Kinne (1995) calculated that this layer of aerosols could heat the earth-atmosphere system above a surface of high solar albedo (ice/snow) even for single-scattering albedos as high as 0.98.

If hygroscopic pollution particles deliquesce and grow sufficiently large they may also impact the radiation balance in the Arctic by interacting with terrestrial (longwave) radiation. This forcing may be significant during the polar night when longwave radiation dominates the energy budget. Measurements made in the Arctic when the sun was below the horizon suggest that Arctic haze can have a detectable direct thermal radiative

forcing by altering the flux of both downward and outgoing longwave radiation (Ritter et al., 2005).

Soot has an additional forcing mechanism when it is deposited to snow and ice surfaces. Such deposition enhances absorption of solar radiation at the surface which can warm the lower atmosphere and induce snow and ice melting. Surface temperature responses are strongly linked to surface radiative forcings in the Arctic because the stable atmosphere of the region prevents rapid heat exchange with the upper troposphere (Hansen and Nazarenko, 2004). Measurements of BC and other tracer species in central Greenland ice cores have been used to determine the source of BC in snow over the past 215 years (McConnell et al., 2007). Chemical analyses combined with air mass back-trajectory modeling indicate that eastern North American boreal forest fires were the major source of BC in Greenland precipitation prior to industrialization (~1850). Since 1850, the BC deposited to Greenland snow appears to have originated primarily from industrial activities in North American (1850–1950) and Asia (1950–present). It is not known how representative these results are for other regions of the Arctic. In addition, boreal forest fires can be an important source of BC throughout the Arctic in years of frequent and intense burning (Stohl et al., 2006).

Climate forcings also result from aerosol-cloud interactions. The aerosol first indirect effect in the shortwave occurs when pollution particles lead to an increase in cloud droplet number concentration, a decrease in the size of the droplets, and a corresponding increase in shortwave cloud albedo (Twomey, 1977). Measurements made at Barrow, Alaska, over a four year period indicate that episodic Arctic Haze events produce high cloud drop number concentrations and small cloud drop effective radii in low-level cloud microstructures (Garrett et al., 2004). Similar aerosol-cloud interactions can also lead to a significant longwave forcing. When the cloud drop number concentration of thin Arctic liquid-phase clouds is increased through interaction with anthropogenic aerosols, the clouds become more efficient at trapping and re-emitting longwave radiation (Garrett and Zhao, 2006; Lubin and Vogelmann, 2006). Over dark oceans when the sun is high, the shortwave indirect effect is expected to cool the surface but for a low

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sun over bright Arctic surfaces, the longwave effect is expected to dominate. Lubin and Vogelmann (2007) performed radiative transfer simulations to assess the relative magnitudes of shortwave and longwave downwelling fluxes due to Arctic haze aerosols. During March and April, shortwave downwelling fluxes were found to be comparable in magnitude to longwave fluxes. During May and June, however, the shortwave fluxes exceeded those in the longwave.

Aerosol-cloud interactions may also increase cloud cover by increasing cloud droplet number concentrations. The result is a decrease in cloud drop size, a decrease in precipitation, and an increase in cloud lifetime (Albrecht, 1989). Finally, increasing cloud drop number concentrations may be associated with a reduced rate of ice formation in mixed-phase Arctic clouds which reduces cloud desiccation by ice and increases cloud longwave emissivity (Girard et al., 2005). However, ice formation mechanisms in common mixed-phase clouds remain very poorly understood (Fridlind et al., 2007).

2.4 Summary

The magnitude of the forcing by each short-lived pollutant depends on the seasonality of a number of inter-related factors including radiation, precipitation, surface albedo, snow and ice coverage, and pollutant transport. In Table 1 estimates are presented of seasonally averaged forcing and the surface temperature response for the short-lived pollutants. Details of the calculations are given in Sect. 3. Although average estimates of temperature response may not be the most informative measure of the impact of short-lived pollutants, they serve as a starting point and can indicate directions for future research and mitigation strategies.

3 Methods

Radiative forcings and temperature response values for methane, tropospheric ozone, and tropospheric aerosols are combined and presented here so that the impact of

these individual forcing agents can be compared in terms of seasonality, forcing at the surface (F_S), forcing at the top of atmosphere (F_{TOA}), and surface temperature response (ΔT_S).

3.1 Surface and top of atmosphere forcing

Seasonally averaged values of F_S, F_{TOA}, and F_{TOA}–F_S are shown in Table 1 for the short-lived forcing agents discussed in Sect. 2. In addition, seasonally averaged values of F_S and ΔT_S are shown in Fig. 2 for each of the forcing mechanisms included in the table. Values of F_S and F_{TOA} due to direct radiative forcing by tropospheric aerosols are based on GISS ModelE GCM calculations (Koch and Hansen, 2005). They are reported as the change in instantaneous forcing due to adding present-day fossil fuel plus biofuel emissions to the baseline simulation where the baseline simulation used present-day biomass burning emissions. For comparison, values also are shown for the forcing contributed by present-day biomass burning emissions based on GISS ModelE GCM calculations. F_S and F_{TOA} were calculated for the "total" aerosol which includes sulfate, organic carbon (OC), and black carbon (BC) and for the individual aerosol species (sulfate, OC, and BC). Forcings derived from these global-scale calculations were averaged over 60° to 90° N.

Values of F_S and F_{TOA} due to indirect radiative forcing by tropospheric aerosols are based on GISS ModelE GCM calculations for direct plus indirect effects where the indirect effects include those of cloud albedo and cloud cover (e.g., Menon and Rotstayn, 2006). Shortwave, longwave, and shortwave plus longwave values of F_S and F_{TOA} are given for the "total" aerosol (sulfate, OC, and BC). As for the direct radiative forcing calculations, forcings are reported as the change in instantaneous forcing due to adding fossil fuel plus biofuel emissions to the baseline simulation where the baseline simulation used present-day biomass burning emissions.

Increased cloud longwave emissivity due to pollution haze is assigned a wintertime range of values of F_S based on the analysis of Garrett and Zhao (2006). Using four years of ground-based aerosol and radiation measurements, Garrett and Zhao (2006)

found that where thin water clouds and pollution are coincident, there is an increase in cloud longwave emissivity resulting from haze layers at altitudes above the surface. Rather than seasonal averages, the range of observed sensitivity and corresponding surface temperature response are reported here.

Forcing by BC in snow due to present-day fossil, bio-fuel, and biomass burning emissions for the Arctic (60° to 90° N) was calculated relative to present-day biomass burning emissions using SNICAR (Snow, Ice, and Aerosol Radiative model) coupled to the NCAR CAM3 general circulation model (Flanner et al., 2007).

F_{TOA} for tropospheric ozone as reported in Table 1 is the instantaneous forcing at the tropopause based on GISS model II′ chemistry calculations for the 1880 to 2003 time period (Shindell et al., 2006). F_{TOA} for methane is calculated at the tropopause from simulations for 1900 to 2001 driven by changes in all well-mixed greenhouse gases (WMGHGs) accounting for the fractional contribution of methane to the total forcing (0.20) and its efficacy relative to the total WMGHG efficacy (1.05/1.02). The role of methane in ozone production is included in the tropospheric ozone calculation.

3.2 Surface temperature response

Seasonally averaged values of the surface temperature response due to forcing by the short-lived pollutants are shown in Table 1. The climate models used to calculate the Arctic response were forced globally with changing atmospheric composition. Values for tropospheric aerosol direct and indirect effects are based on GISS Model E climate simulations (Hansen et al., 2007, Fig. 11). Indirect effects only include the temperature response due to changes in cloud cover. Values are reported as the zonal mean temperature change for 1880 to 2003 at the surface relative to half present-day biomass burning emissions. Biofuel emissions are not included in these calculations. A small fossil fuel source was included for the late 1880s. The temperature response due to deposition of BC on snow and ice surfaces was calculated with the SNICAR (Snow, Ice, and Aerosol Radiative model) coupled to the NCAR CAM3 general circulation model using the same emissions scenario as described in the previous section (Flanner et

al., 2007).

The temperature response due to forcing by tropospheric ozone and methane are based on GISS Model E calculations detailed in Shindell et al. (2006) and Hansen et al. (2007) using the regional averages and time periods described above. The surface temperature response resulting from increased cloud longwave emissivity is based directly on values of F_s reported in Table 1 (Garrett and Zhao, 2006).

4   Seasonality and magnitude of forcing due to short-lived pollutants and surface temperature response

Forcing due to tropospheric ozone is at a maximum during spring (Table 1) when transport of ozone is efficient, radiation is abundant, and substantial ozone precursors persist from the winter buildup that occurs under conditions of low photochemical loss. Summertime forcing could also be significant, particularly when agricultural or boreal forest fire emissions increase ozone levels in the Arctic. The values shown in Table 1 for summertime are based on a standard climatology for present day biomass burning emissions (including forest fires) (Shindell et al., 2006). As such, they do not capture years with exceptionally large boreal fires. Methane forcing, which is not limited by the seasonality of pollutant transport, is at a maximum during spring and summer due to warmer surface temperatures and, hence, a more powerful greenhouse effect. The surface response for both ozone and methane, indicated here as an increase in surface temperature of 0.43° and 0.34°C, respectively (Table 1), is high in winter when the forcing is at a minimum. This offset implies that the Arctic surface temperature exhibits a delayed response to forcing (either local or extrapolar), is dynamically driven by forcings in other regions of the globe during this season, or is enhanced by erosion of the surface-based temperature inversion which is most prominent in winter.

In the Arctic, the magnitude and mechanism of climate forcing due to aerosols is controlled by an interplay among the seasonal timing of transport, available radiation, snow/ice melt, and deposition. In winter and early spring, when transport of pollutants

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from the mid-latitudes is most efficient, solar radiation is limited so that the radiation balance is driven primarily by thermal fluxes. Interactions between the pollutant aerosol haze and the thin water clouds present at that time of year lead to an increase in longwave emissivity of thin clouds. Long-term ground based observations indicate that, when pollution and clouds are coincident, the result is a positive forcing at the surface of +3.3 to 5.2 W m^{-2} which is estimated to yield an enhanced surface warming of 1° to 1.6°C (Garrett and Zhao, 2006).

Concentrations of BC are enhanced in the Arctic atmosphere during winter and spring due to the transport of Arctic Haze from the mid-latitudes. The deposition of the soot onto the highly reflective snow/ice surfaces lowers the surface albedo and yields a positive surface forcing of 0.53 W m^{-2} in the spring, the season of maximum forcing (Flanner et al., 2007). The corresponding increase in surface temperature is about 0.5°C.

Finally, direct shortwave climate forcing by atmospheric aerosols occurs when solar radiation is abundant and springtime Arctic Haze or summertime fire plumes are present leading to a reduction in the amount of solar radiation reaching the surface. The result is a negative surface forcing during the spring (−0.72 W m^{-2} for the total fossil + bio-fuel + biomass burning aerosol) and a change in surface temperature of −0.93°C. As F_S is an instantaneous forcing, this temperature change applies before the surface equilibrates with the warmer atmosphere. Additional effects include a reduction in Arctic sea level pressure and an increase in snow/ice cover. These aerosol impacts on circulation and the cryosphere may contribute to an offset between the season of maximum forcing (spring and summer) and maximum temperature response (winter).

Mentioned in the discussion above but worth reiterating here is the offset between forcing and surface temperature response in several of the climate model simulations included in Table 1. Recently reported modeling results indicate that during the boreal summer, Arctic temperature response is well-correlated with either global or Arctic forcing (Shindell, 2007). During the remaining seasons, however, the surface temperature response follows the global or Northern Hemisphere extratropical forcing more closely

than local Arctic forcing, indicating that distant regions have a large impact on Arctic climate.

Conditions specific to the Arctic must also be considered when comparing the seasonality of forcing and the surface temperature response. For example, during the summer, the tropospheric aerosol indirect effect has the largest value of F_S but the smallest value of ΔT_S. This discrepancy occurs because surface temperatures over the Arctic Ocean are limited as long as sea ice is present. This scenario (discrepancy between seasonal maxima in forcing and response) is likely to change with future decreases in sea ice extent.

5 Near-term Arctic climate mitigation opportunities

Reducing emissions of CO_2 globally will reduce the rate of surface warming and snow/ice melt in the Arctic. However, targeting emissions of short-lived pollutants along with CO_2 has the advantage of impacting Arctic climate on a more immediate timescale. The most effective mitigation strategy will target those pollutants that dominate surface radiative absorption. Specific mitigation opportunities include:

- *Methane.*Reducing methane emissions will require targeting major controllable anthropogenic sources including gas and coal production and use, landfills, wastewater treatment, rice cultivation, and enteric fermentation.

- *Ozone.*Reducing methane emissions will decrease ozone production. Reductions in NO_x emissions also will decrease ozone production but, at the same time, will decrease OH which is the major sink for methane. Hence, an ozone reduction strategy using NO_x controls must also include reductions in methane, non-methane volatile organic carbon species, and/or CO.

- *Black carbon*. Reducing black carbon emissions will require targeting northern hemisphere emissions with a particular emphasis on sources that emit aerosols

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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 black carbon emissions has the added benefit of improving air quality and decreasing associated health hazards.

6   Future directions for research

Many of the impacts of short-lived pollutants on Arctic climate are not well understood or quantified. Specific scientific issues and areas of uncertainty in need of future research include the following:

– *Methane.*Wetland and permafrost methane emissions within the Arctic and sub-Arctic that result from rising surface temperatures are highly uncertain. Quantifying the changes in these emissions is critical to assessing the effectiveness of controlling anthropogenic sources.

– *Ozone.* The effectiveness of controlling near-Arctic or within-Arctic NO_x emissions to reduce tropospheric ozone within the Arctic is unknown. Local NO_x 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.* Black carbon levels appear to be on the rise in the Arctic but source regions and processes are not well characterized. To reduce Arctic warming due to black carbon in snow and ice, combined measurement and modeling efforts

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are needed to identify sources, particularly those that impact the timing and rate of snow/ice melt, and gain a better understanding of transport pathways and deposition processes.

– *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. Understanding the impact of different aerosol types (source regions and chemical composition) is required to reduce this source of warming. 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. 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*. Individual forcing mechanisms are relatively well understood for each of the short-lived pollutants discussed. More uncertain are the feedback mechanisms that come into play due to the combination of forcings from all pollutants and the complexity of the Arctic environment. These feedback mechanisms and the resulting Arctic climate responses (e.g., increased surface temperature and melt rate) require further evaluation through a combination of measurement and modeling studies.

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Table 1. Comparison of the seasonality and magnitude of the forcing as well as the surface temperature response due to short-lived pollutants in the Arctic (60° to 90° N). Values of F_S and F_{TOA} are reported here as the change in the instantaneous forcing due to the addition of fossil fuel and biofuel emissions to present-day biomass burning emissions.

Forcing Agent	Season	F_S W m^{-2}	F_{TOA} W m^{-2}	$F_{TOA}-F_S$ W m^{-2}	$\Delta T_s{}^a$ °C
Tropospheric Aerosols – Direct Effect[b]					
Total* Fossil+Bio Fuel	Winter	−0.04 (−0.001)	0.08 (0.004)	0.12 (0.005)	−1.4[c]
(Biomass Burning)	Spring	−0.72 (−0.1)	0.92 (0.17)	1.6 (0.27)	−0.93[c]
*SO$_4^-$ + OC + BC	Summer	−0.93 (−0.43)	0.11 (0.16)	1.0 (0.59)	−0.47[c]
	Fall	−0.14 (−0.07)	0.08 (0.04)	0.22 (0.11)	−1.1[c]
SO$_4^-$ Fossil Fuel	Winter	−0.006	−0.01	−0.006	
	Spring	−0.26	−0.32	−0.06	
	Summer	−0.50	−0.54	−0.04	
	Fall	−0.07	−0.08	−0.01	
OC Fossil+Bio Fuel	Winter	−0.003 (0)	0 (0)	0.003 (0)	
(Biomass burning)	Spring	−0.06 (−0.05)	0.03 (0.02)	0.09 (0.07)	
	Summer	−0.04 (−0.24)	−0.01 (−0.09)	0.03 (0.15)	
	Fall	−0.008 (−0.04)	−0.001 (−0.02)	0.007 (0.02)	
BC Fossil+Bio Fuel	Winter	−0.03 (−0.001)	0.09 (0.004)	0.12 (0.005)	
(Biomass burning)	Spring	−0.39 (−0.05)	1.2 (0.15)	1.6 (0.20)	
	Summer	−0.39 (−0.19)	0.66 (0.25)	1.0 (0.44)	
	Fall	−0.07 (−0.03)	0.16 (0.05)	0.23 (0.08)	
Tropospheric Aerosols – Indirect Effects					
Total* Fossil+Bio Fuel Cloud	Winter	−0.04, 0.24, 0.2[d]	0.07, −0.1, −0.03[e]	0.11, −0.34, −0.23	−0.77[f]
albedo + cloud cover	Spring	−3.0, 1.9, −1.1	0, 0.1, 0.1	3.0, −1.8, 1.2	−0.68[f]
SW, LW, SW+LW	Summer	−12.2, −0.5, −13	6.6, −0.5, 6.1	19, 0, 19	−0.45[f]
*SO$_4^-$ + OC + BC	Fall	−0.4, −0.1, −0.5	0.49, −0.9, −0.41	0.89, −0.8, 0.09	−0.89[f]
Cloud longwave emissivity	Winter	+3.3 to 5.2[g]			1 to 1.6[g]
Black carbon aerosol – Snow Albedo					
BC Fossil+Bio Fuel	Winter	0.02[h]			0.27–0.61[h]
	Spring	0.53[h]			0.36–0.76[h]
	Summer	0.21[h]			0.24–0.59[h]
	Fall	0.002[h]			0.31–0.76[h]
Tropospheric Ozone GHG warming + SW absorption[i]					
O$_3$ Fossil+Bio Fuel and	Winter		0.13		0.43
Biomass burning	Spring		0.34		0.31
	Summer		0.14		0.11
	Fall		0.24		0.26
Methane – GHG warming[j]					
Methane	Winter		0.29		0.34
	Spring		0.45		0.27
	Summer		0.55		0.15
	Fall		0.34		0.35

Table 1. Foonotes to Table 1.

[a] Zonal mean temperature change at the surface for 60° to 90° N. Climate models used to calculate the Arctic response were forced globally (not just within the Arctic region) with changing composition.

[b] F_S and F_{TOA} are based on the GISS ModelE GCM, using present-day fossil, bio-fuel, and biomass burning emissions relative to present-day biomass burning emissions (Koch and Hansen, 2005). Values for present-day biomass burning emissions are shown in parentheses.

[c] Values are reported as the zonal mean temperature change for 1880 to 2003 at the surface relative to half present-day biomass burning emissions. Biofuel emissions are not included in these calculations. A small fossil fuel source was included for the late 1880s. Taken from Fig. 11 of Hansen et al. (2007).

[d] Direct plus indirect effects (cloud albedo and cloud cover) together. Based on the GISS ModelE GCM, using present-day fossil, bio-fuel, and biomass burning emissions relative to present-day biomass burning emissions (Menon and Rotstayn, 2006). Three values are given: shortwave, longwave, and shortwave plus longwave forcing.

[e] Based on the GISS ModelE GCM, for changes in net cloud radiative forcing using the same emissions scenario as described above. Three values are given: shortwave, longwave, and shortwave plus longwave forcing.

[f] Temperature change due to cloud cover aerosol indirect effect only. Taken from Fig. 11 of Hansen et al. (2007).

[g] Based on measurements of the sensitivity of low-level cloud emissivity to pollution at Barrow, Alaska (Garrett and Zhao, 2006). Not a seasonal average as it only includes times when pollution aerosol and clouds were coincident.

[h] Based on radiative transfer calculations with SNICAR coupled to the NCAR CAM3 using present-day fossil, bio-fuel, and biomass burning emissions relative to present-day biomass burning emissions (Flanner et al., 2007).

[i] Ozone forcing calculated at the tropopause over 60–90° N for 1900–2000 (Shindell et al., 2006).

[j] Methane's forcing and response are estimated based on simulations for 1900–2001 driven by changes in all well-mixed greenhouse gases (WMGHGs), accounting for the fractional contribution of methane to the total forcing (0.20) and its efficacy relative to the total WMGHG efficacy (1.05/1.02). As the well-mixed greenhouse gases are evenly distributed, we believe this is a realistic approach. Values are calculated at the tropopause. Methane's role in ozone production is included in the tropospheric ozone calculation. Based on the contribution to the global increase in tropospheric ozone, it is responsible for ~50% of the overall tropospheric ozone increase. Its percentage contribution to the Arctic ozone concentration will be lower, however, as ozone changes in the Arctic are dominated by increases in NO_x (Shindell et al., 2005).
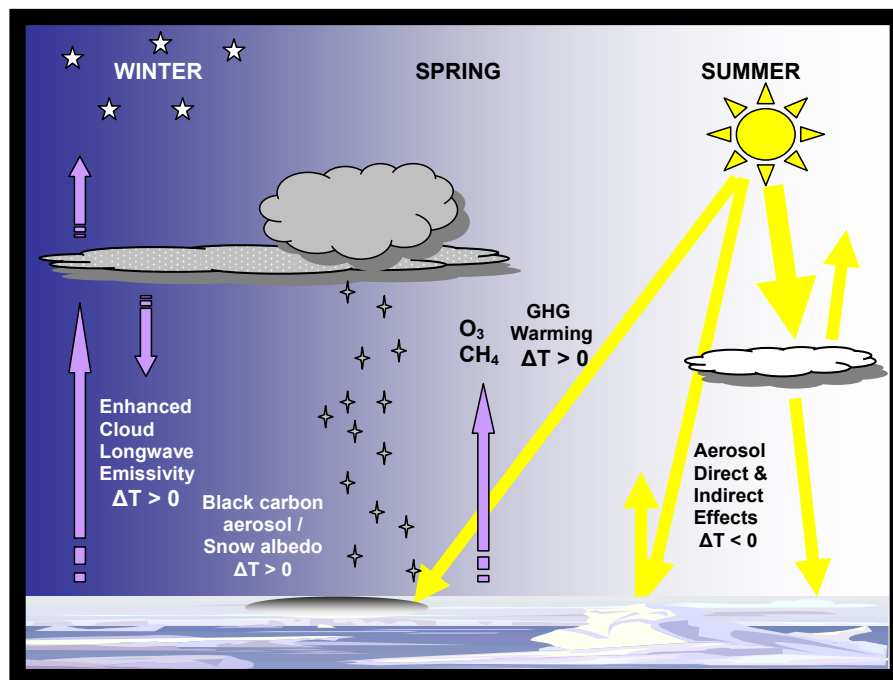
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Fig. 1. Forcing mechanisms in the Arctic environment resulting from the poleward transport of middle latitude gas and particulate phase pollutants. Season of maximum forcing at the surface (F_S) is indicated for each forcing agent. ΔT indicates the surface temperature response.
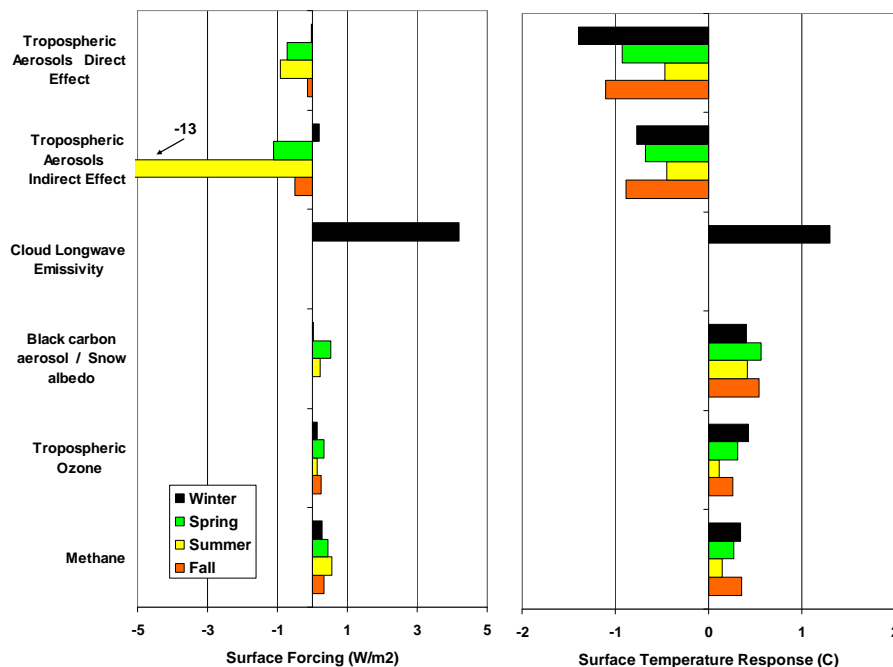
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Fig. 2. Seasonally averaged values of radiative forcing and temperature response at the surface (F_S and ΔT_S, respectively) for 60° to 90° N based on the calculations described in Sect. 2 and Table 1. Values for Cloud Longwave Emissivity are not seasonal averages as they only include times when pollution aerosol and clouds were coincident. Central values of F_S and ΔT_S are plotted in cases where a range of values was reported in Table 1.