Report on model analysis of variations in emissions of SLCFs and their influence on the Arctic and cryosphere

Recent discussion and research has focused on the possible co-beneficial mitigation of short lived climate forcers (SLCFs) which are responsible for both reductions in air quality and regional and global climate change. As the name suggests, SCLFs have a short residence time in the atmosphere (days up to a few months) which means they are inhomogeneously distributed in space and time. Complex interactions and feedbacks over multiple scales mean that the relationship between regional SCLF forcing and climate response is typically not straightforward. Global modeling can be useful tool in isolating and quantifying the regional (including the Arctic) climate response to changes in SLCF forcing.

Aerosols and aerosol precursor gases

Anthropogenic emissions of aerosols and precursor gases have varied strongly with population growth, land use change and industrialization (1) (Figs. 1 & 2). Recognition of the adverse health effects of atmospheric pollution prompted the introduction of legislation to restrict pollutant concentrations. A strong reduction of the sulfur emissions has been achieved through the introduction of the Convention of Long Range Transboundary Air Pollutants (CLRTAP) in the 1980s such that the present emissions are near pre 2nd world war values (Fig. 3). In addition, European emissions of BC have been approximately halved from 1960 to 2000, however, a substantial increase in the emissions over large parts of Asia has occurred over the same time period (Fig. 3). The large change in the magnitude and spatial distribution of anthropogenic aerosol and aerosol precursor emissions is expected to be reflected in regional patterns of climate change.

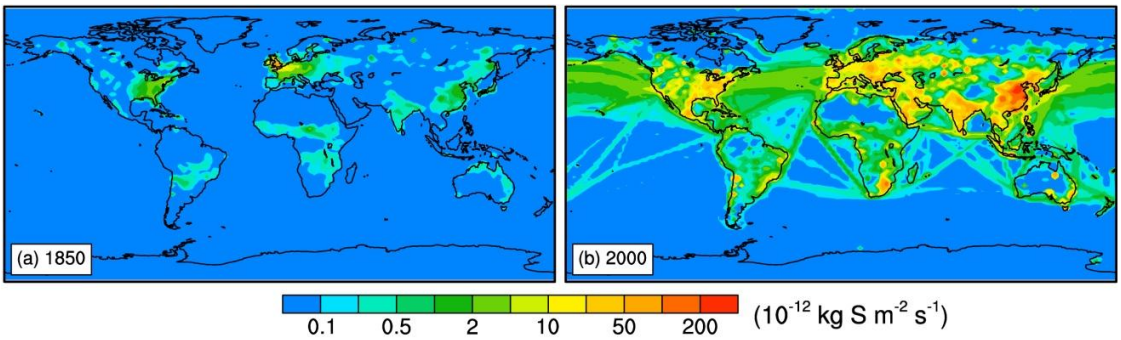

Figure 1: Annual average SO_2 emission estimates for 1850 and 2000 from the IPCC CMIP5 data set (1).

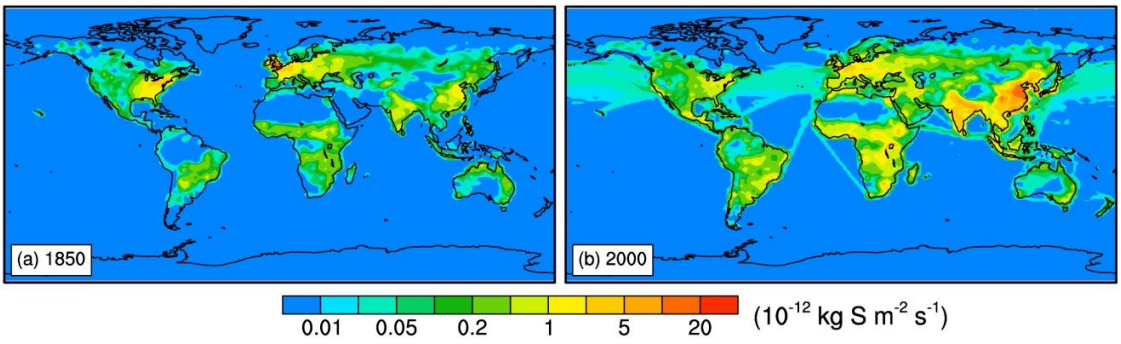

Figure 2: Annual average BC aerosol emission estimates for 1850 and 2000 from the IPCC CMIP5 data set (1).

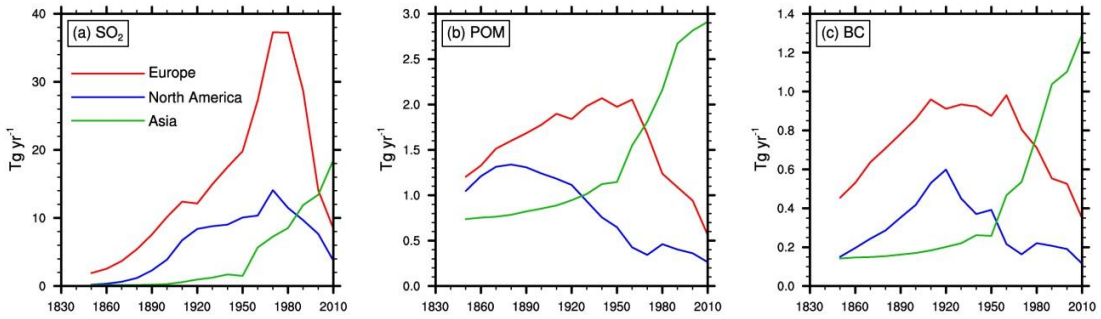

Figure 3: Area averaged time-series of SO_2, POM (particulate organic material) and BC aerosol emissions from the IPCC CMIP5 data set (1).

Shindell and Faluvegi (2009) (2) systematically studied the sensitivity of regional climate response to the location of radiative forcing due to black carbon aerosols, sulfate aerosols, ozone and GHGs using the GEOS-EM model. They found that the mean tropical temperature response is only weakly dependent on the latitude of the imposed radiative forcing unlike mid and high latitude climates response which are more sensitive to local forcings. In other words, tropical temperatures changes generally follow global mean changes whereas significant departures from the global mean temperature trends can be expected in mid and high latitude regions. These conclusions are consistent with observed twentieth century temperature changes. Shindell and Faluvegi also applied an inverse modeling approach to reconstruct aerosol forcing patterns that best explained the observed trends in temperatures of the 20th century. Based on the reconstructed forcing patterns, they concluded that up to 70 % of the Arctic warming since 1976 can be attributed to decreases in sulfate aerosols and increases in black carbon aerosols.

The specific role of black carbon aerosol in Arctic climate change was investigated by Sand et al. (2012) (3) based on a set of idealized climate model simulation using the fully coupled NorESM Earth system model (4). BC forcing in the model was artificially increased by a factor of 10 separately over Northern mid-latitudes (28°N to 60°N) and within the Arctic (60°N to 90°N). For the Arctic BC sensitivity test, the model exhibits a cooling at the surface in response to increased Arctic BC forcing despite an increase in the absorption of incident sunlight. This is explained through a combination of reduced meridional heat transport into the Arctic (due to a reduction in the meridional temperature gradient) and weaker turbulent mixing of heat from the free troposphere to the boundary

layer. NorESM simulates an increase in BC concentration with altitude in the Arctic such that the artificial increase in BC forcing for the Arctic sensitivity simulation increases the static stability of the atmosphere, thus inhibiting turbulent mixing. Sand et al. found that northern mid-latitude BC forcing and Arctic surface air temperatures were positively correlated, attributable in part to an increase in meridional temperature gradients, which is in accord with the results of Shindell and Faluvegi. Both the Sand et al. and Shindell and Faluvegi studies suggest that BC forcing at mid-latitudes may be more important in determining the Arctic surface temperature response than BC forcing in the Arctic itself.

Using the HadGEM2-ES model, Booth et al (2012) (5) demonstrate that changes in aerosol concentrations over the North Atlantic ocean significantly affects the shortwave radiation flux reaching the ocean surface, which in turn influences sea surface temperatures over decadal timescales. Variations in aerosol emissions and volcanic activity can explain a large part of the decadal variability in the detrended North Atlantic sea surface temperatures in their model. Surface shortwave variability in the North Atlantic region coincides with the simulated large scale cloud distribution suggesting that aerosol-cloud interactions simulated by the model are an important factor in determining sea surface temperature variability. Note also that aerosol indirect effects account for more that 80% of the total aerosol forcing in the North Atlantic in the HadGEM2-ES model. Northern hemispheric climate, particularly in the Arctic and European regions has been shown to be sensitive conditions in the North Atlantic. It is known that modes of natural variability such as the North Atlantic Oscillation (NAO) can significantly influence the position of the jet stream which in turn, exerts a strong influence on both Arctic and European climate variability (6) (7) (8) however uncertainties in model-simulated circulation and a lack of mechanistic understanding of the processes involved represent a source of uncertainty in model predictions (9).

An unpublished series of CAM-Oslo equilibrium climate simulations have been completed (10), designed to separate the climate response to different forcing agents (GHG concentrations and aerosol emissions) as well as examine the non-linearity in the combined response. Year 2000 conditions are used as a baseline for comparisons with model sensitivity experiments in which 1970 values of GHG and aerosol emissions were used. Note that CAM-Oslo is a predecessor of the atmospheric model component of NorESM and includes a comprehensive, prognostic aerosol module (11). Figure 6 depicts the modeled mean sea level pressure (MSPL) response to changes in aerosol emissions (present day minus 1970). The dipole pattern in the MSLP response over Greenland and the north Atlantic reflects some characteristics of the NAO variability pattern. Note also that this anomaly pattern is statistically significant at the 95% level based on a two-tailed student's t-test (point by point comparison). These CAM-Oslo simulations suggest that aerosol changes over the period 1970 to 2000 results in a shift towards a more negative phase of the NAO which would tend to increase temperatures in the Arctic and lead to cooler temperatures in northern Europe.

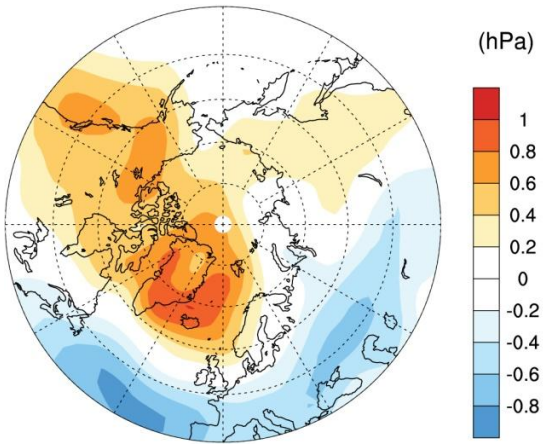

Figure 4: Change (present day minus 1970) in mean sea level pressure attributed to changes in aerosol emissions, simulated by the CAM-Oslo global climate model.

For the same CAM-Oslo simulations, a poor correlation between the top-of-the-atmosphere aerosol radiative forcing due to aerosol emission changes and the 2-meter temperature response was found for the Arctic region (correlation coefficient less than 0.2). Consistent with the findings of Sand et al. and Shindell and Faluvegi, these results suggest that in this model the Arctic temperature response is strongly controlled by non-local changes in aerosol emissions. Also of note, preliminary results demonstrate that the sensitivity of natural aerosol and precursor gas emissions to climate change should be considered in climate model simulations.

The role of changes in aerosols for near term (20 to 30 years from present day) future climate change was studied by Chalmers et al. (2012) (12) using the HadGEM2-ES model. Two IPCC RCP scenarios, RCP2.6 and RCP4.5 were used as boundary conditions for the model simulations. RCP2.6 was developed by the Netherlands Environmental Assessment Agency represents a so called 'peak' scenario with immediate and substantial reductions in GHG and air pollutant emissions (13). RCP4.5 is a stabilization scenario where total radiative forcing is stabilized at 4.5 W m^{-2} before 2100 (14). Based on these scenarios, Chalmers et al. show a rapid global warming from present day until approximately 2025 projected under RCP2.6 which is higher than that simulated using RCP4.5 even though the GHG forcing is lower in RCP2.6. They attributed this result to the substantial reduction in sulfur emissions in RCP2.6 associated with the strong reduction in coal burning without CCS (carbon capture and storage) in this scenario. Reductions of around 40 % in the sulfate optical depth (OD) over Europe and North America are simulated by HadGEM2-ES, in addition around 10% reductions in sulfur OD over northern oceans. A clear feature of the resulting modeled climate response is that the Arctic surface air temperature is approximately 1 K warmer in the RCP2.6 simulation compared to the RCP4.5 case (2018-2037 average). This result suggests that a rapid reduction in anthropogenic sulfur emissions over the coming few decades would add approximately 1 K to the near term projected Arctic warming. Chalmers et al. conclude that aerosol emissions are a key source of uncertainty in near term, global and regional climate change projections, however they also note that the HadGEM2-ES model has one of the highest climate sensitivities of the models contributing to the CMIP5 project.

In summary, there is increasing evidence from global climate models that heterogeneous changes in anthropogenic aerosol emissions and radiative forcing at northern mid-latitudes are responsible for significant changes in Arctic climate. Recent results suggest that Arctic climate response to remote

radiative forcing is linked with changes in the North Atlantic Oscillation mode of variability and that the remote response at least the same order of magnitude as the response to local forcing. Changes in mid-latitude aerosol and precursor emissions are an important source of uncertainty in projections of near future Arctic climate change.

Ozone

The effect of ozone (stratospheric plus tropospheric) changes was included in the study of Shindell and Faluvegi (2009) (2). The 60°N - 90°N surface temperature response to both global and local changes in ozone radiative forcing is significantly lower than that found for sulfate. However, an in an earlier paper, Shindell et al. (2006) (15) studied the Arctic response to increases in tropospheric ozone over the 20th century using the NASA GISS climate model and concluded that the Arctic climate response is large during autumn, winter, and spring. This result was explained by the more abundant transport of pollution in the non-summer months, the relatively long lifetime of ozone in the winter and the fact that ozone can efficiently absorb reflected radiation over high albedo surfaces (16). The model results indicate that tropospheric ozone could have contributed about 0.3°C annual average and about 0.4°C - 0.5°C during winter and spring to the 20th-century Arctic warming.

The long-term ongoing predicted increase in Arctic temperatures is a direct consequence of increases in the concentration of well mixed green house gases, however a growing body of model studies indicate that the Arctic climate is sensitive to both local and remote concentrations of SLCFs. Recent improvements in the representation of processes important for the simulation of SLCFs and their effects within global climate models increases our confidence in the prediction of regional climate responses from these models. Reducing tropospheric ozone concentrations and the emissions of absorbing aerosols potentially offers strong leverage for moderating Arctic warming.

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