Radiative Effects of Aerosols on the Arctic Climate During Spring

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Abstract

As we all know, the most sensitive region to global warming caused by increasing greenhouse gases is over the Arctic. From the observations of recent years, there is still not enough evidence to draw the conclusion of the Arctic warming as most Global Circulation Models (GCMs) suggested. The uncertainties are not only from the lack of observation data, but also from numerical simulation itself. The dehydration-greenhouse feedbacks have been hypothesized early by Blanchet and Girard (1994) to reduce the warming trend from the increasing radiatively active trace gases. In this study, we use the Northern aerosol regional climate model (NARCM) to quantify the aerosol effect on the Arctic climate change. The direct and indirect radiative effects of aerosols such as Arctic haze sulfate, black carbon, organic and dust have been estimated from our NARCM simulations over the Arctic.

To identify the drawbacks of our current climate model simulations, the Arctic Regional Climate Model Intercomparison Project (ARCMIP) has offered an excellent opportunity to validate and inter-compare parameterizations of sea ice, radiation, clouds and surface processes. The enhanced observation datasets such as the Surface Heat Budget of the Arctic Ocean (SHEBA) and the Atmospheric Radiation Measurement (ARM) can be directly compared to our model simulations from October 1997 to October 1998. Results show that the climate effects of aerosols strongly depends on the aerosol composition. Aerosols have significent impacts on the Arctic climate change. From comparison with observations, It is shown that aerosol radiative and microphysical effects must be accounted for to get better simulation of the surface temperature.

1.

Most simulations by global climate models with enhanced greenhouse forcing predict that any warming in the global climate will be amplified at the poles However, measurements have shown no evidence for greenhouse warming over the Arctic Ocean in past decades during autumn and winter (Kahl et al, 1993). Blanchet and Girard (1994, 1995) hypothesized that the microphysical properties associated to Arctic haze aerosols in the Arctic may alter the ice nucleation process and consequently the cloud particle number concentration and mean diameter. As a result, the precipitation efficiency is increased and the dehydration rate of the lower atmosphere is larger. This would lead to a decrease of the downward longwave radiation flux at the surface. Other indirect effects of aerosols such as the Twomay and the Albrecht effects (Twomay, 1991; Albrecht, 1989) may strongly affect cloud microphysical and radiative properties.

The response of climate system to the radiative forcing over the Arctic region are extremely complex due to strong annual variation of the diurnal cycle, polar sphericity and surface characteristics. The high surface albedo of snow and ice and unique atmospheric aerosol composition make the polar climate system very sensitive to the external forcing. Strong feedbacks such as ice-snow feedback, water vapour feedback, aerosol-cloud-radiation feedback can lead of significant climate change over such a region. Most of these physical processes are still not well known and understood.

In this paper, we present our climate model simulations of the direct and indirect effects of aerosols over the Arctic region using the Northern Aerosol Regional Climate Model (NARCM). NARCM is built based on the Canadian Regional Climate Model (CRCM) and the Canadian Aerosol Module (CAM) for simulating the impacts of aerosols on the climate in Northern Hemisphere (Laprise 1997, Gong et al, 1997). The radiation scheme has two wide bands in shortwave radiation and six bands in longwave radiation (Fouquart and Bonnel, 1980, Morcrette, 1990). Scattering and absorption by gases, aerosols and clouds have been considered during the radiation calculation. NARCM uses the Lohman and Roeckner (1996) microphysics scheme. It is a 2-moment scheme with 6 prognostic cloud variables. Aerosols are accounted for in this scheme for water droplet and ice crystal nucleation. Another microphysics scheme from Girard and Curry (2001), it has recently been implemented in NARCM, but was not used in the simulations shown in this paper. The model has 22 vertical level with the top level at 10 mb. Our simulation domain is designed to focus on the inter-comparison of model simulations with measurements provided by the Arctic Regional Climate Model Intercomparison Project (ARCMIP) which covered the Arctic ocean, Alaska, and Eastern part of Russia.

Although aerosol is a prognostic variable in NARCM, it has not been possible to fully take advantage of the model potential due to the ARCMIP domain size which does not include regions with important aerosol sources. A quasi-hemispheric simulation will be needed to provide initial and boundary conditions to smaller domain simulations. During the first of the intercomparision, this simulation was not available. As a first approximation, we initialized the model with 5 aerosol species (sulfate, black carbon, dust, sea salt and organic) provided by transport models (Penner et al., 1992; Chin et al., 1996; Tegen et al.; Gong et al., 1997; Graf et al., 1997). The optical properties of aerosols such as the particle scattering or extinction efficiency, single scattering albedo and asymmetry factor are calculated from the Mie scattering theory. The vertical distribution of aerosol is fitted from the 9-layer 3-D chemical transport model (Chin etal, 1996) with modifications according to recent aerosol observation data such as the AERONET/AEROCAN observation network.

We carried out three experiments in the period between September 1997 and September 1998. Over this time period, the enhanced measurements such as the Atmospheric Radiation Measurements (ARM) and the Surface Heat Budget of Arctic Ocean (SHEBA) are available. In the first experiment, we performed the control run without aerosols while in the second experiment, only sulfate aerosols were considered. In the third experiment, we added all five kinds of aerosols into our model, which are sulphate, soot, dust, organics and seasalt. Gases concentrations are kept constant in these experiments.

For pure sulfate aerosol case, strong scattering of this kind of aerosol leads to surface cooling effect (Plate 1.). In May, we find that strong cooling occurred over the Arctic Ocean. The maximum cooling is up to 6 K. In the meantime, warming occurred over most part of Alaska. In fact, the response of aerosol forcing varies strongly with season. For example, the surface temperature is not changed much over the Arctic Ocean in September 1997 when aerosols are added into our model, but strong warming oc-

curred over Alaska by about 10 K. Three processes contribute to the cooling effect of sulphate aerosols: (1) the enhanced scattering of solar radiation (direct effect), (2) the Twomay effect by which the cloud droplet number concentration increases, thereby increasing cloud reflectivity of solar radiation, and (3) the Albrechet effect which increases cloud lifetime. The surface warming over some areas in the southern part of the domain is likely to be due to complex dynamical feedbacks that can locally change significantly the cloud cover.

Third experiment was performed with five kinds of aerosols added into our model. The results are amazingly different (Plate 2.). In May, a slightly surface warming occurred over the Arctic Ocean, and cooling occurred over some part of Arctic land. The precipitation (not shown) is increased over the Arctic ocean and decreased over broad band of Alaska region. However, there is little change of precipitation for the case of pure sulfate experiment. The cloud cover is increased over the Arctic Ocean by up to 20 percent. Correspondingly, the cloud cover is decreased over the Alaska, Greenland and Eastern part of Russia.

The microphysical and optical properties depend on their composition. For example, the imagery part of refractive index for black carbon aerosols is quite large. As a result, they absorb solar radiation. This contributes to warm the atmosphere and the surface (Kaufman, 2002). In this case, the black carbon radiative forcing seems to counteract the sulphate cooling effect (see Plate 1). Dust, organic aerosols and sea salt are also different in radiative properties. Certainly, the aerosol climate effect strongly depends on what kinds aerosols we considered.

To get confidence in our model simulations, we have compared our results to SHEBA observation that were taken near the ice breaker in May 1998 (Plate 3). Results show good agreement with the observations although the discrepancy can be large on few days. For pure sulfate aerosols, the monthly averaged cooling effect is up to 3.5 K. Surprisingly, there is a little warming by 0.16 K for the case of five kinds of aerosols together. The simulated surface air temperature in the third experiment is closer to observation with an average temperature difference of only 0.8 K. The third experiment also reproduces quite well the variability of the observed surface temperature with a correlation of 0.8. The first and second experiment have a correlation of 0.7 and 0.6 respectively. These results show that it is not sufficient to account for only sulfate aerosols in climate simulations. One has to consider the other major aerosol species. When all aerosol species are accounted for, the results improve significantly.

This research have shown that the radiative effect of combined soot, organic, sea salt, dust and sulphate produces a slight warming over the Arctic during spring. As the aerosol data is climatology, it may coarsely be representive of the real situation. In this circumstance, higher resolution of aerosol simulations and more in-situ measurements are certainly needed. We believe that our simulations could be fitted better to the observation if we added more realistic aerosol data.

In the near future, NARCM will use a new microphysics scheme (Girard and Curry 2001) which will account for effect of aerosol composition on the ice nucleation process. This interaction between cloud and aerosol can be very important in the Arctic given the predominence of solid and mixed-phase clouds. The new microphysics scheme is also able to simulate ice fog and diamond dust which are commonly observed over the Arctic during winter. Giard and Blanchet (2001) have shown that diamond dust can increase the downward infrared radiation flux to surface by up to 60 W m-2. All these phenomena and processes need to be represented in climate models to better simulate the current arctic climate and its change due to anthropogenic and aerosol emission.

The regional climate effect of aerosols over the Arctic is extremely difficult to be assessed due to lack of observation data. In the past, the aerosol effect is usually neglected over the polar regions as the polar atmosphere has been suggested relatively clean. Most GCMs are also predicting strong warming over the Arctic region due to the greenhouse gases. Within our study, we find the aerosol effect is significantly contributed to the Arctic climate change. It would be arbitrary if we ignored those tiny particles.

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Plate 1.
Surface air temperature change due to pure sulfate aerosols (Monthly averaged in May, 1998).

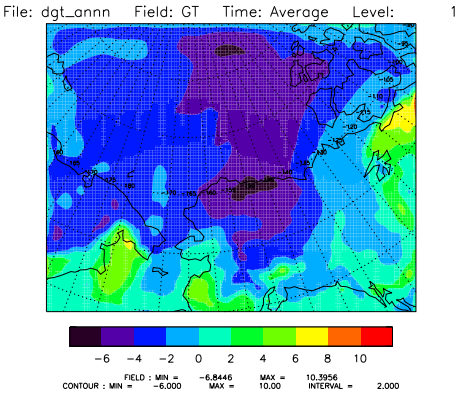

Plate 2.
Surface air temperature change due to five kinds of aerosols together (Monthly averaged in May, 1998).

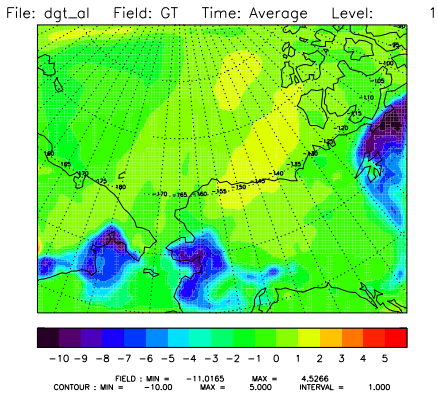

Plate 3.
Inter-comparison of surface air temperature. Black: observation, red: control case, green: sulfate aerosols, blue: 5 kinds of aerosols.