

Evaluation of the direct and indirect radiative and climate effects of aerosols over the western Arctic

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[1] From the observations of recent years, there is still not enough evidence to verify the Arctic warming as most global circulation models (GCMs) suggested. This study is dedicated to quantifying the aerosol effect on the Arctic climate change by Northern Aerosol Regional Climate Model (NARCM). The direct and indirect radiative and climate effects of aerosols such as Arctic haze sulfate, black carbon, sea salt, organics, and dust have been evaluated from our NARCM simulations. Within the Arctic Regional Climate Model Intercomparison Project (ARCMIP) our model simulations have been directly compared with the enhanced observation data sets such as the Surface Heat Budget of the Arctic Ocean (SHEBA) and the Atmospheric Radiation Measurement (ARM) in the time period from October 1997 to September 1998. Results show that the climate effects of aerosols strongly depend on the aerosol composition. The surface radiative forcing of pure sulfate aerosols which includes the direct and indirect components reaches up to -7.2 W/m^2 in annual mean. The climate responses to radiative forcing of pure sulfate and five kinds of aerosols together are amazingly different. The impacts of aerosols present strong seasonal cycle. In comparison with observations we find the simulation with five kinds of aerosols can better represent the surface temperature from observation. The aerosol radiative and microphysical effects must be taken into account in order to better simulate and predict the change of energy and water cycle occurring in polar climate system.

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1. Introduction

[2] Radiative forcing is very important, for first step, to understand the climate change [Intergovernmental Panel on Climate Change (IPCC), 1995]. In spite of past decades effort, the radiative forcing of aerosols is still uncertain. The indirect radiative forcing is more perplexing. One of difficulties is that aerosols vary largely with space and time, in that we cannot simply use globally averaged value to quantify it. In recent work of evaluation of aerosol forcing in General Circulation Models (GCMs) [Jones *et al.*, 1994; Boucher and Anderson, 1995; Lohmann and Feichter, 1997; Penner *et al.*, 1998; Kiehl *et al.*, 2000; Ghan *et al.*, 2001; Menon *et al.*, 2001], the indirect radiative forcing of sulfate aerosols has been estimated from -1.0 W/m^2 to -4.5 W/m^2 . More recently, Lohmann and Lesins [2002] reduced the value from -4.5 W/m^2 to -1.2 W/m^2 after taking the difference in indirect aerosol effect from satellite data and model simulations into account. Nevertheless, the climate forcing of aerosols appears strongly regional characteristics. It is very large over some regions that is enough to offset the positive forcing caused by greenhouse gases and small in other regions. Especially, the radiative forcing over the polar regions is more uncertain [Curry *et*

al., 1996; IPCC, 2001]. Therefore it is essential to examine the aerosol forcing in detail with region by region, then we can get the good evaluation of climate forcing of aerosols.

[3] As the special surface characteristics and atmospheric composition over Arctic region, most GCM simulations show strongly warming due to increasing greenhouse gases [Washington and Meehl, 1989; Manabe *et al.*, 1992; Manabe and Stouffer, 1994]. However, measurements have no evidence for greenhouse warming over Arctic Ocean in past decades [Kahl *et al.*, 1994]. One of reasons is that strong dehydration caused by Arctic aerosols result in colder surface and a warmer temperature aloft [Blanchet and Girard, 1994]. Aerosol is not only directly scattering and absorbing the radiation but also acting as Cloud Condensation Nuclei (CCN) to change the microphysical properties of polar clouds [Curry *et al.*, 1996; Girard and Blanchet, 2001; Garrett *et al.*, 2002]. The aerosol-cloud-radiation interactions over the Arctic region are very complex due to the high surface albedo of snow and ice cover, without solar radiation in long period of the year. Lack of enough observation data, unique surface condition and atmospheric composition, it is extremely difficult for climate modeling in the Arctic region. Until recently, the gap between modeling and observation is still large [Gates *et al.*, 1996; Briegleb and Bromwich, 1998; Washington *et al.*, 2005].

[4] In this study, we try to use the Northern Aerosol Regional Climate Model (NARCM) to quantify the direct and indirect radiative and climate effects over the Arctic region. One of the uncertainties for assessment of aerosol effect is from the complicated chemical composition and size distribution of aerosols. Also, for large particles, the Mie scattering theory using spherical approximation can introduce error as large as 100% [Mishchenko *et al.*, 1995]. In recent studies, the different kinds of aerosols such as sulphate, black carbon, sea salt, dust and organics have been considered in evaluation of their climate forcing in GCMs. The black carbon (“soot”) has been attracted special attention for absorbing the sunlight, heating the air, altering the regional atmospheric circulation and contributing to regional climate change [Ackerman *et al.*, 2000; Kaufman *et al.*, 2002; Menon *et al.*, 2002]. However, the concentration of aerosols simulated by chemical transport model (CTM) is still not consistent well with the measurements. Most aerosols have complicated chemical compositions, which are mixture of different chemical compounds. For example, the aerosols usually observed over the north western part of China, are the dust particles coated with the film of sulfate. The direct and indirect radiative forcings over this region need to be evaluated carefully [Hu and Shi, 1998]. Over the Arctic region, it is more difficult to validate the model results as the available data is so sparse. Certainly, the aerosol forcing over the Arctic is much more uncertain than it over any other regions. The climate response to radiative forcing over Arctic region is more strongly dependent on the complicated physical feedback processes which occur in the unique polar climate system. Arctic Regional Climate Model Intercomparison Project (ARCMIP) is designed to validate the regional climate modeling using observational data set. It is hopeful to improve the physical parameterization such as cloud and radiation scheme in NARCM and better understand the Arctic climate change.

2. Model Description

2.1. Northern Aerosol Regional Climate Model (NARCM)

[5] NARCM is built based on the Canadian Regional Climate Model (CRCM) and the Canadian Aerosol Module (CAM) for simulating the impact of aerosol on climate in Northern Hemisphere. The dynamic kernel is first developed by Robert, which used nonhydrostatic dynamic equation solved with semi-implicit and semi-Lagrangian method for time integration [Laprise *et al.*, 1997; Caya and Laprise, 1999]. The physical parameterization package is the same as the package of the Canadian general circulation model (CGCM) [McFarlane *et al.*, 1992]. The radiation scheme is based on Fouquart-Morcrette radiation (FMR) scheme with two wide wave bands in shortwave radiation and six wave bands in longwave radiation [Morcrette, 1990]. In short wavelengths, we modified the radiation code to use four wave bands to better represent the aerosol effect. The scattering and absorption by gases and clouds have been considered during the radiation calculation. CAM is a size-segregated multicomponent aerosol module including processes such as nucleation, condensation, coagulation, dry deposition, hygroscopic growth, and inter-

action with clouds as well as wet removal [Gong *et al.*, 1997, 2003].

2.2. Direct Effect of Aerosols

[6] Aerosol has been recognized earlier that it scatters the sunlight and leads to cool the global warming. The direct radiative forcing of aerosols has been estimated ranging from -0.3 W/m^2 to -0.9 W/m^2 [IPCC, 2001]. One of uncertainties is the complicated composition of aerosols. If the tiny particles are composed of the sulphates, the strong scattering properties will strengthen the reflectivity of sunlight [Charlson *et al.*, 1992]. However, the particles such as soot have strong absorption, the radiative forcing will become positive. The mixtures of two kinds of aerosols make even more difficult to estimate the radiative forcing of aerosols. The refractive index, size distribution and shape of particles are crucial for evaluation of the radiative and climate effect of aerosols. The other uncertainties come from the radiative forcing definitions, aerosol data and radiative transfer calculations which are also very important to get better evaluation of climate forcings [Hu *et al.*, 2001].

[7] 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. As the sensitivity experiment, we initialized the model with five aerosol species (sulfate, black carbon, dust, sea salt, and organics) provided by chemical transport models [Penner *et al.*, 1992; Chin *et al.*, 1996; Tegen *et al.*, 1997; 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. Refractive indices are calculated according to the data from Toon *et al.* [1976] and Ghan *et al.* [2001]. The vertical distribution of aerosol is fitted from the nine-layer 3-D chemical transport model [Chin *et al.*, 1996] with modifications according to recent aerosol observation data such as the AERONET/AEROCAN [Holben *et al.*, 1998] observation network. A simplified formula of exponential decline of mass concentration with height is used in this study [Hu *et al.*, 2001].

2.3. Indirect Effect of Aerosols

[8] The Arctic haze has been suggested to alter the surface radiation budget by increasing the cloud albedo [Twomey, 1991] and emissivity [Garrett *et al.*, 2002]. As the nucleation processes of cloud droplets or ice particles are still not fully known, it is very uncertain to quantify this kind of forcing. NARCM uses the Lohmann and Roeckner [1996] microphysics scheme. It is a two-moment scheme with six prognostic cloud variables. Aerosols are accounted for in this scheme for water droplet and ice crystal nucleation. As the scheme only considered the sulfate aerosols, we have added black carbon (“soot”), sea salt, and organics to be the candidates of cloud condensation nuclei (CCN). The explicit nucleation parameterization considering the vertical velocity, aerosol number concentration and size distribution has also been introduced for alternate nucleation scheme [Abdul-Razzak *et al.*, 1998]. Ice nucleation is very important for simulation of ice clouds in the Arctic, so both homogeneous and heterogeneous nucleation are accounted for in the model [Girard and Blanchet, 2001]. Although the

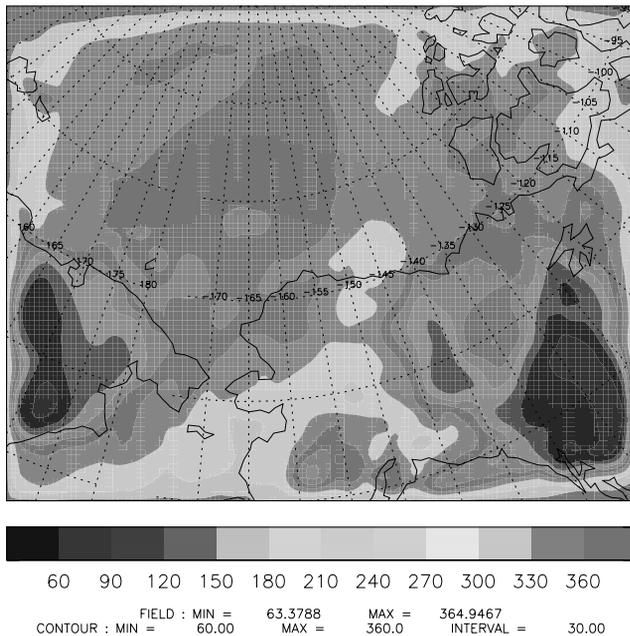


Figure 1. Downward solar radiation at surface (July 1998). See color version of this figure at back of this issue.

microphysical process of ice crystal strongly depends on the particle sizes and shapes, it is impossible to consider all shapes of ice crystals such as column-needle, hexagonal plate, and aggregates. Here, we use hexagonal plate as approximation.

[9] The number concentration and size distribution of cloud droplets and ice particles have been introduced to calculate the radiative flux. For water clouds, the cloud optical depth is related to the liquid water path and effective radius. The asymmetry factor and single scattering albedo are parameterized as the function of optical depth and the effect radius based on the data from *Hu and Stamnes [1993]*. For ice clouds, we have parameterized the optical depth, the asymmetry factor and single scattering albedo as function of effective radius and crystal shape. All the coefficients are derived from the data [*Fu, 1996; Ebert and Curry, 1992*] for every model wave band.

3. ARCMIP Control Simulations

[10] The ARCMIP domain is designed to focus on the intercomparison of model simulations with enhanced measurements such as the Surface Heat Budget of Arctic Ocean (SHEBA) project from October 1997 to October 1998. A large amount of surface observation data with high quality was taken for this period at the SHEBA ice camp in Beaufort and Chukchi Seas and at the Barrow site of the Atmospheric Radiation Measurement (ARM) project. The aircraft, satellite and submarine measurements were also enhanced in that period. We have performed NARCM simulations in this period from September 1997 to September 1998. The atmospheric boundary forcing data is supplied by ECMWF operational analysis updated with 6 hourly intervals. The fields of wind (zonal and meridional), surface pressure, temperature, humidity and geopotential height have been supplied by this data set.

Sea ice has been specified according to the condition of ARCMIP experiment A.

[11] The model has 22 vertical levels with the top level at 10 mbar. Time interval is 20 min for integration. Output has been archived in every 6 hours. Almost all the variables needed by ARCMIP such as surface pressure, temperature, precipitation, total soil water, surface latent and sensible flux, upward and downward longwave and shortwave radiative flux, cloudiness, have been produced. Here we only analyzed several variables to see our model performance.

[12] The monthly mean results have been compared to National Centers for Environment Prediction (NCEP) reanalysis data. The downward solar radiation at surface is a little lower than the NCEP data during summer (Figure 1). This means our model presents excessive absorption of solar radiation by atmosphere. The downward longwave radiation is better than the solar radiation (Figure 2), only the patterns of small scale in our simulation are not consistent very well with the NCEP data. The surface temperature over the Arctic ocean is lower than the NCEP data during winter (Figure 3), but it has good agreement with NCEP data during summer (Figure 4).

[13] The total cloudiness is higher over the Arctic ocean and lower over the land surface during the autumn and winter (not shown). Contrast to the NCEP data, our cloudiness is higher over the Arctic ocean. However, if we compare our results with International Satellite Cloud Climatology Project (ISCCP) data, our simulations are consistent quite well with the observations. The precipitation rate has good agreement with NCEP data.

4. ARCMIP Aerosol Simulations

[14] For the high surface albedo over the Arctic region, the radiative forcing of aerosol is quite different from it over

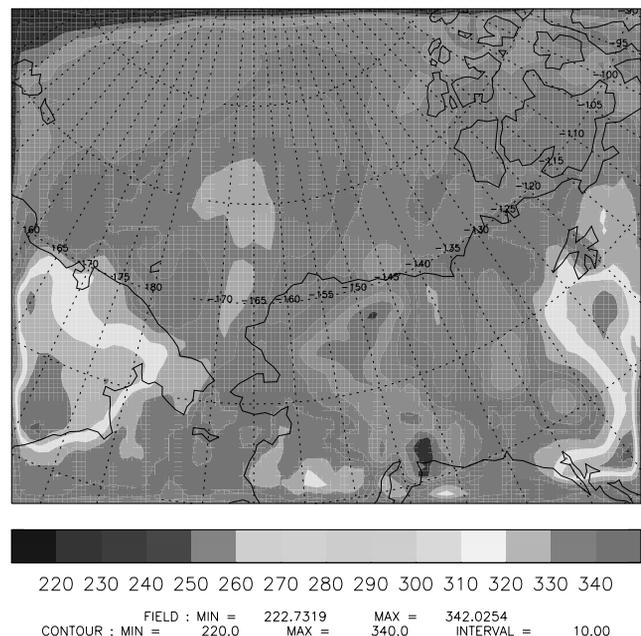


Figure 2. Downward longwave radiation at surface (July 1998). See color version of this figure at back of this issue.

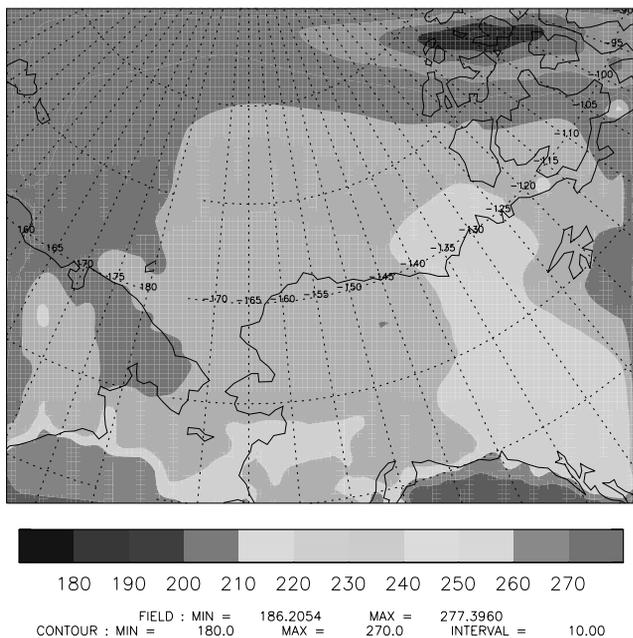


Figure 3. Surface temperature (January 1998). See color version of this figure at back of this issue.

other regions. The sources and components of aerosols over the Arctic are very complicated. From the measurements of recent decades, the major components of Arctic aerosols have been noted to be sulfuric acid, black carbon, sea salt, and dust [Shaw and Stamnes, 1980; Rosen et al., 1981; Barrie, 1986]. The strong direct and indirect radiative effects of aerosols have been suggested to cool the warming trend due to the increasing greenhouse gases [Shaw, 1987; Blanchet, 1989]. As the optical and microphysical properties of aerosols are not well known over this region, it is still

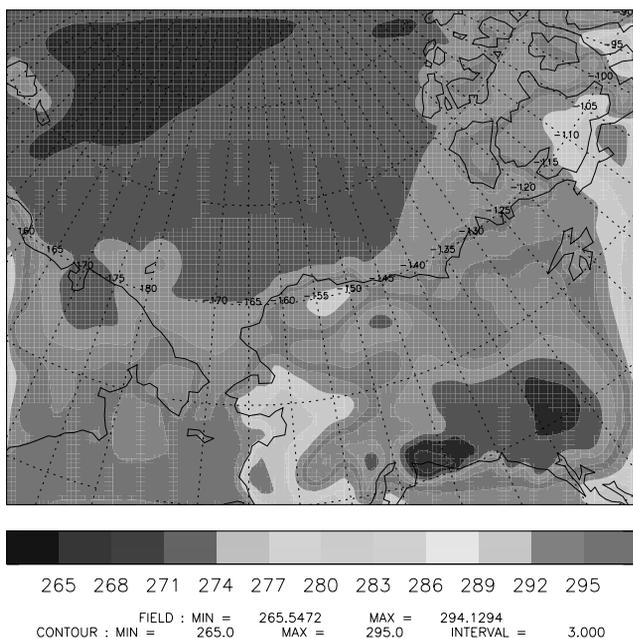


Figure 4. Surface temperature (July 1998). See color version of this figure at back of this issue.

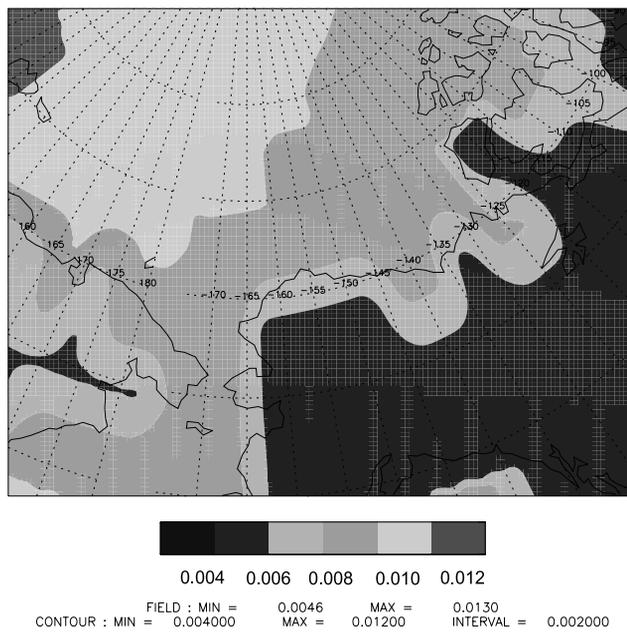


Figure 5. The optical depth of sulfate aerosols in climatology. See color version of this figure at back of this issue.

uncertain to quantify this kind of effect. For the first step we use the five kinds of aerosols (sulfate, black carbon, dust, sea salt, and organics) in climatology from chemical transport model (Figures 5–9). Figures 5–9 show the optical depth of aerosols in annually averaged value. The mass concentration of aerosol is converted from the value of optical depth. As compared with recent aerosol observation data by Sun photometer we found the values in some regions were not consistent very well with the measurements. For example, the AERONET/AEROCAN (Bokoye

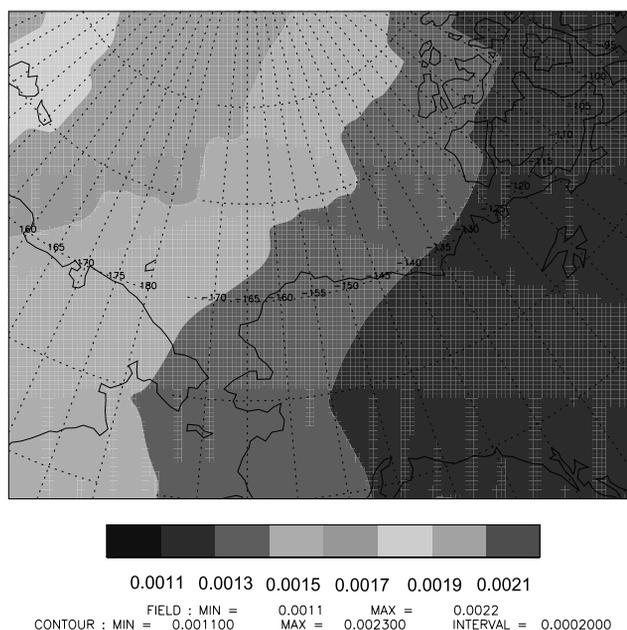


Figure 6. The optical depth of soot aerosols in climatology. See color version of this figure at back of this issue.

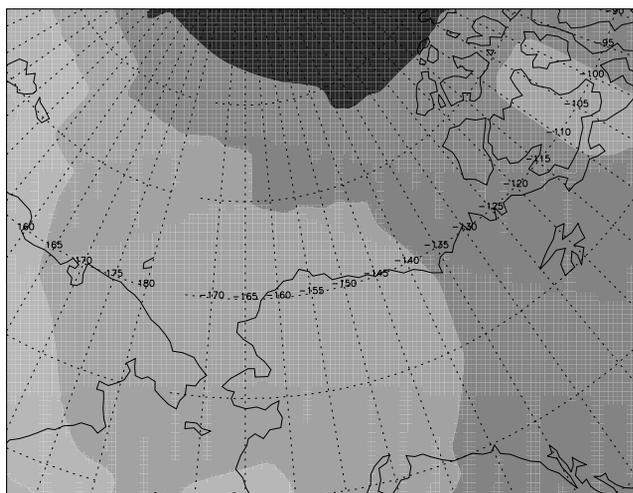


Figure 7. The optical depth of dust aerosols in climatology. See color version of this figure at back of this issue.

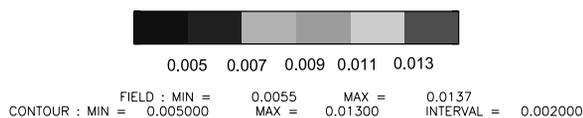
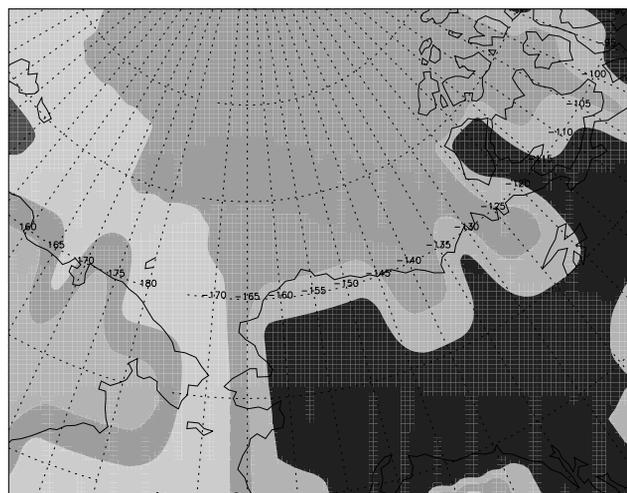


Figure 9. The optical depth of organic aerosols in climatology. See color version of this figure at back of this issue.

et al., unpublished manuscript, 2003) shows the total aerosol optical depth in 500 nm is around 0.064 over Barrow site between 1997 and 2000. However, the model results present a little lower than above measurement. There are rare data to present the composition rates of aerosols, so it is difficult to evaluate the aerosol concentration. For size and vertical distribution of aerosols, it is so uncertain that more in situ measurements are definitely needed.

[15] The aerosol cases have been carried out in two experiments between September 1997 and September

1998. One experiment was performed with pure sulfate aerosols (sulfate case) and the other with all five kinds of aerosols together (all aerosols case). The aerosol concentration with monthly averaged value was added into our model for every month. The gases concentrations are kept constant in these experiments.

[16] For sulfate case, strong scattering of this kind of aerosol usually leads to decrease the downward solar radiation at the surface. This result appears during spring

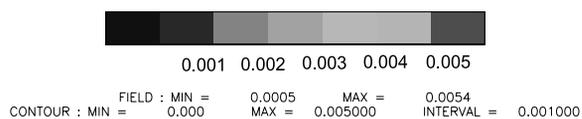
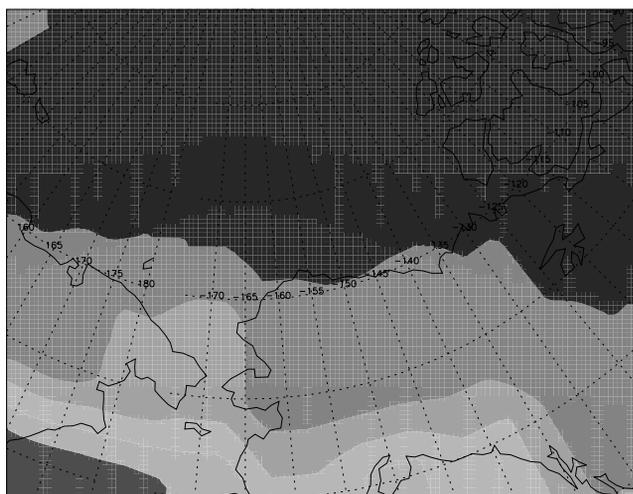


Figure 8. The optical depth of sea-salt aerosols in climatology. See color version of this figure at back of this issue.

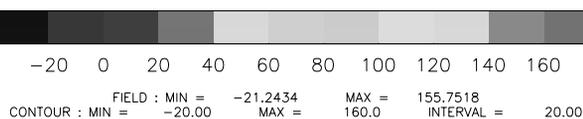
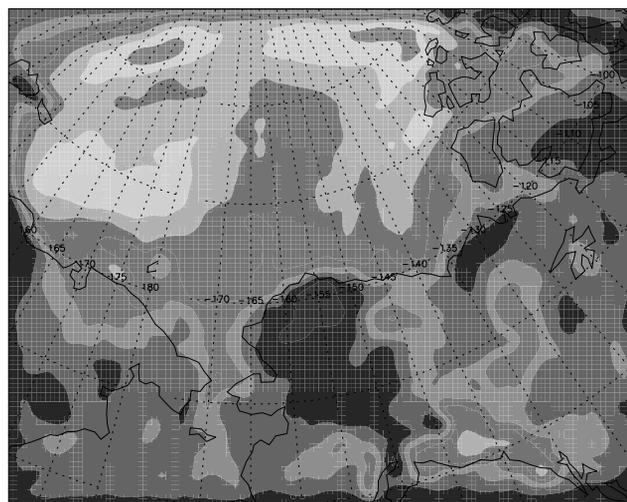


Figure 10. Downward solar radiation change at surface due to five kinds of aerosols together (July 1998). See color version of this figure at back of this issue.

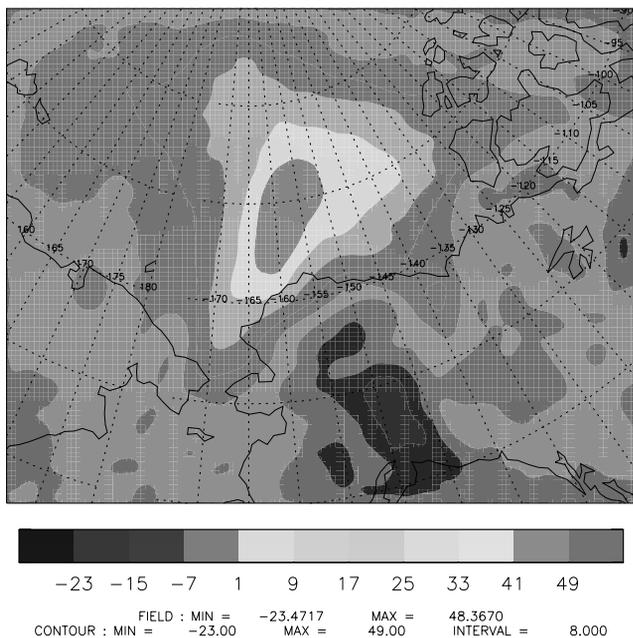


Figure 11. Downward longwave radiation change at surface due to five kinds of aerosols together (January 1998). See color version of this figure at back of this issue.

and autumn. However, the downward solar radiation is increased over the most part of Arctic region, especially over the Arctic ocean during summer. We think it is due to the contribution of cloud feedbacks. For all aerosols case, the downward solar radiation is increased more over the Arctic ocean, but decreased over the most part of Alaska and Eastern Russia (Figure 10). In winter, the aerosols have no much effect on solar radiation for it is almost dark during that period. Surprisingly, we find the downward longwave radiation at the surface is slightly increased over the Arctic ocean and Alaskan region for sulfate case. Such kind of increasing center is more apparent over the Arctic ocean for the all aerosols case. The maximum value has reached to 50 W/m^2 . Contrast to the Arctic Ocean, the downward longwave radiation is decreased over the Alaskan region during winter (Figure 11). During summer, the downward longwave radiation is still increased over the most part of Arctic ocean, and decreased over the most part of land. Combining the indirect radiative forcing of pure sulfate aerosols with direct one at surface, we estimate total radiative forcing at surface to be -7.2 W/m^2 in annual average. Especially, we find the positive contribution to radiative forcing of longwave part is very important in the Arctic.

[17] The pure sulfate aerosols cause a slightly warming over the most part of Arctic region during the winter. For all aerosols case, strong warming occurred over the Arctic Ocean (Figure 12). This is consistent with the strongly increasing of downward longwave radiation at the surface. In summer, the surface temperature has little changed over the Arctic ocean, but strongly warming occurs over the Alaska and Eastern Russia. The dipole of increasing center appears over the western part of Alaskan region. Maximum value goes up to 18 K. However, the dipole of increasing center becomes the decreasing center for the all aerosol case

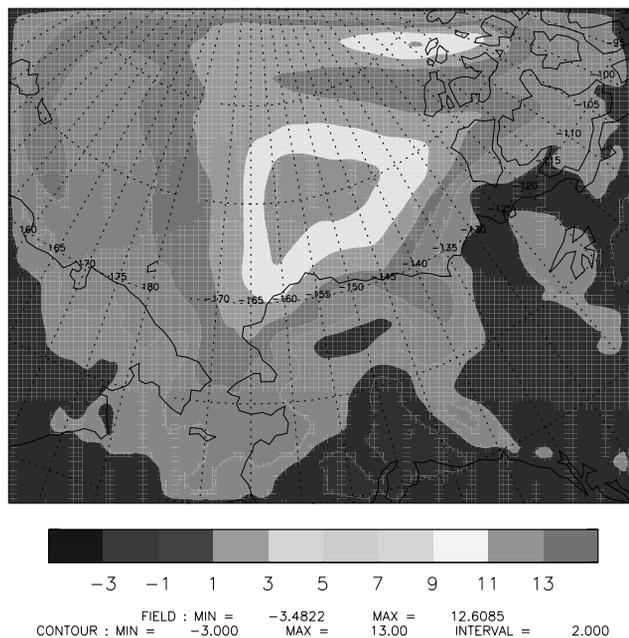


Figure 12. Temperature change at surface due to five kinds of aerosols together (January 1998). See color version of this figure at back of this issue.

(Figure 13). The maximum cooling is up to 8 K. So the response of aerosol forcing varies with seasons and strongly depends on what kinds of aerosols we consider. The cooling effect of aerosols can be (1) the enhanced scattering of solar radiation (direct effect), (2) the Twomey effect by which the cloud droplet number concentration increases, thereby increasing cloud reflectivity of solar radiation, and (3) the Albrecht effect which increases cloud lifetime

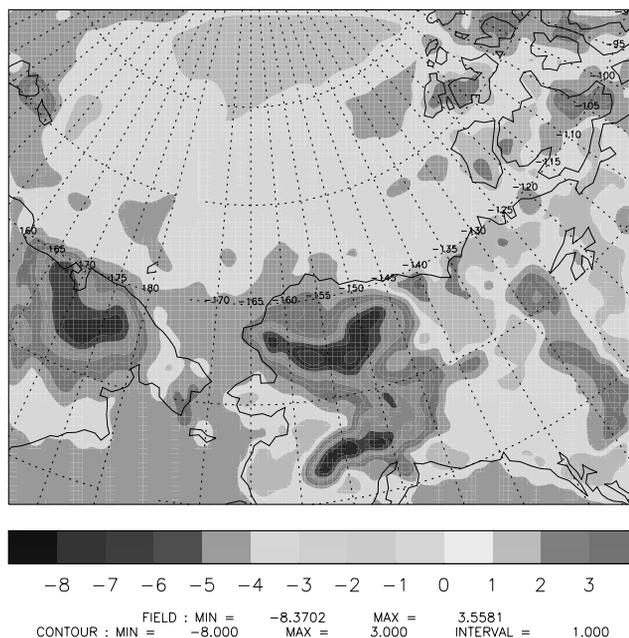


Figure 13. Temperature change at surface due to five kinds of aerosols together (July 1998). See color version of this figure at back of this issue.

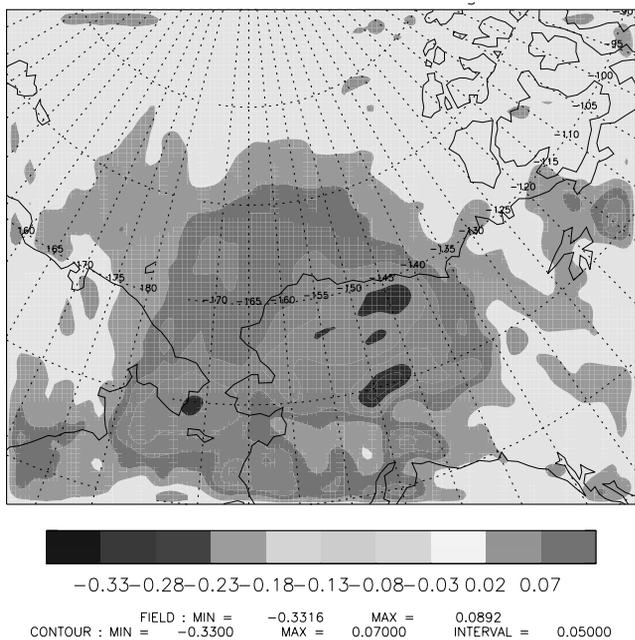


Figure 14. Total cloudiness change due to five kinds of aerosols together (January 1998). See color version of this figure at back of this issue.

[Albrecht, 1989]. Considering strong Arctic Oscillation (AO) over the Arctic Ocean, the contribution of natural variability on Arctic cooling can also not be neglected. The surface warming over some areas in the southern part of the domain is likely to be the heating effect of soot aerosols and complex dynamical feedbacks which can locally change significantly the cloud cover.

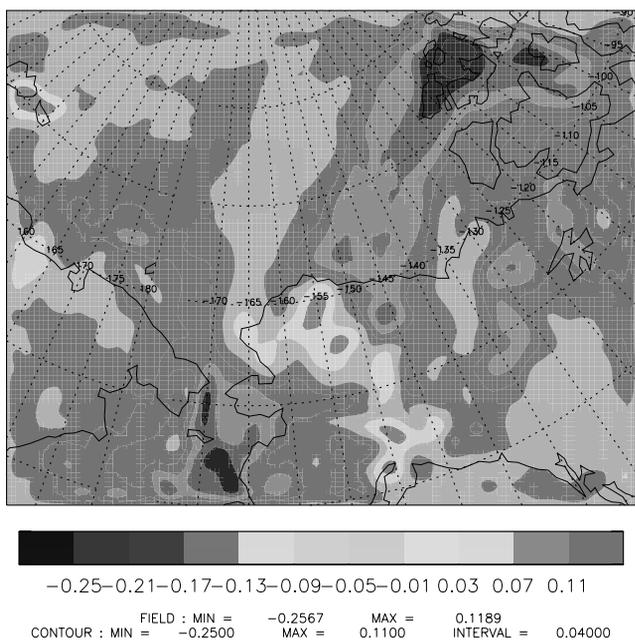


Figure 15. Total cloudiness change due to five kinds of aerosols together (July 1998). See color version of this figure at back of this issue.

[18] The total cloud cover has not changed much for the sulfate case during the winter, but it has strongly decreased by more than 20% over the western part of Alaskan region for the all aerosols case (Figure 14). In July, the cloud cover is increased over the Arctic ocean (Figure 15). Over the Alaskan region, the cloud cover is decreased for pure sulfate case and increased for the all aerosols case. The precipitation is decreased over broad band of Alaskan region during summer. The dipole of increasing and decreasing centers occurs for both aerosol cases. There is a little change of precipitation during winter. The dehydration has not occurred at the surface but occurred at lower troposphere when we check the anomaly of specific humidity (not shown).

[19] The microphysical and optical properties strongly depend on their composition of aerosols. For example, the imaginary part of refractive index for black carbon aerosols is quite large and result in absorbing solar radiation. This contributes to warm the atmosphere and the surface [Kaufman et al., 2002]. In this case, the black carbon radiative forcing seems to counteract the sulphate cooling effect. Dust, organics, and sea salt are also different in radiative properties and effects. Certainly, it is important to see which kind of aerosols plays the key role in total climate effects.

5. Intercomparison With in Situ Measurements

[20] SHEBA (Surface Heat Budget of the Arctic Ocean) project is designed to understand how the atmosphere, ocean, sea ice and snow cover affect the surface heat budget and the climate [Beesley et al., 2000]. The yearlong experiment from October 1997 to October 1998 had been made under and above the sea ice in the Beaufort sea. The measurements based on remote sensing of cloud and radiation had been deployed at the ice stations. We took the 4 simulating points to be averaged along the measured points along the ship track.

[21] The monthly averaged downward solar radiation at the surface simulated by NARCM during May is over-estimated about 30 W/m² with comparison to the SHEBA

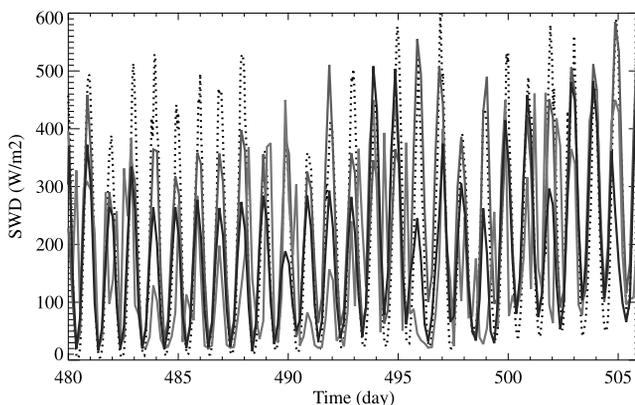


Figure 16. The downward solar radiation at surface simulated by NARCM compared with SHEBA observations in May 1998, blue, five aerosol species; green, sulphate; red, control; black, observations. See color version of this figure at back of this issue.

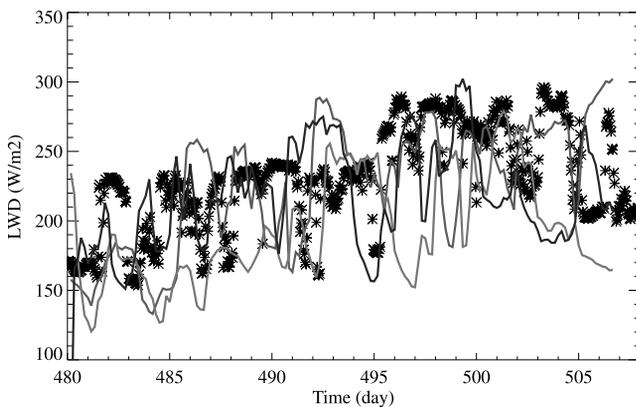


Figure 17. The downward longwave radiation at surface simulated by NARCM compared with SHEBA observations in May 1998: blue, five aerosol species; green, sulphate; red, control; black, observations. See color version of this figure at back of this issue.

data. The simulation for all aerosols case is best represented the observations with discrepancy only about 7 W/m^2 (Figure 16). If model includes the pure sulfate aerosol, strong reflective effect of solar radiation occurs due to the scattering properties of this kind of aerosols. Obviously, soot aerosol has contributed to the absorption in the solar radiation transfer process. If we compare the daily variation of downward solar radiation with the observation at surface, we find the peaks of simulation are underestimated. Still, the simulations for all aerosols case have better agreement with the observations.

[22] The downward longwave radiation at the surface simulated by NARCM has been captured well with the observations (Figure 17). The discrepancy between monthly average simulated value and the observation is only about 3.8 W/m^2 for the case of five kinds of aerosols together. If the model includes no aerosols or only sulfate aerosols, the simulations are overestimated and underestimated as compared with observations respectively. For the daily variation of downward longwave radiation at the surface, our model

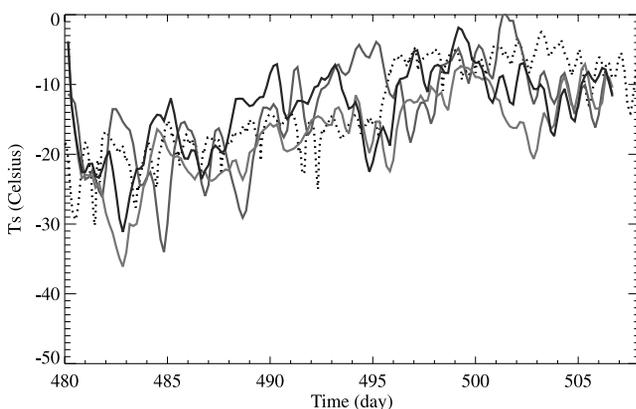


Figure 18. The temperature at surface simulated by NARCM compared with SHEBA observations in May 1998: blue, five aerosol species; green, sulphate; red, control; black, observations. See color version of this figure at back of this issue.

Table 1. Intercomparison of Monthly Averaged Value in May 1998

Variable	Control	Sulfate	Five Aerosol Species	Observation
Ts, K	259.46	255.98	259.62	258.79
LWd, W/m^2	225.35	193.29	216.885	220.69
SWd, W/m^2	227.23	178.38	181.89	189.74
Cloudiness	0.979	0.888	0.890	0.895

simulations have captured the variations quite well except few days. The agreement of simulation with the observation during the spring is better than during winter.

[23] The surface temperature is also simulated with NARCM in three cases (Figure 18). As compared with the SHEBA observations taken near the ice breaker in May 1998, it is encouraging that our simulations have quite good agreement with the observations although the discrepancy is a little large in some days. For sulfate case, the monthly averaged cooling effect is up to 3.5 K . Surprisingly, there is a little warming by 0.16 K for all aerosols case. The simulated surface temperature in all aerosols case is much better than it in sulfate case with an average temperature difference of only 0.8 K . For the other seasons, we find the aerosol effects are much stronger during summer. The results of all aerosols case are much nearer to the observations even the daily variation.

[24] The monthly averaged values of surface temperature, downward longwave and solar radiation at surface, and cloud cover in May 1998 for simulations and correlation coefficients with observations are presented in Tables 1 and 2. We find the aerosols have significant effects on surface temperature, radiative fluxes and cloud cover. The all aerosols case also reproduces quite well the variability of observed surface temperature with correlation of 0.79 . However, the correlations are very lower for cloud cover. Obviously, the cloud cover is very uncertain for the simulation over the Arctic region although the monthly averaged value has good agreement with the observation in May with discrepancy only 0.05 for all aerosols case. In January, the cloudiness of our simulation is overestimated in comparison with the observations. We think it is due to the ice clouds not simulated well during the winter. Especially, it is very clear that the cloudiness has not been captured well in some days. The precipitation is well simulated during spring, but not well during winter (not shown).

6. Summary and Discussion

[25] In spite of much recent work addressing the importance to reduce the uncertainties of aerosol forcing, the issue over the particular region such as the Arctic has not achieved much progress. In this study, we use NARCM to analyze the radiative effect of different kinds of

Table 2. Intercomparison of Correlations and Standard Deviations

Variable	Correlations of Control	Correlations of Sulfate	Correlations of Five Aerosol Species	Deviations of Observations
Ts	0.66	0.62	0.79	6.58
LWd	0.33	0.30	0.38	48.97
SWd	0.78	0.59	0.80	135.65
Cloudiness	0.22	0.14	0.32	0.06

aerosols such as sulfate, black carbon, dust, sea salt, and organic compounds. As the sensitivity experiment, we added the climatology of aerosols into our model. For control case, our model simulation is a little colder over Alaska than result of NCEP data. The total cloudiness is more than the NCEP data, but similar to the result of ISCCP data. The downward solar radiation is underestimated due to excessive absorption of solar radiation while the simulation of longwave radiation has good agreement with the observation. For aerosol case, we find the radiative and climate effects of pure sulfate aerosols and five kinds of aerosols together are amazingly different. The cooling effect over the Arctic ocean has been found for the pure sulfate case partly due to strong reduction of incoming solar radiation at surface, but a slight warming effect occurs for the all five kinds of aerosols together. The response of aerosol forcing varies with seasons. The dehydration process does not occur at the surface but occurs at the lower troposphere. The total cloudiness is decreased more than increased over the Alaska and not changed much over the Arctic ocean. Aerosols may strongly influence on the snowfall and lead to alter the snow cover in the land surface of the Arctic.

[26] The results of climate effect have been combined with both direct and indirect effects of aerosols. In the near future, we will separate those two effects. Also, the indirect effect of ice clouds needs to be highlighted, especially during the cold wintertime. A new microphysics scheme [Girard and Curry, 2001] accounting for effect of aerosol composition on the ice nucleation process has been implemented into NARCM. This will provide the analysis of radiative and climate effects of ice fog and diamond dust which are commonly observed over the Arctic during the cold wintertime. The aerosol-cloud-radiation interactions can be very important in the Arctic with the predominance of ice and mixed phase clouds. We will analyze the in situ measurements of lidar and radar to obtain the composition, size distribution and morphology of these clouds in order to better understand the aerosol, cloud and radiation processes occurring in polar climate system.

[27] From validation of our model results with the ARCMIP measurements. The improvements of cloud and radiative processes are necessary for better simulation of the climate responses to increasing greenhouse gases in such a particular and important region. The aerosol concentration is crucial for evaluation of the climate forcing of aerosols. We are running NARCM with larger domain to produce the realistic aerosol concentration over the Arctic region. Furthermore, it is imperative to analyze the physical feedbacks and evaluate the physical parameterizations before doing scenarios experiments for predicting the future Arctic climate change.

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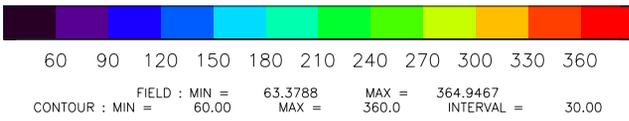
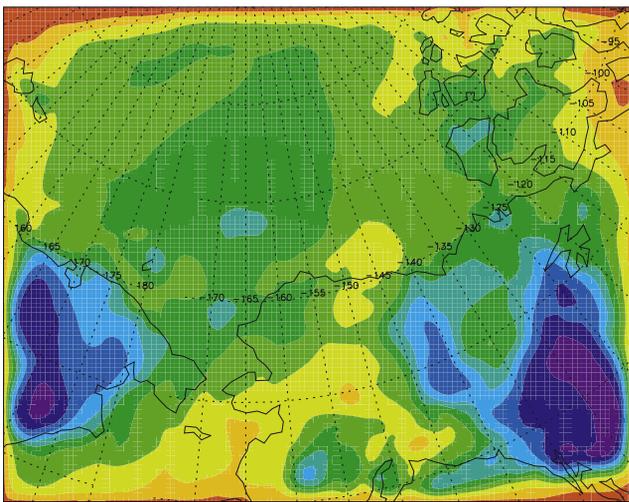


Figure 1. Downward solar radiation at surface (July 1998).

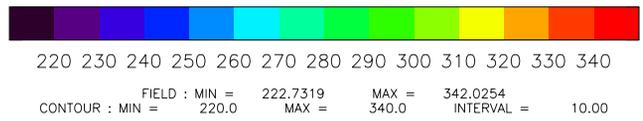
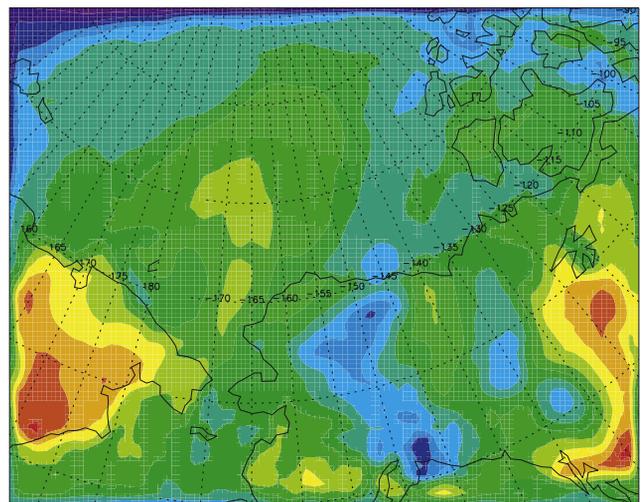


Figure 2. Downward longwave radiation at surface (July 1998).

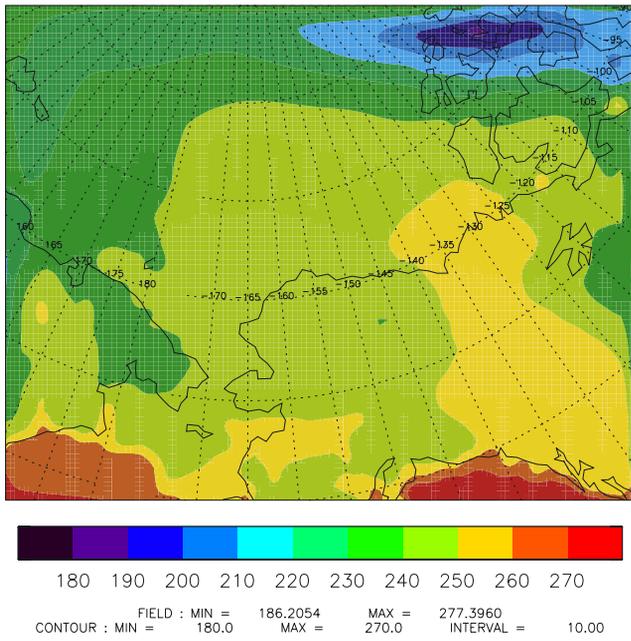


Figure 3. Surface temperature (January 1998).

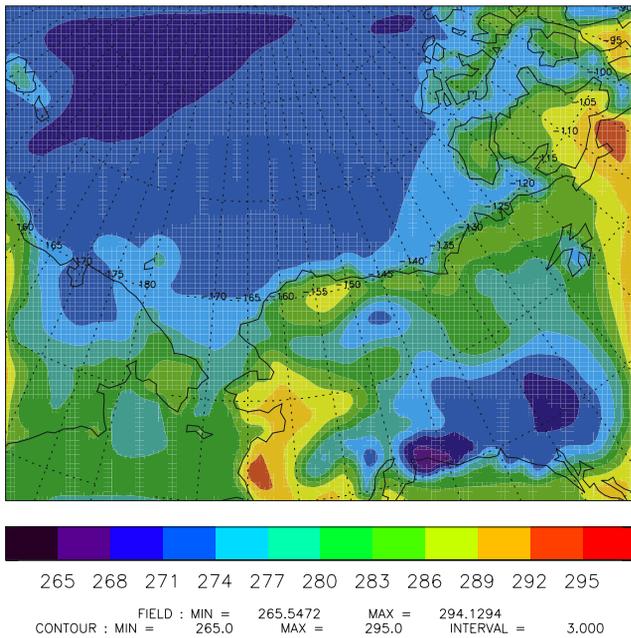


Figure 4. Surface temperature (July 1998).

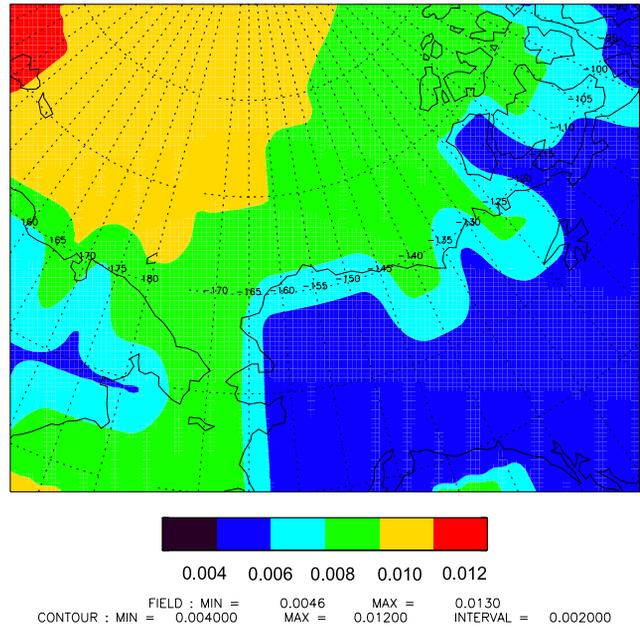


Figure 5. The optical depth of sulfate aerosols in climatology.

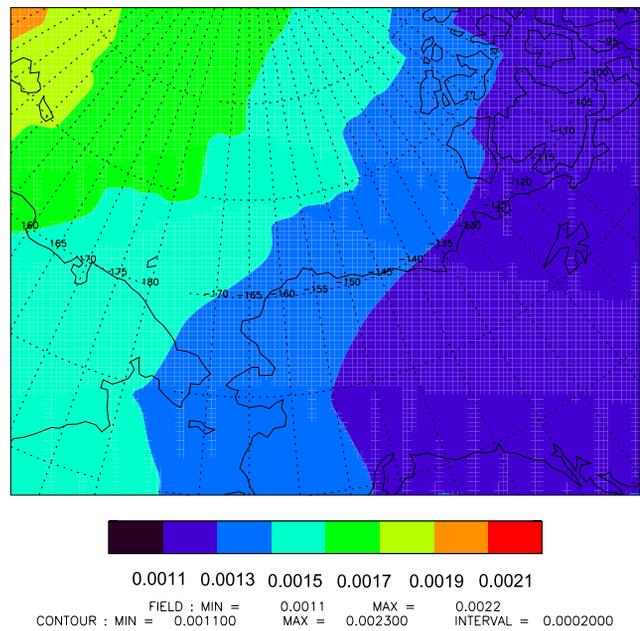


Figure 6. The optical depth of soot aerosols in climatology.

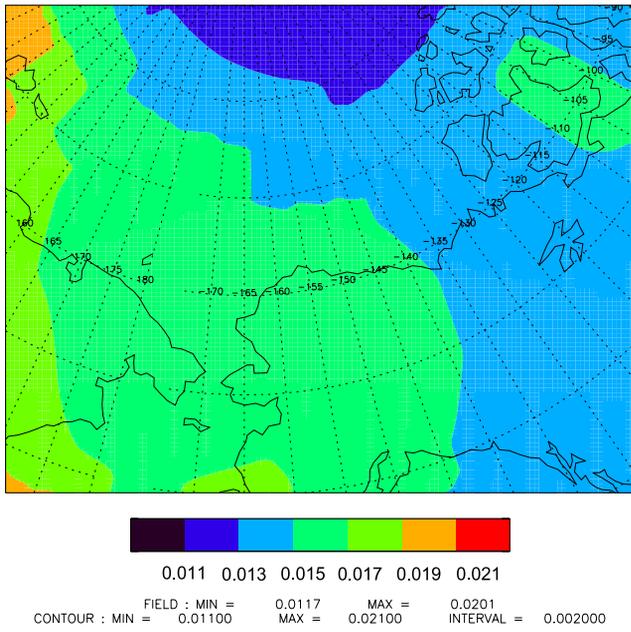


Figure 7. The optical depth of dust aerosols in climatology.

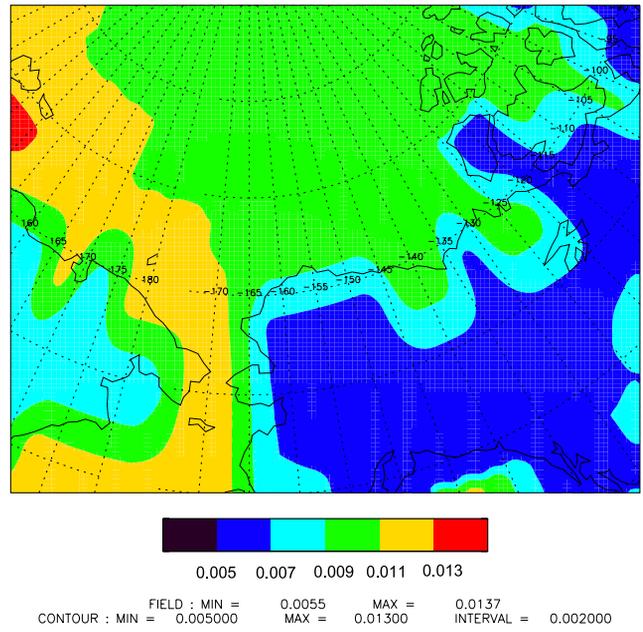


Figure 9. The optical depth of organic aerosols in climatology.

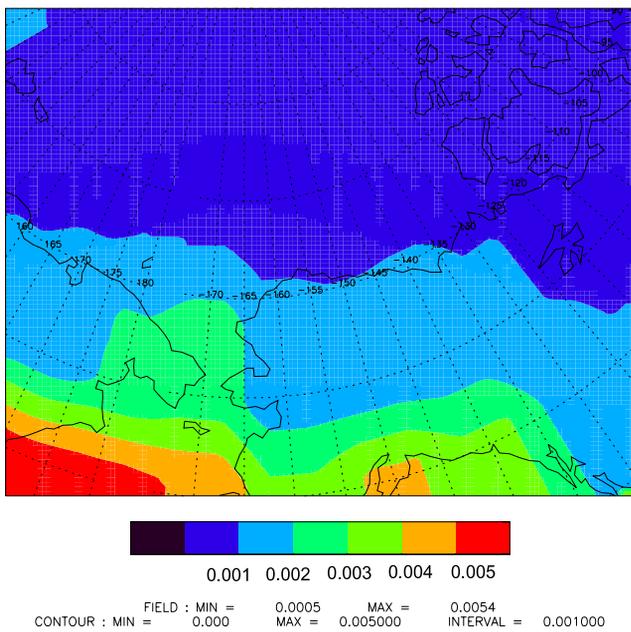


Figure 8. The optical depth of sea-salt aerosols in climatology.

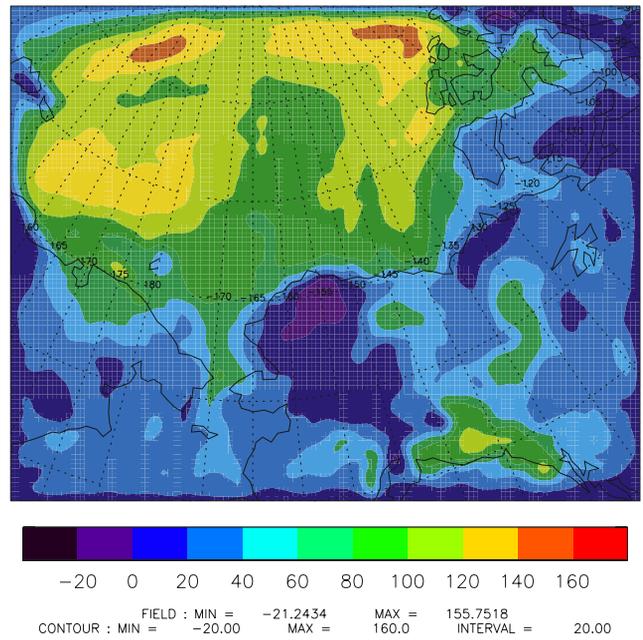


Figure 10. Downward solar radiation change at surface due to five kinds of aerosols together (July 1998).

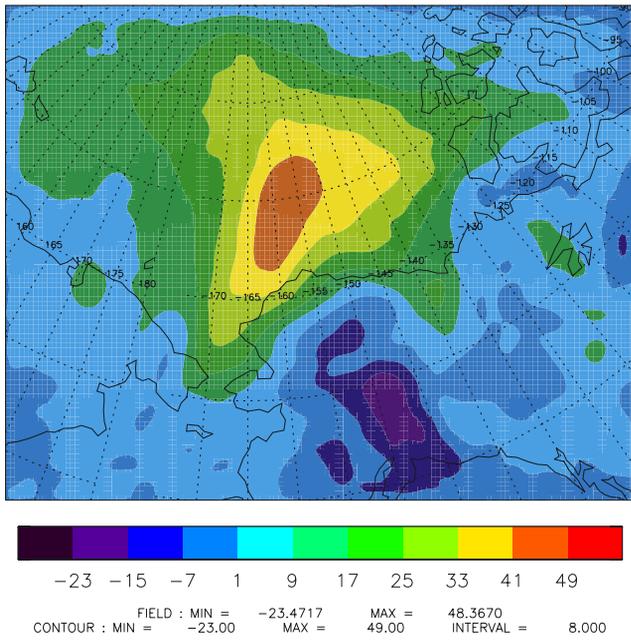


Figure 11. Downward longwave radiation change at surface due to five kinds of aerosols together (January 1998).

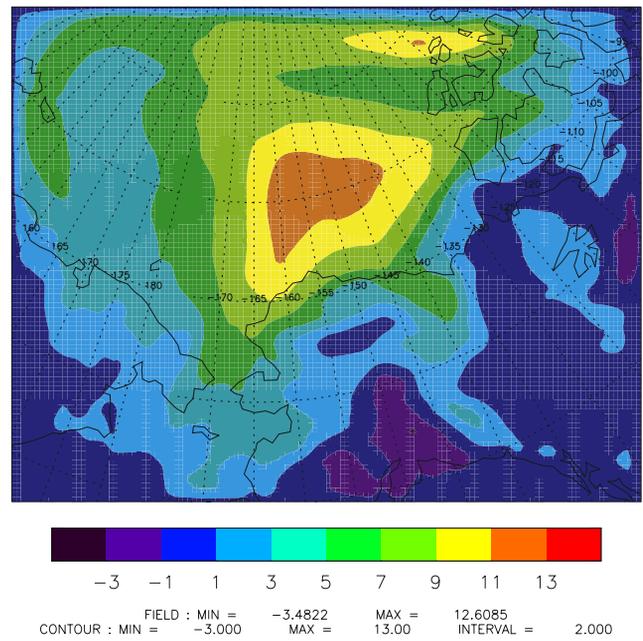


Figure 12. Temperature change at surface due to five kinds of aerosols together (January 1998).

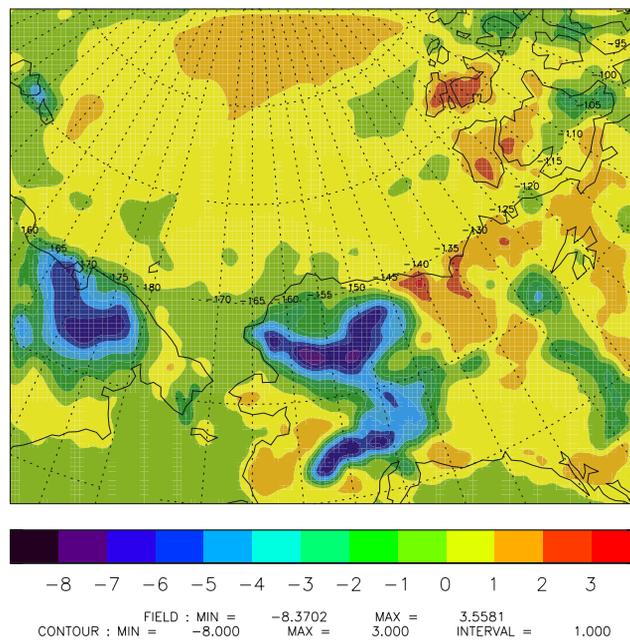


Figure 13. Temperature change at surface due to five kinds of aerosols together (July 1998).

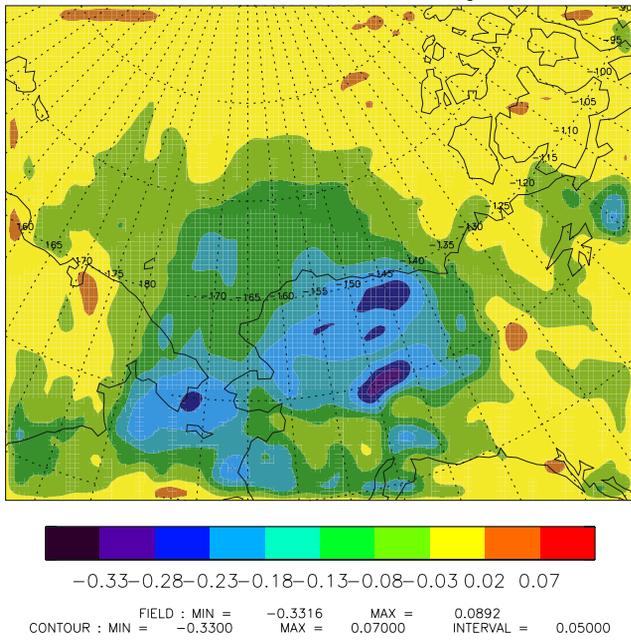


Figure 14. Total cloudiness change due to five kinds of aerosols together (January 1998).

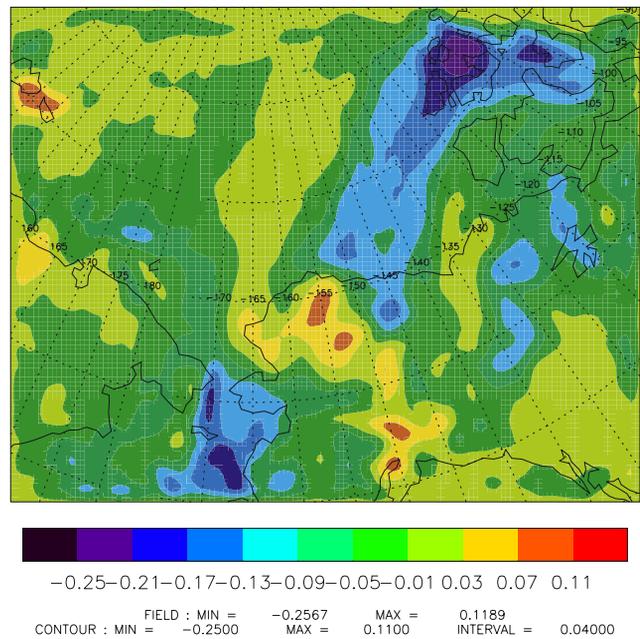


Figure 15. Total cloudiness change due to five kinds of aerosols together (July 1998).

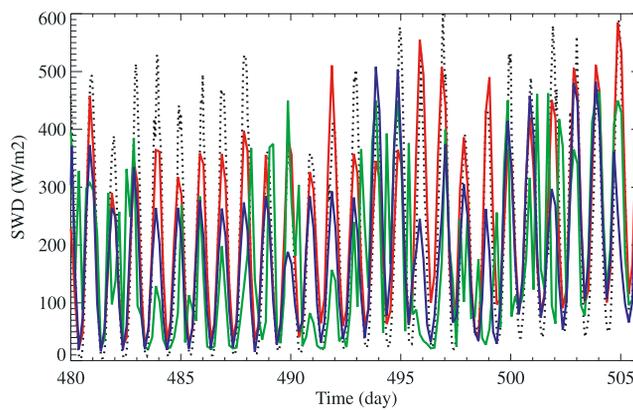


Figure 16. The downward solar radiation at surface simulated by NARCM compared with SHEBA observations in May 1998, blue, five aerosol species; green, sulphate; red, control; black, observations.

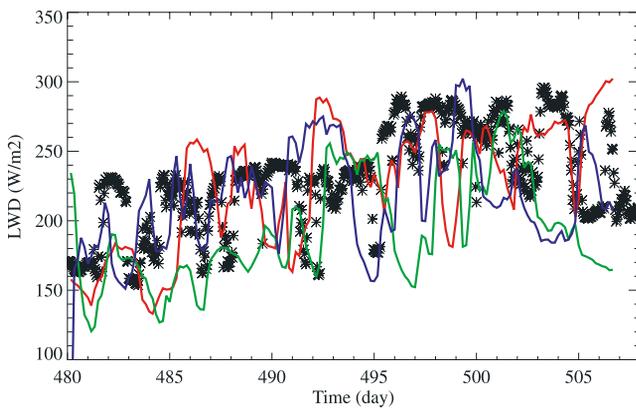


Figure 17. The downward longwave radiation at surface simulated by NARCM compared with SHEBA observations in May 1998: blue, five aerosol species; green, sulphate; red, control; black, observations.

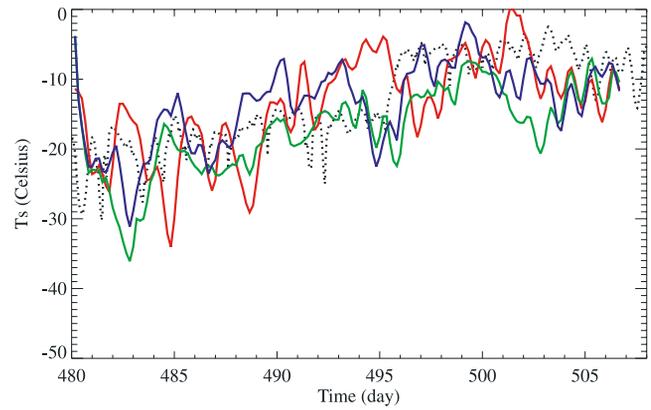


Figure 18. The temperature at surface simulated by NARCM compared with SHEBA observations in May 1998: blue, five aerosol species; green, sulphate; red, control; black, observations.