Monitoring of the effects of light absorbing aerosols on radiation processes of the atmosphere and snow surface (Abstract of the Final Report)

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1. Introduction

The light absorbing aerosols (black carbon and mineral dust) directly heat the terrestrial atmosphere by absorbing the solar radiation and the deposition of light absorbing aerosols on the snow surface reduces the earth surface albedo. These processes facilitate the global warming as well as the green house effect gas such as carbon dioxide and methane. Therefore, these processes are important in the earth climate system. In this study, in order to monitor the spatial and temporal variation of the absorptive aerosols, the ground-based observational sites are constructed in the eastern Asia region, where is the one of the largest source region of the light absorbing aerosols. Furthermore, the deposition of absorptive aerosols on the snow surface and the variation of the snow surface albedo are monitored by the ground-based measurement and the satellite remote sensing. In addition to the above observational study, we validate and improve the numerical global aerosol transportation model using these observational data, and evaluate the effect of the deposition of absorptive aerosols on snow and ice to the Earth's radiation budget through numerical simulation.

2.Research Objective

In order to achieve the objectives of this study, the following three sub-studies are performed.

(1) Monitoring of atmospheric aerosol in the eastern Asia region by the ground-based observation measurements

The light absorbing aerosols are continuously monitored using a various kind of radiometers and the instruments to measure optical properties on the ground-based observation sites in the eastern Asian region and the spatial and temporal variation of the light absorbing aerosols are investigated. Furthermore, the effect of aerosols on the surface radiation budget is also investigated.

(2) Monitoring of snow impurity concentrations and the relevant albedo change by ground based measurements and satellite remote sensing

The light absorbing aerosol depositions on snow/ice surface and the relevant albedo variations are monitored from ground-based measurements and satellite remote sensing. Using these data, a physically based snow albedo model (PBSAM), which can calculate the broadband snow albedos from snow parameters including snow impurity concentrations, is developed and incorporated in general circulation model to improve the estimation of climate impact by light absorbing aerosol in snowpack. Snow impurity concentration and broadband albedo of snow/ice surface in broad areas are monitored by satellite remote sensing.

(3) Numerical simulation of the absorptive aerosol and snow albedo change using a global aerosol model

We aim to evaluate the effect of light absorbing aerosols to the terrestrial radiation budget through numerical simulation by the global climate model developed in the Meteorological Research Institute. The objective of the study is to evaluate the light absorbing aerosols through the direct radiative effect and the albedo reduction by depositing on snow and ice.

3.Research Method

(1) Monitoring of atmospheric aerosol in the eastern Asia region by the ground-based observation measurements

In this study, the radiation field is measured by the pyranometer, pyrheliometer and skyradiometer in order to estimate aerosol optical properties and to investigate the effect of aerosol on the surface radiation budget. Furthermore, the in situ measurements of optical properties of aerosol are performed by the nephelometer and Aethalometer. Using these data, the spatial and temporal variations of absorptive aerosols are monitored and investigated. The observation sites are chosen taking account of the emission and transportation of the black carbon and mineral dust aerosols. Furthermore, in order to maintain the accuracy of measurements by radiometers, the reference solar spectral pyrhliometers are calibrated every year. The pyranometers and pyrheliometers are also inter-compared by the reference ones every year.

(2) Monitoring of snow impurity concentrations and the relevant albedo change by ground based measurements and satellite remote sensing

To monitor the light absorbing aerosol concentrations in snow/ice (snow impurities) and their effect on the albedo variation, the continuous radiation budget and snow pit work measurements are carried out in Hokkaido, Japan. Snow samples collected from snow pit work are analyzed to obtain the concentrations of mineral dust, elemental carbon (EC ~ black carbon (BC)) and organic carbon (OC). Using these data, a physically based snow albedo model and snow grain size calculation scheme are developed and incorporated in an earth system model to estimate the climate impact of light absorbing aerosols in snowpack. Through this process, snow metamorphism and albedo process (SMAP) model, which is a one dimensional snowpack model, is developed and validated with the data measured in Hokkaido. Using the satellite remote sensing algorithms to retrieve snow impurity concentration and broadband albedo of snow/ice surface, those snow parameters in Greenland, where drastic snow and ice melting is presently undergoing, are monitored with (Moderate Resolution Imaging Spectroradiometer) MODIS data

(3) Numerical simulation of the absorptive aerosol and snow albedo change using a global aerosol model

We used the global climate model MRI-CGCM3, which consists of an atmospheric general circulation model (MRI-AGCM3), an ocean general circulation model (MRI.COM), and a global aerosol model (MASINGAR mk-2; Model of Aerosol Species IN the Global Atmosphere) (Yukimoto et al., 2012). The model components were interactively connected by a coupler library called Simple coupler (Scup, Yoshimura and Yukimoto, 2008). MRI-CGCM3 is a part of the MRI Earth System Model (MRI-ESM1) (Yukimoto et al., 2011; Adachi et al. 2013). MASINGAR mk-2 treats five aerosol species, namely sulfate (and its precursors), BC, organic carbon (OC), sea salt, and mineral dust (Tanaka et al., 2003). BC and OC aerosol in this model are divided into hydrophobic and hydrophilic particles, and treated separately. We assume that 80% of BC is emitted as hydrophobic, which will become hydrophilic over time, with an e-folding time of 1.2 days. Following Chin et al. (2002), particle size distribution of BC aerosol is expressed by a lognormal distribution with effective radius of 0.039 μm and geometric standard deviation of 2.0, and particle density is assumed to be 1.0 g cm^{-3}. Hydrophobic BC aerosol is scavenged by dry deposition only, whereas hydrophilic BC aerosol is scavenged by both dry and wet deposition. The particle density of BC is assumed to be 1.25 g cm^{-3}. The aerosols are assumed to be externally mixed in the radiation calculation. The concentrations of the aerosols are transferred to the AGCM and used for the calculation of atmospheric radiative transfer and calculation of cloud properties. To incorporate the effect of deposition flux of light absorbing aerosols on the snow albedo, we improved the MRI-AGCM3 so that the land surface model HAL to take into account the aerosol deposition fluxes calculated with our global aerosol model MASINGAR mk-2. The SMAP model is incorporated into HAL, which was newly developed for the MRI-AGCM3.

To evaluate the radiative effects of black carbon aerosol to the global climate, we performed sensitivity experiments using the MRI-CGCM3. We conducted a series of 25-year simulations for the period of 1 January 2005 to 31 December 2029, setting all GHG concentrations and BC, OC, and SOx emissions to those in 2005. To elucidate the radiative effects of the BC aerosols, we conducted experiments under three sets of conditions. The default setup of the model simulation was used as the “Control” experiment. The second experiment (the “No-BC” experiment) excluded airborne BC from the radiative transfer calculation. The difference between the Control experiment and the No-BC experiment represented the effect of total elimination of BC emissions into the atmosphere.

Secondly, we performed numerical sensitivity experiments to evaluate the effects of the deposition of light absorbing aerosols on snow albedo using a subset model of MRI-CGCM3. The first experiment incorporates both black carbon and mineral dust depositions on snow surface for albedo calculation (Control run). The second experiment considers no black carbon aerosol deposition on snow surface (no BC deposition). The third experiment considers no mineral dust deposition (no dust deposition), and the fourth experiment incorporates no aerosol deposition (no aerosol deposition).

4.Result

(1) Monitoring of atmospheric aerosol in the eastern Asia region by the ground-based observation measurements

In order to get the data to calibrate the solar spectral pyrhliometer, the measurements were performed at Mauna Loa observatory (NOAA) in every November. The sky radiometer, which is an instrument to measure the solar direct irradiance and radiances from the sky, is calibrated by Langley method. The calibration constants (or instrument constants) were determined with the root mean squares (RMS) error less than 1.0%. The radiometers calibrated by the data obtained at Mauna Loa Observatory were utilized for the calibration of the other project such as GOSAT validation and SKYNET.

The continuous measurement of sky radiometer at Beijing, Qingdao, Miyakojima, Fukuoka and Tsukuba were analyzed using by the software MRI-MLM, which is the improved version of SKYRAD.PACK version 4.2. Sky radiometer can be detected the seasonal variation of aerosol optical properties (aerosol optical thickness (AOT), Ångström exponent (α) and single scattering albedo (SSA)).

In this study, the methods to calibrate the solar spectral pyrhliometer and to calibrate the instrument for in situ measurements of scattering and absorption coefficients were established and it enabled us to make the accurate measurement and to monitor the aerosol optical properties.

(2) Monitoring of snow impurity concentrations and the relevant albedo change by ground based measurements and satellite remote sensing

(i) In-situ measurements of snow impurities at domestic sites

The mass concentrations of EC (presumably equivalent to BC), OC and dust in snow at Sapporo, Japan were analyzed from 2007 to 2013 (Fig. 1). These snow impurity concentrations were relatively low during the accumulation season from December to February, while gradually increased in the melting season from March to April. On the other hand, the remarkable long-term trend was not confirmed during the past six winters.

(ii) Improvement of a physically based snow albedo model

A physically based albedo model was developed to calculate the broadband albedos and solar heating profile from any layer structure of snow physical parameters including snow grain size and snow impurity concentrations (Aoki et al., 2011). It was confirmed that albedos simulated by the model with data mentioned in (i) agreed well with the in-situ measurements.

(iii) Development of Snow Metamorphism and Albedo Process model (SMAP)

A 1-dimendional multilayered physical snowpack model SMAP that incorporates a physically based snow albedo model of (ii), was developed to calculate temporal evolution of energy and mass balances of snowpack by taking snow settlement, phase changes, water percolation, and snow metamorphism into account (Niwano et al., 2012). The model evaluation was performed during two winters from 2007 to 2009 at Sapporo, Japan. It was found that accuracy of SMAP was reasonable under dry snow conditions, however, inadequate performance under wet snow conditions highlighted the necessity of further model development. We also investigated the effects of snow impurities on snowmelt with SMAP at Sapporo during the two winters. It was found that snowpack durations at Sapporo were shortened by 19 days during the 2007–2008 winter and by 16 days during the 2008–2009 winter due to radiative forcings caused by snow impurities.

(iv) Satellite remote sensing of snow physical parameters in Greenland

Snow physical parameters retrieved from MODIS data were validated by comparing to the in-situ measurements on the northwestern Greenland ice sheet during 2012 summer. The satellite-derived surface snow grain size and BC concentrations were generally consistent with the in-situ measurement. Analyses for annual variations of satellite-derived snow parameters from 2000 to 2013 with Terra/MODIS data over Greenland revealed that the larger grain sizes were observed in recent summers during 2009-2012, whereas snow BC concentration in accumulation areas was not high enough to detect from satellite sensor. As a result, it was suggested that albedo in Greenland is controlled by mainly snow grain size associated with temperature variation

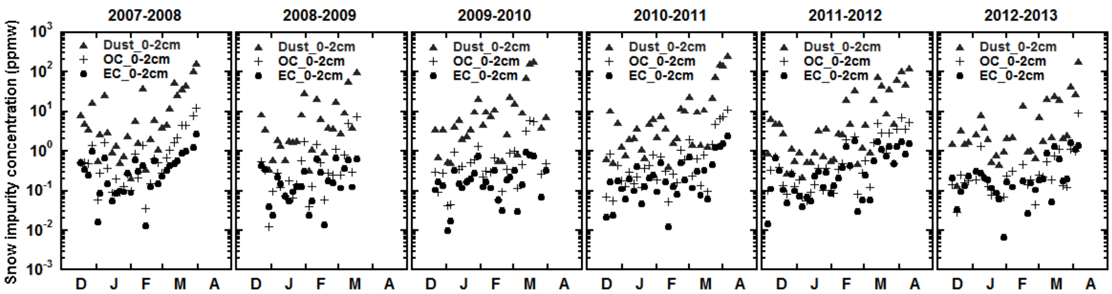

Figure 1. Mass concentrations of elemental carbon (EC), organic carbon (OC) and mineral dust in snow layer 0-2 cm deep at Sapporo from December to April during 6 winters from 2007 to 2013.

(3) Numerical simulation of the absorptive aerosol and snow albedo change using a global aerosol model

The globally averaged direct radiative perturbation of black carbon was +0.3 W m^{-2} at the top of the atmosphere and -0.45W m^{-2} at the ground surface. The direct radiative perturbation of black carbon was large over the source region of black carbon and their downwind regions. The climatic responses in the simulated results showed enhanced convective activity in tropical region due to the atmospheric black carbon aerosol. Precipitation was reduced due to black carbon, and the inter-tropical convergence zone was shifted equatorward. Because of the changes of convective activity, the atmospheric general circulation was also modified, and northward shift of stratospheric jet stream was observed. The simulated results suggested that the atmospheric black carbon aerosol influences not only around the vicinity of the source regions but also over the whole atmosphere through the tropical convective activity. The influence of black carbon aerosol is largely consistent with the previous researches. However, the magnitude of the climatic response may depend on the numerical climate models.

5. Discussion

(1) Monitoring of atmospheric aerosol in the eastern Asia region by the ground-based observation measurements

The calibration constants (or instrument constants) were accurately and stably determined with the root mean squares (RMS) error less than 1.0%. However, the trend of the calibration results of standard sky radiometer from 2009 to 2012 shows the difference of 19 - 41 % at 340 - 400nm and 0.6 – 5 % at 500 – 1020nm. This means the necessity of regular calibration and inter-comparison in order to maintain the accuracy of measurements by radiometers.

Sky radiometer data observed at Beijing, Qingdao, Miyakojima, Fukuoka, and Tsukuba from 2008 to 2013 were analyzed by using the software MRI-MLM. Sky radiometer can be detected the seasonal variation of aerosol optical properties (aerosol optical thickness (AOT), Ångström exponent (α) and single scattering albedo (SSA)).

(i) The features of aerosol optical thickness (AOT) at Fukuoka and Tsukuba are a pattern of larger AOT in the summer and smaller AOT in the winter. In Miyakojima, AOT shows small in summer and large in winter.

(ii) Ångström exponent (α) exhibits a minimum around spring at Fukuoka and Tsukuba. This suggests this season is influenced by yellow dust at Fukuoka and Tsukuba. The summer α is smaller than another season at Miyakojima. In Fukuoka, summer α is larger than another season.

(iii) The summer single scattering albedo (SSA) is larger than other seasons at Beijing and Qingdao. The summer SSA shows smaller than other seasons at Miyakojima. The features of SSA at Fukuoka and Tsukuba are a pattern of larger SSA in the summer and smaller SSA in the winter.

The in situ measurement data of aerosol optical properties at Tsukuba was analyzed to investigate trends of aerosol properties and climatology from 2002 to 2013. The results show that most aerosol characteristics had seasonal variation and decreasing or increasing trends significant at the 95% confidence level.

(i) The extinction coefficient at 550nm and the absorption coefficient at 530nm had statistically significant decreases from 2002 to 2013 of -1.5×10^{-6} and -5.4×10^{-7} m^{-1} $year^{-1}$, respectively.

(ii) The single-scattering albedo at 550nm had a significant increasing trend of 7.4×10^{-3} $year^{-1}$.

(iii) The increasing trend of 2.1×10^{-2} $year^{-1}$ in the absorption Ångström exponent from 2006 to 2013 was significant. This tendency suggests a compositional change of light-absorbing aerosol.

Aerosol characteristics estimated from multi-wavelength integrating nephelometer and absorption photometer data in this study were consistent with those derived from radiometer data. Therefore, ground-based monitoring of aerosol optical properties is useful for monitoring aerosol characteristics and interpreting variations in the surface radiation budget.

(2) Monitoring of snow impurity concentrations and the relevant albedo change by ground based measurements and satellite remote sensing

Light absorbing aerosol in snowpack (snow impurities) has an effect to amplify global warming by reducing the albedo (positive feedback). It is important to clarify the following three issues: how high the impurity concentrations are, how about their trends are, and how much their contributions to albedo reduction and snow melting are.

The mass concentrations of light absorbing snow impurities such as EC (presumably equivalent to BC), OC and dust in snow were monitored at Sapporo and Memuro, Japan by an analysis of snow samples and using a ground-based spectral radiometer (Kuchiki et al., 2009). The result was that there was not a remarkable long-term trend at Sapporo from 2007 to 2013. Additionally, the retrieval result of BC concentrations using the spectral radiometer at Sapporo and Memuro suggested that the mixing state of snow and BC particles was different depending on the site and season. This is the important factor in a modeling of the effect of snow impurities on snow albedo.

A vertical profile of solar heating is investigated using a physically based albedo model. The result showed that most of solar radiation at the wavelengths longer than 1.4 μm is absorbed near the snow surface and that at the wavelengths less than 1.4 μm is absorbed in the thicker layers which depend strongly on snow grain size and impurity concentrations. This could be relevant to the fact that snow grain size in melting period increases within a short period and overall snow layers can melt efficiently.

In order to assess effects of snow impurities on snow-atmosphere interaction, numerical sensitivity tests with SMAP were performed. Figure 2 indicates snow depths simulated by the default settings that input mass concentrations of BC and dust (CTL), and pure snow experiment that assumed no snow impurities (PURE) during 2007-2009 winters at Sapporo. By comparing snowpack durations between CTL and PURE scenarios, we found that snowpack durations at Sapporo were shortened by more than 2 weeks due to radiative forcings caused by snow impurities. Snow impurity effect on snow melting was significant in melting period for the colder first year and continued since January for the warmer second year.

The variation of snow parameters over Greenland, where drastic snow and ice melting is presently undergoing, were examined by satellite remote sensing. First, snow grain size and BC concentration in snow retrieved from MODIS data were validated by comparing to the in-situ measurements on the northwestern Greenland ice sheet. Although the BC concentration derived from the Terra/MODIS data was overestimated due to the sensor degradation, the other snow parameters were confirmed to be retrieved with a reasonable accuracy. The satellite-derived snow grain sizes were large in recent summers during 2009-2012 compared to the previous years in 2000s, particular in 2012 the remarkable snow grain increase was observed overall Greenland ice sheet, while there was no constant increasing trend and the grain size in 2013 was of the order of 2000. Snow impurity concentration was not high enough to detect from satellite sensor, and the impurity variation retrieved was attributed to a degradation of MODIS sensor sensitivity.

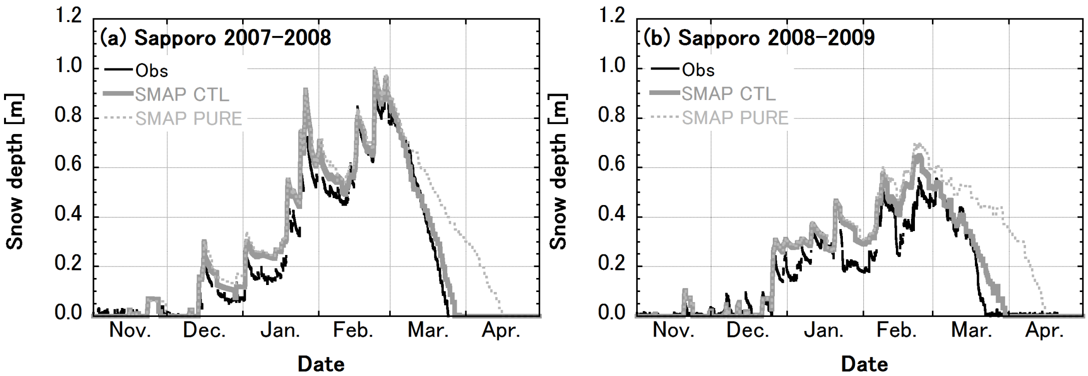

Figure 2. Half-hourly snow depths simulated with SMAP by default settings (CTL: gray solid curve) and pure snow experiment (PURE: gray dots), and the observed snow depths (black solid curve) at Sapporo during two winters: (a) 2007–2008 and (b) 2008–2009.

(3) Numerical simulation of the absorptive aerosol and snow albedo change using a global aerosol model

In this study, we improved the treatment of the light absorbing aerosols by evaluating the radiative effects of the aerosols and incorporating the snow darkening effect by the depositions of black carbon and mineral dust in the global climate model MRI-CGCM3.

We conducted sensitivity experiments to investigate the climatic response to the presence or absence of atmospheric BC aerosols. The results predicted a large atmospheric heating effect of BC in the tropical upper troposphere, mid-latitude regions of the Northern Hemisphere, and the Antarctic region. It also suggested that surface air temperatures in tropical regions, especially the Sahel, India, and Southeast Asia, will be reduced by the presence of atmospheric BC. Therefore, radiative heating of atmospheric BC is predicted to change atmospheric stability conditions and hence the general circulation of the atmosphere and ocean. The simulated results suggested that the atmospheric black carbon aerosol influences not only around the vicinity of the source regions but also over the whole atmosphere through the tropical convective activity. The influence of black carbon aerosol is largely consistent with the previous researches.

The result of the sensitivity experiment of the snow darkening by aerosol depositions, the albedo change with total deposition of absorptive aerosols is greater than the sum of the individual albedo changes of black carbon and mineral dust aerosols. This is because of the non-linear relationship between aerosol deposition amount and its effect on snow albedo. It is suggested that the feedback effects of the climate to aerosol deposition change propagate the temperature change to the regions far away from the snow covered regions.

There are several uncertainties in the simulated results in this study. First, there are still large uncertainties in the emission and atmospheric burden of black carbon aerosol. A recent review of Bond et al. (2013) suggested a three times higher emission of black carbon than the emission inventories used in the current numerical model studies. In addition, the optical properties of the black carbon particles are known to change by the mixture with other aerosol species, with the shape and hygroscopicity, which are not yet implemented in the current global climate model. Moreover, the indirect effects of aerosols, especially role of aerosols as ice nuclei, are poorly constrained. The simulated results of this study suggested large influence of black carbon aerosols to the convective clouds, while the parameterizations for the convective clouds are known to be one of the most difficult processes in general circulation models. To reduce uncertainties in the evaluations of the effect of light absorbing aerosols, it is necessary to perform more detailed sensitivity studies to investigate the roles of direct and indirect effects separately, or the roles of other aerosol species.

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