Study of radiative forcing by atmospheric aerosol
（Abstract of the Final Report）

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1. Introduction

The equilibrium state of the terrestrial climate is determined by the balance of absorption of the solar irradiance and emission of terrestrial radiation (Earth Radiation Budget). These radiative processes are influenced by cloud, aerosol, and absorbing minor constituent gases.

In this study, we focus on the role of the atmospheric aerosols on the Earth Radiation Budget. As described in the report of Intergovernmental Panel on Climate (IPCC), there are many studies on radiative effect of aerosol on climate but the level of scientific understanding on the aerosol is very low (IPCC, 2007). Therefore, it is important to make a measurement of actual aerosol state and to understand the mechanism of radiative forcing by the atmospheric aerosols.

2. Research Objectives

In this study, the effect of the two following subjects on the radiative forcing are investigated,

(1) Hygroscopic property of atmospheric aerosol
(2) Aerosol–snow/ice interaction

The hygroscopic growth changes the optical property of aerosol. The deposition of atmospheric aerosol into the snowpack decreases the snow albedo. We observe these effects and develop a physically based model of these processes. Furthermore, the physically based model is installed in the model of aerosol transportation, which includes the several kind of aerosol; mineral dust, sea salt, sulfate particle and soot. Using this transportation model, we assess the radiative effect (radiative forcing) of these processes.

These studies clarify the effect and mechanism of the aerosol hygroscopic growth and the aerosol–snow/ice interaction and make it possible to estimate the more accurate radiative forcing. In addition, these studies contribute the improvement of global warming prediction model.

3.Research Method

This study consists of three parts. Two of them are observational ones and one is study of numerical model, which includes the parameterization based on the observation studies.

The model study uses these parameterizations and estimates the radiative effect.

(1) Hygroscopic property of atmospheric aerosol

We improved the system to measure the hygroscopic growth factor $f(RH) = \sigma_{sca}(RH) / \sigma_{sca}(RH < 40\%)$ using an integrating nephelometer, which is a key parameter of this study. The hygroscopic growth factor was measured in order to investigate the hygroscopic growth of maritime aerosol at Minamitorishima (MARCUS) in August, 2006, and at Miyakojima in February, 2007 and February, 2008, respectively. And we also measured at Beijing in order to investigate the hygroscopic growth of urban polluted aerosol and mineral dust (Aeolian dust, Kosa) from March to April, 2007. Furthermore, the hygroscopic growth of mineral dust was measured at Tsukuba in April, 2006 and April, 2007.

In order to confirm the trajectory paths measured at Minamitorishima, Miyakojima, Beijing, and Tsukuba, we calculated the backward trajectories by NOAA HYSPLIT model[1), 2)]. The trajectory analysis showed air parcels at Minamitorishima passed thorough Pacific Ocean during the measurement period. The trajectory paths arrived at Miyakojima passed through China and Japan. The trajectory analysis showed air parcels at Beijing and Tsukuba during the dust event arrived from Mongolia or north east area of China.

We fit measured hygroscopic growth factors $f(RH)$ at Minamitorishima (maritime aerosol) and Beijing (Aeolian dust event) to three types fitting curve[3), 4)] in this study. Furthermore, we make hygroscopic growth factors of aerosol particles $r_e / r_{e,dry}$ using OPAC sea salt (SS) model (Hess et al., 1998) [5)] and ADEC-2 dust (AD2) model (Aoki et al., 2005) [6)] to be consistent with $f(RH)$ fitting results.

(2) Studies of aerosol–snow/ice interaction

Reflection properties of snow/ice surfaces in solar spectrum depending on snow physical parameters are investigated from the measurements of radiation, atmospheric aerosols, and snow pit study. Concentrations of the absorptive aerosols in the snow (snow impurities: water-insoluble solid particles in snowpack) are also analyzed from those data, and the optical properties of snow impurities are parameterized. Using a radiative transfer model for atmosphere-snow system, the broadband snow albedos are calculated. Finally a physically based snow albedo model as a function of snow impurity concentration, which will be used in general circulation model, is developed with a radiative transfer model for snowpack contaminated with absorptive aerosols.

(3) Evaluation of the radiative effect of aerosol by a global aerosol model

To investigate the hygroscopic effect of aerosols to the Earth's radiation balance and the effect of the aerosol deposition on snow to the Earth's radiation budget, we have conducted numerical experiments with a chemical transport model called the model of aerosol species in the global atmosphere (MASINGAR) (Tanaka et al., 2003) [2)]. MASINGAR is a global chemical transport model which is coupled with a general circulation model MRI/JMA 98 (Shibata et al., 1999) [3)], and includes the emission, transport and deposition of sulfate, black carbon, organic carbon, sea salt, and mineral dust aerosols.

The hygroscopic dependence of the optical properties of sulfate aerosols is adopted from the approximate functions developed by Kiehl et al. (2001) $^{4)}$. The hygroscopic dependences of the optical properties of black carbon, organic carbon, and sea salt are taken from the method of Chin et al. (2002) $^{5)}$. The optical properties of mineral dust aerosol are taken from ADEC-2 model (Aoki et al. 2005). We performed 6 years integration and later 5-year results are used for analysis for each case.

To take into account the effect on the snow albedo model, a semi-physical snow albedo model that calculates the snow albedo as a function of snow grain size, mixing ratio of snow impurity, and solar zenith angle. We have conducted 4 numerical experiments to investigate the effect of aerosol deposition on snow surface to the radiative balance. The first experiment incorporates both black carbon and mineral dust depositions on snow surface for albedo calculation (Case 1). The second experiment considers no aerosol deposition on snow surface (Case 2). The third experiment incorporates only mineral dust deposition (Case 3), and the fourth experiment incorporates only black carbon deposition (Case 4).

4.Result

(1) Hygroscopic property of atmospheric aerosol

We improved the system to measure the hygroscopic growth factor $f(RH) = \sigma_{sca}(RH)/\sigma_{sca}(RH < 40\%)$ using an integrating nephelometer, which is a key parameter of this study. The hygroscopic growth factor was measured in order to investigate the hygroscopic growth of maritime aerosol at Minamitorishima (MARCUS) in August, 2006, and at Miyakojima in February, 2007 and February, 2008, respectively. And we also measured at Beijing in order to investigate the hygroscopic growth of urban polluted aerosol and mineral dust (Aeolian dust, Kosa) from March to April, 2007. Furthermore, the hygroscopic growth of mineral dust was measured at Tsukuba in April, 2006 and April, 2007.

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(2) Studies of aerosol–snow/ice interaction

A physically based snow albedo model which can be used in climate model was improved and validated with the data sets of snow pit work, snow impurity concentrations (mineral dust, black carbon, and organic carbon) measured from snow samples, and radiation budget observed in Sapporo during a winter of 2003/2004. A radiative forcing due to snow impurities was also estimated with the model and the same data sets.

A physically based snow albedo model calculates the albedos in the visible, shortwave, and near infrared spectra from snow grain size, snow impurity concentrations, solar zenith angle, and a direct/diffuse ratio in global solar radiation. The hygroscopic growth of snow impurities and the revised optical properties of dust particles were introduced to the albedo model. To validate the accuracy of the improved model, snow albedos calculated with the model from snow grain size and concentrations of snow impurities measured in Sapporo were compared with the measured albedos. The calculated visible and near-infrared albedos were somewhat overestimated and underestimated, respectively. In the shortwave spectrum, the calculated albedos agreed well with the measurements. The correlation coefficients between calculations and measurements are 0.926 in the visible and 0.756 in the near-infrared.

Using the model the snow albedos for impurity contained case and impurity free case were simulated. The calculated visible albedo reduction due to snow impurities is larger than that for the near-infrared region. The albedo reductions averaged during four months are 0.111 (visible), 0.085 (shortwave), and 0.033 (near-infrared). From the shortwave albedo reduction and the measured global solar radiation, local radiative forcing due to snow impurities averaged during four months in Sapporo was estimated to be heating of +10 W/m^2.

(3) Evaluation of the radiative effect of aerosol by a global aerosol model

The global averaged radiative effects are –0.54 W m^{-2}, –0.75 W m^{-2}, –1.31W m^{-2}, and –1.46 W m^{-2} for the case that maximum relative humidity of 0%, 50%, 90% and 100%. The results indicate that the hygroscopic effect enhances the cooling effect of aerosol. The results of the hygroscopic effects on the aerosol species show that the hygroscopic effect strengthens the radiative forcing of each aerosol.

The radiative effect of aerosol deposition on snow is strong heating over high latitude (northern Siberia and the Arctic) and high altitude region (Himalayas). If the aerosol deposition does not affect the snow albedo, snow cover remains over these regions in summer, when the strength of solar radiation becomes maxima. The globally averaged radiative effects of depositions of black carbon and mineral dust on snow surface are +0.42 ±0.30 W m^{-2} for whole sky condition and +1.04±0.20W m^{-2} for clear sky condition. The annual and global mean radiative effects of the black carbon and mineral dust deposition on snow are +0.09±0.27 W m^{-2} and +0.04±0.30 W m^{-2} for the whole sky condition.

5.Discussion

(1) Hygroscopic property of atmospheric aerosol

The trajectory analysis using NOAA HYSPLIT model$^{1), 2)}$ showed marine dominated air mass arrived at Minamitorishima during the measurement period. In the case of the trajectory analysis at Miyakojima, the hygroscopic growth factor ($f(80\%)$=2.28) passed through the north east area of China and Japan was larger than that ($f(80\%)$=1.82, 2.06) passed through the north east area of China. And the trajectory analysis at Beijing and Tsukuba indicates Mongolia or north east area of China was main sources of mineral dust during the dust event measurement.

We make hygroscopic growth factor of aerosol particles $r_e/r_{e,dry}(80\%)$ based on OPAC sea salt (SS) model (Hess et al., 1998) $^{5)}$ to be consistent with measured hygroscopic growth factor $f(80\%)$. The hygroscopic growth factors $r_e/r_{e,dry}(80\%)$ of SS-ACC (ACC: accumulation model) and SS-COA (COA: coagulation model) are 1.38 and 1.37 at Minamitorishima, respectively. Our results $r_e/r_{e,dry}(80\%)$ are smaller than that

($r_e/r_{e,dry}(80\%)=2.0$) used by Chin et al. (2002) $^{7)}$.

We fit hygroscopic growth factors $f(RH)$ at Minamitorishima (maritime aerosol) and Beijing (Aeolian dust event) to three types fitting curves$^{3), 4)}$. And we also make hygroscopic growth factors $r_e/r_{e,dry}$, which are consistent with $f(RH)$ fitting curves, based on OPAC sea salt (SS) model (Hess et al., 1998) $^{5)}$ and ADEC-2 dust (AD2) model (Aoki et al., 2005) $^{6)}$. The aerosol optical properties in MASINGAR (Model of aerosol species in the global atmosphere $^{8)}$) are based on the particle radius $r_e/r_{e,dry}$. We can investigate the radiative forcing by atmospheric aerosol using MASINGAR taken in our hygroscopic growth factor $r_e/r_{e,dry}$.

(2) Studies of aerosol–snow/ice interaction

The albedos calculated with a physically based snow albedo model are somewhat overestimated in the visible and underestimated in the near-infrared, and the calculated shortwave albedos agree well with the measurements as a result. The model treats one snow layer, whereas the natural snow is vertically inhomogeneous. From the viewpoint of one-snow-layer model, we may say the performance of the model is high. Since the visible and near-infrared albedos depend theoretically on snow impurities and snow grain size, respectively, we need furthermore to investigate the optical properties of snow impurities for the possible cause of the overestimate in the visible albedo and to reconsider the issues on identification technique of optically equivalent snow grain size for the underestimate in the near-infrared albedo.

The estimated local radiative forcing due to snow impurities in Sapporo is estimated to be +10 W/m^2 of heating (albedo reduction: 0.085). This means the snow impurities have large effect on radiation budget at snow surface. From the analysis of snow impurity factor (SIF) indicating amount of absorption and concentration of snow impurities, the snow impurity with larger contribution to albedo reduction was black carbon during a period from December to February and dust in March when dust event was observed.

(3) Evaluation of the radiative effect of aerosol by a global aerosol model

The hygroscopic effect of radiative effect of aerosols is stronger over the ocean, due to the presence of abundant sea salt aerosol and high relative humidity. Over the east Asia, the hygroscopic effect of aerosol is strong, because of the presence of sulfate and carbonaceous aerosols.

The magnitude of the simulated radiative effect of aerosol deposition on snow (+0.42 W m^{-2}) is comparable to the direct or indirect effect of aerosol on radiative budget. The results suggest that the aerosol deposition on snow albedo has potentially strong effect on the radiation budget, and should not be neglected. The total radiative effect of black carbon and mineral dust (+0.42 W m^{-2}) is not equal to the simple addition of the effects of black carbon (+0.09 W m^{-2}) and mineral dust (+0.04 W m^{-2}). This is due to the positive feedback of snow cover and albedo.

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