論文内容の要旨

論文題目　An evaluation of the direct aerosol radiative forcing from satellite remote sensing and climate modeling
（衛星リモートセンシングと気候モデルによるエアロゾル直接放射強制力の評価）

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Anthropogenic and natural aerosols affect the Earth's radiation budget both in direct and indirect way. The direct aerosol effect on Earth's radiation budget is caused by direct scattering and absorption of solar and thermal radiation, and can be quantified by the radiative forcing. In this study, shortwave direct aerosol radiative forcing (SWDARF) is estimated by using satellite observation data and climate modeling, and the uncertainties of estimated SWDARF are discussed.

In 2006, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite was launched with the space-borne lidar, CALIOP (the Cloud-Aerosol Lidar with Orthogonal Polarization). CALIOP, for the first time, provides us with a global data of aerosol and cloud vertical profiles [*Winker et al.*, 2009, 2013]. In addition, CALIOP has capability to detect aerosols existing above the optically thick clouds which are not observed by passive remote sensing and ground based lidar [*Winker et al.*, 2010]. Several studies reported that absorbing aerosols above low-level clouds produce a large positive forcing over the Atlantic Ocean off southwest Africa [e.g. *Keil and Haywood*, 2003; *Chand et al.*, 2009]. SWDARFs of aerosols above clouds have never been estimated in the global scale using observation data.

I investigate four scenarios for estimating the SWDARF at the top of the atmosphere (TOA) using data of CALIPSO lidar and data of MODIS sensor. The first scenario, which is called as clear-sky case, is the case that aerosols are observed in clear-sky condition. High cloud reflectance changes the SWDARF from negative to positive [*Haywood and Shine*, 1997]. Hence, I made three scenarios under cloudy-sky condition. The first is a case of aerosols existing above clouds (above-cloud case). The second is a case of aerosols existing below high-level clouds such as cirrus (below-cloud case). The third is a case of aerosols undetected by CALIOP lidar exist below/within the optically thick clouds (cloudy-undetected case). The cloudy-sky SWDARF is calculated by SWDARFs of above-cloud, below-cloud, and cloudy-undetected cases weighted by the

occurrence probability of each scenario. The all-sky SWDARF is then calculated by combination of clear-sky and cloudy-sky SWDARF weighted by the cloud occurrence probability. In this study, the global scale estimate of cloudy-sky SWDARF is performed for the first time by using observation data. My analysis of the CALIPSO Version 3 product shows the occurrence probabilities in clear-sky, above-cloud, below-cloud, and cloudy-undetected cases are 38%, 4%, 16%, and 42%, respectively. This indicates that CALIOP can observe 58% of aerosols in all-sky condition, whereas the aerosol observation by passive remote sensing is limited only in clear-sky condition, i.e. 38% of aerosols.

In clear-sky and below-cloud cases, aerosols mainly scatter sunlight and SWDARF shows negative values, except for bright surfaces. On the other hand, SWDARF globally shows positive value in above-cloud case. In this case, the absorption of aerosols is enhanced by the high reflectance of clouds and changes the SWDARF at TOA from negative to positive. As for the cloudy-undetected case, I assume the SWDARF to be zero, because optically thick clouds dominantly scatter the incident sunlight. The above mentioned method of analysis is applied to CALIPSO Version 2 and Version 3 products to obtain SWDARFs between 60°S and 60°N under clear-sky, cloudy-sky, and all-sky conditions as -3.7 ± 0.8, -3.7 ± 0.7, and -2.0 ± 1.2 Wm^{-2}. The result indicates the difference of the version of the CALIPSO product is as large as 50% in all-sky forcing.

According to previous studies of the global aerosol model intercomparison project AeroCom, SWDARF simulated by MIROC-SPRINTARS is smaller negative than the mean value of other model estimates [*Yu et al.*, 2006; *Schulz et al.*, 2006; *Myhre et al.*, 2013]. In this study, SWDARF is also calculated by the latest version of MIROC [*Watanabe et al.*, 2010]. In the MIROC model, the optical properties of aerosols and clouds are separately calculated in SPRINTARS aerosol module and mstrnX radiation module. By detailed investigation of aerosol optical thickness (AOT) and and single scattering albedo (SSA) from the two modules, I found that the mstrnX AOT and SSA are smaller than those of SPRINTARS, because aerosol size indices of mstrnX is different from that of SPRINTARS in order to save CPU time. In order to make the two modules consistent with each other, I modified the interface between the two modules to set common optical aerosol models with 6 size bins of mineral dust, 4 types of carbonaceous aerosols, sulfate, and 4 size bins of sea salt. In this study, this new model is referred to as the SPnew model. I confirmed that AOT of each aerosol component and SSA of mstrnX agree with those of SPRINTARS within 4% in the SPnew model. Absorption of dust and carbonaceous aerosols becomes smaller from the standard model to the SPnew model. Zonal averages of SWDARF between 60°S and 60°N under clear-sky, cloudy-sky, and all-sky conditions change from −2.0, +0.3, and −0.7 Wm^{-2} in the standard model to −2.1, −0.1, and −1.1 Wm^{-2} in SPnew model.

The vertical profiles of aerosols are globally observed by CALIPSO lidar under clear-sky condition. High concentrated aerosols are globally observed by CALIPSO lower than 2 km altitude; in particular, aerosol extinction coefficient is larger than 0.05 at altitude lower than 1 km. On the other hand, the aerosol extinction coefficient in SPnew model is underestimated globally below 2 km altitude, while aerosols are elevated up to 7 km altitude around source regions of carbonaceous aerosols and dust in the model. These results indicate that aerosols are transported higher than the observation in a vertical direction, but are hardly transported in a horizontal direction in MIROC.

I compared the the obtained geographical distributions of AOT and SSA from satellites and models. The geographical distribution of CALIPSO AOT is found similar to that of MODIS observations, while CALIPSO AOT is smaller than MODIS AOT by 20%. Compared with CALIPSO and MODIS AOT, SPnew AOT is underestimated in almost all regions. This causes smaller negative SWDARF under clear-sky condition in the model. It is also found that under clear-sky condition the aerosol extinction coefficient of SPnew is smaller below 4 km altitude and larger above 4 km altitude than that of CALIPSO. The ratio of CALIPSO AOT to SPnew AOT (CALIPSO AOT / SPnew AOT) is 2.14 below 4 km and 0.29 above 4 km altitude. In order to study the effect of this difference, I performed a model simulation that aerosol concentrations multiplied by 2.14 below 4 km altitude and 0.29 above 4 km altitude in the SPnew model. This simulation is referred to as the SP4km experiment.

Zonal averages of SWDARF between 60°S and 60°N under clear-sky, cloudy-sky, and all-sky conditions are calculated in the SP4km experiment as −3.2, -0.3, and −1.7 Wm^{-2}. The zonal average AOT between 60°S and 60°N for SP4km is comparable to CALIPSO AOT and the modeled SSA is overestimated, but the zonal average of clear-sky SWDARF for SP4km is smaller negative than CALIPSO by 0.5 Wm^{-2}. This difference is mainly caused by an underestimation of aerosol extinction coefficient below 2 km altitude over ocean in the Southern Hemisphere.

MIROC frequently simulate optically thicker clouds than observation. Off southwest Africa, absorbing aerosols emitted by biomass burning in Africa are transported above low-level clouds. Aerosols usually undetected below 1.5 km altitude by CALIPSO observations in above-cloud case, whereas aerosols are simulated from surface to 5 km altitude in the model. In cloudy-sky condition, the modeled SWDARF is more positive than the observation, because the absorption of aerosols within/above clouds is largely enhanced by higher cloud reflectance derived from optically thick clouds. Over central and northern Pacific, optically thick clouds are simulated from the lower to upper troposphere in the model, so that clouds mainly scatter sunlight and aerosols cause less negative forcing than the CALIPSO case. From these results, the cloudy-sky SWDARF in MIROC is considered to be smaller negative than that of CALIPSO.

Summarizing the results in this study, I like to propose the best estimates of clear-sky and all-sky SWDARF of –4.1 and –1.9 Wm^{-2}. On the other hand, the global averages of SWDARF from the past studies are –4.8±0.8 and –2.7±0.9 Wm^{-2} under clear-sky and all-sky conditions [*Liu et al*., 2007; *Kim and Ramanathan,* 2008; *Ma et al.,* 2012; *Zhang et al.,* 2012; *Kinne et al.,* 2013]. My estimate of the clear-sky SWDARF is located in between the CALIPSO values obtained in this study and the average of previous studies. This conclusion suggests that both the satellite-borne lidar and modeling methods have their own characteristic errors in SWDARF estimation. The present analysis is considered to be useful to identify causes for errors found in this study.