Estimation of aerosol direct radiative forcing by Asian dust using sun/sky radiometer and lidar measurement

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Abstract: This paper determines the aerosol forcing due to Asian dust using actual measurements of aerosol optical properties. We suggest a method of determining aerosol parameters for the radiative transfer model from the AErosol RObotic NETwork (AERONET) data set. Since the AERONET measurements are made at only four wavelengths, we use a linear regression method for extending these measurements to the full wavelength spectrum of the model. The aerosol forcing in the presence of dust layer has been compared to the aerosol forcing in the absence of dusts. The aerosol profiles measured by lidar are included to estimate the influence of the altitude of the aerosol layer. Instantaneous radiative heating is believed to contribute to increase the static stability within the dust layer. This fact is verified by the temperature profile measured by the sonde and may explain the longevity and consequently long-range transport of Asian dust.

1. Introduction

Despite numerous studies, the level of understanding of the aerosol effects on climate change is still very low (IPCC, 2001). To estimate radiation changes due to the atmospheric aerosols, the appropriate optical parameters of aerosols are necessary for constructing radiative transfer calculation. Although there have been a few international campaigns focused on aerosol effects on global environmental change, these have been limited to a few locations over relatively short
periods. It is therefore necessary to use a data set that has many observation sites operating continuously for investigating the climatological effect of aerosols. A data set that might satisfy this need is the AErosol RObotic NETwork (AERONET).

In this study, we suggest a method of calculating aerosol direct radiative forcing using AERONET data processed by Dubovik’s retrieval algorithm (Dubovik and King, 2000; Holben et al., 2001). The measured aerosol optical properties are used in the radiative transfer calculation to compare the aerosol forcing by Asian dust aerosols with that of no-dust aerosols. We also investigated the influence of the aerosol vertical distribution in the troposphere by calculating the vertical profiles of the radiation flux and the heating rate.

2. Data set and Methodology

The radiative transfer model used in this study is Column Radiation Model (CRM-2.1.2), the stand-alone version of radiative code implemented in NCAR Climate Community Model (CCM-3.6). It has 19 wavelength bands for the short wave length regime, 0.2-5.0 μm (Briegleb, 1992; Yu et al., 2001), and it’s vertical coordinate is modified to have 55 pressure levels from the surface to 1 hPa. The AERONET sun/sky radiometer was operated at the Gosan super-site at Jeju Island, S. Korea during ACE-Asia Intensive Observation Period (IOP), in April 2001. A new cloud-screening scheme is applied to reduce the contamination by clouds (A. Omar and J.G. Won, manuscript in preparation, 2002). After screening, 65 of 132 Dubovik’s retrieval data were classified as that of the aerosols influenced by Asian dust. Table 1 shows the averaged values of the optical parameters of dust, meaning Asian dust, and no-dust aerosol in April 2001.

The parameters needed for calculating the aerosol forcing are optical thickness $\tau$, single scattering albedo $\omega$, and asymmetry factor $g$. These are determined using a Mie scattering code
from the Dubovik’s retrievals. The Dubovik’s inversion algorithm retrieves size distributions with 22 size bins from 0.05 to 15 µm and the complex refractive indices at 440, 670, 870, and 1020 nm (Dubovik and King, 2000). Since AERONET provides the refractive indices at only four wavelengths, it is necessary to estimate the optical parameters for the wavelength bands of CRM. We used a linear regression method on log $\lambda$-log $\chi$ (where $\chi$ stands for $\tau$, $\omega$, $g$, and $\lambda$ is the wavelength) plane to determine the aerosol parameters at 19 wavelength-bands. Fig. 1 shows two examples of the regression method with averaged parameters of Asian dust, Fig. 1 a), and no-dust aerosols, Fig. 1 b), measured at Jeju in April 2001. The slope of the regression line in log $\lambda$-log $\tau$ is the Angstrom exponent. By analogy, the same method is applied to $\omega$ and $g$ in the log $\lambda$-log $\omega$ and log $\lambda$-log $g$ plane respectively. The linear regression method represents the optical characteristics adequately in visible and near IR region (Quijano et al., 2000). In the past, fixed values of aerosol parameters from laboratory experiments have been used to estimate the aerosol radiative forcing (Kiehl and Briegleb, 1993; Yu et al, 2001). There is no need to assume the aerosols properties in advance with this linear regression method, because it is possible to use real time measurement data.

The aerosol profiles in the troposphere were measured by Micro Pulse Lidar (MPL) at Jeju Island (R. Kahn et al., Relationships between surface, airborne, and satellite multi-anlge aerosol observations during ACE-Asia Field Campaign, submitted to the Journal of Geophysical Research, 2002). During Asian dust events large amount of mineral aerosols are transported from the inner region of China to the Korean peninsula and Japanese islands (Sun et al., 2001; Murayama et al., 2001). It is therefore necessary to investigate the influence of dust aerosols on the radiation budget considering its vertical distribution. Fig. 2 shows two Asian dust events during ACE-Asia IOP 2001; one is the elevated dust layer event on April 10th, Fig. 2 a) and b),
and the other is an event showing the dust settled into the Planetary Boundary Layer (PBL) on April 13th, 2001, Fig. 2 c) and d). Fig. 2 also shows the averaged aerosol profiles during the daytime (from 6:00 to 18:00 LST) for the two cases. These profiles were utilized for estimating aerosol forcing using CRM.

3. Dependency of aerosol direct radiative forcing on the optical properties of aerosols

Fig. 1 a) and b) also show the wavelength dependence of single scattering albedo and asymmetry factor of Asian dust aerosols compared to no-dust aerosols. The slope of the linear regression line is almost zero or slightly positive for dust aerosols, meanwhile it is negative for no-dust aerosols. The bigger single scattering albedo, which is more distinct at longer wavelength regime, means dust aerosols absorb less short wave radiation. We calculated aerosol direct radiative forcing with two types of aerosols, dust and no-dust aerosols, to investigate their effects due to the differences in their optical properties.

The aerosol direct radiative forcing is defined as the difference between the net radiative flux calculated with and without aerosols. Experiments 2 and 3 in Table 1 show the optical parameters of dust and no-dust aerosol, and aerosol forcing values at the top of the atmosphere (TOA) and at the surface. The surface albedo was set to 0.053, and the daily variation of solar zenith angle was assumed to be same as that of April 15th for both experiments. Fig. 3 shows the diurnal variations of instantaneous aerosol direct radiative forcing for the two experiments. The features of both the surface and the TOA forcing are similar to those obtained by other studies (Redemann et al., 2000; Yu et al., 2001). Aerosol forcing at the TOA is a factor of two larger for the dust case than that for the no-dust case, while the differences at surface are quite small. It is because dust aerosols have a larger single scattering albedo and smaller asymmetry factor. The
larger single scattering albedo implies less absorption (more scattering or reflection), and the smaller asymmetry factor implies less forward scattering. Therefore short wave radiation is reflected (or backscattered) more by dust aerosols, and the magnitude of the aerosol direct radiative forcing by dust can be larger at the TOA.

We also performed sensitivity tests for the aerosol direct radiative forcing calculation by varying the aerosol optical properties, $\omega$ and $g$. 5% increase of $\omega$ from Ex. 3 causes 15% increase of the TOA forcing and 11% decrease of the surface forcing (Ex. 4). 5% increase of $g$ causes 11% decrease of the TOA forcing and 4% decrease of the surface forcing (Ex. 6). If $\omega$ or $g$ were decreased, the change of aerosol forcing would be reversed (Ex. 5 & 7). The time of calculation was set to 9:00 am for these sensitivity tests. Redemann et al. (2000) have done the error propagation study for the aerosol forcing calculation and showed similar results. This also implies that a small error in determining the aerosol parameters could cause relatively large errors in calculating aerosol direct radiative forcing. It is important to use accurate values of the optical parameters that represent the actual aerosols properties well. The regression method described above is a practical way of determining the aerosol parameters from the real time measurement such as AERONET data set. And it is also possible to apply this method to all the other AEROENT sites to investigate the aerosol effects on global scale.

4. Dependency of aerosol forcing and heating rate on aerosol profiles

For estimating aerosol direct forcing, it is generally assumed that most of aerosols are confined within the PBL or within the first few km from the surface. This is a reasonable assumption for clean marine or urban regions. However it is often found that the dust layer with 1~2 km thickness is elevated by several km above the ground from lidar measurement. In such case, the
aerosol forcing calculation must take into account the aerosol vertical distribution. The aerosol direct radiative forcing at the TOA or at surface can be similar with the same optical thickness because the aerosol forcing is strongly dependent on the aerosol amount. However the aerosol profile can influence the flux profile and the vertical distribution of the heating rate. This can also influence the atmospheric temperature profile and the static stability.

Fig. 4 a) shows the heating rate change profiles computed by CRM for the aerosol profiles of April 10th and 13th. The heating rate is retrieved from the convergence of the net flux (Quijano et al., 2000), and it should be large at the layer where the gradient of the net flux is large. The time of the calculation was also set to 9:00 AM LST. The heating rate change is the difference between the heating rate calculated with and without aerosol, which denotes the aerosol effects on radiative heating. For the elevated dust layer case (April 10th), a significant heating by aerosols is indicated at 550–700 hPa layer and below 850 hPa again. On the other hand, for the case of dust deposited into the PBL (April 13th), radiative heating by aerosols is found only below 800 hPa level. On both days, the heating rate of the aerosol layers is calculated larger than 2 K/day and the maximum values reaches 3.0 K/day on April 13th.

When a dust storm is triggered, large amounts of aerosols are blown up out of the PBL and transported at high altitude before they deposit several hundred kilometers away from the source. As shown in Fig. 4 a), the heating rate of the upper part of the dust layer can increase the static stability and helps maintain the dust layer structure for longer periods of time. Fig. 4 b) show the temperature and potential temperature profiles measured by a sonde, which was launched at 9:00 AM at Gosan, Jeju on April 10th, 2001. A temperature inversion layer is noticed between 600–700 hPa layer and the short wave radiative heating by the dust aerosol layer is likely to be one of the factors which cause this inversion. Other factors that could contribute to the formation
of the inversion are nocturnal absorption of long wave radiation by the dust layer and the fact that Asian dusts are originated from elevated surfaces in their source regions (Sun et al., 2001). Consequently the radiative heating within the elevated dust layer may have an intrinsic self-sustaining mechanism, which makes the long-range transport of dust aerosols possible. The elevated dust layer of April 10th, which lasted more than one day, was a good example of the long-range transport event of Asian dust.

4. Summary

A method of determining the aerosol optical parameters, such as optical thickness $\tau$, single scattering albedo $\omega$ and asymmetry factor $g$, for the calculation of aerosol direct radiative forcing has been suggested using the AERONET data. The linear regression method in the log-log plane makes it possible to include the actual measurements of the aerosol optical properties for the radiation flux calculation. The differences of aerosol forcing caused by the optical properties of Asian dust and no-dust aerosols have been examined. Dust aerosols, which have larger single scattering albedo and smaller asymmetry factor, cause a factor of two increase in the aerosol radiative forcing compared to no-dust aerosols. The sensitivity tests show that a small errors of single scattering albedo or asymmetry factor can cause relatively large errors in calculating aerosol direct radiative forcing. The profiles of the radiative heating rate change by dust aerosols are also calculated for Asian dust events using lidar measurement data. Lidar data was used to show the difference of the radiative heating effects by an elevated dust layer and a PBL dust layer. A significant heating rate larger than 2 K/day in the elevated dust layer was found and it corresponded to the elevated inversion layer measured by sonde. This may explain the integrity of the dust layer over many days allowing for long-range transport.
Acknowledgements

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References


IPCC, Climate Change 2001 : The scientific basis, 2001


Table 1. Summary of the aerosol parameters at 4 wavelengths, 440, 670, 870 and 1020nm and the aerosol profiles used for the radiation flux calculation. The time of calculation was set to 9 o'clock AM on April 15th LST (zenith angle $\Theta$ is 54.8°).

<table>
<thead>
<tr>
<th>Aerosol Profile</th>
<th>Aerosol optical thickness ($\tau$)</th>
<th>Single scattering albedo ($\omega$)</th>
<th>Asymmetry factor (g)</th>
<th>Forcing at TOA (W/m$^2$)</th>
<th>Forcing at surface (W/m$^2$)</th>
<th>Absorption by atmosphere (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex. 1 (4/10 dust)</td>
<td>April 10$^{th}$</td>
<td>0.618, 0.496, 0.458, 0.439</td>
<td>0.904, 0.915, 0.913, 0.918</td>
<td>0.677, 0.668, 0.673, 0.692</td>
<td>-51.1</td>
<td>-97.0</td>
</tr>
<tr>
<td>Ex. 2 (4/13 dust)</td>
<td>April 13$^{th}$</td>
<td>Same as Ex. 1</td>
<td>Same as Ex. 1</td>
<td>Same as Ex. 1</td>
<td>-50.2</td>
<td>-97.0</td>
</tr>
<tr>
<td>Ex. 3 (no-dust)</td>
<td>Aerosol layer till 800 hPa</td>
<td>0.520, 0.373, 0.328, 0.298</td>
<td>0.843, 0.833, 0.815, 0.817</td>
<td>0.698, 0.677, 0.667, 0.685</td>
<td>-30.5</td>
<td>-96.5</td>
</tr>
<tr>
<td>Ex. 4 ($\omega + 5%$)</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Ex. 3 + 5%</td>
<td>Same as Ex. 3</td>
<td>-35.0 (+15%)</td>
<td>-86.0 (-11%)</td>
</tr>
<tr>
<td>Ex. 5 ($\omega - 5%$)</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Ex. 3 - 5%</td>
<td>Same as Ex. 3</td>
<td>-26.2 (-14%)</td>
<td>-106.8 (+11%)</td>
</tr>
<tr>
<td>Ex. 6 (g + 5%)</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Ex. 3 + 5%</td>
<td>-27.0 (-11%)</td>
<td>-93.0 (-4%)</td>
</tr>
<tr>
<td>Ex. 7 (g - 5%)</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Same as Ex. 3</td>
<td>Ex. 3 - 5%</td>
<td>-33.9 (+11%)</td>
<td>-100.0 (+4%)</td>
</tr>
</tbody>
</table>

Figure 1. Aerosol parameters, $\tau$, $\omega$ and g, retrieved from the AERONET measurement at Gosan, Jeju, Korea in April 2001. The optical parameters at four wavelengths and linear regression lines are displayed for a) dust aerosol case and b) no-dust aerosol case.
Figure 2. Evolution of the aerosol extinction profile during daytime and the daily averaged profiles measured by Micro Pulse Lidar at Gosan, Jeju, Korea. Upper panels are for April 10th 2001, a), b) and lower for April 13th 2001, c), d).
Figure 3. CRM result of diurnal variation of the instantaneous direct radiative forcing by Asian dust and no-dust aerosols at Gosan, Jeju, in April 2001.

Figure 4. a) The profiles of heating rate by Asian dust on April 10th and April 13th, 2001. b) the temperature and potential temperature profiles measured by sonde launched at Gosan, Jeju at 9 o’clock on April 10th, 2001.