Observation of enhanced water vapor in Asian dust layer and its effect on atmospheric radiative heating rates

Sang-Woo Kim,1,2 Soon-Chang Yoon,3 Anne Jefferson,3,4 Jae-Gwang Won,1 Ellsworth G. Dutton,3 John A. Ogren,3 and Theodore L. Anderson5

Received 17 March 2004; revised 12 August 2004; accepted 24 August 2004; published 30 September 2004.

[1] This study investigates the effect of water vapor associated with mineral dust aerosols on atmospheric radiative heating rates using ground-based lidar, aircraft, radiosonde measurements and a radiation model during Asian dust events in the spring of 2001. We found enhanced levels of water vapor within the dust layer relative to the air above and below the dust layer. The water vapor led to an increase in the net radiative heating rate within the dust layer, changing the heating rate vertical structure. A net cooling was calculated above the dust layer as a result of low aerosol and drier conditions. Our finding suggests that the presence of water vapor within dust layer acts to enhance the temperature of this layer, potentially influencing the static stability of the dust layer. This finding is supported by an increase in the potential temperature at the top and bottom of the dust layer.


1. Introduction

[2] Wind-blown atmospheric mineral dust affects Earth’s radiation budget through the absorption and scattering of solar radiation and by interacting with thermal infrared (IR) radiation [Sokolik et al., 2001]. Previous studies suggest that atmospheric mineral dust causes significant atmospheric radiative heating in solar wavelengths (SW) and a cooling in long wavelengths (LW) [Carlson and Benjamin, 1979; Quijano et al., 2000; Won et al., 2004]. This effect of dust on radiative heating/cooling rates can affect the atmospheric temperature profile and thermodynamics. Quijano et al. [2000] showed that the magnitudes of the SW heating and the LW cooling depend on the optical properties of the dust layer, the vertical distribution of the dust loading, the solar zenith angle and the surface albedo. Won et al. [2004] found an instantaneous SW heating rate larger than 2 K/day in the elevated dust layer. Previous studies of radiative heating rates by mineral dust are not based on measurements of the dust vertical distribution and usually do not consider the role of atmospheric water vapor within the dust layer.

[3] This study presents an analysis of the radiative heating rates of the Asian dust layer with and without water vapor under the cloud-free conditions. The model of the radiative heating/cooling rates of the dust layer in both the SW and the LW regions uses surface and aircraft measurement data as input.

2. Observations of Enhanced Water Vapor in Elevated Dust Layers

[4] We carried out ground-based micro-pulse lidar (MPL) [Won et al., 2004] measurements of the Asian dust at Gosan (33.29N, 126.16E), South Korea in the spring of 2001. Radiosonde observations of the vertical profile of pressure (P), temperature (T) and relative humidity (RH) were made twice daily at the site by the Korea Meteorological Administration. Measurements of the aerosol extinction coefficient as well as vertical profiles of meteorological parameters such as P, T and RH were obtained aboard the C-130 research aircraft during the ACE-Asia field campaign [Huebert et al., 2003].

[5] Figure 1 shows a plot of the MPL-derived aerosol extinction coefficient, σext, the observed water vapor mixing ratio (WVMR), and the potential temperature (θ) at Gosan. An extinction-backscattering ratio (Sa) of 50 sr was used for the σext profile retrieval from the MPL return signal. This value is based on the Sa measured on board the C-130 during ACE-Asia. Figure 1a is the σext profile and WVMR for the baseline case. The baseline case WVMR exhibits high values in the marine boundary layer (MBL) and gradually declines with altitude, having little correlation to the elevated aerosol layer between 1 ~ 3 km. We chose this WVMR profile as our baseline profile because it occurred in the same week as the dust profiles and had a similar transport route as the dust laden air except that the 5 day back trajectory calculations, arriving at 1 km above the surface, indicate the source region to be just south of the desert regions of China. The aerosol optical depth (AOD) at 500 nm wavelength is low during this time (0.11) and the Angström exponent (α) is relatively high (1.32 for the 412 and 862 nm wavelength pair), indicating the presence of small pollution aerosol. In contrast, later in the day on April 16 (Figure 1c) a dust layer was present and the AOD and α at 09 UTC were 0.70 and 0.28, respectively. Our use of a baseline profile is to show...
that the WVMR above the MBL declines linearly in the lower troposphere for an airmass that doesn’t have significant entrainment of water vapor or dust into it. Determination of a typical baseline water vapor profile from the dust source region that does not have an additional entrainment of water vapor is difficult because it varies with the transport route and meteorology.

The usual entrainment process of Asian mineral dust into the lower or middle troposphere is by a cyclonic depression and frontal system that sweep over the arid and semi-arid regions of China and Mongolia. The dust is further transported by strong westerly jets \[\text{Murayama et al., 2001}\]. The atmosphere usually is considered to be dry during dust events. However, we found elevated levels of WVMR within the Asian dust layer (ADL) relative to the air above and below the ADL. On April 13, 2001, Figure 1b, the WVMR in the dust plume at 3 km is about twice that of baseline case on April 16, Figure 1a, at the same altitude. The high WVMR values near the surface are due to a humid MBL. A high correlation between the \(\sigma_{\text{ext}}\) and the WVMR vertical profiles on April 16, 2001 at 12UTC, Figure 1c, was also observed along the airmass transport route. A similar correlation was observed at Hefei, China by lidar on April 14, 2001 (http://info.nies.go.jp:8094/AD-Net/) and east of Jeju Island by the Twin Otter aircraft on April 17, 2001 (RF #11; 33\(^{\circ}\)C/24\(^{\circ}\)E). We base the identification of the aerosol plume in Figures 1b and 1c as dust on the low values of the column \(\sigma\) derived from sunphotometer measurements. Although the profiles Figures 1b and 1c were at 12UTC (21 Local Time) during the night, the MPL vertical profiles show little change in the aerosol plume characteristics between the measurements at 12UTC and those of the closest measurements of the clear sky column \(\sigma\). The value of the \(\sigma\) on April 13 at 09UTC is 0.15 and that at 22UTC on April 16 is 0.28. Five day back trajectory calculations of the aerosol layers observed on April 13 and 16 using the NOAA HYSPLIT model (R. R. Draxler, HYSPLIT_4 user’s guide, version 4.7, www.arl.noaa.gov/data/web/hysplit/index.htm) also show the air masses to have originated in the dust regions of China and Mongolia, particularly the Gobi Desert and Loess Plateau regions. Other ACE-Asia studies of continental outflow from China during this time period also report observations of dust from these regions [i.e., Uno et al., 2003]. We found a steep change in \(\theta\) at the upper and lower parts of the ADL in all cases presented in this study. This change in \(\theta\) across the ADL may increase the static stability of the ADL.

Figure 2 shows aircraft-based measurements of the vertical aerosol optical properties, WVMR and \(\theta\), about 20 km south of Gosan and the MPL-derived \(\sigma_{\text{ext}}\) profile at Gosan on April 18, 2001. Low values of both the \(\sigma\) (0.4 for the 450 and 700 nm wavelength pair) and sub micron fraction (0.14) of the scattering coefficient indicate the presence of two dust layers: 0.7 ~ 2.2 km (ADL-1) and 2.3 ~ 2.6 km (ADL-2). The WVMR did not decline with altitude in the dust layers, but remained high. Between ADL-1 and ADL-2 and above ADL-2, the atmosphere is relatively dry. The high WVMR below 0.4 km is due to the damp MBL air.

3. Radiative Heating Rates of Asian Dust Layer in the Absence and Presence of Water Vapor

A combined shortwave (0.3 ~ 4.0 \(\mu\)m) and longwave (4.0 ~ 40 \(\mu\)m) radiative transfer model SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer 2.0) [Ricchiazzi et al., 1998] was used to determine the radiative heating rates of the ADL with and without water vapor for

![Figure 1](image1.png)

**Figure 1.** The MPL extinction coefficient (green line) at 523 nm and WVMR (red crosshair) and potential temperature (black line) derived from radiosonde measurements at Gosan, Korea: (a) April 16, 2001 (00UTC), (b) April 13, 2001 (12UTC), (c) April 16, 2001 (12UTC). The shaded areas indicate the dust layer.

![Figure 2](image2.png)

**Figure 2.** Vertical profiles of aerosol total (thick blue line) and sub-micron (thin blue line) scattering coefficient, WVMR (red crosshair) and potential temperature (black line) were obtained from onboard C-130 instruments during research flight 10 on April 18, 2001 (5.36 ~ 5.98UTC). The C-130 flew about 20 km south of Gosan. The MPL-derived vertical extinction profile (green line) measured at Gosan during the C-130 flight. The label ‘ADL-1’ and ‘ADL-2’ indicate the dust layer.
cloud-free atmospheric conditions. The parameters needed for calculating the radiative heating rates are the AOD, single scattering albedo and asymmetry factor, which are all wavelength dependent. In this study, these parameters were determined with a Mie scattering code using AERONET sunphotometer retrievals in SW region (see Won et al. [2004] for a complete description) and using the mineral dust refractive index given in OPAC (Optical Properties of Aerosols and Clouds) [Hess et al., 1998] for the LW region. The aerosol properties and fluxes in the LW region were not measured on either the C-130 platform or at the Gosan site. Other important inputs such as vertical profiles of the \( \sigma_{\text{AOD}} \), WVMR, T, and P were taken from the ground-based MPL, aircraft C-130 and radiosonde measurements described above.

[9] Because little information of the dust optical properties across a broad spectral range is available, the uncertainty in the model calculated radiative heating rate is unknown. However the focus of this study is on the role of enhanced water vapor associated with dust on atmospheric radiative heating. Uncertainty in the radiative heating rate due to water vapor is highest in the upper ADL and decreases in the lower ADL as a result of pressure changes across the layer. Alternatively, cooling in the upper ADL is a result of a large decrease in LW flux across the upper ADL from higher IR emission from that layer compared to absorption. Sensitivity tests show that a 50% increase in the WVMR causes a 20% increase in the instantaneous net heating rate integrated over the entire ADL.

Figure 3. Vertical profiles of (a) measured MPL aerosol extinction (green line), WVMR (red crosshair) and potential temperature (black line) at 00UTC, (b) and (c) calculated instantaneous (00UTC, 54° solar zenith angle) and diurnal averaged solar (circles), infrared (squares) and net (triangles) radiative heating rates for the presence (closed symbol) and the absence (opened symbol) of water vapor in ADL at Gosan on April 17, 2001. The blue circles in (a) are the assumed WVMR profile, which excludes water vapor in ADL, for sensitivity test.
vapor in these elevated layers is yet to be determined, the amount of water vapor in the ADL likely depends on the surface moisture conditions in the dust outbreak region, the transport route and the magnitude of updraft stream in the cold fronts. The possible processes of water-vapor uptakes are: (a) The surface moisture is advected up out of the boundary layer with dust particles, and (b) Post-cold frontal marine boundary layer air recirculated into ascending airstreams of upstream cyclones.

[17] 2. We demonstrated that the water vapor within the ADL led to a significant net heating of the ADL for the instantaneous measurements which influence the heating rate vertical structure. A steep increase in the potential temperature in the upper region of the ADL was found. This increased static stability in the ADL is due to the radiative heating of enhanced water vapor in the ADL and to the radiative cooling above the ADL from low aerosol and drier conditions. The elevated water vapor in the ADL contributes to maintaining a warmer ADL and increasing the static stability of the ADL, which may help maintaining the ADL structure for a longer period of time.

[18] Acknowledgments. We are grateful to Gosan weather station staff for providing radiosonde data and to B. Holben for providing AERONET data. This research was supported by the BK21 and by the SRC programs. We thank the NOAA Office Global Programs for support of the CMDL measurements.

References


