THE CALIPSO LIDAR DUST MEASUREMENT: A TRANS-PACIFIC TRANSPORT EVENT OF ASIAN DUST IN APRIL 2010

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ABSTRACT

Multiple dust storms occurred in East Asia during April 2010 and dust was transported to North America. Seven orbits of the CALIPSO lidar measurements are selected over the North Pacific and analyzed to examine possible changes in the intrinsic optical properties of Asian dust during the course of transport. The derived dust depolarization ratio ranges between 0.2-0.3 over Pacific, similar to that (0.26±0.03) observed by an airborne HSRL for Asian dust transported over the central East US, but smaller than that observed in the source region. The mean value of the dust lidar ratio derived for each orbit varies between 30 sr and 50 sr, while the airborne HSRL measured a value of 42±12 sr in central East US.

1. ASIAN DUST AND A TRANSPORT EVENT IN APRIL 2010

There are numerous dust sources in East Asian. Dust storms occur frequently each year especially in spring. Dust particles can be lofted into the air and then transported eastward over long distances. On occasion, dust can cross the Pacific Ocean and reach North America. Asian dust has even been observed to travel for one full circuit around the globe [1]. Because Asian dust tends to influence the atmosphere and oceanic ecosystem on a global scale, studies on Asian dust generation and transport as well as on its optical and radiative properties are required for a better estimation of its impact on the atmosphere and climate.

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, launched in April 2006 on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, has been providing nearly continuous global measurements of aerosol and cloud. CALIOP is a two-wavelength (532 nm and 1064 nm), polarization-sensitive (532 nm) elastic backscatter lidar, suitable for measuring dust [2] and tracking dust long-range transport [3]. In April 2010, an exceptionally intense yet persistent dust cloud was observed over North America by CALIOP (http: //www.nasa.gov/topics/earth/features/dustcloud.html) and other lidars. The CALIOP measurement showed that multiple dust layers, with large horizontal extents of several thousand kilometers, occupied almost the full troposphere for more than one week (see, for example, Figure 1c). We tracked the dust back to East Asia based on the CALIOP measurement and model simulations.

A previous study based on the CALIOP measurements and the global Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) [4] revealed that frequent dust emissions occurred in northwestern China in April 2010 because of stronger-than average near surface winds. Strong stable westerly winds then carried the dust eastward across the Pacific Ocean. A negative pressure anomaly, located in the eastern Pacific Ocean, hindered the air flow movement and yielded multiple transport pathways. This situation resulted in the complex yet spatially extensive dust structure over the North America (see Figure 1).

We also have simulated this dust transport event using the GEOS-Chem chemical transport model [5]. Composite column dust mass (mg m^{-2}) simulated for a time period of 9–23 April is shown in Figure 1a. In general, the GEOS-Chem simulation produces a result similar to the SPRINTARS result. In the central Pacific, the horizontal extent of dust covered a large latitudinal band (20˚N – 60˚N). When approaching North America, the dust path shifted northeastward. Much of the dust was transported into the Arctic, and a southern branch changed the transport direction southeastward. This southern branch was transported back to mid-latitudes into the US and West Pacific. The Langley Research Center's airborne HSRL observed an Asian dust layer over Virginia (central East US) during its validation flight along a CALIPSO orbit (labeled with number 8 in Figure 1b) on April 22.

In this paper we derive the optical properties of Asian dust along the transport path using an opaque water cloud constraint technique [6]. One focus is to determine if the intrinsic optical properties of Asian dust, namely, lidar ratio (LR) and particulate depolarization ratio (PDR), change during the course of transport. Our previous study based on the CALIOP measurements [3] showed an African dust plume that had remained largely unchanged in LR and PDR during its trans-Atlantic transport from the Saharan Desert to the Gulf of Mexico in summer of 2006. Saharan dust transport over the Atlantic Ocean by summer trade winds is typically well confined within a layer several kilometers thick above the marine boundary layer (MBL). In situ measurements indicate that the size distribution of Saharan dust particles generally does not change after a long-range travel across the Atlantic Ocean [7].

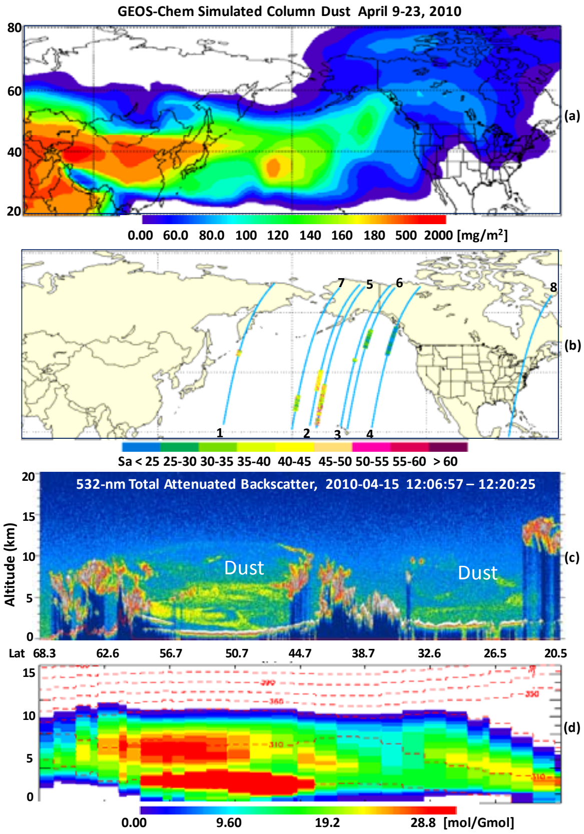

Figure 1. (a) Column dust mass (mg/m^2) simulated using the GEOS-Chem chemical model for a time period of April 9 – 23 in 2010. (b) Selected CALIPSO orbits (light blue lines) where opaque water clouds are observed underneath dust layers and constrained retrievals of dust lidar ratios are possible. Overlaid on the orbit tracks are the retrieved dust lidar ratios (color coded). The corresponding orbit tracks are labeled as: 1 = 04-11T15-49-08; 2 = 04-12T13-14-41; 3 = 04-13T12-19-09; 4 = 04-14T11-23-37; 5 = 04-14T13-02-32; 6 = 04-15T12-07-00; 7 = 04-15T13-45-51; 8 = 04-22T07-17-07. (c) An example of 532-nm attenuated backscatter observed during the CALIPSO orbit 6. Yellow-greenish colored features are dust; red-grey-white colored features are clouds. (d) GEOS-Chem simulated dust vertical distribution (color coded) along the CALIPSO track 6 along with the potential temperature (red contour).

Unlike Saharan dust transport across the Atlantic Ocean, which occurs typically at low latitudes (tropical and subtropical regions) and in the free troposphere (below ~7 km), Asian dust trans-Pacific transport is widely scattered both vertically and horizontally. In the vertical direction, the Asian dust transport that typically reaches long distances occurs generally in the upper troposphere along the westerly jet. Horizontally, the transport covers a large latitudinal band that can extend into the Arctic. The differences in transport patterns, physical properties and mineral compositions of the dust originating in the Saharan Desert and in East Asia may yield differences in the dust optical properties that will be examined in the following.

2. CALIOP DATA AND RETRIEVAL METHOD

CALIOP provides measurements of backscattered intensity at 532 nm and 1064 nm. At 532 nm, two polarization components are also measured, thus providing information about particle shape (spherical vs. nonspherical). In the example shown in Figure 1c, two dust plumes (yellow-greenish features) are seen with one between ~45N and ~60N and the other one south of ~35N. These dust plumes have large spatial extents with the northern one reaching an altitude of ~12 km. The structure of the dust plume is complex and inhomogeneous. Low and high clouds (red-grey-white colored features) are also observed. For this particular scene, clouds are seen in almost all air columns.

In this paper, the well-established optical depth (OD) constrained retrieval is applied to the dust layers where opaque water clouds, such as the ones (grey-white colored layer of ~1 km thick below 3 km) shown in Figure 1c, are found beneath the dust. The dust OD can then be derived from the integrated signal of the underlying opaque water cloud [6] using

$$\tau_{dust} = -\frac{1}{2} ln\left(2\, S_{WC}\, \gamma'_{WC} \left(\frac{1-\delta_{WC}}{1+\delta_{WC}} \right)^2 \right) - \tau_m \quad (1)$$

where γ'_{WC} and δ_{WC} are, respectively, the layer-integrated attenuated backscatter and volume depolarization ratio between the top and apparent base of the underlying opaque water clouds. τ_m is the OD due to the molecular scattering and ozone absorption in the atmosphere between the cloud top and the lidar. S_{WC} is the LR for water clouds, and is known to have a uniform value very near 19 sr (± ~1% at 532 nm and ± ~6% at 1064 nm) for a large number of cloud particle size distributions measured in situ with the effective radius within 2-14 μm [8]. Thus, τ_{dust} can be determined and used as a constraint to analyze dust layer overlying opaque water clouds.

3. RESULTS AND DISCUSSIONS

We selected seven nighttime CALIPSO orbits (lines in light blue labeled with numbers of 1-7 in Figure 1b) over the Pacific Ocean where CALIOP observed dust over low opaque water clouds. The retrieved dust parameters are shown in Figure 1b and in Figure 2. We note that only the data segments where the underlying water clouds are opaque, horizontally extensive and relatively homogeneous are analyzed and shown in these figures. For example, for the scene shown in Figure 1c, only the dust between 45N-55N was analyzed. The latitudinal extent of dust in each orbit is larger than what is shown in Figures 2 and 1b.

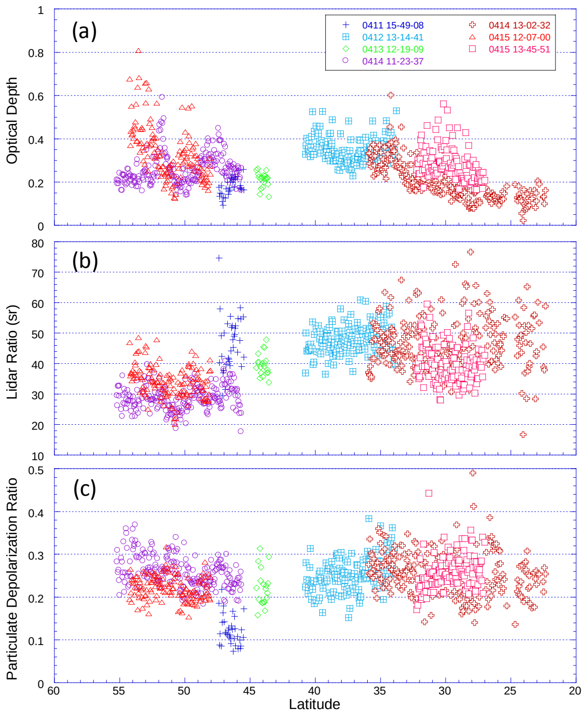

Figure 2. Retrieval results at a resolution of 5 km for Asian dust observed by CALIOP during the orbits shown in Figure 1b. (a) Optical depth at 532 nm determined using Eq. (1) from underlying opaque water clouds, (b) retrieved lidar ratio using optical depth as a constraint, and (c) depolarization ratio. Variations in these measurements are due mainly to noise and some large outliers in OD are due to contamination of clouds.

The dust OD (Figure 2a) remains large (0.2 - 0.4) for this dust event, even after long-range transport to the East Pacific (orbit 4, 0414 11-23-37). Considering the large spatial extents, this may imply a large amount of dust in the air. Model simulations indicate that multiple dust storms occurred in the source regions in the East Asia for the time period simulated. Each individual dust event experienced complex transport paths crossing the Pacific Ocean, then slowing down and stagnating over the East Pacific and North America.

From Figure 2c, we know that the PDR for these dust cases varies primarily within a range of 0.2-0.3 and does not show a significant latitudinal dependence, except for the 0411 case (orbit 1 in Figure 1b). The 0411 case only analyzes a small part of a spatially extensive dust layer observed during orbit 1, and this layer is actually a mixture of dust and pollution. For comparison, Figure 3 shows a histogram of PDR measured by CALIOP for Asian dust over the Tarim basin during March, April and May (MAM) of 2007-2011. A peak is seen in between 0.3 and 0.4. The PDR values measured for the transported dust over the Pacific are thus smaller than those found in the source region. Figure 4 presents the airborne HSRL measurement during its validation flight along the CALIPSO orbit 8 as shown in Figure 1b. The HSRL data has much higher SNR and spatial resolution than CALIOP, and thus can provide a great deal of additional detail. Dust is clearly observed (Figure 4b). The model simulation indicates that the dust was transported from the other side of the globe via a complex pathway. The structure of aerosols is also complex and multiple layered. The lower part of the dust below ~3 km is mixed with a significant amount of another type of low PDR aerosol. For the dust dominant part (3-4 km at the left hand side and 3-8 km at the right hand side), the PDR is larger. Figure 4c presents a histogram of PDR at 3-4 km altitudes that has a mean value of 0.26 (±0.03), similar to that derived over the Pacific (Figure 2c) but lower than that observed in the source region (Figure 3).

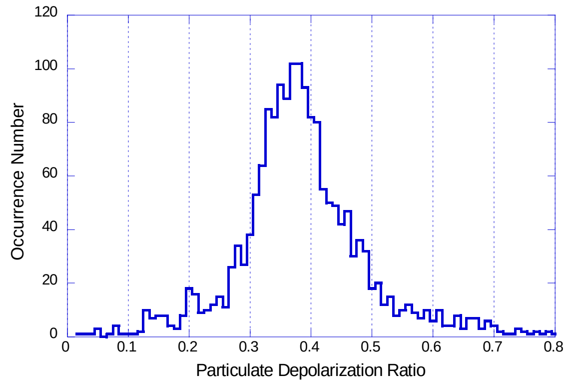

Figure 3. PDR measured by CALIOP during March, April and May (MAM) of 2007-2011 for dust over the Tarim basin where the Taklimakan desert is located.

The retrieved LR for the Asian dust observed by CALIOP over Pacific (Figure 2b) appears to have a dependence on latitude. Variations in LR in each orbit are due largely to noise. The mean value of LR for each orbit varies in a range of 30 - 50 sr, typical for Asian dust. The HSRL measured LR in the central East US on April 22 (Figure 4d) has a mean value of 42±12 sr. We note that the HSRL reports range-resolved values for LR and PDR, and therefore selective analysis can be done for the densest part of dust. However, LR can only be retrieved from the CALIOP measurement for the entire column above an opaque water cloud, and a column averaged PDR is calculated correspondingly.

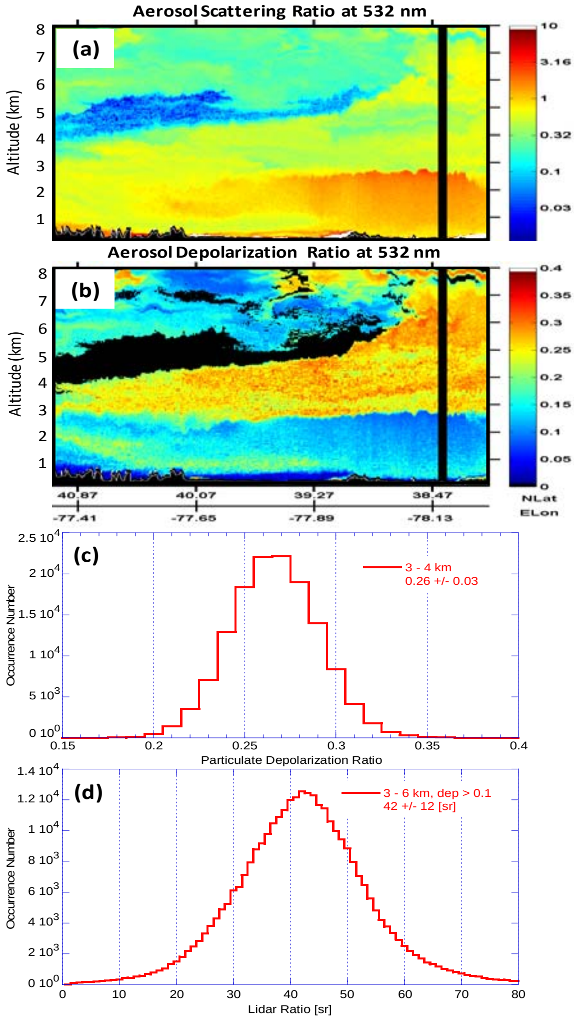

Figure 4. Airborne HSRL measurement on April 22 2010 over Virginia along the CALIPSO orbit #8 shown in Figure 1b. (a) Aerosol scattering ratio, (b) depolarization ratio, and histograms of (c) particulate depolarization ratios (PDR) and (d) lidar ratios calculated for the dust layers above ~3km.

We now discuss briefly possible uncertainties in the derived parameters. The HSRL can directly measure the aerosol LR and PDR, and the data is well calibrated at 532 nm. Therefore, errors in the HSRL measured LR and PDR at 532 nm are due mainly to random noise in the data. The CALIOP measurement, on the other hand, is much noisier, and can contain some calibration biases [9]. Furthermore, the determination of dust OD as well as LR using the underlying opaque water clouds is limited by how well we know the lidar ratio of water clouds (i.e., S_{WC} in Eq. 1). LR for water clouds is related to the cloud microphysical properties. Although previous theoretical work [8] showed that S_{WC} varies by only a few percent for a large number of in-situ measured particle size distributions of water clouds with effective radii smaller than ~14 µm, our examination of MODIS measurements indicates that the effective radius of water clouds on a global scale is generally larger and falls into a region where S_{WC} can vary more than 10%. The possible error caused by S_{WC} can be reduced when aerosol-free clear air is available immediately above some part of the underlying opaque water, so that estimates of S_{WC} can be determined as in [3, 6]. However, no aerosol-free regions of clear air were found in the orbits selected for this study. As a result, a mean value of S_{WC} determined from opaque water clouds with clear air above them found during April 2010 was used. This can yield an error of 10-15% in OD and LR. We are not sure if the latitudinal dependence in the retrieved LR is due to a possible natural variation in the microphysical properties of selected water clouds. More work is being done to quantify the relation between S_{WC} and effective radius of water clouds.

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