Lidar observations of long range dust transport over Mauna Loa Observatory

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ABSTRACT

A bistatic CCD camera lidar (CLidar) was used at the National Oceanic and Atmospheric Administration's Mauna Loa Observatory (MLO) to map aerosol light scattering. Laser light from a 532 nm, Nd:YAG laser was vertically transmitted into the atmosphere and the scatter off clouds, aerosols and air molecules was detected using a CCD camera with wide angle optics and a laser line filter. The intensity of each CCD camera pixel imaging the beam was normalized to a molecular scattering model in an aerosol free region for subtraction of molecular scattering. Aerosol extinction was derived using a column average aerosol phase function derived from AERONET sun photometer measurements at MLO. The CLidar design allows measurements of aerosol scattering all the way to the ground without an overlap correction. MLO, at 3397 m.a.s.l., typically receives free tropospheric air. During spring months, prevailing winds can occasionally transport dust from Asian sources with high dust activity over MLO. Aerosol scattering measurements were taken by the CLidar during spring months at MLO and revealed extinction peaks at mid-range altitudes. Back trajectories of air parcels from MLO at the altitudes of these peaks were conducted using NOAA's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model and it was found that they passed over regions of Eastern Asia known as sources of high dust activity. Relative humidity data from radiosondes and the NOAA stratospheric lidar's water vapor channel were examined to differentiate aerosol scattering from tenuous cloud scattering. This paper presents aerosol extinction data with observations of Asian dust as measured by the CLidar during spring months at MLO.

Keywords: Asian dust, dust transport, dust, CLidar, lidar, Mauna Loa Observatory, Eastern Asia, aerosol, aerosol extinction

1.) INTRODUCTION

Laser radar, or lidar, has been an effective technique to study characteristics and dynamics of the earth's atmosphere. Lidar has the capability to temporally map vertical atmospheric aerosol distributions remotely. This helps characterize atmospheric constituents over time, in contrast to the single snapshot of the vertical atmosphere columns often provided by in situ measurements. Lidar systems are vital in studies of long-term atmospheric changes, atmospheric boundary layer dynamics, and other atmospheric studies. An important study of the atmosphere is the transportation of mineral dust aerosols in long-range atmospheric dynamics. Aerosols are small, man-made or natural liquid or solid particulates suspended in the atmosphere. Mineral dust aerosols have significant influence on global climate due to their impact on the radiative balance of the atmosphere. A particular mineral dust aerosol known as Asian dust has been of wide interest to scientists. Asian dust is a meteorological phenomenon that has strong, direct impacts on Eastern Asia during spring months, when dust activity in East Asian deserts is intense [1]. Intense dust activity in Northern Chinese and Southern Mongolian deserts develops as a result of high-speed surface winds in the region. High-speed surface winds that develop

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intense dust activity in arid desert regions were found to be associated with Mongolian cyclonic depression and regional frontal systems [2,13]. The desert mineral dust is lofted up by surface-winds and further entrained in high altitude westerlies through the upward transport by complex, turbulent motion. Westerly prevailing winds transport the mineral dust across Eastern Asia and some across the Pacific Ocean [3,11]. Results from studies have shown that the impact of mineral dust transport to the Pacific Ocean has been significant, with atmosphere to ocean surface mineral dust deposition flux equaling about thirty percent of the rate of accumulation for deep sea sediments [4, 5]. The significance of Asian dust deposition in the Pacific Ocean helps exhibit the importance of mineral dust observations over the Pacific Ocean. As the results of previous studies have concluded, Asian dust can be transported across the Pacific Ocean by westerly prevailing winds. Interests lie in the observation of these aerosols at locations in the path of these prevailing winds, as the transport and deposition of Asian dust impacts climate. Mauna Loa Observatory (MLO) is an observatory located at Mauna Loa, HI, (figure 1) in the path of the wind currents known to entrain and transport Asian dust. MLO is run by the National Oceanic and Atmospheric Administration. The observatory hosts several aerosol measurement systems, including a charge-coupled device (CCD) camera lidar (CLidar), stratospheric lidar, nephelometer, robotic sun photometer.

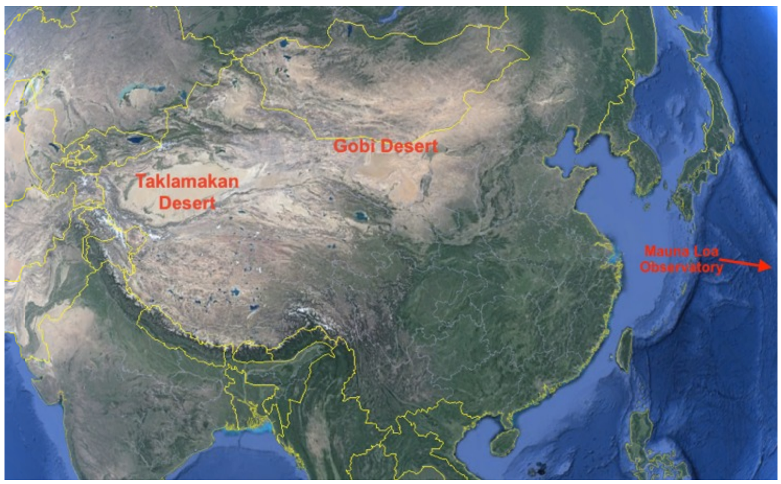


Figure 1: Mauna Loa Observatory in path of westerly winds carrying Asian dust

Previous studies investigating Asian dust transport found that the mineral dust can be entrained in air at altitudes of 5000 m and higher [2]. MLO is located at 3,397 meters above sea level (m.a.s.l.). Observations of Asian dust at MLO would hence be made at altitudes of about 1,600 meters above ground level (m.a.g.l.). Most popularly used ground-based lidar systems, elastic backscatter lidars, have a coaxial transmitting laser beam and photodetector. The coaxial nature of elastic lidars generates uncertainty in measurements taken in the very-near and near ground regions due to the lack of overlap in the detector's field of view and laser beam, despite overlap region correction schemes. The CLidar is a bistatic lidar system, a lidar system with a spatially separated detector and transmitted laser beam. The system's bistatic nature prevents it from being influenced by overlap effects. Additionally, the fact that the length of the laser beam imaged by each pixel grows with altitude allows the CLidar to be effective in the very-near and near-ground range while still maintaining reasonable altitude resolution at intermediate altitudes. The CLidar's measurement range overlaps the altitude range above MLO at which Asian dust transport is expected. Routine CLidar observations in conjunction with other atmospheric measurements set up the opportunity to track Asian dust transport across the Pacific Ocean.

2.) METHODOLOGY

2.1 Experimental Method

The MLO CLidar [6,12] is a bistatic lidar system that uses a charge-coupled device with wide-angle optics and laser-line filter to image a linearly polarized, 532 nm, Nd:YAG laser beam vertically pulsed (with energy levels ranging from 300-

600 mJ and a pulse width of 8 ns). The CLidar is different from elastic lidar systems in that its detector and transmitter are not located coaxially but separated by a large distance (139 m in this study). Light scattered from aerosols in the path of the laser beam is collected and imaged by the system's wide-angle CCD camera, measuring side-scatter from the laser beam as opposed to the backscatter measured by elastic lidars. The CLidar system's bistatic design [6] permits the measurement of side-scatter from all altitudes simultaneously. A diagram of the CLidar's setup can be seen in figure 2.

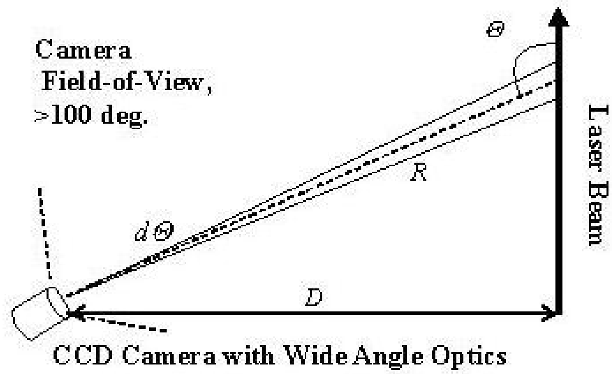


Figure 2: CLidar system with individual pixel scale illustration

CCD cameras use an array of pixels with constant pixel scales. Each pixel in the image images a constant angle dΘ, which corresponds to a length dz of the vertical column illuminated by the laser. The length dz is small (sub-meter) near the ground but grows at higher altitudes, even though dΘ remains constant. This results in pixels that image the "top" of the beam having significantly lower altitude resolution than their lower beam counter parts. This system design allows the CLidar to have good resolution from the ground to several kilometers above it. The specific altitude resolution is determined based on the perpendicular distance between the laser and the camera, D in figure 1. The CCD camera at MLO was positioned 139 m away to have relatively small lengths of beam measured by each pixel. A CLidar system was set up at Mauna Loa Observatory to take routine lidar measurements of the atmosphere from 2006 to 2013. CLidar measurements were usually taken year-round. CLidar data of interest for this study was taken during spring and early summer months, months during which high dust activity in Eastern Asia occurs. The CCD camera's wide angle optics and laser line filter limit the system to taking measurements only after sundown.

2.2 Image Corrections

Once the experiments are completed, the raw CCD 332 second images are collected as sets from each experiment, each to be corrected for dark currents, molecular scatter, and transmission to determine the extinction of laser light from aerosols, referred to as aerosol extinction. The CLidar's wide-angle CCD camera generally functions through the use of photosensitive camera pixels. When irradiated, the pixels store the irradiation information as electron flow. Even when these pixels receive no light, small levels of current are read to have been detected by the pixels. This is caused by heat generation during CCD operation and is an experimental artifact. Some pixels may also receive a significant level of this dark current, resulting in higher intensity pixels called hot pixels. The goal of the CCD image corrections is to determine the aerosol extinction. The first step to achieve this is through the subtraction of the dark current. At the beginning of each CLidar experiment, the CCD camera is blocked from receiving any light through the covering of the wide-angle lens with an opaque lens cover. The CCD camera takes a 332 second exposure with the opaque covering over the lens. This exposure, or "dark frame" is subtracted from every exposure taken of the laser beam for the respective experimental run, subtracting the artifact-intensity portions measured by each pixel. Once subtracted, the dark current has been corrected. Bias counts are also removed. Signal received is the result of aerosol scatter and atmospheric molecular scatter and background light, of which only aerosol scatter is of interest. Background light is subtracted. Intensities of pixels were normalized to a molecular scattering model in the aerosol free region of the atmosphere to obtain aerosol scatter and aerosol extinction. Once molecular scattering is corrected for, corrections for signal scattering in transmission are made. Laser light scattered by aerosols in the path of the beam have scattering efficiencies that depend on the scattering angle. This variation between the received signal and scattered light is corrected for through the application of aerosol phase functions. The Aerosol Robotic Network (AERONET) is a network that hosts robotic ground-based sun photometers at locations across the globe [7]. An AERONET sun photometer at Mauna Loa Observatory regularly takes angular irradiance measurements near the site of the CLidar and during the daytime prior to the time of the experiments. AERONET sun photometer measurements that corresponded to the temporal and spatial coordinates of measurements taken by the CLidar were spline-fit to determine angular scattering efficiencies for 532 nm light. This calculation was based off four sets of sun photometer measurements with wavelengths of light ranging from 400 nm to 1000 nm. The spline-fit phase function was then applied to the set of CCD images to correct for losses in transmission. Using the aerosol phase function, aerosol side scatter is converted to aerosol extinction, with the additional assumption of a single scattering albedo. These corrections were applied to each image taken in sets that typically spanned several hours on each measurement night.

3.) DATA ANALYSIS

Mauna Loa Observatory is a world-standard atmospheric facility situated at a very high altitude. The vertical atmospheric column above MLO typically consists of clean air. The limited aerosols that exist in the column are often of interest and can provide valuable information about the atmospheric transport and air flow patterns above the observatory. This study was interested in the observation of Asian dust over MLO. CLidar data taken during spring and early summer months were investigated, as the intense mineral dust activity that results in trans-Asian and trans-Pacific aerosol transport occurs during this time of year. Figures 3-5 show examples of average aerosol extinction profiles which indicated potential higher altitude aerosol layers.

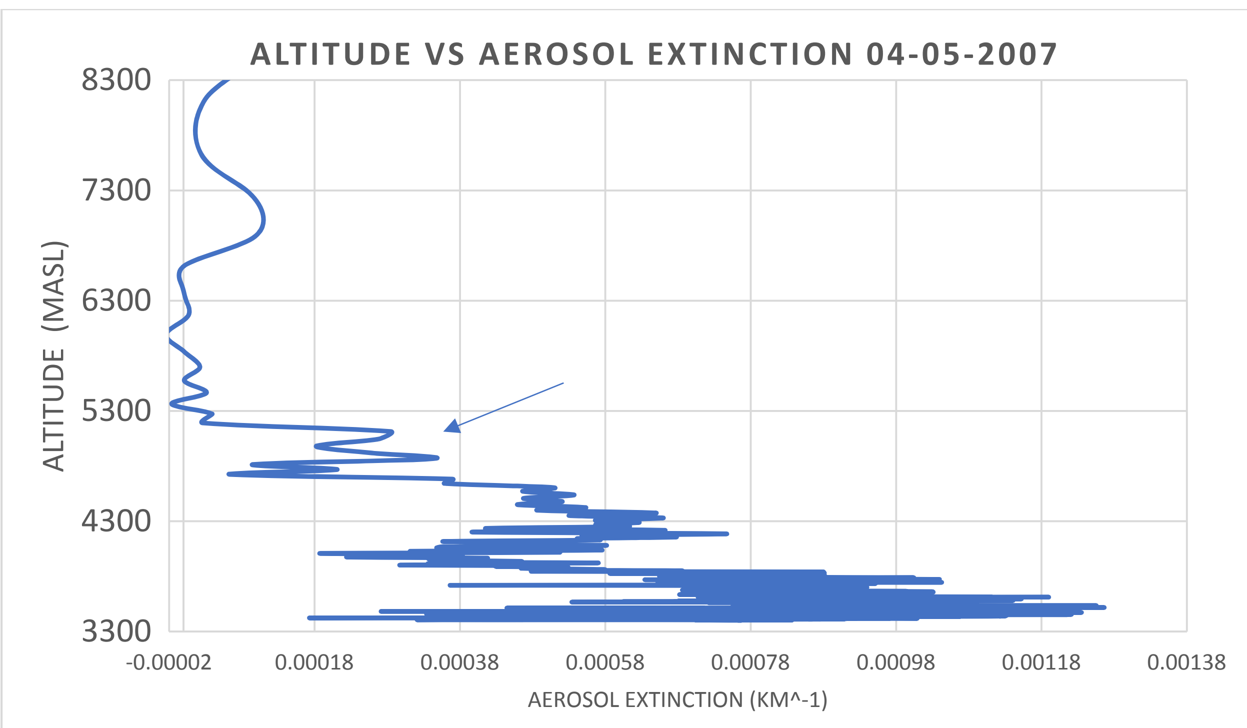


Figure 3: Average aerosol extinction for April 05, 2007 UTC

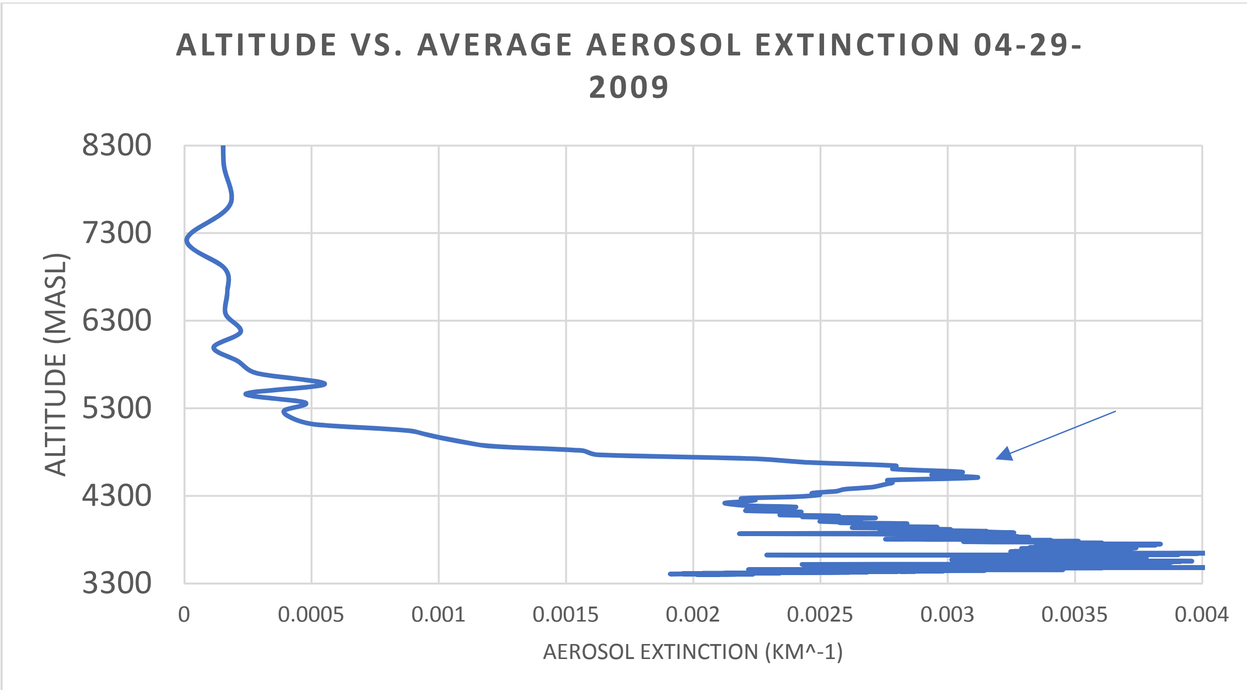


Figure 4: Average aerosol extinction for April 29, 2009 UTC

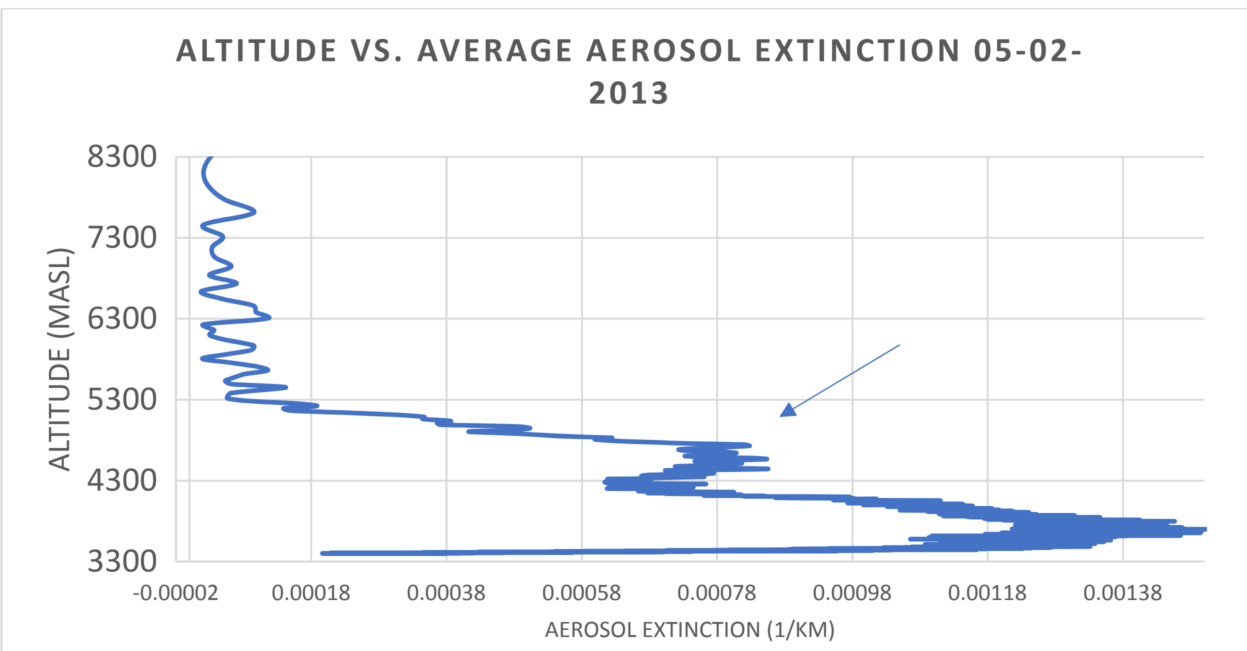
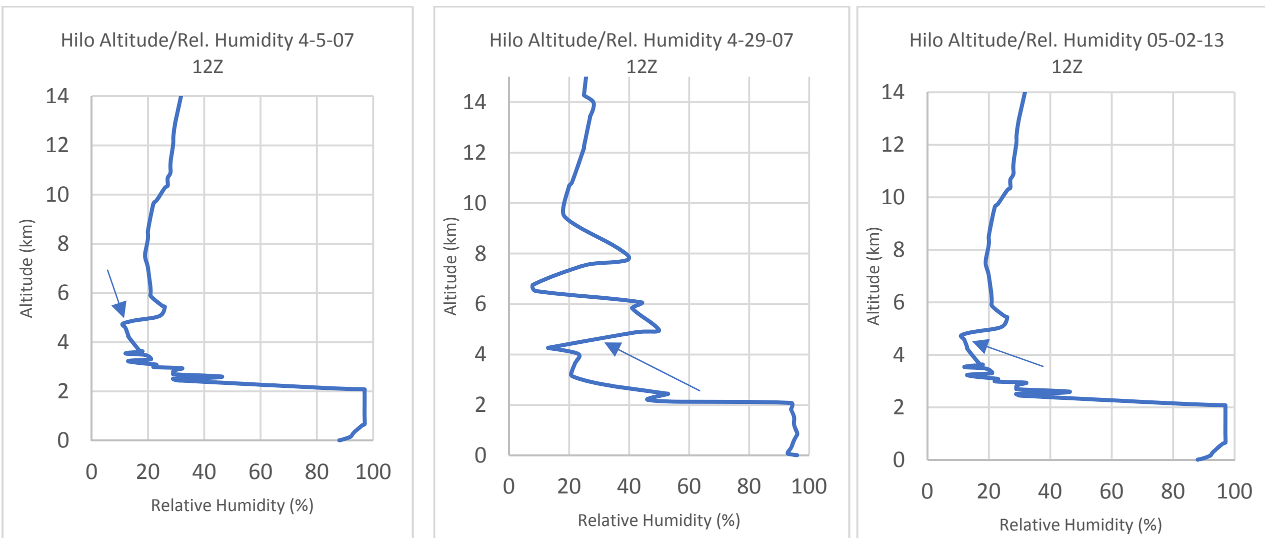


Figure 5: Average aerosol extinction for May 02, 2013 UTC

Figures 3-5: Average aerosol extinction profiles showing possible Asian dust aerosol extinction peaks

Figures 3-5 show average aerosol extinction profiles calculated from CLidar experiments ran on April 5, 2007 UTC, April 29, 2009 UTC, and May 2, 2013 UTC respectively. Each of the profiles shown in the figures show a layer of high aerosol extinction relative to the adjacent air, pointed out by arrows. Data from April 5, 2007 UTC shows an aerosol layer ranging 4,900-5,120 m.a.s.l., April 29, 2009 UTC shows an aerosol layer ranging 4,450-4600 m.a.s.l., and May 2, 2013 UTC shows signs of a significant aerosol layer ranging 4,500-4,700 m.a.s.l.. Layers of Asian dust transported in westerly winds from the Taklamakan and Gobi deserts are expected to be able to exist at around 5,000 m.a.s.l. with similar peak profiles. Layers of high aerosol extinction signify higher scattering and absorption levels than the surrounding air but do not necessarily provide information about the aerosols' nature nor their geographic origins. Tenuous water and ice clouds should be excluded as candidates to generate these enhanced extinctions. Storm et al [8] and Ovarlez et al [9] note that typical dry regions outside of ice clouds have relative humidity levels lower than 70% but ice clouds have been found to have relative humidity levels as low as 35%. Relative humidity data taken by radiosondes in Hilo, HI, along with water vapor data from the NOAA Stratospheric lidar at MLO were used to filter out days with potential aerosol higher altitude extinction peaks that exist at MLO for the time of CLidar measurements and the specific altitudes based on levels of relative humidity. Relative humidity data taken by radiosondes in Hilo, HI are shown in figures 6-8 for the Clidar measurement dates of figures 3-5.

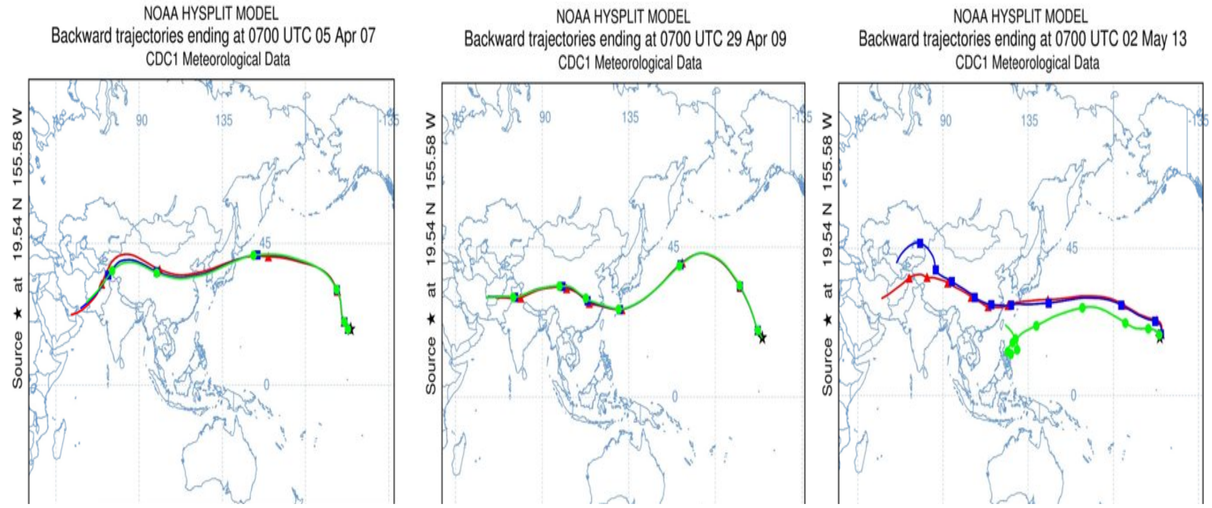


Figures 6-8: Relative humidity data corresponding to CLidar data with aerosol layers of interest

The relative humidity levels at the aerosol layers' altitudes from figures 2-5 are lower than that found in tenuous ice clouds. Air with low humidity levels and high aerosol extinction indicate possible mineral dust aerosols. Layers of air that displayed high aerosol extinction and relative humidity levels lower than the 30% threshold had their geographic air origins traced using NOAA's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. HYSPLIT is capable of computing complex air mass transport. The model is a hybrid of the Eulerian fixed-reference frame method, which uses a fixed frame to calculate concentrations of pollutant air, and the Lagrangian moving-reference frame method, which computes air mass diffusion and advection as the particles move in space [10]. The results of these back trajectories are discussed in the results section.

4.) RESULTS

The HYSPLIT model was used to conduct back trajectories on the aerosol layers that maintained relative humidity levels below the minimum threshold for ice-clouds. Back trajectories for April 5, 2007 UTC, April 29, 2009 UTC, and May 2, 2013 UTC were conducted. The back trajectory results are shown in figures 9-11.



Figures 9-11: HYSPLIT model back trajectories of air hosting aerosol layers contributing to high extinction

Figures 9-10 each show three back trajectories of air parcels at various altitudes. Each altitude's back trajectory is represented by a unique color (red, blue, green). The three back trajectories in figure 9 (red: 4867 m.a.s.l., blue: 5045 m.a.s.l., and green: 5115 m.a.s.l.) and the three back trajectories in figure 10 (red: 4508 m.a.s.l., blue: 4550 m.a.s.l., and green: 4571 m.a.s.l.) are all of air located within the aerosol layers noted in figures 3 and 4. Figures 9 and 10 show three back trajectories at three different altitudes within the respective aerosol layer to show the consistency of the layers' geographic origins. Figure 11 shows two back trajectories (red: 4450 m.a.s.l. and blue: 4730 m.a.s.l.) of air parcels within the aerosol layer noted in figure 5 and one back trajectory (green: 6095 m.a.s.l.) of cleaner air above the layer in figure 5 to help illustrate the significance of the aerosol layers at MLO. The back trajectory in figure 9 shows that the aerosol layer found in figure 3 consisted of dry aerosols entrained in air that passed over the Gobi and Taklamakan Deserts and took four to six days to travel to MLO. The back trajectory in figure 10 shows that the aerosol layer observed on April 29, 2009 UTC was entrained in air that passed over the Southern Gobi Desert and took five to seven days to travel to MLO. The back trajectory in figure 11 shows that the aerosol layer observed on May 2, 2013 UTC was entrained in air that passed over the Taklamakan desert and took six to eight days to travel to MLO.

5.) DISCUSSION

This study aimed to track Asian dust movement after its entrainment in westerly flows over Eastern Asia using a CLidar system. The massive amount of mineral dust being transported from the East Asian desserts has important impacts on the earth's radiative balance and on remote nutrient and sediment deposition. Mauna Loa Observatory is a premier atmospheric baseline station that lies in the path of westerly winds that transport the dust, making it an optimal location to make observations of it. The aerosol extinction, geographic origins, and relative humidity levels of the aerosol layers shown in figures 3-5 are consistent with identification of these layers as Asian dust being transported over the observatory. The CLidar system at MLO can detect these aerosol layers and make observations of Asian dust transport, in collaboration with water vapor and relative humidity measurements. Longitudinal tracking of these layers using the CLidar at MLO can serve an important role in monitoring Asian dust activity.

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