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A trans-Pacific Asian dust episode and its impacts to air quality in the east coast of U.S.

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HIGHLIGHTS

- Observe a persistent trans-Pacific transport of Asian dust in the northeast U.S.
- Quantify the Asian dust optical properties and time-height variations.
- Evaluate the dramatic impacts of Asian dust on the air quality.

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ABSTRACT

The transport of an intense trans-Pacific Asian dust episode to the Northeast United States (U.S.) is studied using a synergistic suite of observations and models including a ground-based lidar, AERONET-sunphotometer, satellite measurements and global aerosol transport model for New York City (40.821°N, 73.949°W). During the dust intrusion on March 17–19, 2010, the multi-wavelength lidar observations indicate dense dust plumes (~80% of total column AOD) located between 3 and 9 km altitudes with the lower layer mixing toward the planetary boundary layer (PBL). The column AOD shows a significant increase from 0.08 to 0.38 at 532-nm while the Angstrom exponent indicates a decrease from 1.3 to 0.7. The linear particle depolarization ratio is estimated to be 0.1–0.15 and the single-scattering-albedo shows the dust-like spectral dependence with the value of 0.9–0.95 at 440-nm. The NOAA-NCEP reanalysis and HYSPLIT model indicate that this long-range transport is driven by the strong western jets and travels for 6 days to arrive the U.S. east coast versus the western and northern U.S. Both the NAAPS aerosol transport model and satellite CALIPSO observations for multiple orbits clearly illustrate the dust-dominated aerosol along the transport path. In addition, coincident increase of both particulate matter (PM) and fine soil concentrations indicate the potential impact of transported dust on the air quality that is found to be associated with a large area of sinking air along the U.S. east coast.

1. Introduction

Asian dust storms, originating from the deserts of eastern and central Asia, often inject large amount of dust particles into atmosphere which can be transported to North America (NA) across the Pacific Ocean due to the combined effects of active extratropic cyclones and the strong mid-latitude western wind (Huebert et al., 2003; Stith et al., 2009; Uno et al., 2011). Somewhat surprisingly, even after long range transport, trans-Pacific Asian dust can pose significant impacts on the air quality and climate radiation in NA. Yu et al. (2012) show that because of the long-range transport, Asian dust can make a substantial contribution of AOD away from strong anthropogenic sources, resulting in strong contributions to the direct radiative effect. On the other hand, during the long-range transport process, the aloft dust plumes may mix with the local anthropogenic/industrial pollution downwind and mix down into the planetary boundary layer (Liang et al., 2004), or alter cloud and precipitation process by modifying ice cloud nuclei (Creamean et al., 2013). In the continental U.S. the enhanced particulate matter (PM) from the Asian dust transport is mostly observed at high elevation sites in the Western U.S. before undergoing the arduous transport over the mountains to the East U.S. (VanCuren and Cahill, 2002). Episodic high concentration dust events are most frequently observed at the surface in spring time, e.g. the Asian dust events in April 1998 and April 2001 that are responsible for the significant increases in PM_{10} and $PM_{2.5}$ (particulate matter with diameter

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<10 μm and 2.5 μm, respectively) and fine soil concentration from the west coast to east coast of NA (Jaffe et al., 2003; Szykman et al., 2003; DeBell et al., 2004). The analysis of surface PM data in the western US, combined with satellite data, has identified significant inter-annual variation in the amount of transported Asian dust and pollution (Fischer et al., 2009). In addition, several Asian dust events in April 2006 were observed in western Canada resulted in considerable enhancements of both sulfate aerosol, crustal material of Asian origin and organic compounds (McKendry et al., 2008; Leaitch et al., 2009). Though Asian dust primarily affects the western U.S. and Canada due to closer proximity and difficulties in transport over the mountains (Fairlie et al., 2007; Zhao et al., 2008), sufficiently strong high-level western jets can push the lofted plumes to the eastern U.S. For instance, an event of Asian dust transport to the mid-Atlantic U.S. was observed during Apr.17–20, 2006 (Delgado et al., 2011). Uno et al. (2011) show a few Asian dust transports to the eastern U.S. with a global aerosol transport model and CALIPSO data in spring 2010; and Cottle et al. (2013) also demonstrate these pervasive Asian dust events in both western and eastern Canada but in this case, avoiding the most treacherous mountain obstructions. To our best knowledge, in contrast to the extensive analysis of Asian dust impacts in the western U.S. and Canada, quantitative demonstrations are not well documented in the eastern U.S.

In this study, we present the synergistic observation of long-range transported Asian dust in the U.S. east coast using a combination of a ground-based multiple-wavelength lidar, an AERONET-sunphotometer, satellite sensors such as Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and MODIS (Moderate Resolution Imaging Spectroradiometer) as well as the outputs of an aerosol transport model. A thick and persistent aloft Asian-dust layer was observed and transported to U.S. east coast from East Asia driven by strong western jet stream; and the dramatic impact on the surface air quality is indicated with the coincident increases of PM_{10}, $PM_{2.5}$ and fine soil mass on the ground. Range-resolved distribution and optical characteristics of the aloft aerosol plume are analyzed, and the optical classification of Asian dust is confirmed. The trans-Pacific transport pathways and sources are investigated using a combination of NOAA-HSPLIT backward trajectories (Draxler and Rolph, 2003), NCEP reanalysis wind field (Kalnay et al., 1996), NAAPS (Navy Aerosol Analysis and Prediction System) aerosol transport model and satellite observations. In the end, the potential impacts of transported dust on the surface air quality are analyzed with favorable large-area air subsidence in the east coast of U.S. to enhance mixing down into PBL.

2. Instruments and methodology

2.1. Ground-based observations

A ground-based multi-wavelength elastic-Raman scattering lidar has been operating at New York City (NYC) since March, 2006 (Wu et al., 2009). A Nd:YAG laser (Spectra-physics Quanta-Ray 320) emits the laser beams at 1064-, 532-, and 355-nm with a repetition rate of 30 Hz. Receiver telescope (diameter 50.8 cm) collects the three elastic-scattering and two Raman-scattering returns by nitrogen and water vapor molecules excited by 355-nm. The signals are acquired by a LICEL transient recorder (TR40-160) and recorded with 1-min average and range resolution of 3.75 m. The 1064-nm channel is highly sensitive to the thin aerosol layer since the molecular backscatter is usually much weaker than the aerosol. The multiple-wavelength configuration is used to obtain the wavelength dependence of aerosol extinction coefficient, which helps to discriminate the coarse- or fine-mode dominance of aerosol.

In addition, an AERONET Cimel sun/sky radiometer (CE-318) is deployed at the same building roof of lidar. AERONET sunphotometer obtains aerosol optical depth (AOD) at wavelength 340–1640 nm and Angstrom exponent (Holben et al., 1998). Aerosol microphysics parameters (volume size distribution and refractive index) can be inverted from sky radiance measurements (Dubovik et al., 2000); subsequently the single-scattering-albdedo can be calculated. With the spheroid-shape assumption on dust aerosol, the linear particle depolarization ratio can be estimated with the above microphysical parameter (Dubovik et al., 2006; Müller et al., 2010), which can be used to distinguish aerosol shapes particularly for the non-spherical dust. Typically the uncertainty in AERONET-sunphotometer AOD under cloud-free conditions is within ±0.01 for $\lambda > 440$ nm and less than ±0.02 for shorter wavelengths (Holben et al., 1998; Eck et al., 1999). Error in the amount of aerosol size distribution is estimated to be ~15–25% of the radius between 0.1 and 7 μm (Dubovik et al., 2000). In this study, Level-2 product of AOD and Angstrom exponent are used which are applied with the pre- and post-field calibration, cloud-screen and quality-assurance (http://aeronet.gsfc.nasa.gov/).

To obtain aerosol extinction from elastic lidar returns, a constant lidar ratio and a far-end boundary of aerosol are usually assigned in the inversions (Fernald, 1984). The far-end reference altitude is often chosen in the upper troposphere (6–12 km altitude) where air is relatively free-aerosol. As the lidar-ratio varies from 10 to 100 sr depending aerosol size distribution and chemical species, the large uncertainty of the solution could be caused from an arbitrary lidar-ratio. To reduce this uncertainty, we use sunphotometer-measured aerosol optical depth (SP-AOD) to constrain the lidar-ratio or lidar-derived aerosol extinction profile, which means that the initially selected value of lidar ratio can be iteratively adjusted over 10–100 sr until the lidar-derived aerosol optical depth (integrating extinction profile with the range) matches SP-AOD (Pelon et al., 2002). In addition, we consider the influence from aerosol contribution in the lidar overlap region (0–0.5 km) by using the ceilometer-measured backscatter profile if available or by extending a constant of aerosol extinction at 0.5 km to the surface (Vladutescu et al., 2012). Stratospheric aerosol contribution to the column AOD is neglected because it is sufficiently small in non-volcanic periods in comparison to the troposphere (Thomason et al., 2008). This approach has been verified by comparing with other independent measurements from the high spectral resolution lidar and Raman-lidar (Burton et al., 2010; Wu et al., 2012). Generally the uncertainty of lidar-derived aerosol extinction is estimated to be within 20% (Russell et al., 1979; Sasano et al., 1985). Finally, with the lidar-measured multi-wavelength aerosol extinction coefficient profiles, Angstrom exponent profile can be estimated as follows:

$$\mathring{a} = -\frac{\log[\alpha(\lambda_1)/\alpha(\lambda_2)]}{\log(\lambda_1/\lambda_2)} \tag{1}$$

where, $\mathring{a}$ is Angstrom exponent, α is aerosol extinction coefficient where the subscripts represent two different wavelengths. Generally, small particles such as the smoke aerosols have the larger Angstrom exponent whereas the large particles such as dust and sea salt have the small Angstrom exponent (Eck et al., 1999). Thus it can be used to discriminate aerosol type.

Additionally, the surface $PM_{2.5}$ and PM_{10} mass concentrations are routinely monitored by New York State Department of Environment Conservation (NYDEC) with several sites nearby the CCNY-lidar-site. $PM_{2.5}$ is usually called as fine particle while the particle with the diameter at 2.5–10 μm is referred to coarse mode. The dust aerosol usually corresponds to coarse mode particles (PM_{10}- $PM_{2.5}$) and have more soil or crustal chemical component