Continental wildfire smoke transport and strong mixing into urban PBL in New York City, as observed by synergistic satellite, LiDAR, and other complementary measurements

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Abstract: Wildfire smoke in North-America are frequently observed in New York City (NYC, 40.82°N, 73.95°W) area. It is important to investigate the transported smoke mixing with urban planetary boundary layer (PBL) for assessing their impacts on air quality (AQ). This study presents an integrated observation of transported smoke from the Canadian wildfires with co-located elastic-Raman lidar, ozone-DIAL and Coherent Doppler Wind lidar in June 2023. Two episodes of dense smoke are analyzed that show variations of smoke optical properties, ozone (O_3) and $PM_{2.5}$ concentrations during the period of smoke intrusions on June 6-8 and June 29-July 1, 2023. Different advection and vertical mixing processes in the PBL are indicated for the two episodes. Smoke plume mixing in the PBL are indicated that results in large exceedance of National Ambient Air Quality Standard (NAAQS) of $PM_{2.5}$ concentration. The variations of Angstrom exponent and lidar-ratio indicate different microphysical properties of aged smoke particles. In addition, near-surface O_3 mixing ratios decrease for the Episode-1 (June 6-7) due to heavily-dense smoke attenuating sunlight whereas for the Episode-2 (moderately-dense smoke) O_3 concentrations increase in the PBL and at near-surface.

1. Introduction

The frequency and intensity of wildfire events in the western United States (US) and Canada are expected to increase because of climate change [1, 2]. This is critical for air quality since wildfires can emit large amounts of particulate matter (PM) and gaseous compounds, i.e. carbon monoxide (CO), nitrogen oxides (NOx) and volatile organic compounds (VOCs) [3,4]. Observations and model simulations indicate co-currently high concentrations of O_3 and carbonaceous aerosols in the transported wildfire smoke [5-8]. The model simulations indicate that the transported VOCs in the smoke layer can mix with the abundant NO_x in urban areas and then produce O_3 [7, 8]. It is a challenge to quantify transported smoke contribution to surface O_3 and $PM_{2.5}$ in the downwind urban area due to complex interactions with local emissions, and meteorology-chemistry processes. On the other hand, co-located measurements of vertical distribution of aerosol, O_3, and meteorological parameters are important to understand the smoke plume interplay with PBL and their impacts on local air quality.

This paper will present two unprecedented episodes of dense smoke plume that were observed by CCNY lidars and ground samplers in June 2023. The purpose of this study is to (1) demonstrate the transported smoke plumes (aerosol and O_3) mixing in the urban PBL, (2) quantify the aged smoke optical properties and impacts on ground AQ, and (3) investigate the relationships among $PM_{2.5}$, CO, OC and EC for exploring chemical processes involving smoke.

2. Methodology and Observation

At the City College of New York (CCNY) site (40.82° N, 73.949° W), the remote sensing and in-situ instruments for air quality and meteorological observations include: a 3-wavelength elastic-Raman lidar, an ozone-DIAL, a coherent Doppler wind lidar (Vaisala WindCube 200S), a ceilometer (Lufft CHM15k), an AERONET (Aerosol Robotic Network) Cimel sunphotometer, a microwave radiometer (Radiometrics MP-3000A), and the samplers for O_3, NO_2 and aerosol size distribution. These observations are mostly operated with a 1-min averaging window. Meanwhile, a standard surface air quality monitoring station is operated by the NYSDEC on the CCNY campus for $PM_{2.5}$, O_3 and CO measurements.

The aerosol lidar transmits three laser wavelengths (1064-, 532- and 355-nm) and uses a receiver telescope (Ø50-cm) collecting three elastic scattering and two Raman-scattering returns by nitrogen and water vapor molecules excited by the 355-nm laser output [9]. The Cimel sunphotometer-measured aerosol optical depth is used to constrain the lidar-ratio for retrieving aerosol extinction and backscatter profiles in the troposphere; and the results have been compared with NASA airborne HSRL measurements [10]. The CCNY O_3-DIAL shares the same large telescope receiver with the aerosol lidar but uses a separated 4-channel signal detection unit for O_3 detection at far-range and near-range, respectively [11]. A co-located coherent Doppler Wind Lidar was operated to measure 3D wind profiles at CCNY. In addition, there are several other wind-lidar sites in NYC area as part of NYS-Mesonet [12, 13].

3. Results and Discussions

Figure 1 shows the air quality index (AQI for $PM_{2.5}$), smoke dispersion area and air backward trajectories from NOAA-HYSPLIT on June 7 and 30, 2023, respectively. Unhealthy (red circles) and very unhealthy (purple circles) air can be seen according to the $PM_{2.5}$ AQI in NYC area. The air backward trajectories at 0.5-1.5 km ending at CCNY-site indicate that the air are originated from Quebec, Canada. The trajectories heights show air subsidence below 1-km on both days. However, the transport paths and duration are different on these two days. In comparison to the trajectories on June 7, the transports on June 30 took longer (3-day), firstly fist moving to the southwest of NYC then moving to NYC under southwesterly flows.

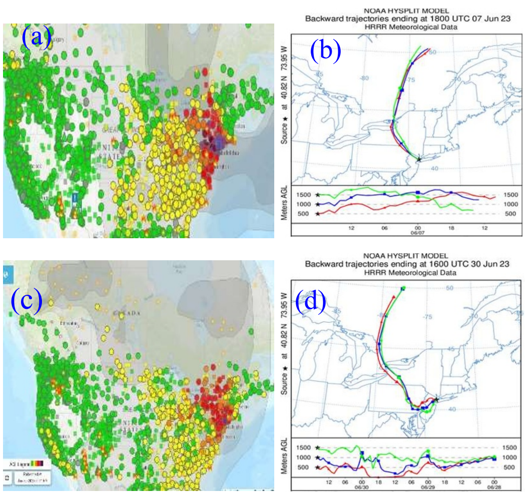

Fig.1 (a) and (c) Air quality index and smoke dispersion (gray in color), (b) and (d) air backward trajectories from HYSPLIT on June 7 and 30, 2023.

Figure 2 shows the daily variation of $PM_{2.5}$, CO and O_3 observed at the selected air quality stations in NYC area in June 2023. Two episodes of air pollution can be seen during June 6-8 and June 29-July 1, 2023, respectively. The hourly average of $PM_{2.5}$ are much larger than the National Ambient Air Quality Standard (NAAQS, 35 μg/m^3 over 24-hr average), with the maximum value reaching 400 μg/m^3 on June 7 and 100 μg/m^3 on June 30, respectively. The CO concentrations indicate the corresponding enhancements that usually indicates combustion smoke plumes. Importantly, the surface O_3 concentrations decrease during the Episode-1 period, e.g. hourly O_3 = 60 ppb at local noon on June 6 at CCNY, and hourly O_3 = 40 ppb on June 7. However, for the Episode-2, the surface O_3 show dramatic increase, e.g. hourly O_3 = 60 ppb at local noon on June 29 at CCNY, and hourly O_3 = 92 ppb on June 30, 2023.

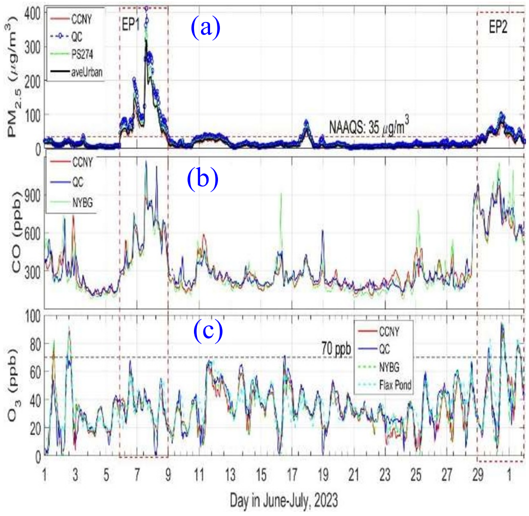

Fig.2 (a-c) Daily variation of ground-level $PM_{2.5}$, CO and O_3 measured at air quality sites in NYC in June, 2023.

The aerosol vertical distributions on June 7 and 30 are shown in Fig.3. It can be seen that most aerosols are located in the PBL (≤ 2~3 km). Aerosol backscatter coefficients are larger on June 7 than June 30, this indicates more dense concentrations which is consistent with the ground $PM_{2.5}$ temporal variation. In addition, there are few low-level clouds and high cirrus above 7-km altitude that make passive remote sensing of aerosol optical depths (AOD) difficult (e.g. satellite sensor and AERONET Sunphotometer). Thus, a constant of lidar-ratio is used to retrieve aerosol backscatter coefficient for CCNY aerosol-lidar in Fig.2. In addition, co-located AERONET sunphotometer Level-2 product indicate the AOD=0.5-4.0 at 1020-nm for Episode-1 and 0.4-0.7 at 1020-nm for Episode-2. Therefore, the heavily-dense smoke for Episode-1 largely attenuated the solar radiance reaching the ground and thereby suppressed chemical production of O_3 [14].

Figure 4 shows the time-height distribution of O_3 mixing ratios observed by CCNY-DIAL on June 30, 2023. Large O_3 concentrations in the PBL are clearly indicated, which are associated with the transported smoke plume. However, strong attenuation at the UV lasers beams of the lidar by the dense smoke on June 7 made the O_3 detections very difficult. Overall, the transported smoke plumes in the PBL made large impacts on the ground air quality.

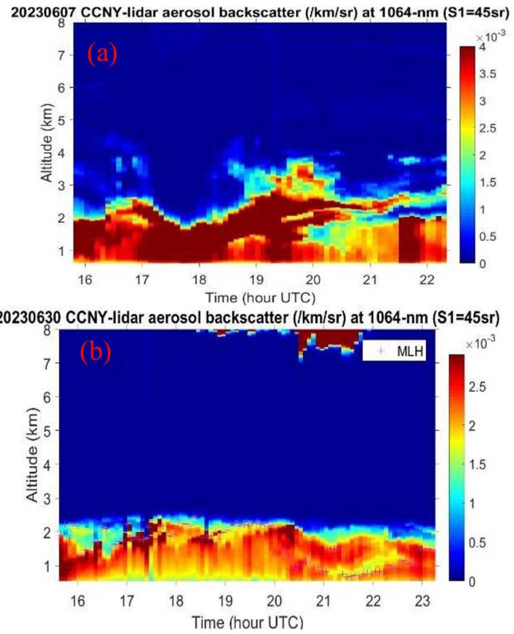

Fig.3 (a)-(b) Vertical distribution of aerosol backscatter coefficients at 1064-nm from CCNY lidar on June 7 and 30, 2023.

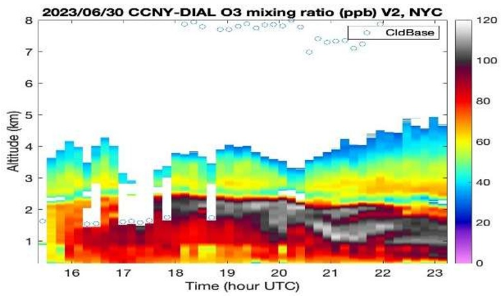

Fig.4 Time-height distribution of O_3 mixing ratios observed by CCNY DIAL on June 30, 2023.

For the Episode-2, the 3D wind information in the PBL are given in Fig.5 during June 28-July 1, 2023. In the PBL, the winds show a shift from prevailing northwest winds on June 29 to prevailingly southwest winds on June 30. The air transport trajectories from HYSPLIT model (Fig.1d) 1 are consistent with the wind lidar observations. Vertical wind velocities indicate strong updraft at noon on June 30th. The variances of vertical velocity are calculated with 10-min average, then the mixing-layer-height (MLH) are obtained and shown in Fig.5 (d).

Vertical mixing intensity, MLH and other meteorological factors (temperature and relative humidity) play important roles on the transport, formation and accumulation of O_3 and secondary aerosols at near-surface and in the PBL. More analysis at other wind lidar sites will be investigated for the two episodes of smoke intrusions. Correlation analysis among organic carbon, elemental carbon, CO and $PM_{2.5}$ will shed light on the meteorological-chemical process of aged smoke in the NYC urban area.

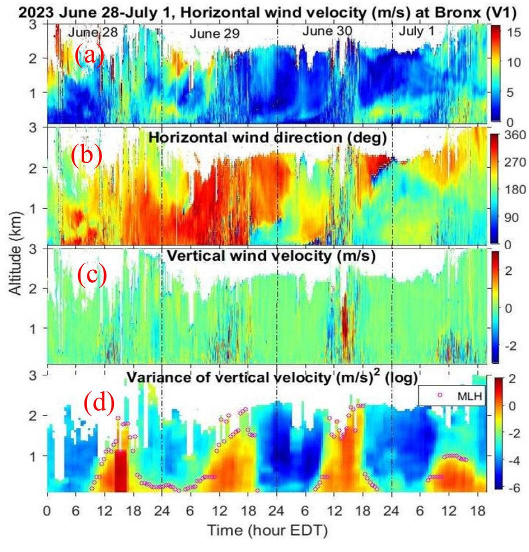

Fig.5 (a)-(d) Wind speeds and directions, variance of vertical velocity and mixing-layer-height (MLH) during June 28-July 1, 2023 in NYC.

4. Summary

This study focused on two episodes of transported dense Canadian fires smoke plumes in June 2023 to New York City, that mixed into the PBL and interacted with urban emissions and pollutants in New York City area, resulting in unprecedented level of particulate pollution. The smoke plumes took 2-3 days to reach to the eastern coast of US. The combined lidar and ground in-situ observations reveal major impacts of transported smoke plumes on ground-level air quality. The Angstrom exponents from the lidar and sunphotometer measurements indicate the smaller particle size of aged smoke. The ozone concentrations at near-surface decreased during the Episode-1 period (from June 6 to June 7) but increased during the Episode-2 period (from June 29 to June 30) at near-surface and in the PBL, which is related to the dense smoke concentrations and their radiative-chemical effects. The two episodes were distinct from each other in the transport paths, travel duration and vertical mixing intensities in the PBL. The dramatic increase of ground $PM_{2.5}$, CO, organic carbon and black carbon can be attributed to the low-altitude transport and mixing of wildfire smoke in the urban PBL.

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