

Article

Synergic Lidar Observations of Ozone Episodes and Transport During 2023 Summer AGES+ Campaign in NYC Region

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Abstract

We present coordinated observations from ozone Differential Absorption lidar (DIAL), aerosol lidar, and Doppler wind lidar at the City College of New York (CCNY) in northern Manhattan during the summer 2023 AGES+ campaigns across the New York City (NYC) region and Long Island Sound (LIS) areas. The results highlight significant ozone formation within the planetary boundary layer (PBL) and the concurrent transport of ozone/aerosol plumes aloft and mixing into the PBL during 26–28 July 2023. Especially, 26 July experienced the highest ozone concentration within the PBL during the three-day ozone episode despite having a lower temperature than the following two days. In addition, the onset of the afternoon sea breeze contributed to increased ozone levels in the PBL. A mobile ozone DIAL was also deployed at Columbia University’s Lamont–Doherty Earth Observatory (LDEO) in Palisades, NY, 29 km north of NYC, from 11 August to 8 September 2023. A notable high-ozone episode was observed by both ozone DIALs at the CCNY and the LDEO site during an unusual heatwave event in early September. On 7 September, the peak ozone concentration at the LDEO reached 120 ppb, exceeding the ozone levels observed in NYC. This enhancement was associated with urban plume transport, as indicated by wind lidar measurements, the HRRR (High-Resolution Rapid Refresh) model, and the Copernicus Sentinel-5 TROPOMI (TROPOspheric Monitoring Instrument) tropospheric column NO₂ product. The results also show that, during both heatwave events, those days with slow southeast to southwest winds experienced significantly higher ozone pollution.

Keywords: lidar; ozone; urban plume transport



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1. Introduction

Ground-level ozone is one of the key air pollutants in the United States. Ozone is formed by a series of photochemical reactions of precursor air pollutants, such as nitrogen oxide (NO_x), volatile organic compounds (VOCs), methane (CH₄), and carbon monoxide (CO), in the presence of sunlight. Ozone is harmful to human health [1]. Long-term exposure to excessive ozone is associated with respiratory and cardiovascular diseases, and it can lead to premature death [2–4]. To protect public health, the US Environmental Protection Agency (EPA) established the National Ambient Air Quality Standards (NAAQS) Maximum Daily 8 h Average Ozone Level (MDA8O3) to be 70 ppb in 2015 (EPA, 2015). Although air quality has notably improved in recent decades, with a 26% decline in the national average of ozone daily Max 8-Hour Average from 1980 to 2023

(<https://www.epa.gov/air-trends/ozone-trends> (accessed on 29 April 2025)), excursions of NAAQS frequently occur in the densely populated urban coastal regions [5–9]. The New York metropolitan area (NY Metro), including New York City (NYC), Long Island (LI), the Mid- and Lower Hudson Valley, and upwind and downwind areas in New Jersey (NJ) and Connecticut, often experience summertime ozone-exceeding events [10,11].

Many factors can contribute to elevated ground-level ozone concentrations and impact regional variations. High vehicle and industrial emissions in the NY Metro area provide abundant precursors for ozone photochemical production. The hot, clear sky, and stagnant meteorological conditions are favorable for the accumulation of ground-level ozone [12]. Stagnation tends to increase the resident time of ozone precursors near the surface, leading to higher ozone production [13]. A higher likelihood of ozone pollution events was found under calm wind conditions [14]. In addition, ozone and its precursors can be transported by prevailing wind patterns from the city to surrounding areas, affecting the air quality of the downwind regions. Tzortziou et al. found that high-NO₂ pollution events in Manhattan are associated with southeast to southwest winds, which carry pollution from Queens and Brooklyn, lower Manhattan, and northern NJ, where major power plants and economic activities are located [15]. Also, some of the highest ozone concentrations occurred downwind of urban and industrial areas due to higher ozone production efficiency with lower NO_x [16–18]. Moreover, small-scale sea–land circulations introduce additional complexities to ozone variations in urban coastal areas [19], creating sharp surface ozone spatial heterogeneity [20] and vertical structure [21].

Due to the interplay of the meteorological conditions, non-linear chemical reactions, transport processes, and heterogeneous terrains, the ozone variation in the NY Metro area and its downwind regions exhibits high complexity and therefore has led to wide research interests. To understand how these factors interact with each other to affect ozone variation in the area, in the summer of 2023, several field campaigns, collectively called AGES+ (AEROMMA+CUPiDS, GOTHAAM, ECAPE, STAQS, and others <https://csl.noaa.gov/projects/ages/> (accessed on 29 April 2025)), were conducted by multiple agencies and institutes in the NYC region and LIS areas. These campaigns included Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA), the Coastal Urban Plume Dynamics Study (CUPiDS) led by the National Oceanic and Atmospheric Administration (NOAA), and Synergistic TEMPO Air Quality Science (STAQS) by the National Aeronautics and Space Administration (NASA), among others. During the campaigns, a suite of satellite, airborne, and ground-based instruments were taking comprehensive observations of both columnar and profile quantities of ozone and its precursors, as well as other aerosol and gaseous species. Particularly, multiple ozone DIALs from the NASA Tropospheric Ozone Lidar Network (TOLNet, <https://tolnet.larc.nasa.gov/> (accessed on 29 April 2025)) were deployed, providing tropospheric ozone profile measurements with high temporal and spatial resolutions in the region. As part of TOLNet, the City College of New York (CCNY) deployed two ozone DIALs and conducted extensive observations with in situ and remote sensing instruments during the summer 2023 campaign. One ozone DIAL was stationed at the CCNY in Manhattan, while the other was integrated onto a transportable trailer and deployed at the Columbia University Lamont–Doherty Earth Observatory (LDEO) in Palisades, NY, approximately 29 km north of NYC along the Hudson River. Although the surface ozone in the NYC urban area is routinely observed, the surface measurements themselves cannot distinguish whether the ozone enhancement originates from local production or transport. To better understand the formation and transport process of ozone and its precursors, it is vital to observe the evolution of ozone vertical profiles. The routine observations of

ozone vertical profiles from the CCNY ozone DIAL in the NYC urban area fill the gap of understanding the ozone formation in the PBL and the transport process.

In this study, we present the synergistic observations from two ozone DIALs, an aerosol lidar, a wind lidar, ceilometers, and surface ozone measurements. The findings highlight elevated ozone formation within the PBL and regional ozone transport associated with smoke aerosol plumes. In addition, a notable high-ozone episode was observed during a heatwave in early September 2023. Simultaneous ozone DIAL measurements at the CCNY and the LDEO revealed that ozone at the LDEO can reach higher levels than in NYC, attributed to urban plume transport under prevailing south/ southwest winds. Section 2 describes the methods and materials used for this study. Section 3 presents the results. Section 4 is the discussion, and the conclusion follows.

2. Materials and Methods

The main observations for this study were conducted the CCNY (40.82°N, −73.95°W), located in uptown Manhattan. A set of remote sensing and in situ instruments for air quality and meteorological parameters collected measurements during the summer of 2023. Figure 1 shows the locations of the observation sites.



Figure 1. Locations of CCNY (purple star), the LDEO (blue star), Weather Station at Central Park (deep blue marker), and air quality monitoring sites (CCNY, Queens College (yellow), White Plains (green), and Flax Pond (red)) used for surface ozone measurements (source: Google Maps).

The CCNY ozone DIAL was developed in 2022 and has been taking regular measurements since May 2022 during the summer and under favorable weather conditions. The transmitter of the ozone DIAL utilizes a quadrupled Nd:YAG Laser (Q-smart 450, LUMIBIRD, Lannion, France, 266 nm, repetition rate at 20 Hz and power at 1 W), to pump a CO₂-filled Raman cell generating 287 nm (“on” line) and 299 nm (“off” line) as the differential wavelength pair through Stimulated Raman Scattering principle [22–25]. The ozone DIAL’s receiver incorporates a large Newtonian telescope (diameter = 50.8 cm and F# = 3.5) for detecting ozone at far range and a small telescope (diameter = 5.08 cm, F# = 3) for detecting ozone at near range. The wavelength separation (287 nm/299 nm), selection, and signal detection are achieved using a detector block, which consists of a dichroic mirror, two ultra-narrow bandpass filters (one centered at 287.2 nm and the other at 299.1 nm, each with a full width at half maximum (FWHM) of less than 1 nm and a transmittance of 35–37%), and lenses, followed by photomultiplier tubes (PMTs) (R9880U-113, Hamamatsu Photonics, Hamamatsu, Japan). A Licel data acquisition unit (TR40-16bit-3U, Licel, Berlin,

Germany) digitizes the signals and transmits them to a computer for analysis. The raw signals are collected with a 1 min averaging time and a range resolution of 3.75 m, with each vertical profile consisting of 8000 bins, corresponding to an altitude of approximately 30 km. The raw signals are then integrated over a 10 min time interval. For the final lidar-retrieved ozone profile, the effective vertical resolution varies to reduce statistical uncertainty [25–27]. The detection range of ozone DIAL is about 0.25–8.5 km under clear sky condition. In addition, since the cloud and aerosol can impact the retrieved ozone concentration, cloud screening and aerosol correction are applied to the ozone retrieval [25,28]. The signals that are contaminated by clouds are removed, as well as the signals above the cloud that are significantly attenuated. The aerosol correction is carried out using an iterative method on the 299 nm channel [28].

The CCNY Raman–Elastic Scattering lidar utilizes a Nd:YAG Laser (Quanta-Ray PRO-230, Spectra-Physics, Milpitas, CA, USA) coupled with second- and third-harmonic generators to transmit three wavelengths at 1064 nm, 532 nm, and 355 nm [29]. The Raman–Elastic lidar shares the same 50.8 cm diameter Newtonian telescope with the ozone DIAL. The receiver includes five detecting channels, three elastic scattering channels and two Raman-scattering channels excited by the 355 nm Raman scattering from the nitrogen and water vapor molecules in the atmosphere. The Raman–Elastic lidar can provide the aerosol backscatter and extinction coefficient profile at up to 5 min resolution from around 0.5 km to 8 km under clear sky condition [30]. Additionally, it can measure the aerosol plume height and planetary boundary layer height (PBLH). However, low- and mid-level clouds make it difficult to retrieve aerosol backscatter and extinction coefficient as they reduce the lidar signal-to-noise ratio and make it difficult to search for a clean air layer for the calibration with molecular scattering signals in the free troposphere [31].

The Doppler wind lidar (Leosphere WindCube 200S, Vaisala, Finland) measures profiles of horizontal wind direction as well as horizontal and vertical wind speeds using the Doppler-Beam Swing (DBS) technique. The data product has a time resolution of 2–5 s and a range resolution of 25 m, covering altitudes from 0.2 km to the top of boundary layer, as high as 3 km, depending on the signal-to-noise ratio (SNR).

The Lufft CHM15k ceilometer (OTT HydroMet Fellbach GmbH, Fellbach, Germany) provides the 24/7 h continuous measurements of cloud base height, attenuated backscatter coefficient profiles, and PBLH with temporal resolution as high as 15 s. The quality-controlled PBLH, retrieved aerosol backscatter coefficient profile, and extinction coefficient profiles have temporal resolution of 10 min [32]. The detection range for the cloud height is up to 15 km. But, due to the low SNR at far-range and the non-overlap zone in the near range, the range for aerosol backscatter and extinction retrieval is 0.2–6 km.

Continuous 1 min surface ozone mixing ratio measurements are provided by an ozone monitor (model 202/205, 2B–Technologies, Boulder, CO, USA) at the CCNY. Quality-controlled hourly surface ozone data are also obtained from the New York State Department of Environmental Conservation (NYSDEC) Air Quality (AQ) sites at the CCNY, White Plain (41.05°N, −73.76°W), Queens College (40.74°N, −73.82°W), and Flax Pond (40.96°N, −73.14°W) (<http://www.nyaqinow.net/> (accessed on 29 April 2025)). The quality-controlled hourly meteorological parameters, including air temperature, surface wind speed, wind direction, and relative humidity, are obtained from the National Weather Service, Central Park (40.78°N, −73.97°W).

To study the influence of urban plume transport from NYC to the downwind region, we also deployed another mobile ozone DIAL at the Columbia University Lamont–Doherty Earth Observatory (LDEO) (41.00°N, −73.91°W) in Palisades, NY, approximately 29 km north of NYC (shown in Figure 1) and conducted observations from 11 August to 8 September 2023 under favorable weather conditions.

The mobile DIAL is housed in a transportable trailer and has similar optical design as the CCNY ozone DIAL stationed in the lab, except that it uses a Cassegrain Telescope (diameter = 50.8 cm and $F\# = 3.5$) for the far-range channel. Before moving to the LDEO site, the mobile ozone DIAL was calibrated and validated against the stationary ozone DIAL at the CCNY [33]. In addition to the mobile ozone DIAL, a Vaisala CL-31 ceilometer (Vaisala, Finland) and an ozone monitor (2B-Techologies, USA) were installed at the LDEO and took measurements at the LDEO from 31 July 2023 to 22 September 2023. The Vaisala CL-31 ceilometer provides the uncalibrated attenuated backscatter coefficient or range-corrected backscatter signal profile and PBLH at 10 min resolution. The ozone monitor collects surface ozone concentration at 1 min resolution.

The Tropospheric Monitoring Instrument (TROPOMI) is an advanced spectrometer aboard the Copernicus Sentinel-5 Precursor (S5P) satellite mission. TROPOMI is designed to monitor a wide range of atmospheric constituents with high spatial resolution, including nitrogen dioxide (NO_2), ozone (O_3), formaldehyde (HCHO), sulfur dioxide (SO_2), etc. The TROPOMI Tropospheric NO_2 product (version 2) is used to study the urban plume transport with spatial resolution of 5.5 km and 3.5 km at nadir. There are approximately 1–2 swaths available each day in NY Metro region depending on the season.

The HRRR is a real-time hourly updated high-resolution (3 km) atmospheric model developed by NOAA [34]. In this study, we leveraged 80-m wind data from the High-Resolution Rapid Refresh (HRRR) model to analyze wind patterns in NYC and its surrounding areas and assess pollution transport, providing insights into how wind patterns influence air quality in the region. The HRRR dataset was accessed and processed using the Python 3.10 Herbie library [35].

3. Results

3.1. Overview

Figure 2 displays the 8-h running mean ozone concentration from 1 June to 8 September 2023, measured at NYSDEC AQ stations in the NY Metro area, including the CCNY, White Plains, Queens College, and Flax Pond (the locations of the AQ stations are shown in Figure 1). The periods where the 8-hour running mean ozone concentration exceeded 70 ppb (0.07 ppm) at least at one station (marked by red dashed lines) are highlighted.

At the CCNY station, six exceedance days were recorded during this period: 2 June, 30 June, 1 July, 5 July, 17 July, and 26 July. The results also reveal distinct spatial patterns of high-ozone days. For example, 27–29 July was a heatwave event with peak temperatures exceeding 90 °F (32.2 °C), while the peak temperature on 26 July was lower. However, the ozone levels in northern Manhattan (CCNY) and northeast of NYC (White Plains) exceeded 70 ppb on 26 July but were lower during the following heatwave days. In contrast, the ozone levels in the east of NYC over Long Island (Flax Pond) were below 70 ppb on July 26 but rose above 70 ppb on 29 July, which is influenced by sea breeze and low PBLH at the coast. At Queens College (Queens, NYC), the ozone levels surpassed 70 ppb on both 26 July and 28 July. This spatial variability in ozone distribution is influenced by localized meteorological conditions, chemical reactions, and urban plume transport.

Understanding the mechanisms behind high-ozone formation and transport requires synergistic profiling observations of ozone concentration, wind, aerosols, and temperature. To illustrate this, we present two case studies focusing on the 26–28 July and 5–7 September episodes, both of which occurred during heatwave days. The following discussion will focus on these two episodes using multi-instrument observations.

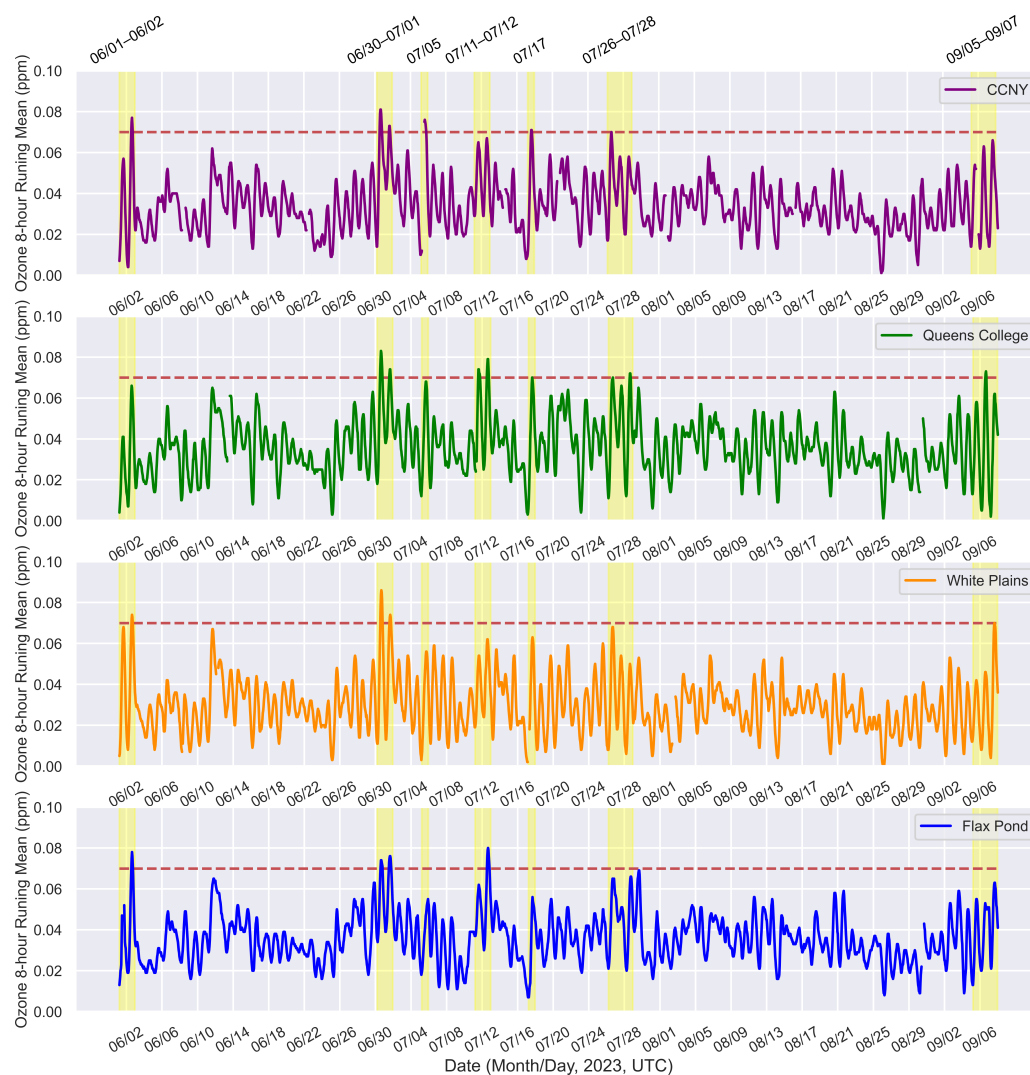


Figure 2. Observed 8-hour running mean ozone concentrations in the NY Metro and Long Island area from 1 June to 8 September 2023. The red dashed line indicates the 70 ppb (0.07 ppm) National Ambient Air Quality Standards (NAAQS).

3.2. Case Study 1: Ozone Formation and Aloft Ozone/Aerosol Plume Transport and Mixing into the PBL (26–28 July 2023)

The first case is characterized by high-ozone formation within the urban PBL, with aloft ozone plumes associated with transported smoke plumes mixing into the PBL. The wind lidar data reveal that distinct wind patterns, combined with pollutant transport, modulate the local ozone concentration.

Figure 3 illustrates the hourly air temperature recorded at Central Park weather station from 26 July to 28 July 2023. On 26 July, the highest temperature was close to but below 90 °F (32.2 °C), while, on the following two days, the peak temperature exceeded 90 °F (32.2 °C).

Figure 4 displays the time–altitude curtain plots of the range-corrected backscatter signal, PBLH, and cloud base height observed by the CCNY Lufft CHM15k ceilometer from 26 July to 28 July 2023. On 26 July, the sky was mostly clear, with the PBLH varying from 0.4 km in the early morning to 2.1 km in the afternoon, and aerosol plumes were observed above the PBL. On 27 July, scattered clouds appeared at the top of the PBL and at higher altitudes, with the PBLH ranging from 0.25 km to 1.6 km. A quick shower occurred around 02:00 UTC on 28 July, washing away pollutants. Clouds were present at altitudes of 1.2–1.6 km and persisted until 21:24 UTC.

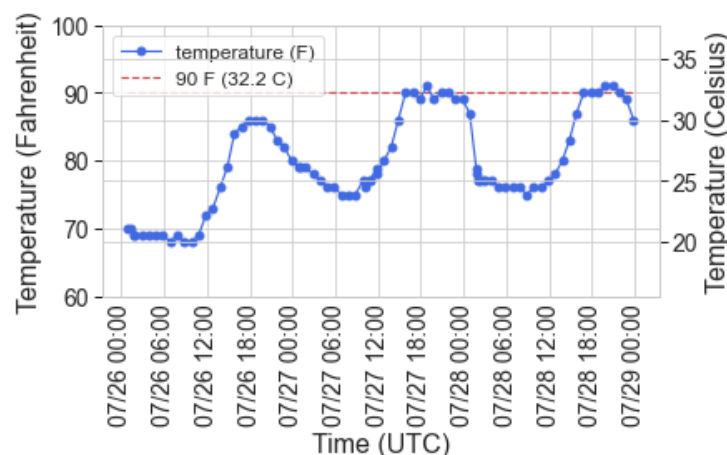


Figure 3. Hourly air temperature at NYC Central Park during 26 July–28 July 2023. On 26 July, the highest temperature was close to but below 90 °F (32.2 °C), while, on the following two days, the peak temperature exceeded 90 °F (32.2 °C).

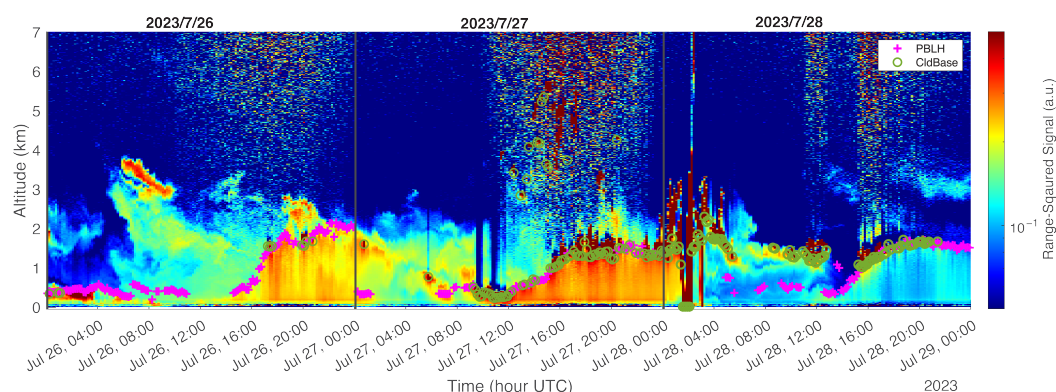


Figure 4. Time–altitude curtain plots of the range-squared corrected backscatter signal from the Lufft CHM15k ceilometer at the CCNY during 26–28 July 2023. The PBLHs and cloud base heights are indicated by magenta and green markers, respectively.

Figure 5a–c show the time–altitude plots of the ozone mixing ratios (ppb) measured by the ozone DIAL at the CCNY from 26 July to 28 July 2023. Figure 6a–c present the time series of ozone mixing ratios measured by the 2B-Tech ozone monitor at the CCNY air quality station and by the lidar at 250 m, 350 m, and 450 m on the same days. Overall, the lidar-retrieved ozone mixing ratios within the PBL match well with the ozone monitor measurements, demonstrating the feasibility of ozone DIAL capturing the ozone variation near the surface. The relative difference between the lidar measurements at 250 m and the ozone monitor is within 20% during 15:00–21:00 UTC (11:00–17:00 EDT), which is consistent with our drone-based observations that surface concentrations can be lower than elevated ozone concentrations in urban areas [25].

Among these three days, 26 July experienced the most significant ozone production despite having a slightly lower temperature than the following two days. As indicated by Figure 6a, before 15:00 UTC (11:00 EDT), the ozone was vertically stratified, with a lower ozone concentration near the surface and increasing with height. Between 16:00 and 18:00 UTC (12:00–14:00 EDT), the ozone within the PBL was uniformly distributed due to stronger vertical mixing of the air, and its value increased with time. At 18:00 UTC (14:00 EDT), the PBL ozone levels suddenly increased from 80 ppb to 90 ppb, as indicated by both surface and ozone DIAL measurements (Figures 5a and 6a). This sudden increase in ozone is likely attributed to a combination of pollution transport from the NY/NJ/PA corridor and sea breeze recirculation from the NY/NJ Bight. Wind lidar ob-

servations (Figure 7a,d,g) illustrate that, in the morning, before 15:00 UTC (11:00 EDT), the wind was characterized by a weak west/northwest flow. Between 15:00 and 18:00 UTC (11:00–14:00 EDT), the convective mixed layer began to develop. Winds within the PBL were calm, representing stagnant conditions that suppressed pollutant ventilation and facilitated ozone accumulation. At 18:00–19:30 UTC (14:00–15:30 EDT), the PBL winds shifted to a south/southwest direction with a speed of 6–8 m/s, which is a feature of sea breeze in this region. Previous studies have indicated that, on hot days, early morning northerly background wind often leads to the development of an abrupt sea breeze in this area [36]. The northwest/westerly winds in the morning can transport NO_x-rich air from the urban area toward the Atlantic Ocean, where ozone is formed and undergoes less titration. In the afternoon, the developed sea breeze can recirculate the ozone from the Atlantic Ocean back into city, leading to a sharp ozone increase in the afternoon. The HRRR 80 m horizontal wind is consistent with the wind lidar observations (Figure 8a–d), demonstrating the air flow from the NY/NJ Bight to the NYC urban area from 18:00 UTC to 20:00 UTC.

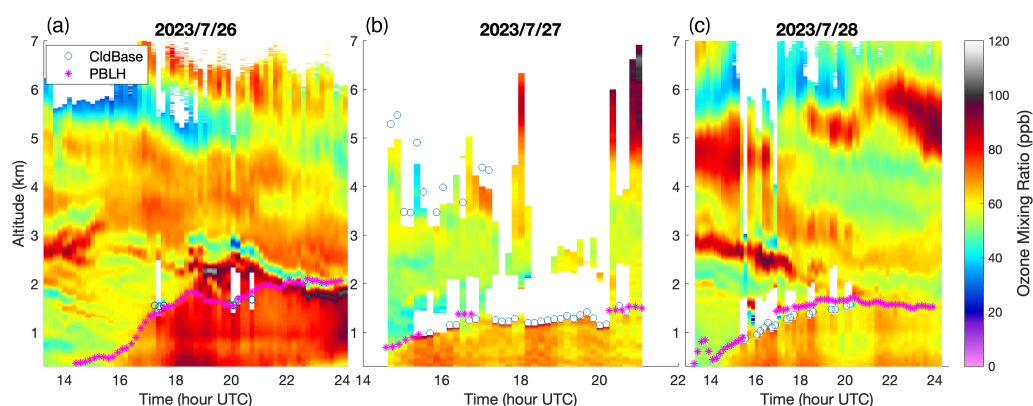


Figure 5. Time–altitude curtain plots of ozone mixing ratios (ppb) retrieved by the ozone DIAL at the CCNY on (a) 26 July, (b) 27 July, and (c) 28 July 2023. The PBLHs retrieved by the Lufft CHM15k ceilometer are indicated by magenta asterisks, while cloud base heights are represented by blue circles.

In addition to ozone production and transport within the PBL, elevated ozone plumes were observed above the PBL on 26 July. An ozone plume between 2 and 3 km in altitude was associated with an aerosol plume, as shown by both the ozone DIAL and aerosol lidar (Figures 5a and 9a). This aloft plume interacted with the top of the PBL around 19:00 UTC (15:00 EDT). The aerosol lidar showed a higher aerosol concentration, indicated by a stronger backscatter signal in the upper PBL (1.5 km) around 20:00 UTC (16:00 EDT). Concurrently, the ozone DIAL detected an increased ozone concentration above 1 km at 20:00 UTC (16:00 EDT), suggesting that the transported aerosol/ozone plume mixed into the upper PBL. However, this mixing did not extend into the lower PBL and thus did not impact the surface ozone levels. The wind lidar data show that the aerosol/ozone plume at around 2–3 km was transported from the southwest/west direction (Figure 7a). Another plume above 4 km showed an enhanced ozone concentration, but no aerosol plume was detected at that altitude, implying a different source for this higher-altitude ozone. After 22:00 UTC (18:00 EDT), vertical mixing decreased, and ozone was no longer uniformly distributed vertically. The surface ozone levels decreased rapidly, likely due to ozone titration by increased NO emissions during the evening rush hour. Meanwhile, the ozone levels in the upper PBL (1–2 km) continued to rise despite the reduced solar radiation.

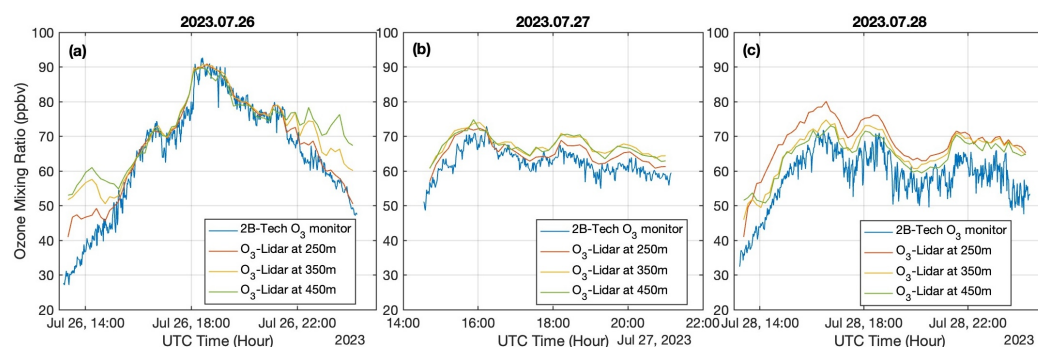


Figure 6. Time series of ozone mixing ratios measured by the ground ozone monitor (2B-Tech) and ozone DIAL at 250 m, 350 m, and 450 m on (a) 26 July 2023; (b) 27 July 2023; and (c) 28 July 2023. The relative difference between the lidar measurements at 250 m and ozone monitor is within 20% during 15:00–21:00 UTC (11:00–17:00 EDT).

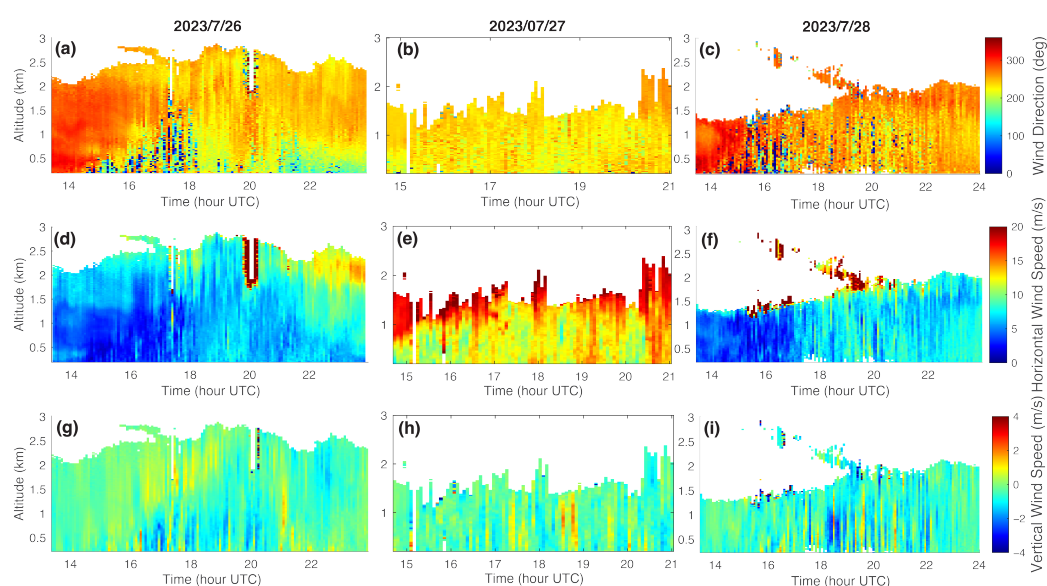


Figure 7. Time–altitude plots of (a–c) horizontal wind direction (degrees from true north), (d–f) horizontal wind speed (m/s), and (g–i) vertical wind speed (m/s) (positive values indicate upward movement) from 26 July to 28 July 2023, measured by the CCNY Doppler wind lidar.

On 27 July, although the air temperature was higher than July 26, the ozone within the PBL was lower, ranging from 60 to 70 ppb (Figures 5b and 6b). This relatively lower ozone level is likely due to clouds at the top of the PBL, which blocked sunlight and reduced the ozone photolysis rate. Additionally, the wind pattern was characterized by a steady south/southwest wind throughout the day with relatively high speed, around 10–15 m/s (Figures 7e and 8e–h), which can facilitate the dispersion of ozone and precursors pollutants. This explains that, although the temperature on 27 July remained around 90 °F (32.2 °C) for extended hours (Figure 3) and higher than the previous day, clouds reduced the ozone production, and the strong steady south/southwest wind prevented ozone accumulation in the region.

On July 28, ozone increased in the PBL from 13:30 to 16:23 UTC (9:30–13:23 EDT) with increasing solar radiation and temperature. After that, the ozone level fluctuated around 70 ppb. Both the ozone monitor and lidar observed dips in ozone levels during 16:23–18:13 UTC and 18:30–21:30 UTC, which may be due to clouds reducing ozone production (Figures 5c and 6c). In addition, multiple elevated ozone layers were observed: a lower plume appeared around 3 km, gradually descended, and reached the top of the PBL around 22:00 UTC; a higher ozone layer appeared at 5 km and descended to 3 km but did

not interact with the PBL (Figure 5c). Both elevated ozone layers coincided with aerosol plumes, indicated by the aerosol lidar observation (Figure 9c). Furthermore, the horizontal wind direction from the wind lidar suggested that the lower aerosol/ozone plume was transported by westerly winds (Figure 7c,f). Vertical wind measurements showed a down-draft around 21:00–22:00 UTC (Figure 7i), which likely mixed the high-ozone plume down into the PBL, leading to the observed increase in ozone levels at 22:00 UTC. The wind lidar observed that the horizontal wind was light before 17:00 UTC (13:00 EDT) and changed to westerly wind after 17:00 UTC (13:00 EDT), with a speed of 5–8 m/s.

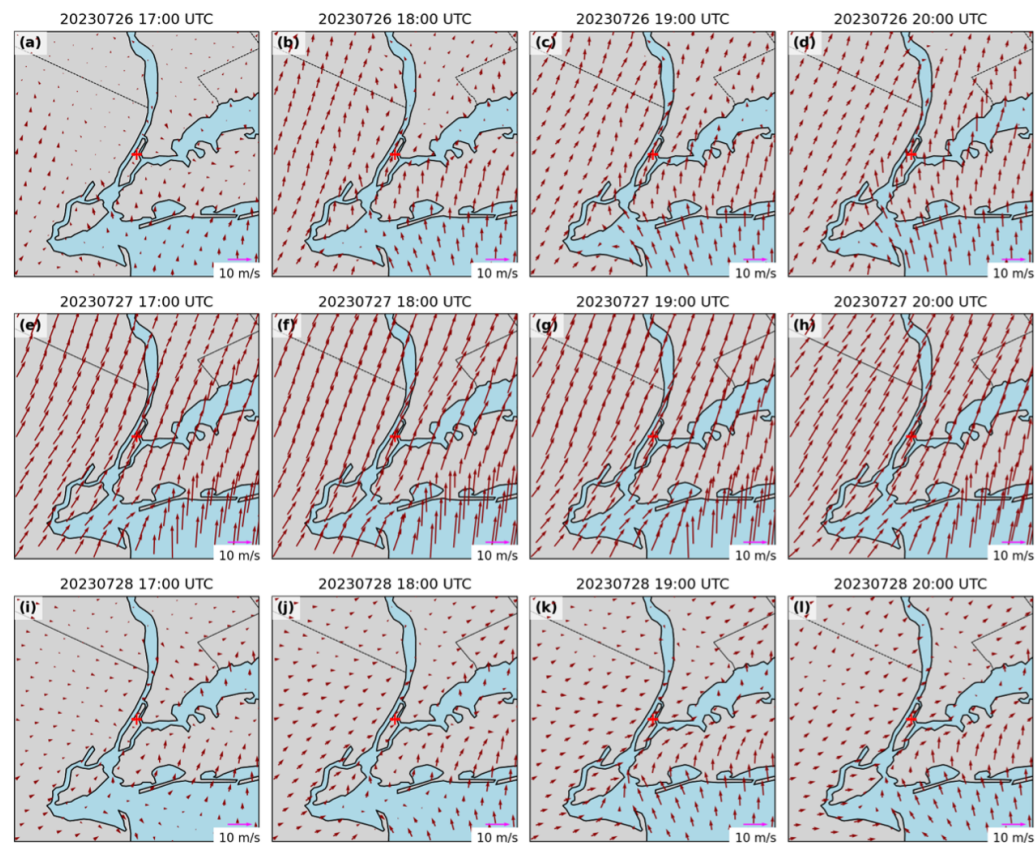


Figure 8. The 80 m wind field from the HRRR model over a 50 km domain centered on the CCNY (indicated by a red plus sign) at 17:00–20:00 UTC on (a–d) 26 July, (e–h) 27 July, and (i–l) 28 July 2023. The scale bar (10 m/s) is displayed in the lower right corner. On 26 July, winds were calm in the NY Metro region before 18:00 UTC; after 18:00 UTC, a sea breeze developed, bringing airflow from the NY–NJ Bight into the NYC urban area. Strong persistent southwesterly winds dominated the region on 27 July, while winds on 28 July were light and from the southwest/west direction in the NYC urban area.

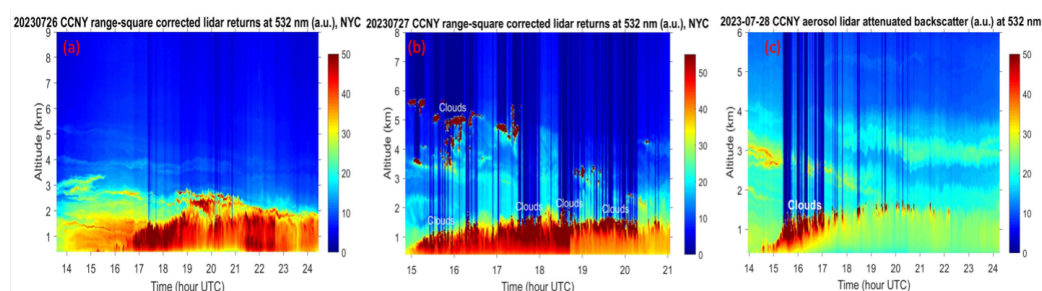


Figure 9. Time–altitude curtain plots of range-squared backscatter signal return of the aerosol LiDAR at 532 nm on (a) 26 July 2023; (b) 27 July 2023; (c) 28 July 2023.

3.3. Case Study 2: Ozone Urban Plume Transport to Downwind Suburban Area (5–7 September 2023)

Case 2 features a high-ozone episode and urban plume transport to a downwind suburban area, observed using two ozone DIALs at the CCNY and LDEO sites. During a heatwave event on 5–7 September 2023, the maximum temperatures in NYC reached or exceeded 90 °F (32.2 °C) for 3 days, as shown in Figure 10. The surface ozone measurements (1–5 min average) were obtained using two ozone monitors (2B-Tech) at the CCNY and the LDEO throughout this period. On September 5, the temperatures were relatively high, surpassing 90 °F (32.2 °C) from 16:30 to 21:00 UTC (12:30–17:00 EDT). However, the surface ozone levels remained moderate, around 60 ppb in the afternoon at both sites. After 21:00 UTC (17:00 EDT), the surface ozone at the CCNY decreased more rapidly than at the LDEO. On 6 September, the peak temperatures were slightly higher than the previous day. The surface ozone concentrations at the CCNY site exceeded 70 ppb between 17:00 and 21:00 UTC (13:00–17:00 EDT), while the surface ozone levels at the LDEO remained around 60 ppb between 15:30 and 23:30 UTC (11:30–19:30 EDT). Notably, the ozone at the LDEO peaked at 67 ppb at 22:30 UTC (18:30 EDT) before decreasing. During nighttime, the ozone levels at the LDEO were consistently higher than at the CCNY. On September 7th, the air temperatures were similar to those on 6 September. The surface ozone at the CCNY increased from 11 ppb at 13:00 UTC (9:00 EDT) to a peak value of 103 ppb at 18:00 UTC and then declined. The surface ozone at the LDEO increased from 30 ppb at 13:00 UTC (9:00 EDT) to a peak value of 119 ppb at 19:15 UTC (15:15 UTC) before decreasing.

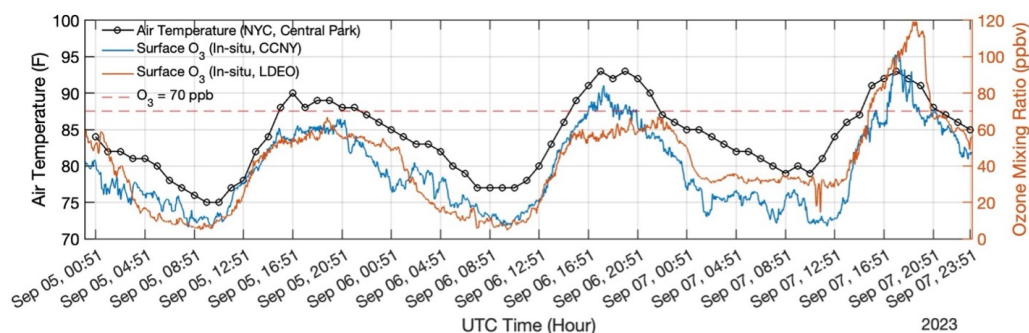


Figure 10. Time series of air temperature measured at the NYC Central Park weather station and surface ozone mixing ratio (1 min average) measured by the 2B-Tech ozone monitor at the CCNY and the LDEO from 5 September to 27 September 2023. The left y-axis represents air temperature (°F), while the right y-axis corresponds to the ozone mixing ratio (ppbv).

Figure 11a–f show time–altitude plots of ozone mixing ratios from lidar observations at the CCNY and the LDEO on 5–7 September 2023. The PBLHs were retrieved from the Lufft CHM15k ceilometer at the CCNY and the Vaisala CL-31 ceilometer at the LDEO. On 5 September, the ozone concentrations within the PBL were moderate, around 50–60 ppb at both sites. An elevated ozone layer was observed at approximately 1.5–2 km altitude at both locations (Figure 11a,d). On 6 September, the PBL ozone at the CCNY increased between 16:00 and 18:00 UTC (12:00–14:00 EDT), peaking at 86 ppb at 18:00 UTC (14:00 EDT) before decreasing. At the LDEO, ozone began accumulating in the PBL from 17:00 UTC (13:00 EDT) and was higher than the previous day. The elevated ozone layer persisted around 1.5–2 km, slowly descended, and interacted with the PBL at 19:00 UTC.

The highest-ozone episode during the study period occurred on 7 September at the LDEO. At the CCNY, the near-surface ozone increased from 16:00 to 18:00 UTC (12:00–14:00 EDT), exceeding 70 ppb, and then declined to below 60 ppb after 19:00 UTC, while elevated ozone levels persisted at the upper PBL until 20:10 UTC (16:10 EDT) (Figure 11c). As shown in Figure 11f, the PBL ozone at the LDEO increased from 16:00 to 19:00 UTC (12:00–15:00 EDT), surpassing 100 ppb after 18:00 UTC (14:00 EDT). Ozone

DIAL measurements were unavailable between 19:00 and 21:00 UTC due to excessive temperatures in the lidar trailer. However, surface ozone data (Figure 10) indicated that the ozone concentration at the ground level reached the maximum value of 119 ppb around 19:30 UTC (15:30 EDT) before declining. In addition, an aloft ozone layer appeared at about 1.5 km and entrained into the PBL at 17:00 UTC (13:00 EDT).

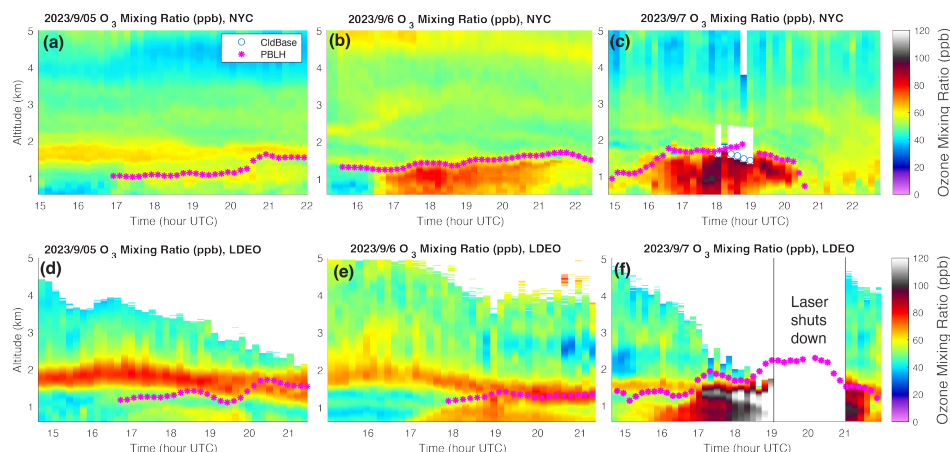


Figure 11. Time–altitude curtain plots of ozone mixing ratios (ppb) retrieved from ozone DIAL measurements: (a–c) at the CCNY and (d–f) at the LDEO, from 5 to 7 September 2023, respectively. The PBLHs (magenta asterisks) and cloud base heights (blue circles) are retrieved by the collocated Lufft CHM15k ceilometer at the CCNY and Vaisala CL-31 Ceilometer at the LDEO.

Figure 12a–i display the horizontal wind direction, wind speed, and vertical wind speed from the wind lidar measurements at the CCNY. On September 5, the winds within the PBL were northerly at 3–5 m/s. On September 6, light north winds were observed near the surface, with northwest winds above 0.5 km. On 7 September, before 19:00 UTC (15:00 EDT), the winds were light and variable, at 2–5 m/s, predominantly from the south and southwest directions, facilitating ozone accumulation. After 19:00 UTC (15:00 EDT), the PBL winds strengthened to 9–11 m/s and from a south/southeast direction. The stronger wind dispersed the surface ozone at the CCNY and transported the ozone pollution from the NYC/NJ urban area toward downwind north/northwest of NYC.

Although these three days were under similar high temperatures and mostly clear sky conditions, different wind patterns caused distinct ozone concentrations at the observation sites. Indeed, 7 September, with light southwest/south wind, clearly experienced higher ozone than the previous two days. From 6 to 7 September, the peak ozone level increased by 10 ppb at the CCNY and by 60 ppb at the LDEO. On 7 September, the peak ozone was 20 ppb higher at the LDEO than at the CCNY. This dramatic increase in ozone at the LDEO was likely associated with the plume of ozone precursors transported from the NYC–NJ urban area. Figure 13 shows the 80 m horizontal wind in the region from the HRRR model on 5–7 September from 17:00 to 19:00 UTC. On 5 and 6 September, the prevailing wind patterns were light and northwesterly. On 7 September, the prevailing wind shifted to southerly wind, which is consistent with the wind lidar measurements.

Furthermore, we analyzed the spatial distribution and temporal variation regarding NO_2 using the TROPOMI level-2 tropospheric NO_2 column product, as shown in Figure 14. Two swaths covering the NY Metro area were available for each day on 6 and 7 September, capturing changes in the NO_2 distribution over time. Figure 14a,b display the tropospheric column NO_2 (mol/m^2) on 6 September at 17:15 UTC and 18:56 UTC, respectively. At 17:15 UTC, elevated NO_2 levels were observed near the southern part of Manhattan. By 18:56 UTC, the NO_2 concentration decreased, while its spatial distribution did not change significantly. On 7 September, a notable NO_2 hotspot appeared over NYC

at 16:57 UTC (Figure 14c), which was higher than that of the previous day around the same time. By 18:37 UTC (Figure 14d), this elevated NO_2 shifted northward, moving closer to the LDEO site.

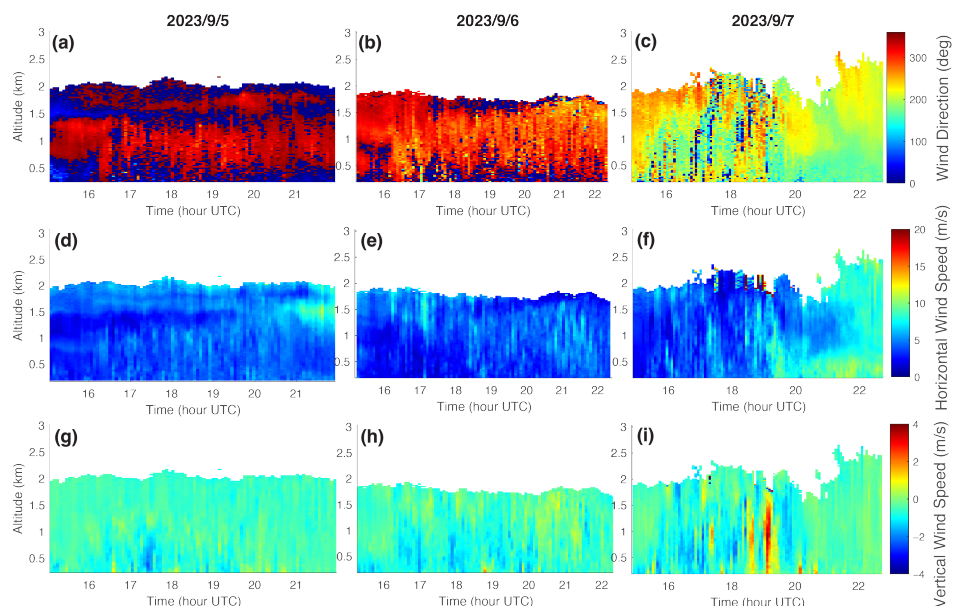


Figure 12. Time–altitude plots from 5 September to 7 September 2023, measured by the CCNY Doppler wind lidar: (a–c) horizontal wind direction (degrees from true north), (d–f) horizontal wind speed (m/s), and (g–i) vertical wind speed (m/s).

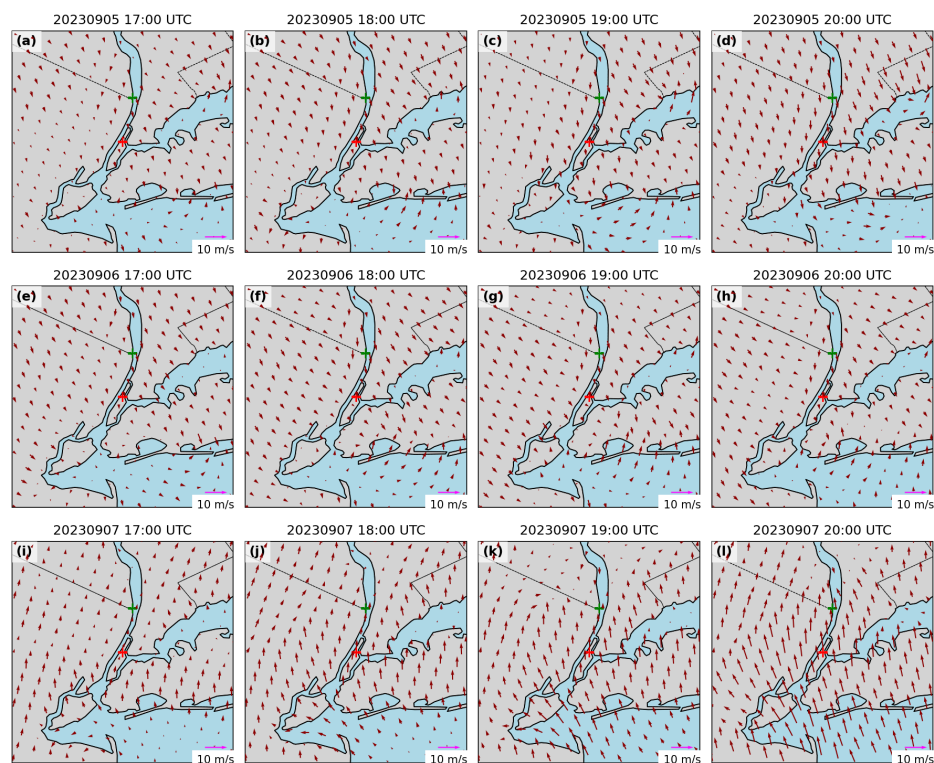


Figure 13. (a–c): HRRR 80 m wind at 17:00–20:00 UTC on (a–d) 5 September, (e–h) 6 September, and (i–l) 7 September 2023. The scale bar (10 m/s) is displayed in the lower right corner. The CCNY and the LDEO location are indicated by the red and green plus signs, respectively. On 5 and 6 September, winds were calm and from the northwest. On 7 September, winds shifted to a southerly direction, transporting pollutants from the NYC urban area to the LDEO.

Considering that ozone production in urban areas is typically VOC-limited, while suburban regions often experience NO_2 -limited ozone production due to the abundance of biogenic VOCs [37–40], NO_2 transported from NYC to the LDEO site likely contributed to substantial ozone production. This resulted in higher ozone peak levels at the LDEO compared to NYC.

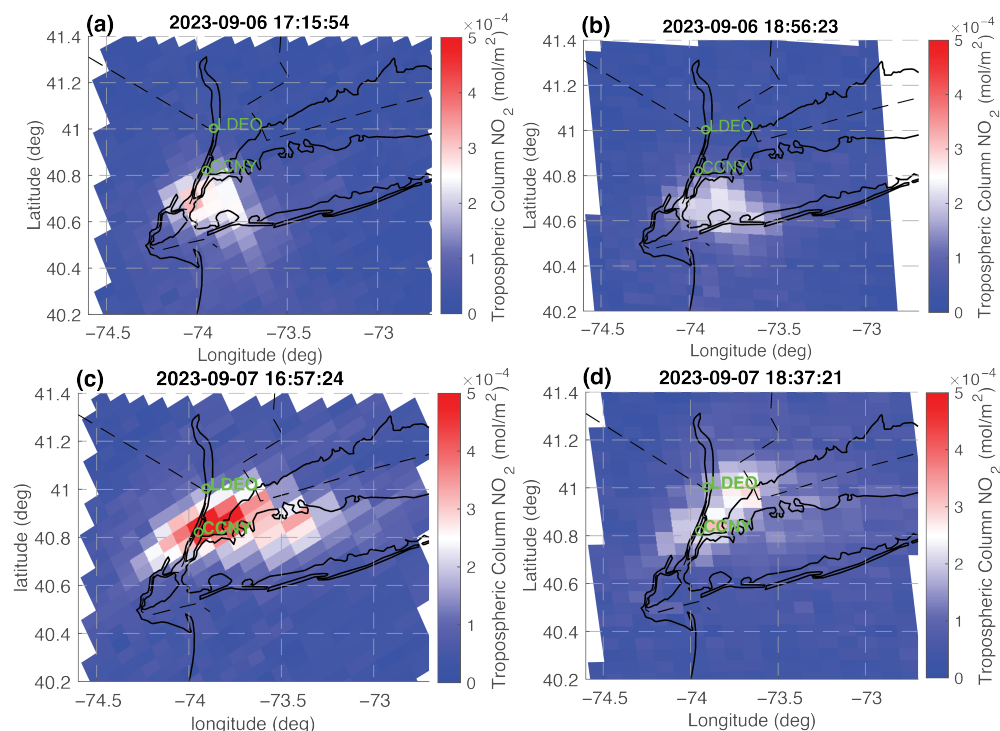


Figure 14. TROPOMI-derived level-2 tropospheric column NO_2 (mol/m^2) on (a) 6 September 2023 at 17:15 UTC; (b) 6 September 2023 at 18:56 UTC; (c) 7 September 2023 at 16:57 UTC; and (d) 7 September 2023 at 18:37 UTC. Circles indicate the locations of the LDEO and the CCNY. On 6 September at 17:15 UTC, elevated NO_2 levels were observed near the southern part of Manhattan, NYC. By 18:56 UTC, NO_2 concentrations had decreased, but the spatial distribution remained largely unchanged. On 7 September at 16:57 UTC (c), a pronounced NO_2 hotspot appeared over NYC, higher than that observed the previous day at a similar time. By 18:37 UTC (d), this elevated NO_2 region had shifted northward, approaching the LDEO site.

4. Discussion

The ozone formation and transport in the New York City (NYC) area are significantly influenced by the meteorological conditions, particularly during the summer months. The interplay of local circulations, temperature variations, boundary layer dynamics, and chemical reactions plays a crucial role in determining the ozone levels. In this paper, coordinated observations of ozone DIAL, aerosol lidar, and wind lidar were used to characterize the ozone formation within the PBL and ozone/aerosol plume transport in the NY Metro region and downwind areas during the 2023 summer AGES+ campaign.

The first case study demonstrated an ozone episode in the NYC urban area. In particular, on 26 July, the weather conditions were conducive to ozone formation, including clear sky or mostly clear sky, weak south/southwest wind, and a relatively high temperature ($>85^\circ\text{F}$). Within the PBL, ozone accumulated from late morning to afternoon and reached a maximum value of 90 ppb. A sea breeze developed after 18:00 UTC (14:00 EDT) and recirculated the ozone pollution from the Atlantic Ocean back to the city, further enhancing the PBL ozone levels by 10 ppb. Additionally, lidar observed the transported aerosol/ozone plume mixing into the PBL, which increased the ozone level in the upper PBL but did

not affect the surface ozone levels. The following two days had higher temperatures, but the ozone level was lower than the first day of the heatwave event, possibly due to increased cloud coverage reducing the ozone photochemical production and different wind patterns. The 28 July case also highlights the coincidence of aloft elevated ozone layers and transported aerosol plumes. The ozone/aerosol plumes can be entrained into the PBL by vertical mixing of air masses, eventually influencing the PBL ozone level.

Another significant high-ozone episode was observed by the ozone DIALs at the CCNY in Manhattan and the LDEO, 29 km north of Manhattan, during a heatwave event from 5 to 7 September 2023. Especially, on 7 September, the peak ozone concentration in the PBL at the LDEO reached 120 ppb, exceeding NYC's ozone level by 20 ppb. The peak ozone level at the LDEO increased by 60 ppb on 7 September compared to 6 September, while, at the CCNY, it increased by 10 ppb. Analyses of the wind lidar data, NOAA HRRR model, and TROPOMI column NO₂ data reveal that the significant increase in ozone at the LDEO was attributed to plume transport under the prevailing southwesterly to southerly winds. While enhanced ozone episodes along the LIS east of NYC due to urban plume transport have been widely studied, this shows that similar events can also occur north of NYC depending on the meteorological conditions.

Although both episodes occurred during a heatwave event characterized by high temperature, we found that wind patterns play an important role in ozone formation and transport. In both of the cases, 26 July and 7 September, significantly higher ozone levels were observed under calm SE/S/SW winds compared to other heatwave days within each episode that had different wind patterns. In addition, we observed that southerly winds transport the NO_x pollution from high-emission urban areas where major power generation facilities and human activities are concentrated, providing abundant precursors for ozone production. Multi-year analyses from previous studies have similarly shown that high-ozone events in the NYC region are strongly associated with heatwave conditions, with the most severe exceedances typically occurring on extremely hot days [7,41,42]. These high-ozone episodes are often driven by recurring meteorological patterns—especially stagnant air or local sea-breeze circulations under a prevailing southerly flow—which together facilitate ozone accumulation and transport of pollutants from urban sources [9,36]. Moreover, Luo et al. [36] found that specific wind patterns modulate the ozone spatial distribution regardless of the temperature levels. In particular, sea-breeze events, characterized by calm morning conditions followed by southerly winds during the afternoon, tend to favor elevated ozone levels along the Philadelphia–NYC–Long Island Sound corridor, even at moderate temperatures. Our observations are consistent with these findings, demonstrating that high temperatures and weak southerly to southwesterly flow are favorable for ozone episodes in the urban core and suburban area in north NYC.

We estimated the uncertainty in the results from 26 July 2023 (Figure 5a) following the method presented in Kuang et al. [28]. The statistical uncertainty is related to the SNR (signal-to-noise ratio) and the vertical resolution. The effective vertical resolution varied from 0.03 to 0.2 km in the 0.2–0.9 km altitude range (near-range channel) and from 0.03 to 1.5 km in the 0.9–10 km altitude range (far-range channel). The resulting statistical uncertainty is less than 10% within the PBL and remains below 20% up to 5 km before 17:00 UTC and below 4.5 km after 17:00 UTC, primarily due to increased sky background noise later in the day. We applied aerosol correction to the ozone retrieval, as described in [25,28]. Sensitivity studies show that varying the lidar ratio (aerosol extinction-to-backscatter ratio) from 40 sr to 60 sr and Ångström exponent from 1.5 to 1.7 introduces less than 4.5% uncertainty in the ozone retrieval. The molecular extinction correction accounts for less than 1% uncertainty regarding the total ozone. Corrections for other interfering gases (NO₂ and SO₂) introduce about 0.5% uncertainty [25].

A key contribution of this study is the use of vertical ozone profile measurements, which provide high temporal and vertical resolution. Lidar revealed a clear buildup of ozone within the PBL and transport of aloft ozone that would not be detectable with traditional in situ surface observations alone. Notably, we utilized two ozone lidar systems operating simultaneously, combined with aerosol and wind lidar measurement, enabling us to track ozone plumes from the NYC urban core to the suburban regions in the north of the city. These results provide the first direct evidence of ozone outflow to the northern NYC region under specific synoptic and mesoscale conditions, highlighting the significance of enhanced vertical profiling in understanding regional ozone dynamics and informing air quality management. The synergic lidar observation approach provides a methodology for studying critical episodes of tropospheric ozone formation and transport.

5. Conclusions

Ozone variation in urban coastal areas, such as NYC, is highly complex due to the combined effects of local production and regional transport. We demonstrated that, by leveraging synergistic observations from ozone DIAL, aerosol lidar, wind lidar, and satellite observations, we can effectively distinguish between these processes, providing valuable insights for environmental policymaking and air quality management. This study primarily focuses on demonstrating the influence of meteorological conditions on ozone variability, which can aid in further research work in evaluating emission estimates and improving chemical transport models. The vertically resolved ozone lidar measurements demonstrated here can be used to validate model results or assimilated into chemical transport models [43] to improve the representation of boundary layer processes, pollutant mixing, and ozone forecasting under complex meteorological conditions. Furthermore, the deployment of multiple ozone lidars in both urban and downwind locations illustrates the scientific value of regional ozone lidar observations in areas that are not in attainment of the ozone NAAQS (National Ambient Air Quality Standards). These observations enhance our understanding of ozone transport.

In addition to modeling applications, ozone lidar data serve as a critical reference for validating satellite retrievals of tropospheric ozone [44,45], including new-generation instruments such as NASA's TEMPO (Tropospheric Emissions: Monitoring of Pollution) [46]. The high-resolution vertical profiles provided by lidar complement column-integrated satellite data, supporting the evaluation and improvement of satellite-based air quality products.

As climate change is expected to increase the frequency of extreme heat events, the need for vertically resolved observational datasets will grow. This integrated observational approach thus provides a critical framework for advancing both the scientific understanding and regulatory strategies aimed at mitigating ozone pollution in metropolitan and downwind regions.

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Abbreviations

The following abbreviations are used in this manuscript:

DIAL	Differential Absorption Lidar
CCNY	City College of New York
PBL	Planetary Boundary Layer
LDEO	Lamont–Doherty Earth Observatory
HRRR	High-Resolution Rapid Refresh
TROPOMI	TROPOspheric Monitoring Instrument
NO _x	Nitrogen Oxide
NO ₂	Nitrogen Dioxide
NO	Nitrogen Monoxide
VOC	Volatile Organic Compound
CH ₄	Methane
CO	Carbon Monoxide
EPA	Environmental Protection Agency
NAAQS	National Ambient Air Quality Standards
MDA8O3	Maximum Daily 8 h Average Ozone Level
NYC	New York City
NY Metro	New York Metropolitan Area
LIS	Long Island Sound
NJ	New Jersey
PA	Philadelphia
AGES+	AEROMMA+CUPiDS, GOTHAAM, EPCAPE, STAQS, and others
AEROMMA	Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas
CUPiDS	Coastal Urban Plume Dynamics Study
NOAA	National Atmospheric and Oceanic Administration
STAQS	Synergistic TEMPO Air Quality Science Mission
NASA	National Aeronautics and Space Administration
TOLNet	Tropospheric Ozone Lidar Network
FWHM	Full Width at Half Maximum
PMT	Photomultiplier Tube
PBLH	Planetary Boundary Layer Height
DBS	Doppler-Beam Swing
SNR	Signal-to-Noise Ratio
NYSDEC	New York State Department of Environment Conservation
AQ	Air Quality
UTC	Coordinated Universal Time
EDT	Eastern Daylight Time

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