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Vertical Profiling of Canadian Wildfire Smoke in the Baltimore-Washington Corridor - Interactions with the Planetary Boundary Layer and Impact on Surface Air Quality

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Abstract: The 2023 Canadian wildfires yielded record-breaking emissions that were transported long distances over large sections of the mid-Atlantic region, significantly impacting regional surface air quality. In this study, we analyzed the effect of long-distance transported wildfire smoke on the Baltimore-Washington Corridor (BWC), a highly populated and industrialized metropolitan region prone to air quality exceedances. Central to the analysis is the Vaisala CL61 ceilometer in Beltsville (suburban BWC), whose *linear depolarization ratio* (LDR) profiles provide a continuous, altitude-resolved fingerprint for distinguishing wildfire smoke from locally generated urban aerosols. By combining the LDR-derived with satellite imagery, surface air quality observations, and NOAA HYSPLIT trajectory analysis, we analyzed four discrete smoke events to characterize smoke's vertical distribution and interaction with the planetary boundary layer (PBL). One of the cases showed that the timing of smoke plume descent in relation to synoptic frontal passage was decisive in determining its impact on air quality. In contrast, those events with well-mixed smoke in the PBL during the advection-driven conditions exhibited a clear deterioration in air quality near the surface, with particulate levels exceeding the regulation threshold. The results underscore the importance of accurately representing vertical mixing in smoke forecasts and illustrate the added value of routine ceilometer LDR measurements for real-time identification of lofted smoke plumes—information not attainable from column-integrated satellite products or surface monitors alone.

1 Introduction

Wildfire smoke, particularly intense plumes, which is distinct from other kinds of air pollution, represents a significant and growing contributor to episodes of poor air quality in the Mid-Atlantic region (Black et al., 2017; Dreessen et al., 2016; Jaffe et al., 2020; Yang et al., 2022). The chemical species detected in smoke from a specific wildfire occurrence are determined by various characteristics unique to the burn location, including the type of plant burned and weather conditions (Urbanski, 2013). These smoke plumes are typically rich in particulate matter (PM) and ozone precursors. Fine particles fall out of the atmosphere more slowly than coarse particles, dispersing farther away from the source (Kinney, 2008). Their presence substantially degrades air quality, especially in downwind areas, even those located considerable distances from the fire

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source (Hung et al., 2020; Jaffe and Wigder, 2012; Liu et al., 2016; Shen et al., 2025). The summer of 2023 starkly illustrated Canadian history's most severe wildfire seasons (Jain et al., 2024). By the end of the year, almost 6,000 fires destroyed an astounding 15 million hectares of boreal forest across numerous provinces (Natural Resources Canada, 2024). The Canadian wildfires in 2023 outnumbered previous significant wildfire occurrences, including the severe 2015 fire season, which burned roughly 4 million hectares, already 60% over the 10-year normal (Natural Resources Canada, 2016). The heavy smoke produced by the 2023 Canadian wildfires crossed continental boundaries, reaching densely populated areas of the United States at an alarming rate. The hot, dry weather was a primary cause of the fire spread, with 2023 being the warmest and driest year since 1980 (Jain et al., 2024). Episodic anomalies with implications for public health, atmospheric chemistry, and regulatory compliance with air quality standards followed.

In the last few decades, we have seen a disproportionate rise in the frequency and scale of wildfires. Historically, the boreal forest did not burn very often. When it did, it was not over an extensive area (UNEP, 2022), but presently, the boreal forest is undergoing fire activity at an abnormal rate. According to reports, wildfires are already spreading across bigger regions, leading to record-breaking emissions year after year (Herr, 2022). These extensive wildfires devastated local ecosystems and generated massive plumes of smoke that traversed long distances, significantly impacting air quality in regions across North America. During the 2015 wildfire season, long-range smoke transport led to a doubling of volatile organic compound (VOC) concentrations and a threefold rise in harmful reactive nitrogen species (NO_x derivatives) levels in Maryland. Ozone levels also increased during this period, exceeding the national recommended thresholds (Dreessen, 2016). In contrast, the 2023 smoke plume exhibited behaviour that diverged from projected expectations upon reaching Maryland. This deviation underscores the importance of analysing the variability in smoke transport processes under differing atmospheric conditions, particularly concerning the timing and nature of interactions between smoke plumes and the planetary boundary layer (PBL).

The Baltimore-Washington Corridor (BWC) is a major cosmopolitan region in the densely populated mid-Atlantic region of the U.S. It is particularly vulnerable to various air pollutants because of its geographical location and high level of urbanization. While anthropogenic emissions dominate local exceedance events during the summer, long-range transport of intense smoke from events such as wildfire can significantly change background aerosol concentrations and disrupt photochemistry (Dreessen et al., 2023). Notably, the extent to which increased smoke plumes impact ground-level air quality relies heavily on their vertical distribution and interaction with the PBL (Pahlow et al., 2005; Wang et al., 2015). Smoke layers lingering in the free troposphere can stay aloft for several days. However, its intrusion into the PBL can lead to a sudden increase in surface PM levels, prompting exceedance events (O'Dell et al., 2019). For the BWC, the Canadian 2023 wildfire smoke impact was most pronounced during the first week of June, when visibility dropped significantly, and air quality index (AQI) values frequently reached "Unhealthy" or "Very Unhealthy" levels. Using integrated observational datasets, the smoke event's spatial extent and temporal persistence provided a unique opportunity to study its atmospheric and surface-level impacts.

Even though satellite observations and chemical transport modelling clearly show the long-range movement of wildfire smoke (Jaffe et al., 2020; Val Martin et al., 2010), much uncertainty remains about the vertical distribution of aged smoke

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plumes and how they interact with the dynamics of the regional PBL. Understanding these processes is crucial, especially in the Mid-Atlantic area, where background precursor concentrations and local meteorological variables impact midsummer ozone formation. Some of the past studies indicate entrainment of the aloft smoke layers. These layers typically transport ozone precursors such as oxides of nitrogen (NOx) and volatile organic compounds (VOCs), as well as carbon monoxide (CO), into the diurnally developing PBL; thus, impacting surface ozone concentrations (Dreessen et al., 2016; Lara et al., 2022). To analyse the interaction of smoke plume with the PBL, it is equally important distinguish the smoke layer from that of the surface aerosols. Light Detection and Ranging (LIDAR) based observations, particularly with polarization capability, provide new opportunities to study the aerosol layer's vertical structure and phase composition, which also acts as a proxy of the PBL height. Depolarization ratio measurements may be used to distinguish wildfire smoke, which is often made up of solid-phase, fractal-like soot aggregates, from liquid-phase boundary layer aerosols and clouds (Haarig et al., 2018; Tesche et al., 2009). Several past studies have utilized automatic lidar ceilometer capabilities to analyse smoke particles (Dreessen et al., 2023; van der Kamp et al., 2008; Wu et al., 2012). However, with the latest addition of depolarization capability in ceilometers, such as the Vaisala CL61, investigations characterizing smoke plumes remain scarce.

While some previous research has described Canadian wildfire smoke's near-source effects, relatively few have examined the vertical extent and plume-mixing dynamics for BWC when smoke arrives (Dreessen et al., 2016, 2023; Yang et al., 2022). Even fewer studies have integrated high-resolution ceilometer depolarization data with trajectory analysis to detect smoke plumes, the degree of their mixing, and the impact on surface pollution concentrations. The events of 2015 and 2023 Canadian wildfire smoke making it to BWC and interacting with the PBL underscored two long-standing research needs: (I) a clearer systematic understanding of how elevated smoke layers are transported, entrained, and ultimately mixed into the PBL and (II) the development of observational strategies capable of resolving the vertical aspect of that process in real-time. In this context, the present study aims to fill a critical observational gap by examining smoke intrusion events over the BWC during the summer of 2023.

This manuscript is structured as follows. Section 2 describes this study's observational and modelling data, comprising the ceilometer-derived backscatter and depolarization profiles, surface air quality measurements, and the HYSPLIT trajectory analysis framework. It also describes the procedure for detecting and classifying smoke intrusion events. Section 3 presents the findings, analysing four representative case studies for different plume-PBL interaction scenarios. These cases document different degrees of vertical mixing, surface concentration enhancement, and synoptic transport regimes. Section 4 concludes with a synthesis of important findings, implications for air quality prediction in smoke-affected regions, and suggestions for future observational and modelling work for enhancing vertical resolution within wildfire smoke estimation.

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2 Methodology

2.1.1 Study region

This study focuses on the Baltimore-Washington Corridor (BWC), extending approximately 30 miles, which includes the densely populated and industrialized region between Baltimore, Maryland, and Washington, D.C. The BWC has complicated air quality dynamics due to the unique interaction of local urban pollutants, meteorology, and proximity to natural areas such as the Chesapeake Bay (Karle et al 2024, Dreessen et al 2016). It is characterized by a dense network of congested highways, railways, industrial facilities as well as the presence of coal-fired power stations (L-W, 2002), all pollution sources which degrade the local air quality through the emission of nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter ($PM_{2.5}$); thus, contributing to ground-level ozone and smog formation. The corridor's high population density exacerbates air quality concerns, particularly during events when external pollution sources are transported into the region. Historically, the BWC has experienced episodes of degraded air quality notably during the 2015 and 2023 Canadian wildfire seasons. This highlighted the region's vulnerability to transboundary air pollution and emphasized the growing impacts of climate change on air quality caused by external occurrences such as smoke transport from wildfires.

2.1.2 National Ambient Air Quality Standards (NAAQS) for NO_2, $P.M_{2.5}$, O_3

Globally, the inhalation of ambient particulate matter (PM) is approximated to cause between 7.5 and 10.3 million premature deaths annually. Fine particulate matter ($PM_{2.5}$) is especially hazardous due to its ability to penetrate deep into lung tissue, deteriorating cellular structures and, with prolonged exposure, contributing to lung cancer, cardiopulmonary mortality, and suppression of the immune system (Manavi, 2025). The significant health impacts of $PM_{2.5}$ underscore the critical need for accurate modelling of transport in the case of distant wildfires, from point sources to densely populated urban areas.
The following table shows the current Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) that need to be complied with by the US for three major air pollutants referenced in this study. Concentrations exceeding these values are detrimental to both human health and the environment (EPA, 2024). Exceedances are also violations of the EPA's NAAQS, which are required to be attained by the Clean Air Act.

Table 1: Environmental Protection Agency: NAAQS

Air Pollutant	Harmful Concentration Levels
Nitrogen Dioxide (NO_2)	100 ppb averaged over 1 hr
Ozone (O_3)	70 ppb averaged over 8 hrs
$PM_{2.5}$	35 $\mu g/m^3$ averaged over 24 hrs

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2.2 Measurements and Instrumentation

To evaluate the effects of Canadian wildfire smoke on the BWC, we used a multi-instrument observational method that included satellite imagery, ground-based air quality monitoring, wind trajectories and remote sensing from a ceilometer. Detailed descriptions of each measurement approach are provided below.

2.2.1 Linear Depolarization and Smoke Detection

Vaisala CL61 ceilometer, a vertically pointing, single wavelength lidar with both attenuated backscatter and linear depolarization ratio (LDR) measuring capability, performed continuous aerosol profiling. Its high temporal and spatial resolution dataset enabled the detection of high-altitude aerosol layers and their interaction with the PBL. For this study, we extensively used the linear depolarization ratio, one of the key characteristics of the CL61, to identify the smoke plume. The LDR is calculated by dividing the perpendicular component by the parallel component from the backscattered signal (Bedoya-Velásquez et al., 2022; Bellini et al., 2024; Inoue and Sato, 2023). It indicates the shape and phase state of the detected particles; spherical particles, such as cloud droplets, precipitation, have higher depolarization, whereas nonspherical particles, such as smoke from wildfires, dust, and volcanic ash, typically have depolarization somewhere in the range of 0.06-0.08 (Vaisala CL61 White Paper, 2022). We used this information to discriminate smoke from wildfires from hydrometeors. Days with high aerosol layers detected through ceilometer profiles that showed increased depolarization over the PBL were marked as probable fire smoke occurrences. They were further confirmed with cross-validation by satellite imagery and wind trajectory analysis.

To diagnose the vertical distribution and optical nature of the aerosols aloft, we used a case from 5 June 2025 (Figure 1). We paired high resolution ceilometer measurements with a collocated radiosonde released at 06:32 UTC from Beltsville site. Fifteen-minute averages of the CL61 LDR were compared to the radiosonde's temperature and relative humidity profiles to verify particle phase. The radiosonde confirmed a deep isothermal layer with maximum humidity between 8-9 km (pink shade), coincident with ceilometer LDR values of ~ 0.35; this combination is characteristic of ice crystals and, therefore, attributed to a cirrus cloud deck. In contrast, a relatively dry but above freezing layer between 3-4.5 km aligned (yellow shade) with markedly lower LDR values (~ 0.05), consistent with weakly depolarizing, predominantly spherical biomass-burning smoke particles. Selecting this day when both cloud and smoke layers were present during a routine launch allowed us to cross validate ceilometer derived phase discrimination against independent thermodynamic soundings and to establish representative LDR thresholds (≥ 0.3 for ice cloud; ≤ 0.08 for smoke) used throughout the case study analysis.

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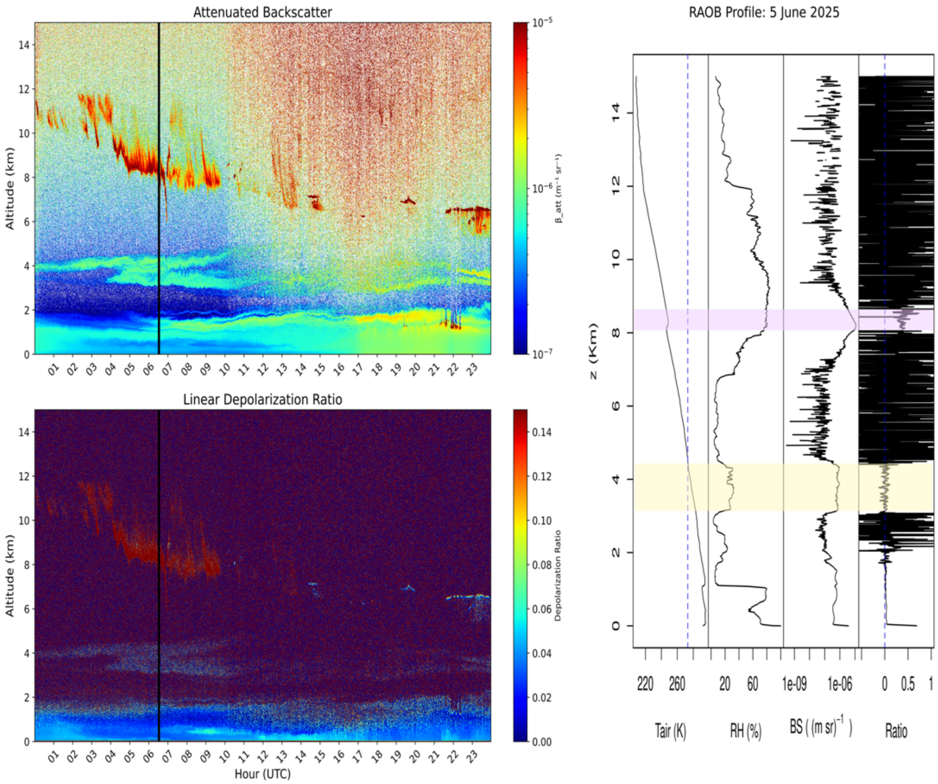

Figure 1. Vertically resolved aerosol and thermodynamic observations from HU-Beltsville on 5 June 2025. **(Top left):** Time-height cross section of attenuated backscatter coefficient (β (m sr)$^{-1}$) from the Vaisala CL61 ceilometer, illustrating a persistent smoke layer between 3-4 km and elevated cirrus cloud structures between 8-12 km before 10 UTC. **(Bottom left):** Corresponding LDR, highlighting enhanced depolarization between 2-4 km, indicative of non-spherical aerosol particles (smoke), and elevated LDR values near 8-9 km, consistent with optically thick, ice-containing cloud layers. Black vertical line at 06:32 UTC indicate radiosonde launched from the site. **(Right):** Vertical profiles from the radiosonde; **(column 1)** air temperature (K), **(column 2)** relative humidity (%), and **(column 3)** total backscatter and **(column 4)** LDR averaged from ceilometer data over a 15-minute window centred on the launch time. Blue horizontal dashed lines mark altitudes and shaded regions of the identified smoke layer (yellow) and cloud (pink) layers.

2.2.2 Satellite Observations

True-colour satellite images taken by the Visible Infrared Imaging Radiometer Suite (VIIRS) on board NOAA-20 were employed to identify the regions of the fire sources and evaluate the horizontal extent and transport paths of upper-level smoke plumes. Satellite images of the North American continent offered visual verification of large-scale smoke cover and helped monitor its transport towards the Mid-Atlantic region. Days identified by the Vaisala CL61 ceilometer as having a

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high aerosol layer above the PBL were further analysed with images from VIIRS to confirm the presence of transported smoke. This combined methodology ensured that only those instances with elevated aerosol detection by ceilometer and satellite-verified smoke signatures were chosen for detailed analysis.

2.2.3 HYSPLIT Back-Trajectories

NOAA's HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model provides backward trajectory analyses, crucial for identifying the potential source regions and transport pathways of air parcels arriving at a specific location. We computed 72-hour backward trajectories for the Baltimore-Washington Corridor for several different cases of interest. Howard University Beltsville Campus (HUBC) the study site (latitude: 39.05 and longitude: -76.87) was used as the source for these back trajectories. All the trajectories were computed for three arrival heights: 500 m, 1500 m, and 2000 m above ground level (AGL), using HRRR (High-Resolution Rapid Refresh) meteorological data.

2.2.4 Continuous Ambient Air Monitoring Station

Maryland's Department of the Environment (MDE) has several continuous ambient monitoring stations (CAMS) scattered throughout the state of Maryland. One of their supersite which is part of the EPA's Chemical Speciation Network (CSN) is hosted within Howard's University Beltsville campus (latitude: 39.05 and longitude: -76.87), right along the WBC (Karle et al., 2024). The university works in collaboration with MDE performing continuous air quality monitoring including particulate matter speciation, $PM_{2.5}$, O_3, and NO_x measurements. This site plays a key role in monitoring atmospheric aerosols in the Mid-Atlantic region of the USA. It contributes to the understanding of regional air quality and long-range transport of pollutants on both public health and our evolving climate. Data collection from this site has been analysed as part of the backbone of this research.

2.2.5 AERONET

AERONET (Aerosol Robotic Network) is a globally distributed network of remote sensing instruments, such as ground-based sun photometers, used to study the optical properties of aerosols in the atmosphere. One of the most important aerosol features studied is the Aerosol Optical Depth (AOD), a measurement that sheds lights on the concentration and nature of aerosols in a particular region of the sky. AERONET data allows not only in situ observations and characterization of atmospheric particulate composition, but also allows scientist to validate satellite data retrievals, improve climate models, and allows for the quantification of aerosol radiative forcing on the climate system. The primary purpose of employing AERONET data in this analysis was to identify and characterize smoke events that occurred during the transport of the smoke from Canadian wildfire. We used the Ångström exponent, calculated from the AOD at different wavelengths (often including 440 nm and 870 nm). It offered an indication of the dominant size of aerosol particles; higher values (typically > 1.5) suggest a greater proportion of fine particles, characteristic of smoke (Schuster et al., 2006).

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3 Results

3.1 Case 1: 22-26 May 2023

End of May 2023, the wildfires in the western part of Canada were brewing, and the smoke was spreading over a long distance. The satellite image from NOAA-20 provided a comprehensive overview of the wildfire smoke transport from Canada into the mid-Atlantic region, as seen in (Figure 2(a)). A notable greyish-white smoke extended across much of the western and central Canada and plunged into the northern USA. The red-outlined region in the upper-left portion of the image highlights the core area of active wildfires in May 2023 based on the information from Canadian Wildland Fire Information System (https://cwfis.cfs.nrcan.gc.ca/). The plume appears to flow eastward, following upper-level atmospheric circulation. It expanded into a broad haze that covered large sections of the Canadian prairie provinces before stretching into parts of the USA Midwest. NASA's Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) revealed a predominantly westerly flow over North America. Figure 2 (b) illustrates the atmospheric dynamics at the 500 hPa level from 21-24 May 2023, demonstrating the evolving synoptic scale conditions that facilitated the transport of wildfire smoke. On May 21, a pronounced trough over the northwestern USA initiated a strong north-westerly wind along its axis, effectively channelling smoke southward. Over the next few days, the trough deepened and expanded eastward. The jet stream also facilitated the long-distance transmission of dense smoke. Concurrently, a downstream ridge in the eastern USA created steady subsidence conditions, allowing the smoke to settle and concentrate over the mid-Atlantic region. This allowed for the development of optimal synoptic conditions for wildfire smoke propagation over large distances. As a result of the arrival of the smoke plumes, regional air quality was projected to deteriorate, particularly in the BWC region.

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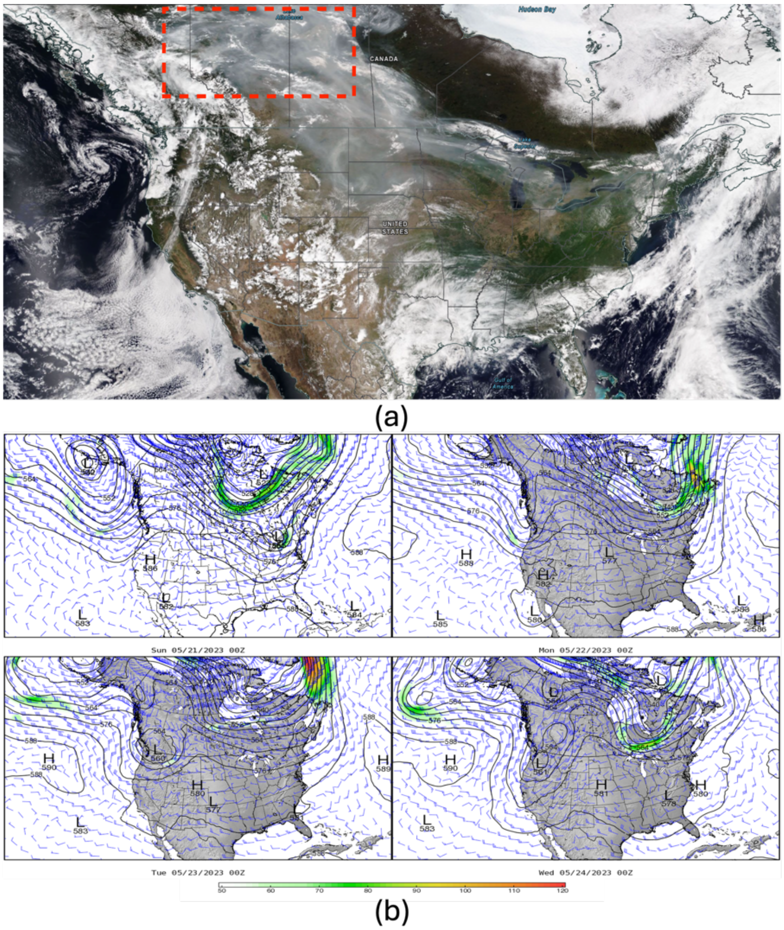

Figure 2. (a) Satellite imagery from NOAA 20/VIIRS with corrected reflectance for 21 May 2023 with the red dashed rectangle showing the region with active fires in northwest of Canada (VIIRS Characterization Support Team, 2016). **(b)** Wind speed and directions at 500 hPa from MERRA-2 from 21-24 May 2023.

The HYSPLIT backward trajectory analysis for 1200 UTC on 25 May 2023 demonstrated that air masses arriving in the BWC region at 500 m (red), 1500 m (blue), and 2000 m (green) above the ground level originated from regions impacted by Canadian wildfire smoke (Figure 3). The 500 m trajectories show a direct, coherent south-eastward pathway from Quebec into the mid-Atlantic, indicating efficient boundary layer transport of smoke-laden air. The 1500 m trajectories revealed a more complex pattern, with some parcels descending from higher altitudes while others passing over the Great Lakes before reaching the study site. Thus, highlighting the role of subsiding elevated smoke layers. The 2000 m trajectories, while originating further west over the upper Midwest, also converge towards the BWC region, albeit remaining generally above the surface boundary layer throughout their transport. Overall, the trajectory ensemble confirms that the study region sat downstream of multiple smoke-laden airstreams, with the vertical distribution of those plumes largely controlled by synoptic subsidence and boundary-layer entrainment.

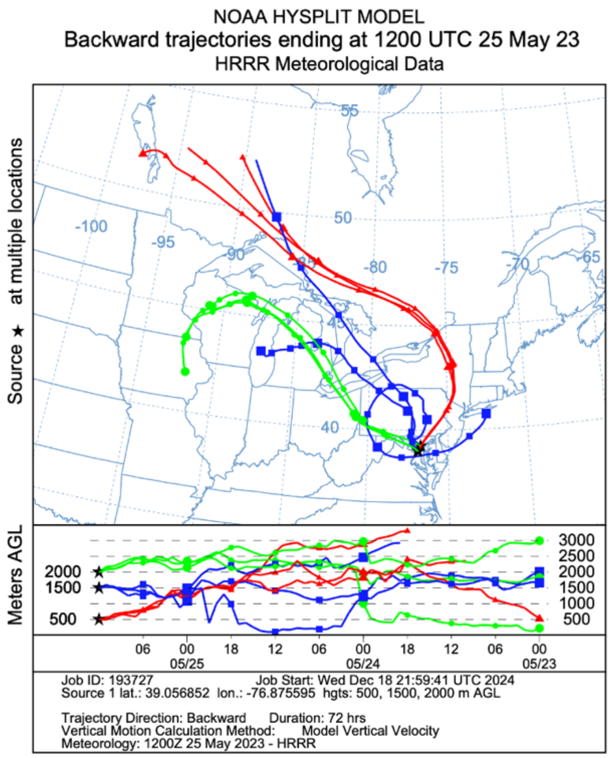

Figure 3. HYSPLIT 72-hour back trajectories for air parcels arriving at the study site between 23 May 00 UTC and 25 May 1200 UTC. Trajectories terminating at 500 m above ground level (AGL) are shown in red, those at 1500 m AGL in blue, and those at 2000 m AGL in green.

While HYSPLIT traced the horizontal and vertical origin of the smoke, it provided limited information on the plume's subsequent interaction with the evolving PBL. This aspect was resolved by analysing the CL61 measurements (Figure 4), whose attenuated backscatter profiles and LDR documented the temporal descent of the aerosol layer. On 21 May, a minimal aerosol backscatter signal, characterized by low depolarization ratios, was observed within and above the PBL, indicative of relatively clear conditions. However, as time progressed from 22 May onwards, as indicated in Figure #, the backscatter data reveals the emergence of a distinct aerosol layer aloft, approximately between 3 to 6 km altitude, exhibiting depolarization ratios between 0.05 to 0.1.This elevated depolarization signal is consistent with non-spherical smoke particles, corroborating satellite observations that showed extensive smoke transport from Canadian wildfires towards the mid-Atlantic region.

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By May 23 and 24, the smoke plume systematically descends, penetrating the PBL, clearly visualized as a layer below 2 km altitude around 24 May 21 UTC – 25 May 03 UTC. The pronounced increase in depolarization ratio within the boundary layer during these periods (ratios reaching up to ~0.1) suggests significant intrusion and mixing of smoke aerosols into the lower troposphere, coinciding with reduced PBL dynamics typical of evening stabilization. Notably, around 03 UTC on 25 May, a strong aerosol signal is observed, corresponding precisely to a frontal passage confirmed by synoptic maps (supplementary figure). Interestingly, despite the temporal coincidence between the smoke intrusion into the boundary layer and the arrival of this cold front, surface observations did not show a significant spike in PM concentrations (Figure #). This absence of surface PM level observed at the study site is most likely caused by the cold front effectively flushing the smoke away. The 21-26 May 2023 case revealed intricate connections between meteorological dynamics and aerosol dispersion. Such situations show the complex link between synoptic events and aerosol behaviour, underlining the significance of combining observational methods for comprehensive atmospheric characterization.

Based on ceilometer evidence of smoke descending into residual and mixed layers, we assessed the impact of these aloft smoke plumes on surface air quality. Figure 4 presents time-series of ozone (O_3), nitrogen dioxide (NO_2), and particulate matter $PM_{2.5}$ concentration measured at the study site from 21-27 May 2023, overlaid with wind vectors, Aerosol Optical Depth (AOD), and Angstrom Exponent (AE). The separation of the 440nm and 870nm AOD values from each other and the high AE values are a clear indication of smoke presence. The shaded portion indicates the smoke-intrusion window identified using the ceilometer backscatter (24 May 21 UTC – 25 May 06 UTC), while the pink dashed line marks the cold-front passage at around 25 May 03 UTC. Prior to the arrival of the smoke plume, diurnal photochemistry dominated surface trace-gas behaviour, as seen from the in-situ observations (Figure 4). Ozone built up each afternoon to 45-55 ppb under strong insolation, while NO_2 remained below 5 ppb except for a brief pulse on 22 and 24 May, before the plume's arrival. $PM_{2.5}$ data was unavailable until late 23 May and hovered below 20 µg m^{-3}, indicative of a clean regional background. When the ceilometer showed the descending smoke layer intersecting the residual layer, $PM_{2.5}$ level rose to 12–15 µg m^{-3}— three to four times the baseline, yet still well below NAAQS limits. The increase coincided with very light, variable winds (<0.3 m s^{-1}), a condition favourable for vertical mixing of lofted smoke into the stagnant surface layer. NO_2 responded modestly (peaking near 6 ppb), whereas O_3 dipped to <10 ppb overnight owing to titration under shallow, stable conditions. Immediately following the frontal passage, wind speed jumped to ~1 m s^{-1} and veered to a persistent northerly. Within two hours, $PM_{2.5}$ dropped below 5 µg m^{-3} despite continued ceilometer evidence of smoke aloft, confirming that the front effectively flushed the near-surface layer. Daytime O_3 recovered to >40 ppb under cleaner post-frontal air, demonstrating that regional photochemistry quickly re-established once the smoke was displaced.

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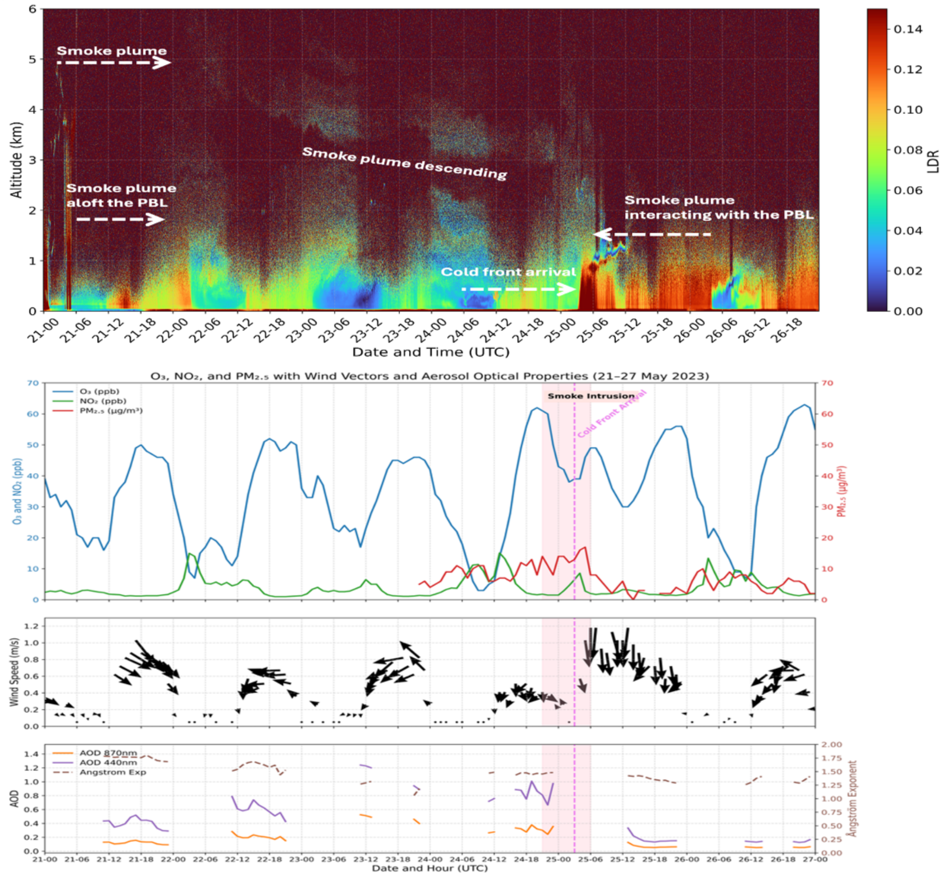

Figure 4. Top: Ceilometer LDR (21-27 May 2023 UTC) showing a wildfire smoke layer descending into the PBL. **Middle:** Surface O_3, NO_2 and $PM_{2.5}$ time series with wind vectors, highlighting smoke-intrusion on 25 May. **Bottom:** AOD at 440 nm and 870 nm and Ångström exponent, indicating enhanced fine-mode aerosol loading during the smoke event.

3.2 Case 2: 05-10 June 2023

Having established the processes that governed Case 1 in late May, we now turned to the early June episode, which differed in both synoptic setting and surface impact. GOES true colour imagery on 6 June 2023 (Figure 5) revealed a broad strip of whitish-grey haze stretching from southern Quebec across the Great Lakes and into the mid-Atlantic. The diffuse signature and areal extent point to well-mixed smoke that had traversed from intense fire region in eastern Canada (red dashed rectangle) in (Figure 5 (left)). HYSPLIT back trajectories terminating at 2300 UTC on 6 June 2023 (Figure 4(right)) confirm that all three arrival-heights originated within the Canadian smoke plume. In contrast to the May event, this case trajectories display a stronger westerly component, with air parcels sweeping across Lake Superior and the Lower Peninsula of Michigan before

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entering the mid-Atlantic region. The lowest trajectory spent extended time (< 500 m AGL) over the Ohio valley, suggesting potential accumulation of boundary layer pollutants en route. The 1500 m path exhibited marked descent during the final 24 hours, indicative of subsidence that would promote vertical mixing of elevated smoke into the regional boundary layer.

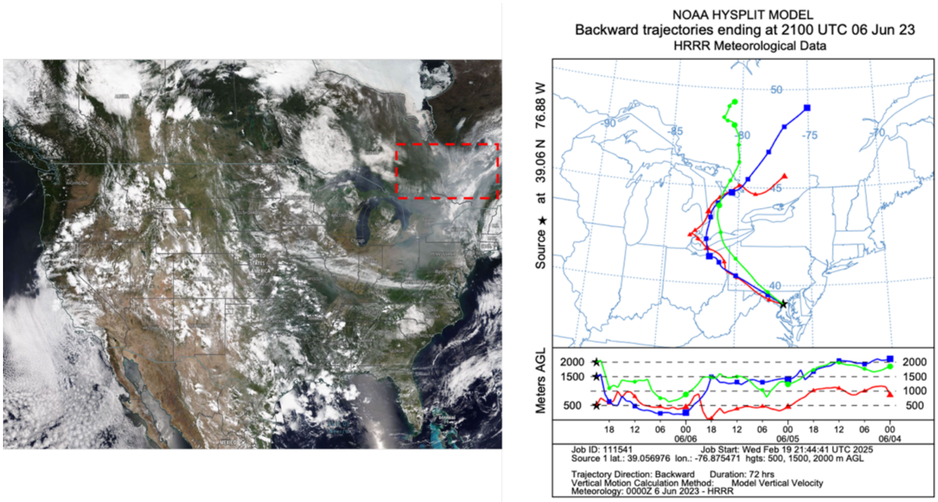

Figure 5. Left: Satellite image on 06 June 2023 showing the wildfire smoke plume and fire source (red dashed box) (VIIRS Characterization Support Team, 2016). **Right:** 72-hour HYSPLIT back trajectories ending at 2100 UTC 06 June 2023.

The depolarization ratios for 5-10 June (Figure 6) shows a remarkably coherent slab that originated near 4 km at 00 UTC on 6 June and descending almost linearly, crossing 2 km at ~ 1000 UTC before reaching <1 km by 1500 UTC. The implied subsidence rate mirrors the downward motion identified by the HYSPLIT trajectories in (Figure 3). As soon as the layer intersects the top of the mixed layer, backscatter intensities below 500 m strengthened sharply, clearly indicating that the elevated aerosol was rapidly entrained. From 9 June onward the ceilometer recorded a separate, spectrally distinct return between 3 to 5 km which was identified as the mid-level clouds rather than smoke plume.

Fine particulate concentrations begin to climb after 12 UTC on 6 June precisely when the ceilometer first detected the smoke plume (shaded) penetrating the PBL (Figure 6). During this interval surface winds were exceptionally weak (< 0.2 m s^{-1}) and variable, suppressing horizontal dilution and allowing local accumulation. Ozone remained anomalously low (< 15 ppb) throughout the smoke episode, consistent with both attenuated photolysis under the dense plume and titration by co-transported NOx (NO_2 peaks ≈ 15 ppb). $PM_{2.5}$ climbed steadily to ~40 µg m^{-3} by late 6 June in tandem with light (≤ 0.6 m s^{-1}) north-westerly winds, affirming local accumulation of the mixed-down plume.

A much larger $PM_{2.5}$ levels spiked (~ 215 µg m^{-3}) on 8 June followed the return of stagnant conditions but occurred well after the primary descending plume. The increase coincided with the ceilometer's cloud-top signature at 3-5 km (Figure 6). While

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the cloud layer itself was not a particulate source, its shading and moisture effects could have altered boundary layer stability and humidity, promoting secondary aerosol formation and inhibiting dispersion. Disentangling the relative roles of continued smoke advection versus in-situ processes will require chemical speciation and additional trajectory analysis beyond the scope of the present study.

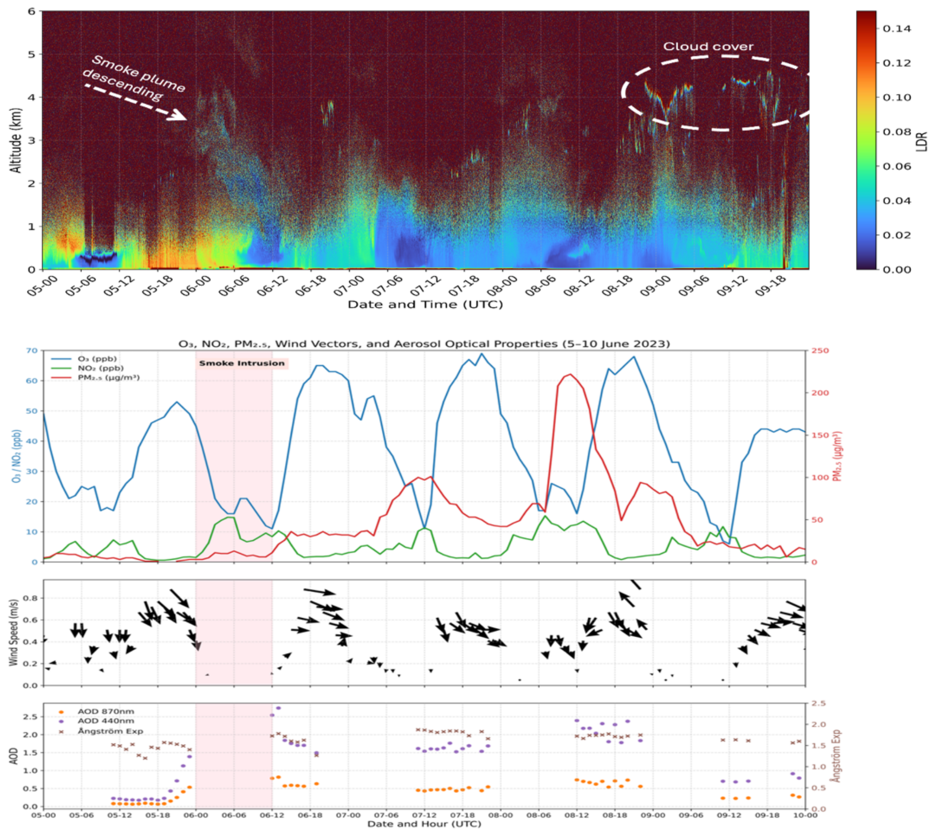

Figure 6. Top: Ceilometer LDR (5-10 June 2023 UTC) showing a wildfire smoke layer descending into the free troposphere early on 5 June and later cloud cover around 9-10 June. **Middle:** Surface O_3 (blue), NO_2 (green), and $PM_{2.5}$ (red) time series with wind vectors, highlighting the smoke-intrusion period (shaded) on 5–6 June. **Bottom:** AOD at 440 nm (orange) and 870 nm (brown) with Ångström exponent (purple), indicating elevated fine-mode aerosol loading during the smoke event.

3.3 Case 3: 15-19 June 2023

Case 3 captured a multilayer smoke incursion into the BWC that resulted from two geographically distinct Canadian fire complexes (West and Central) and differential transport pathways aloft and within the PBL (Figure 7). The NOAA-20 true-colour imagery from 15 June 2023 shows dense plumes emanating predominantly from west and central part of Canada (red

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dashed boxes). HYSPLIT back trajectories confirm that the air reaching 2 km AGL (green) and 1.5 km AGL (blue) descended gradually, while the PBL air at 500 m AGL (red) descended rapidly during the final 12 hr. The trajectory altitudes (bottom panel) show that there was a gently subsiding elevated layer versus a sharply descending near-surface layer.

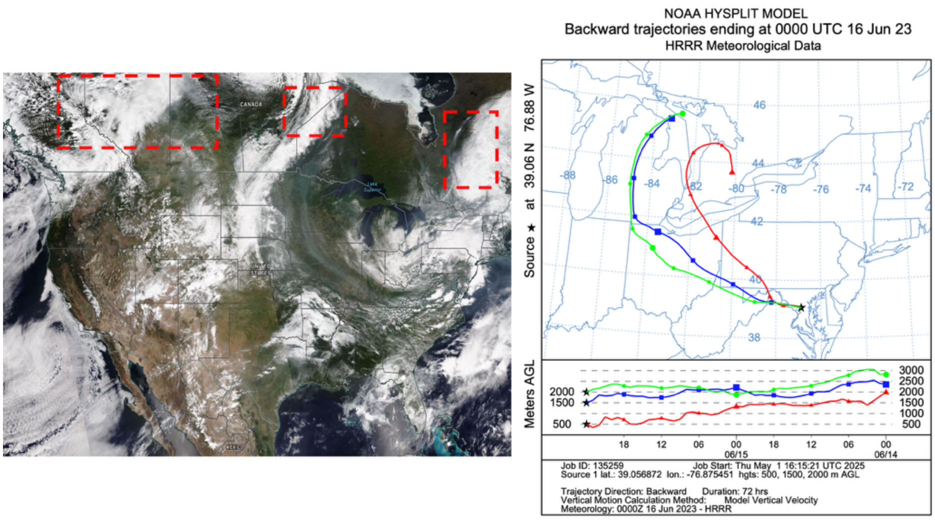

Figure 7. Left: True color satellite image on 15 June 2023 UTC showing the wildfire smoke plume over the mid-Atlantic and three prominent sources of fire (red dashed square) (VIIRS Characterization Support Team, 2016). **Right:** 72-hour HYSPLIT backward trajectories ending at 00 UTC 16 June 2023 for air parcels.

On 15 June around 1800 UTC, the LDR profiles revealed three distinct smoke layers between 4-7 km altitude. As the labelled markers in Figure 8 indicate, the elevated smoke layer demonstrated a descending pattern that gradually moved toward lower altitudes. The depolarization values during this descending plume ranged between 0.05 and 0.10, again consistent with the observations done by the ceilometer manufacturer in their white paper (CL61 White Paper, 2021). Once again, these values provided significant information and confirmed that the depolarization measurements can effectively differentiate between different types of aerosols based on particle shape and composition, especially in the free atmosphere (CL61 White Paper, 2021). Between 06-13 UTC of 16 June, the smoke interacted with the residual PBL, as seen based on the depolarization signals at the interface. Precipitation was also recorded around 15 UTC on 16 June, as indicated by the higher depolarization ratio values (0.15-0.25). Hence, we do not observe a significant smoke signal during that time. The smoke plume is seen again between 2-3 km and 1900-2300 UTC on 16 June. The smoke seemed present in the residual layer and later interacted with the emerging convectively driven PBL on 17 June. In the figure, PBL is also visible as the region with varying depolarization values and reaching an average height of 2-2.5 km during this case study.

Surface ozone levels gradually declined from 65 ppb to 10 ppb during the smoke intrusion phase, with a gradual increase in the NO_2 levels. The ozone levels recovered on 16 June at 0900 UTC by going up 5 ppb. However, they dropped again, likely

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due to the NO_x-mediated titration, as the smoke plume is known to carry substantial NO_x emissions, as indicated by increasing levels of NO_2. Simultaneously, we noticed increased $PM_{2.5}$ levels, especially after the smoke intrusion into the PBL. The increasing ozone levels after 1200 UTC of 16 June slowed down between 1200-1500 UTC. They could be attributed to aerosol-induced UV attenuation and some cloud coverage suppressing photochemical ozone production. Ozone level recovered after the warm front passage (denoted by pink dashed line) and was associated with a wind shift, which may have introduced an urban NO_x/VOC mixture that synergized with smoke-derived precursors to reignite photochemical ozone formation.

Pre-frontal calm winds during the smoke intrusion facilitated the vertical mixing of the descending plume. Post-frontal winds promoted horizontal advection of the smoke. As observed near the surface, the wind shifts aligned with the warm front's passage, which is followed by brief precipitation, as seen by the strong strip of LDR (green, yellow, and red). This likely caused a brief collapse of the PBL, which rapidly recovered around 1700 UTC. By 1800 UTC, the evolving convectively driven PBL was coupled with the residual layer comprising a smoke plume. The AOD values at 440 and 870 nm were relatively higher throughout 16 June, confirming the dominance of smoke aerosols in the lower atmosphere.

In this case, the initial ozone suppression phase demonstrated the smoke plume's capability to locally counteract photochemical production through combined NO_x titration and radiative effects. At the same time, post-frontal recovery highlighted how synoptic shift used the ozone precursors from the smoke plume along with regional urban pollutants. We also observed $PM_{2.5}$ levels gradually and consistently increased post-smoke intrusion, reaching its peak at 1800 UTC on 17 June. While smoke plumes were also seen lingering on 18 June, strong surface winds affected the ozone levels, capping its peak to 50 ppb.

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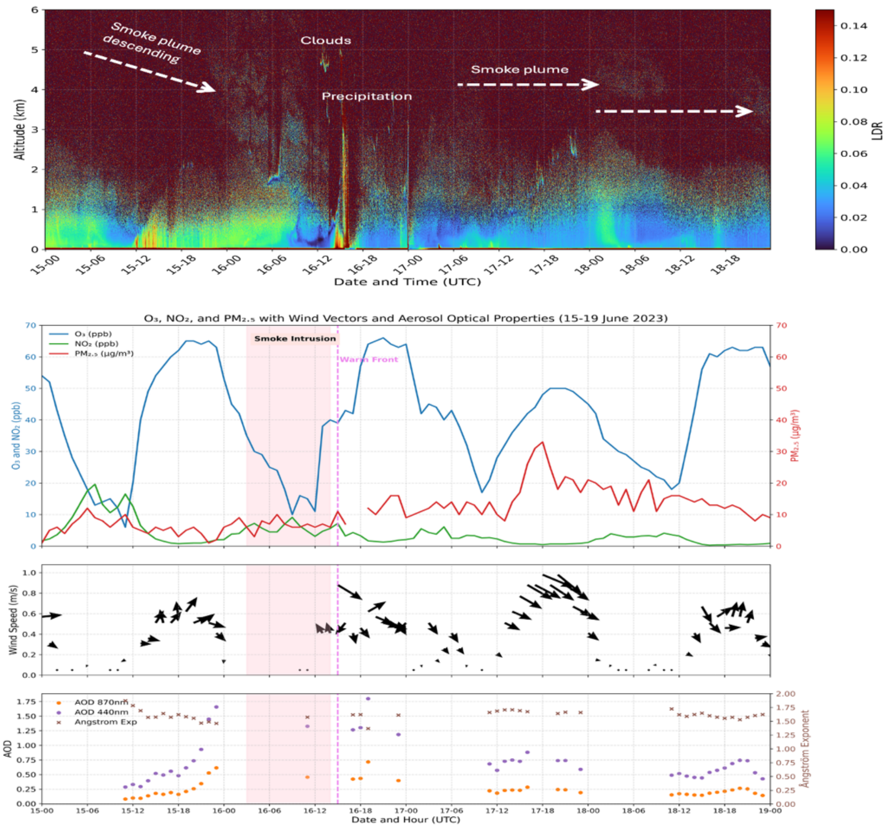

Figure 8. Top: Ceilometer LDR (15-19 June 2023 UTC) showing wildfire smoke layer descending into the PBL, followed by cloud and precipitation on 16 June, and a separate elevated smoke plume on 17 June. **Middle:** Surface O_3 (blue, left axis), NO_2 (green, left axis), and $PM_{2.5}$ (red, right axis) with wind vectors, highlighting the 15–16 June smoke intrusion (shaded pink) and a warm front passage (dashed magenta line) on 16 June. **Bottom:** AOD at 440 nm (orange) and 870 nm (brown) with Ångström exponent (purple, right axis), indicating enhanced fine-mode aerosol loading during the elevated smoke episodes.

3.4 Case 4: 28 June to 1 July 2023

Satellite true-color imagery on 28 June (Figure 9 (left)) depicts a dense smoke plume originating from active fire sources in eastern Canada and extending south-eastward into the mid-Atlantic. HYSPLIT 72-hour back trajectories terminating at 1800 UTC on the same day (Figure 9 (right)) revelaed that air parcels at 500, 1500 and 2000 m remained below 1.5 km for most of their journey, implying horizontal advection within the PBL rather than lofted free tropospheric transport. Consistent with this pathway, the CL61 detected no elevated LDR signature in the 3-6 km layer, confirming that the smoke was already well mixed into the regional PBL upon arrival.

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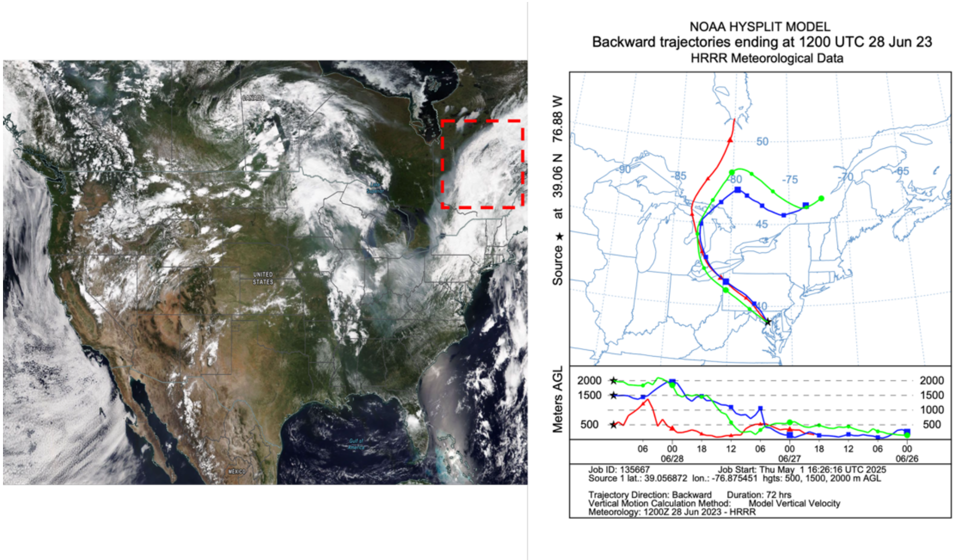

Figure 9. Left: True color satellite image on 28 June 2023 UTC showing the wildfire smoke plume over the mid-Atlantic and one of the prominent sources of fire (red dashed square) (VIIRS Characterization Support Team, 2016). **Right:** 72-hour HYSPLIT backward trajectories ending at 1200 UTC 28 June 2023 for air parcels.

Surface observations respond promptly to this low-level influx. Beginning near 0900 UTC on 28 June, $PM_{2.5}$ rose steadily, surpassing 60 µg m^{-3} by late evening, while ozone peaked at ~ 55 ppb in the afternoon before collapsing below 10 ppb overnight (Figure 10). These divergent trends suggest that the incoming pollutants carried a substantial primary PM load but only moderate ozone precursors; nocturnal titration by accumulated NO and reduced photolysis likely contributed to the sharp ozone decline. The following day, a weaker north-westerly flow sustained the PM built up. The $PM_{2.5}$ levels exceeded 130 µg m^{-3} by 1800 UTC on 29 June, whereas ozone exhibited two step rise, first to ~ 80 ppb then, after a brief lull, to > 90 ppb. The midday ozone dip coincided with a transient wind speed and direction.

Surface wind-vector analysis provided the dynamical context to the increasing levels of pollutants. On 28 June, moderate north-westerlies (0.4 - 0.8 m/s) channelled the smoke directly into the BWC. Night-time winds slackened to < 0.2 m/s, promoting pollutant stagnation and observed plateau in $PM_{2.5}$ levels. Around 1500 UTC on 29 June the surface flow veered abruptly to southerly; whithin three hours $PM_{2.5}$ levels began to fall, confirming the ventiallation by cleaner maritime air. By 30 June persistent sourtherlies exceeded 1m/s and both $PM_{2.5}$ and ozone levels dropped to values well below the previous day maxima. Compared with the earlier May and early June cases, this cases illustrated a distinct mechanistic pathway: smoke advected entirely within the mixed layer can yield extreme particulate concentrations without an accompanying elevated layer signature in lidar, and its surface impact is modulated primarily by horizontal wind shifts rather than vertical mixing process.

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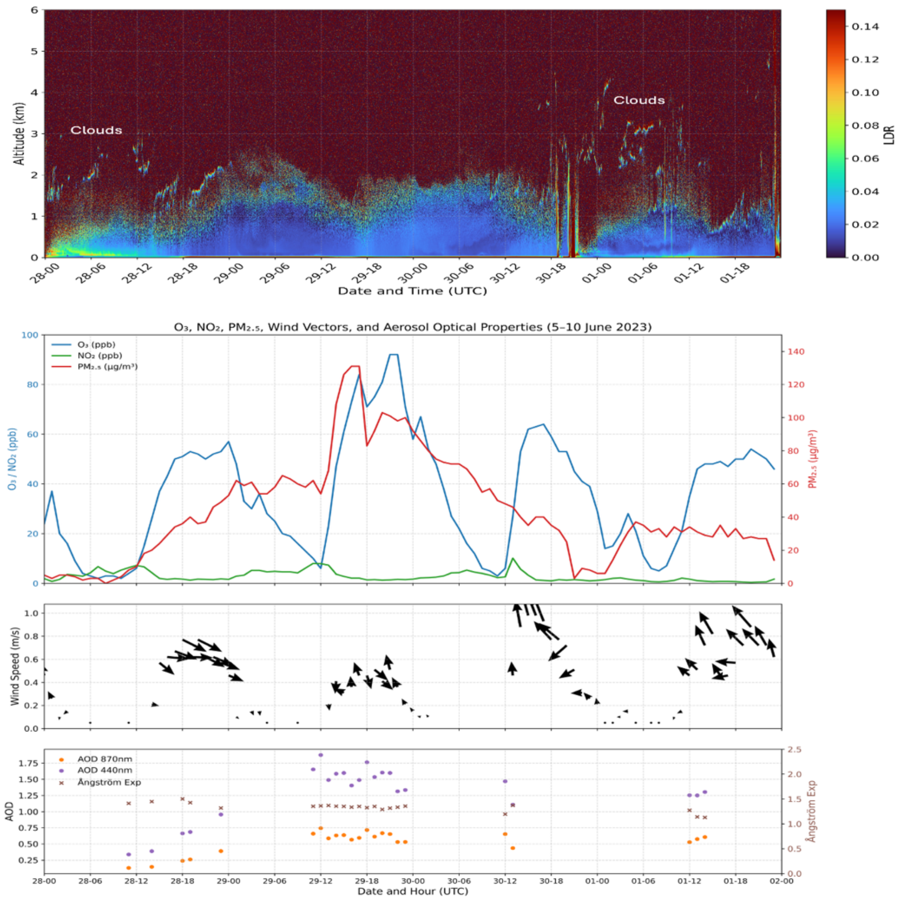

Figure 10. Top: Ceilometer attenuated backscatter (28 May 00:00 UTC–2 June 02:00 UTC 2023) displaying persistent cloud layers between ~1–3 km and intermittent elevated returns. **Middle:** Surface O_3 (blue, left axis), NO_2 (green, left axis), and $PM_{2.5}$ (red, right axis) time series with overlaid wind vectors. **Bottom:** AOD at 440 nm (orange) and 870 nm (brown) with Ångström exponent (purple, right axis), indicating variations in fine-mode aerosol loading over the same period.

Discussion and Conclusions

The 2023 Canadian fire season delivered three mechanistically distinct smoke episodes to the Baltimore–Washington Corridor: (i) lofted–subsiding transport (24–25 May and 15-19 June), (ii) subsidence–entrainment under stagnation (6 June), and (iii) advection-dominated boundary-layer transport (28 June–1 July). Each case unfolded under a unique combination of synoptic forcing, boundary-layer depth, and local wind regime, producing markedly different pollutant footprints at the surface. In the May case, an elevated plume interacted transiently with the nocturnal residual layer but was rapidly flushed by a post-frontal northerly surge; $PM_{2.5}$ never exceeded 15 µg m^{-3}, and ozone rebounded once cleaner air arrived. The 6 June episode highlighted the importance of timing: a smoke slab descended into a shallow, weak-wind PBL, allowing $PM_{2.5}$ to exceed 150 µg m^{-3} while photolysis suppression kept O_3 anomalously low. The late June event demonstrated that extreme particulate loading could arise even without an elevated lidar signature when smoke is advected entirely within the mixed layer; here, horizontal wind veers, rather than vertical mixing, controlled the pollution trajectory. These contrasts emphasize that public health risk cannot be inferred solely from satellite optical-depth fields, or an elevated aerosol layer detected by lidar. The vertical stage at which the plume arrives, and the contemporary ventilation state of the boundary layer jointly determine whether smoke aloft remains a distant spectacle or becomes an acute surface hazard.

A key contribution of this study is the first systematic use of the Vaisala CL61 depolarisation channel over the Mid-Atlantic to disentangle wildfire smoke from other aerosol types. While ceilometer backscatter alone can misclassify dense boundary-layer haze or low clouds as smoke, the LDR of biomass-burning particles (≈ 0.05–0.15) provides a robust discriminator. In the May and early June cases, elevated LDR signatures were pivotal in confirming the descent of non-spherical smoke into the PBL, a distinction that conventional backscatter or satellite AOD could not securely provide. Conversely, the absence of an LDR enhancement during the late June event corroborated the trajectory analysis, indicating that the plume was already embedded in the mixed layer. These findings advocate for the wider inclusion of depolarisation lidar in regional air-quality networks and the assimilation of near-real-time LDR fields into smoke-forecast systems.

For operational air quality models not to over-predict ozone when large smoke burdens coincide with high photolysis suppression or under-predict $PM_{2.5}$ when smoke layers descend abruptly overnight, the case studies here suggest possible avenues for improvement. The height-resolved emission placement accurately representing pyro-convection injection heights is essential to reproduce the subsequent subsidence timelines observed in the May and June events. Capturing the diurnal growth–collapse cycle and its interaction with weak-wind stagnation, as evidenced on 6 June. Assimilating ceilometer-derived PBL height, and LDR can constrain model dilution rates and aerosol speciation, improving $PM_{2.5}$ forecasts during advection-dominated episodes. We also want to emphasize that this analysis is limited to a single lidar site and relies on total $PM_{2.5}$ concentrations without detailed elemental carbon or VOC tracers. Multi-lidar networks coupled with airborne in-situ sampling would permit full three-dimensional mapping of smoke layers and their chemical aging. Additionally, direct measurements of photolysis rates would clarify the relative contributions of smoke shading versus precursor availability to the observed ozone responses.

Three transport regimes—subsiding lofted layers, stagnation-aided entrainment, and boundary-layer advection—produced markedly different surface impacts despite similar satellite optical signatures. $PM_{2.5}$ ranged from < 15 µg m^{-3} in the ventilated May case to > 130 µg m^{-3} under late-June stagnation, while O_3 effects varied from titration-driven minima (< 15 ppb) to photochemically driven maxima (> 90 ppb). Depolarisation lidar proved indispensable for diagnosing smoke layers' vertical and microphysical character. LDR thresholds allowed discrimination between elevated smoke, boundary-layer aerosols, and cloud tops, reducing false positives in smoke detection. The timing of plume-PBL intersection

relative to local wind and stability conditions emerged as the dominant control on surface exposure. Forecast guidance should prioritize accurate simulation of PBL dynamics and incorporate near-real-time lidar constraints.
Satellite AOD alone is insufficient to gauge surface risk. Remote-sensing products must be blended with height-resolved observations and trajectory analyses to resolve whether smoke is aloft, entraining, or already well mixed. Future research should combine multi-site depolarization lidar, chemical speciation, and data-assimilative modelling to refine exposure estimates and to develop targeted health advisories during transboundary smoke events. In an era of intensifying boreal wildfire activity, such interdisciplinary approaches are essential for safeguarding air quality in the densely populated mid-Atlantic and beyond.

Data Availability

Data and additional graphs related to this article are available upon request to the corresponding author.

Author Contributions

The conceptualization was performed by NNK, RKS and SC. RR and AF provided the ground measurements, and NNK and RKS curated the data. The methodology was completed by NNK and RR. The thorough investigation was performed by NNK and RKS. NNK, RKS, and SC performed the analysis. NNK drafted the original paper, which was reviewed by RKS and SC, edited by RR. The entire team contributed significantly to improving this work. SC acquired funding for this project.

Competing Interests

The contact author has declared that none of the authors has any competing interests.

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