



Evidence for impacts on surface-level air quality in the northeastern US from long-distance transport of smoke from North American fires during the Long Island Sound Tropospheric Ozone Study (LISTOS) 2018

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Abstract. Biomass burning is a large source of uncontrolled air pollutants, including particulate matter (i.e., PM_{2.5}), black carbon (BC), volatile organic compounds (VOCs), and carbon monoxide (CO), which have significant effects on air quality, human health, and climate. Measurements of PM_{2.5}, BC, and CO made at the Yale Coastal Field Station in Guilford, CT, and five other sites in the metropolitan New York City (NYC) area indicate long-distance transport of pollutants from wildfires and other biomass burning to surface-level sites in the region. Here, we examine two such events occurring on 16–17 and 27–29 August 2018. In addition to regionally consistent enhancements in the surface concentrations of gases and particulates associated with biomass burning, satellite imagery confirms the presence of smoke plumes in the NYC–Connecticut region during these events. Back-trajectory modeling indicates that air masses arriving at surface-level sites in coastal Connecticut on 16–17 August passed over the western coast of Canada, near multiple large wildfires. In contrast, air parcels arriving on 27–29 August passed over active fires in the southeastern United States. The results of this study demonstrate that biomass burning events throughout the US and Canada (at times more than 4000 km away), which are increasing in frequency, impact surface-level air quality beyond regional scales, including in NYC and the northeastern US.

1 Introduction

Biomass burning, which occurs on a large scale during wildfires and some controlled burns, is a major source of air pollutants that impact air quality, human health, and climate (Lewis et al., 2008; Liu et al., 2015; Reid et al., 2016; Urbanski et al., 2008). During these events, gases such as carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), nitrogen oxides (NO_x), and gas-phase organic compounds (including volatile organic compounds – VOCs) are directly released into the atmosphere (Akagi et al., 2011; Urbanski et al., 2008; Vicente et al., 2013; Yokelson et al., 2013). Biomass burning produces particulate matter (PM), including black carbon (BC) and other primary organic aerosol (POA) in the PM_{2.5} size range (i.e., particles with a diameter $\leq 2.5 \mu\text{m}$; Akagi et al., 2011; Urbanski et al., 2008). Biomass burning is also a source of reactive precursors to the production of secondary compounds, such as ozone (O₃) and secondary organic aerosol (SOA; Urbanski et al., 2008; Ward and Hardy, 1991). The chemical composition of PM resulting from biomass burning depends on many factors, such as the type of fuel and combustion conditions (Calvo et al., 2013). In addition to the environmental impacts of biomass burning emissions, elevated PM_{2.5} concentrations have been associated with respiratory and cardiovascular disease and higher mortality rates (Brook et al., 2004; Dockery et al., 1993; Reid et al., 2016).

The pollutants emitted from biomass burning events not only affect local air quality but can also be transported

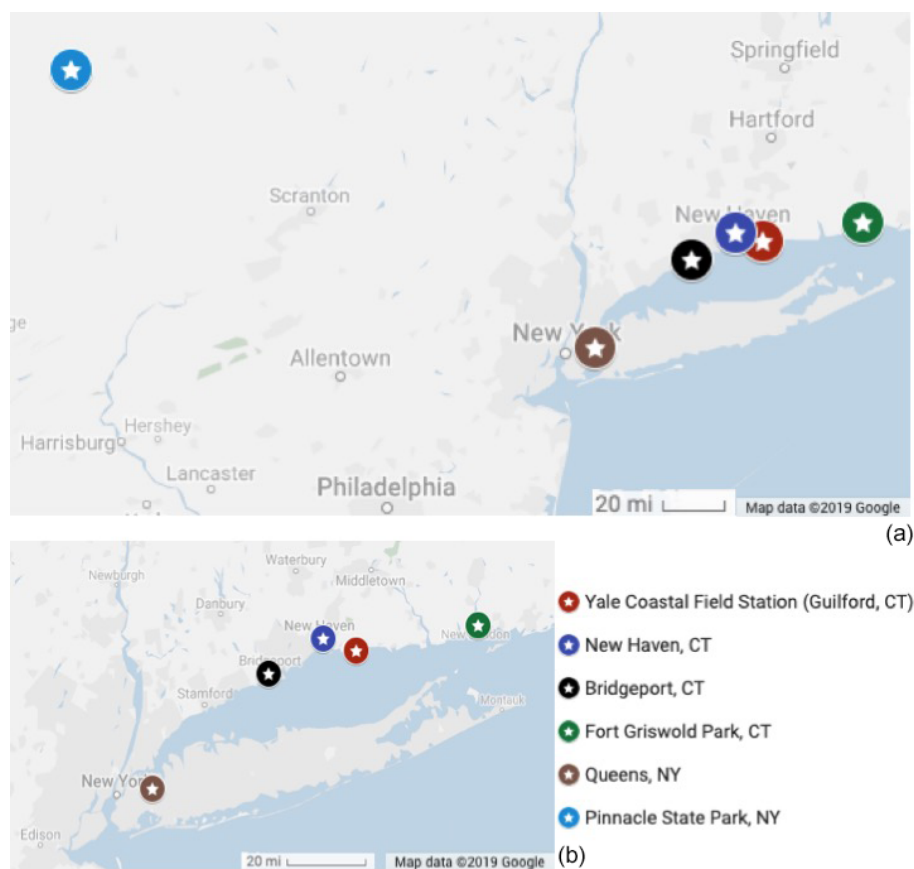


Figure 1. Location of air quality monitoring sites used for $\text{PM}_{2.5}$, BC, and CO measurements. (a) shows all six sites, while (b) shows a close-up of the five sites directly on the Long Island Sound. ©Google Maps.

over long distances (Barnaba et al., 2011; Burgos et al., 2018; Forster et al., 2001; Martin et al., 2006; Niemi et al., 2005; Stohl et al., 2003). Colarco et al. (2004) used satellite and other remote-sensing tools, combined with back-trajectory and 3-D models, to confirm the presence of pollution from July 2002 wildfire smoke that originated in Quebec, Canada, and was transported and detected at the surface level in Washington, DC. Similar studies have described the long-range transport of wildfire smoke from Canadian wildfires to Maryland (Dreessen et al., 2016), Siberian wildfires to British Columbia (Cottle et al., 2014), and examples in Europe and Asia (Diapouli et al., 2014; Jung et al., 2016). Over the course of this long-distance transport, the gas- and aerosol-phase compounds undergo aging and dilution. Organic gases and aerosols are transformed chemically by photo-oxidation, interaction with atmospheric oxidants, and reaction with other atmospheric compounds (Cubison et al., 2011; Hennigan et al., 2011). While more reactive components will age more quickly, this study focused on tracers which are less likely to react over our transport timescales. For example, BC is primarily removed via particle deposition to the Earth's surface, which is largely dependent on height above ground level. Mixing of plumes aloft

from the free troposphere is variable and can range from 1 week to 1 month with altitude, vertical transport conditions, and weather (Jacob, 1999), and $\text{PM}_{2.5}$ losses due to physical processes will follow similar timescales. Losses of these tracers are possible, depending on timescales and weather conditions (e.g., wet deposition) during long-distance transport. However, they are generally long-lived in the free troposphere, and many previous studies have used BC, CO, and/or $\text{PM}_{2.5}$ as indicators of long-distance transport of biomass burning smoke (Burgos et al., 2018; Cottle et al., 2014; Diapouli et al., 2014; Dreessen et al., 2016; Forster et al., 2001; Martin et al., 2006; Niemi et al., 2005).

The impacts of wildfire smoke, both regionally and at long distances, will become increasingly important in the coming years, with the number and severity of wildfires predicted to increase with climate change. Barbero et al. (2015) used 17 global climate models to evaluate the effect of anthropogenic climate change on large-scale wildfires in the US and found that the likelihood of forest fires will increase across most historically fire-prone regions, likely due to an earlier onset of summer and extended summer season. Abatzoglou and Williams (2016) similarly found that wildfires are likely to increase in the coming years due to climate change

impacts such as increased temperature and decreased atmospheric water vapor pressure. As the risks of climate change and its relation to wildfires are realized, it is increasingly important to understand the environmental and health effects that may be associated, including long-distance transport.

The NYC metropolitan area (including parts of Connecticut and New Jersey) is home to approximately 20.3 million people (U.S. Census Bureau, 2017) and has historically struggled with attaining air quality standards. The objective of this work is to evaluate the influence of North American biomass burning events on air quality in NYC and the north-eastern US using measurements from the Yale Coastal Field Station (YCFS) in Guilford, Connecticut (on the Long Island Sound), and other sites in the metropolitan NYC area, combined with satellite imagery and air parcel back-trajectory modeling. We focus on observations of two multi-day air pollution events during the month of August 2018 during the LISTOS (Long Island Sound Tropospheric Ozone Study) 2018 field campaign, both of which coincided with the NYC air quality advisory period for ozone on 16, 28, and 29 August (New York Department of Environmental Conservation, 2018).

2 Materials and methods

We perform a multi-platform-based analysis to determine whether specific regional air pollution events occurring in coastal Connecticut and the NYC area can be attributed to long-distance transport of emissions from wildfires and other biomass burning. This analysis combines results from pollutant measurements taken at the YCFS and other regional sites, satellite imagery (NOAA smoke maps), and the NOAA HYSPLIT back-trajectory model. Each of these techniques provides some evidence of the long-distance transport of wildfire pollutants, and we combine these methods to evaluate potential sources and transport times.

2.1 Yale Coastal Field Station air quality measurements

Ambient surface-level measurements were collected at the YCFS, located on the Long Island Sound in Guilford, CT (41.2583° N, 72.7312° W), using reference instrumentation for PM_{2.5}, BC, and CO at 1 h resolution for PM_{2.5}, 1 min for BC, and 1 s for CO (BC and CO then averaged to 1 h intervals). An AE33 Aethalometer (Magee Scientific) was used to measure BC, a BAM-1020 monitor (Met One) was used to measure PM_{2.5}, and a 48i CO analyzer (Thermo Fisher) was used to measure CO. All instrument flow rates were calibrated, relevant zeroing procedures were performed for the BC and PM_{2.5} measurements, and the CO instrument zero and span concentrations were calibrated (using house-generated zero air and a CO standard from Airgas: ±5 % standard 10 ppm CO in nitrogen diluted with Alicat mass

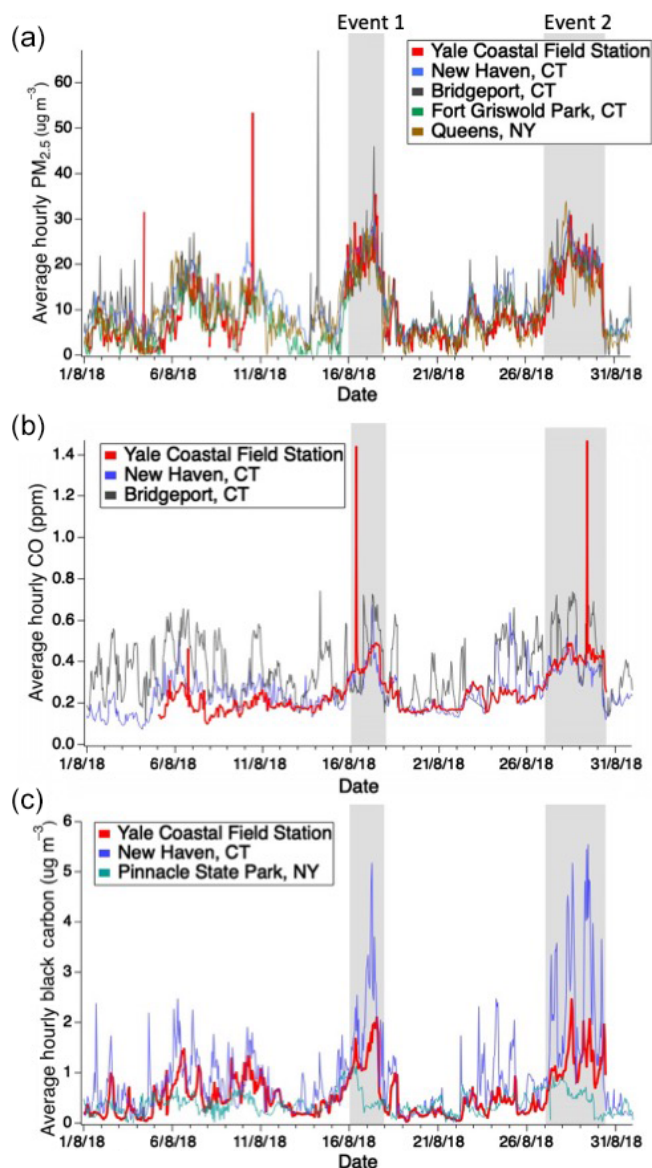


Figure 2. Concentrations of PM_{2.5} (a), CO (b), and BC (c) measured at the YCFS over the month of August 2018. Grey areas represent the two event periods identified as pollution spikes potentially caused by biomass burning smoke transport (16–17 and 27–29 August). These events all show simultaneous increases in PM_{2.5}, CO, and BC across all field sites, well above baseline concentrations. Meteorological dynamics at Pinnacle, NY (more than 300 km west), appear to be significantly different and lead to different absolute concentrations and earlier event dissipation compared to the other sites to the east. Note that the two outlier spikes in CO at the YCFS (b) are not ascribed to long-distance transport and are likely due to a hyperlocal source near the site (e.g., vehicle or other engine) that caused a brief spike above background levels, evidenced by concurrent NO_x spikes (NO_x is not discussed further in this analysis).

flow controllers). We corrected for CO calibration drift when necessary by adjusting the baseline to regional background levels. Inlets for each of these instruments were positioned ~ 5 m from the water on a small tower 2.5–3 m above the ground, facing south (i.e., towards the Long Island Sound), with direct inflow from the water during southerly onshore winds. Particulate inlets used PM_{2.5} cyclones and metal tubing (BC: copper; PM_{2.5}: stainless steel). The CO inlet was constructed of FEP tubing (1/4 in. outer diameter), and PM was removed at the inlet using a PTFE filter (Tisch) and PTFE filter holder. The YCFS is strategically positioned to minimize local urban influence from Connecticut while also being in the NYC metro area. Thus, it serves as a regional background site with less local influence than more urbanized stations.

These YCFS measurements were compared to data from other field sites (for the pollutants available) in the region (Fig. 1), including EPA-related sites in New Haven, CT (site 09-009-0027); Bridgeport, CT (site 09-001-0010); Fort Griswold Park, CT (site 09-011-0124); and Queens, NY (site 36-081-0124), as well as data from the New York Department of Environmental Conservation's rural site in Pinnacle, NY. Sites were selected for regional proximity to the YCFS as well as data availability.

2.2 Satellite imagery of smoke plumes

The NOAA Hazard Mapping System (HMS) generated smoke maps (NOAA, 2018) once a day based on satellite imagery of the spatial distribution of visible smoke plumes across North America. The data were downloaded from the NOAA smoke product's website and mapped via Google My Maps. While these maps do not provide vertical resolution on the distribution of the smoke plumes, they provide information on the horizontal distribution and density of the smoke plumes in the region.

2.3 NOAA HYSPLIT air parcel back-trajectory modeling

The NOAA HYSPLIT online software (Stein et al., 2015) was used to run back-trajectory models of air parcels arriving at the YCFS during the two periods of elevated PM_{2.5}, BC, and CO. The HYSPLIT model used archived meteorological data to trace the transport of an air parcel both vertically and horizontally through the atmosphere. The back-trajectory model was run using GDAS1.0 meteorological data over a 240 h (i.e., 10 d) period. While longer backward trajectories can lead to greater uncertainty, the general trends remain valuable, and 10 d is within a time length commonly studied in past work that utilized HYSPLIT back-trajectory modeling (Bertschi and Jaffe, 2005; Córdoba-Jabonero et al., 2018; Creamean et al., 2013; Huang et al., 2010; Smith et al., 2013). A new backward trajectory was simulated for air parcels arriving every 3 h at the YCFS at a final elevation

of 10 m a.g.l. We combined all trajectories simulated during each event observed at the YCFS and the reported North American fires during the period of interest into collective maps using ArcGIS.

3 Results and discussion

3.1 Elevated PM_{2.5}, BC, and CO at the Yale Coastal Field Station and other regional sites

Two main events in August (16–17 and 27–29 August) caused regional concentrations of PM_{2.5}, BC, and CO to all significantly increase for approximately 2 and 3 d periods, respectively. Figure 2 shows the concentrations measured at the YCFS compared to concentrations measured at nearby sites. The pollution events are multi-day enhancements that are significantly elevated from typical baseline concentrations with some short-term variability in the hourly data observed at only a single site and thus attributed to local emissions. PM_{2.5} concentrations show strong agreement between different field sites in CT and NY, especially during the two events, confirming that the concentration enhancements were caused by regional changes and not just local sources. Regional BC concentrations show general agreement across the sites with BC data as well as apparent diurnal patterns at the urban New Haven site, likely from local emissions. However, daily baseline concentrations from the New Haven site are in good agreement with the YCFS site up the coast. The Pinnacle site, more than 300 km west in upstate New York, is affected by the initial arrival of smoke plumes, but BC concentrations decrease sooner than at the YCFS or New Haven, CT, site, which is consistent with the eastward movement of the plumes in the satellite imagery (Figs. 3 and 4) and backward trajectories (Figs. 5 and 6). CO concentrations have clear multi-day increases at all three field sites during the two identified pollution events. The two urban sites, especially Bridgeport, CT, have greater diurnal changes in CO, potentially caused by local sources (e.g., gasoline-powered motor vehicles), while the YCFS site is generally less affected by local urban emissions.

Some smaller pollutant enhancements are observed earlier in August (6–7 and 10 August). However, these events have overall lower concentrations than the two events identified on 16–17 and 27–29 August, and satellite smoke maps show minimal smoke influence in the NYC region, with the exception of 6 August (Fig. S2 in the Supplement). Thus, they were not included in the primary analysis. However, it should be noted that 5, 6, 7, and 10 August were all days on which the state of New York issued an Air Quality Health Alert, primarily for high ozone (New York Department of Environmental Conservation, 2018).

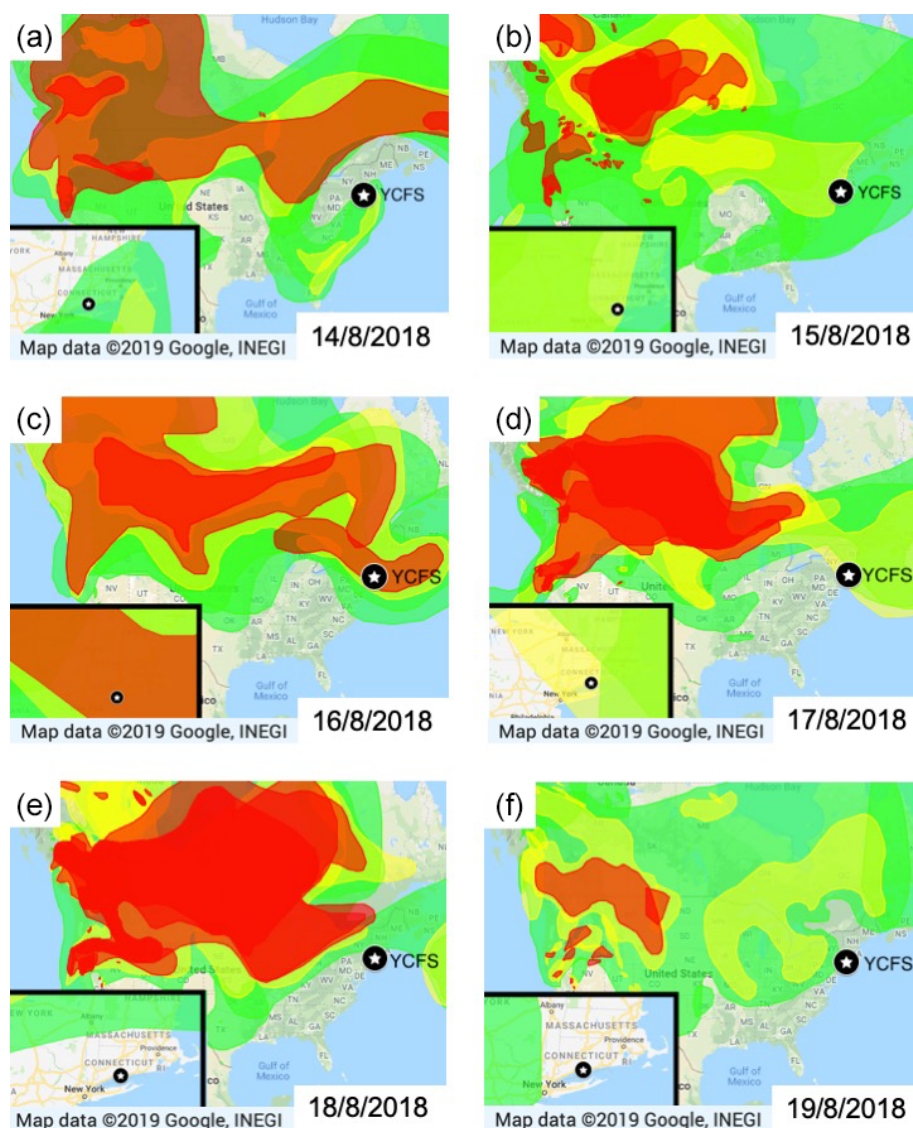


Figure 3. Smoke maps (NOAA) based on satellite imagery for total column measurements for 14–19 August 2018: before (a–b), during (c–d), and after (e–f) the first surface-level pollution event. The YCFS is indicated by a star. A new smoke plume begins to arrive aloft on 15 August before the surface-level pollution event on 16 and 17 August, with the total column smoke density aloft peaking on 16 August. The decrease in panels (e)–(f) is consistent with the sharp decrease in surface-level concentrations on 18 August. Colors indicate the intensity of the smoke plume, with red being the most dense, yellow intermediate, and green the least dense. Insets provide a magnified view of the YCFS site. ©Google Maps.

3.2 Satellite imagery: NOAA smoke maps

NOAA smoke maps confirm the presence of smoke over the Long Island Sound area during the regional pollution events, with simultaneous enhancements in surface-level concentrations of $\text{PM}_{2.5}$, BC, and CO (Fig. 2). This satellite imagery provides evidence that the transport of smoke from biomass burning may have impacted surface-level air quality during the two pollution events. The daily NOAA smoke maps in Figs. 3–4 show vertically integrated smoke density before, during, and after these events. Figure 3 shows the arrival of

a smoke plume aloft, with the total column smoke density peaking at YCFS on 16 August and remaining until 17 August, consistent with the surface-level pollution event on 16 and 17 August (Fig. 2). The sharp decrease in surface-level concentrations on 18 August is consistent with the departure of the plume in the satellite imagery (Fig. 3e). During the second surface-level pollution event at the end of August, smoke was observed in the region, although it was less dense than in mid-August. Figure 4 shows a plume lingering over the NYC and CT region from 27–29 August until the morning of 30 August, which is consistent with surface-level

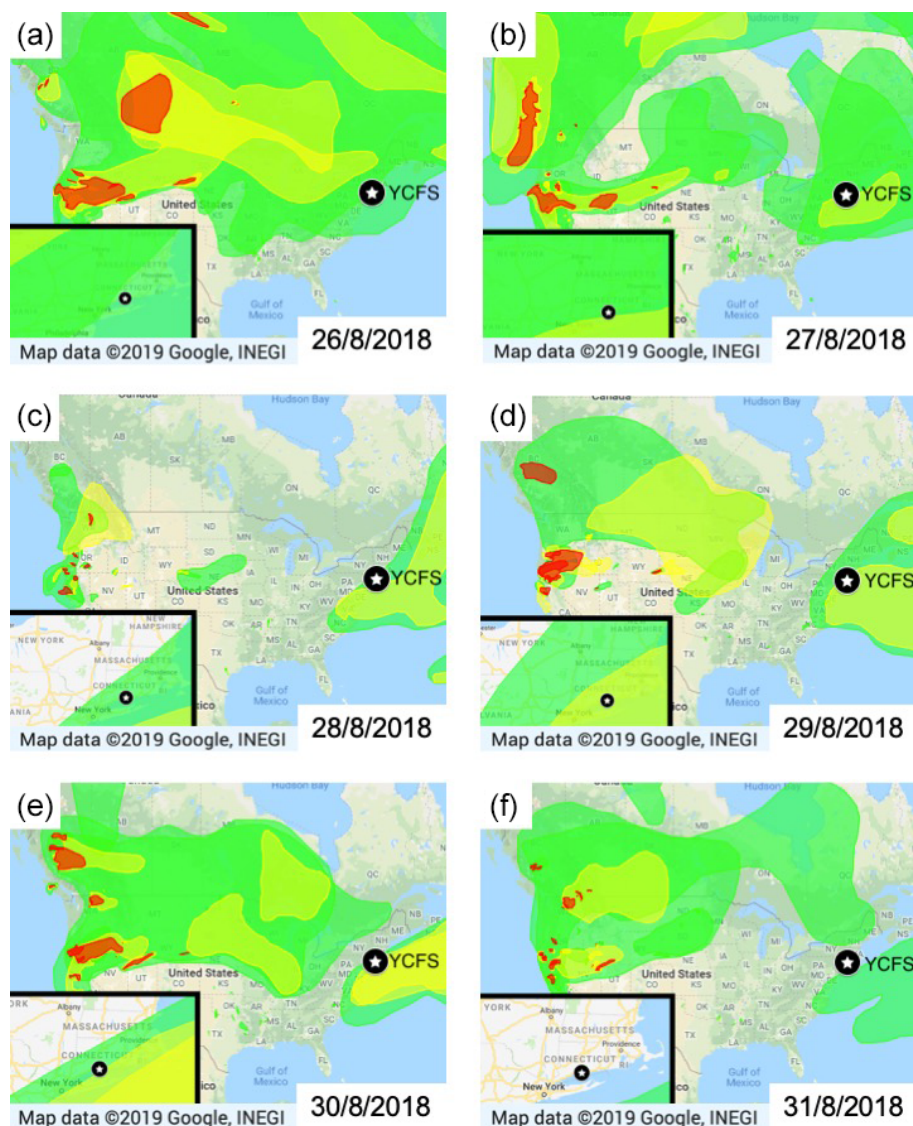


Figure 4. Smoke maps (NOAA) based on satellite imagery for total column measurements for 26–31 August 2018: before (a), during (b–e), and after (f) the second surface-level pollution event. The YCFS is indicated by a star. The satellite imagery shows a plume lingering over the region during the period of the surface-level event that spanned from 27–29 August to the morning of 30 August, which is reflected in the satellite imagery. The absence of smoke aloft in panel (f) is consistent with low surface-level concentrations. Colors indicate the intensity of the smoke plume, with red being the most dense, yellow intermediate, and green the least dense. Insets provide a magnified view of the YCFS site. ©Google Maps.

data. No smoke plumes are observed in the area on 31 August (Fig. 4f), which is consistent with low surface-level concentrations (Fig. 2).

While the satellite imagery lacks vertical distribution data, the presence of smoke in the region during the same periods when surface-level concentrations increase supports the hypothesis that smoke from aloft was near the surface or available for transport to the surface and led to the increase in concentrations of $\text{PM}_{2.5}$, BC, and CO at the YCFS and other regional sites. However, the vertically integrated column measurements represented by the smoke maps are not a perfect

prediction of surface-level influence, as shown in the days prior to the actual events (i.e., 14–15 and 26 August). On 14–15 August, leading up to the first event, there are lower levels of smoke aloft over the region that are visible in the satellite imagery (Fig. 3a and b). On 26 August, leading up to the second event, there is again a low density of smoke over the region (Fig. 4a). However, the presence of smoke visible in satellite imagery on days when the surface measurements do not show an increase in air pollutants is not in conflict with surface-level results, since it may have been exclusively at higher altitudes. On the days prior to the surface-level events

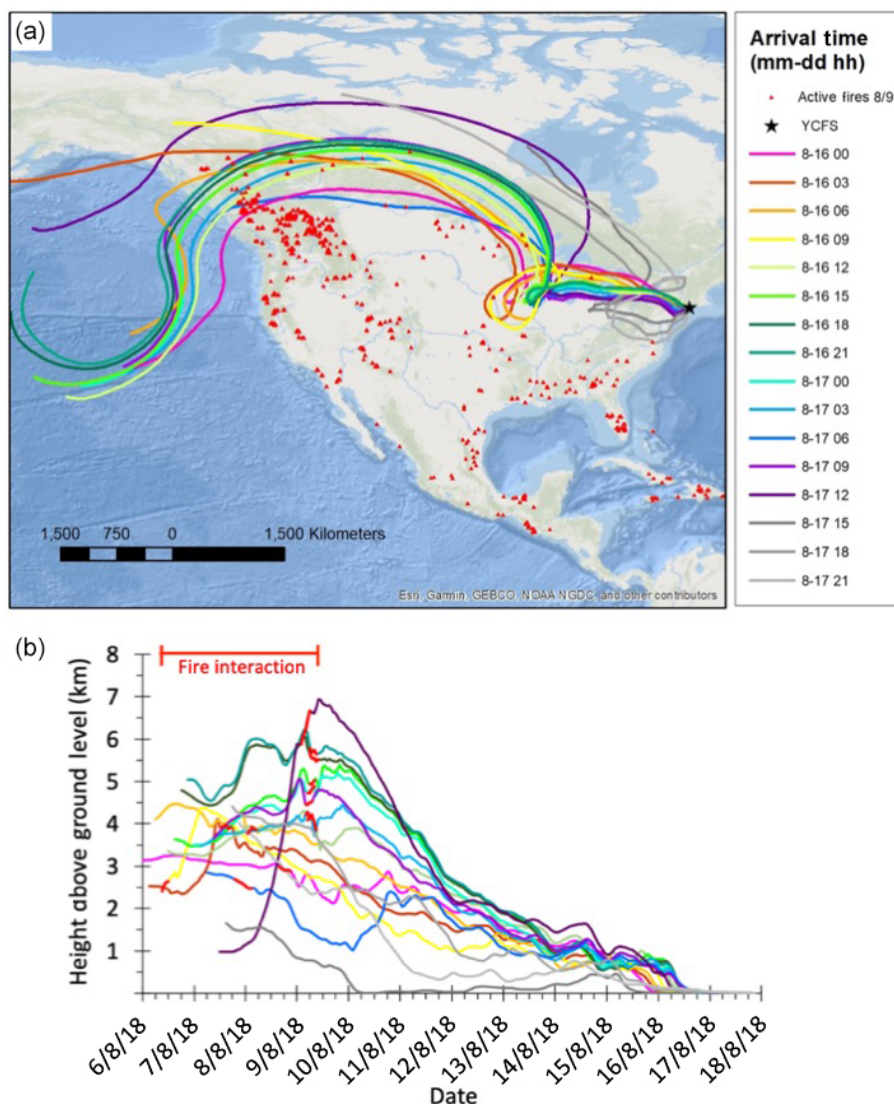


Figure 5. NOAA HYSPLIT back-trajectory model results for air parcels arriving on 16 and 17 August 2018 to surface-level YCFS site. Each line represents the backward trajectory for an air parcel arriving every 3 h throughout the course of the day. The location of fires on 9 August (when most trajectories intersect the wildfire zone on the western coast of North America) is depicted with red triangles (from NOAA HMS fire maps). The top map (a) shows the full 10 d trajectory, and the bottom figure (b) shows the vertical height of each air parcel along its trajectory as well as the times where it may have intercepted wildfire smoke plumes (highlighted in red on each individual trace and bracketed above). The last three trajectories on 17 August have no major fire interaction and have thus been colored grey.

when there is smoke observed aloft in satellite data, it is possible that it had not yet been transported down to the surface sites at the YCFS and others in the region, which is further explored using vertically resolved backward trajectories at a higher time resolution.

3.3 HYSPLIT back-trajectory model results

Air parcels originating at the surface level in areas with wildfires or controlled burns, or passing aloft over regions where wildfires were burning, are likely to pick up aerosols and trace gases associated with biomass burning. Here, we use

NOAA HYSPLIT air parcel back-trajectory models to provide additional information on the horizontally and vertically resolved transport pathways as a function of time of day and potential sources that influenced the observed surface-level pollution events in the NYC metropolitan area (Figs. 5–6).

The backward trajectories for air parcels arriving during the first event (16–17 August) show very similar paths passing over the central coast of western Canada (Fig. 5), where NOAA's records of fire locations indicate the presence of wildfires in this region during the air parcels' transit. On 16 August, the air parcels' backward trajectory through Canada and then the northern part of the United States

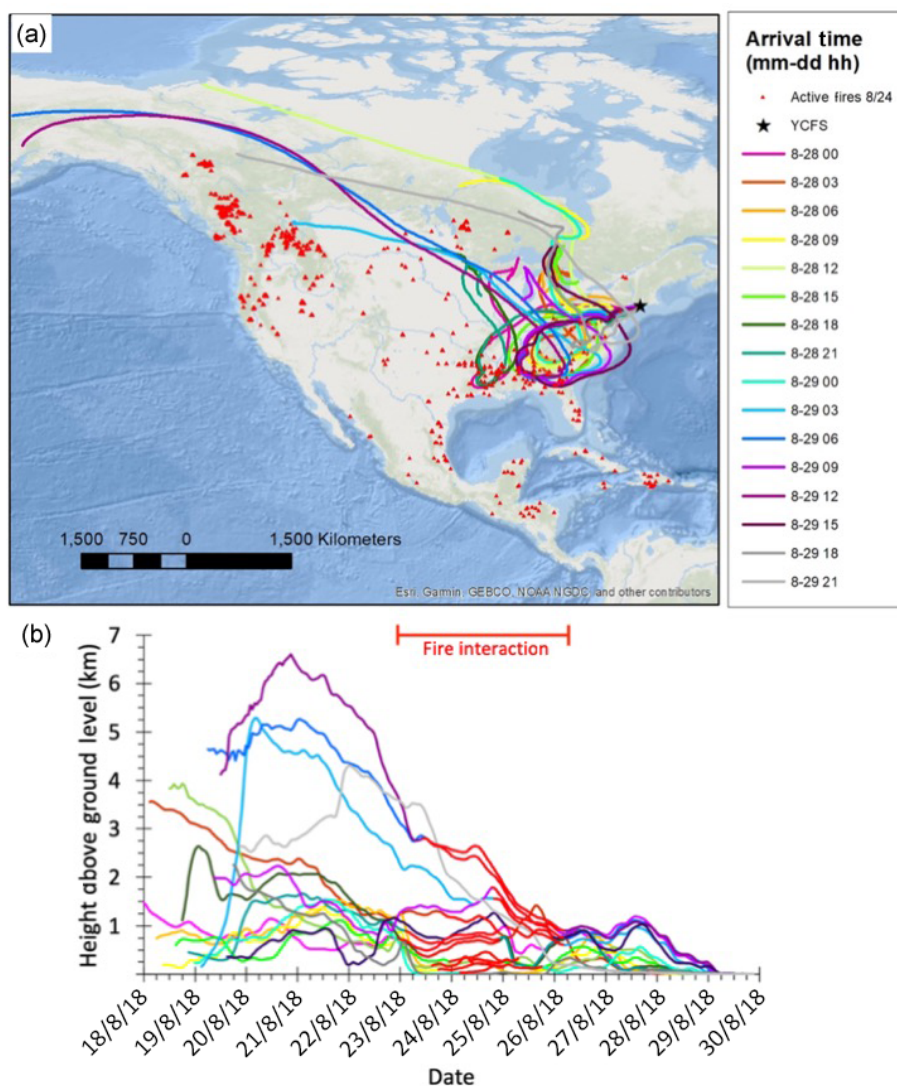


Figure 6. NOAA HYSPLIT back-trajectory model results for air parcels arriving on 28 and 29 August 2018 to surface-level YCFS site. Each color represents the backward trajectory for an air parcel arriving every 3 h throughout the course of the day. The location of fires on 24 August (when most trajectories intersect the fire zone in the southeastern US) is depicted with red triangles (from NOAA HMS fire maps). The top map (a) shows the full 10 d trajectory, and the bottom graph (b) shows the vertical height of each air parcel along its trajectory as well as the time where it may have intercepted fire smoke plumes (highlighted in red on each individual trace). The last two trajectories on 8–29 have no major fire interaction and have thus been colored grey.

demonstrates that the air parcels passed through an area with numerous active wildfires and descended from aloft to the surface level in the NYC region on 16 August. On 17 August, arriving air parcels follow a similar trajectory to the previous day until later in the day (i.e., 15:00 onward), when air masses did not pass over the western coast of North America within the prior 10 d but stayed in the eastern half of the United States and Canada in areas without reported fires (Fig. 5b). This change in transport pathways corresponds with a sharp drop in concentrations of pollutants measured at the YCFS observed at the end of 17 August (Fig. 2); as wind patterns shifted at the end of 17 August, cleaner air parcels

that had not passed through wildfire regions were transported to the YCFS (Fig. 5; greyed out), and thus concentrations of associated pollutants dropped. These trajectories reaffirm that the spike in pollutant concentrations measured at the YCFS may have originated from western North American fires for the first event. It is important to note that while most of the backward trajectories that passed through active fire regions did not pass within 2000 m of the surface (Fig. 5b), emissions in forest fire plumes rise due to the heat of combustion and have been shown to commonly reach heights 2000–7000 m a.g.l. (Colarco et al., 2004; Labonne et al., 2007).

For the air pollution event occurring on 27, 28, and 29 August, back-trajectory modeling shows that the majority of air parcels originated around the Great Lakes region 10 d prior and then circulated in the southeastern US before arriving to the YCFS. While a few trajectories originate on the western coast of North America, the majority do not pass through the region during the 10 d period. However, these air parcels pass over the southeastern US near the surface level (~ 1500 m and below), where active fires were reported 4–5 d prior to the observed pollution event in the metropolitan NYC region (Fig. 6b). This demonstrates the potential role of biomass burning in the southeastern US for air quality in the NYC region and northeastern US as well. Many of these fires are likely not wildfires but other biomass burning events such as intentional crop fires (McCarty et al., 2007). Backward trajectories for 27 August (the start of the second event) show a similar southeastern circulation pattern to those for 28 and 29 August (Fig. S3). The last two trajectories on 29 August do not encounter reported fires (Fig. 6; greyed out), which are shortly before the dissipation in concentration at the surface site in the early morning on 30 August (Fig. 2).

While satellite smoke maps (Figs. 3–4) show the spatial distribution of (vertically integrated) smoke across the US during these two events, backward trajectories provide more specific evidence that the air parcels observed at the ground-level YCFS site previously passed over active fires and mixed with biomass burning emissions (e.g., BC and CO). The fact that smoke is observed via satellite outputs over the YCFS and the NYC metropolitan area during the same time periods as the ground-level events discussed here, in combination with the fact that the backward trajectories passed over reported fires (at altitudes where it was reasonable to expect the rising concentrated smoke plumes), provides three different pieces of evidence that long-distance transport of biomass burning emissions impacted air quality in the NYC metropolitan area. In contrast, on many non-event days, NOAA smoke maps do not show plumes in the YCFS region and backward trajectories do not show significant interactions with fire locations (examples in Figs. 3–4 and S4–S7).

4 Conclusions

This study provides three pieces of evidence for the potential influence of long-distance transport of emissions from wildfires and other biomass burning on air quality in metropolitan NYC and the northeastern US. Together, surface-level measurements made at multiple regional sites, satellite smoke plume imagery, and air parcel back-trajectory model results indicate that biomass burning smoke was transported to the metropolitan NYC area during two separate events in August, leading to elevated levels of $\text{PM}_{2.5}$ and BC across the region. First, prolonged regional concentration enhancements in tracers associated with biomass burning – $\text{PM}_{2.5}$,

BC, and CO – indicate the potential influence of biomass burning smoke on 16–17 and 27–29 August. Second, NOAA smoke maps confirm the arrival and presence of smoke plumes over the Long Island Sound YCFS region on all 5 d of interest and their absence after the events. Finally, back-trajectory models provide additional information on the origin of air parcels and the associated pollutants. Air parcels from 16 and 17 August passed over western Canada, whereas air parcels arriving on 28 and 29 August passed over the southeastern US. The sets of trajectories during both events passed over regions with numerous active fires, including wildfires in western Canada, and most likely controlled agricultural burning in the southeastern US. Regardless of the cause of the fire, these results show that fires in multiple places in North America can impact air quality in metropolitan NYC, in Connecticut, and, more broadly, in the northeastern US.

This work, in conjunction with previous studies on the long-distance transport of biomass burning pollutants to other locations (Colarco et al., 2004; Cottle et al., 2014; Dreessen et al., 2016; Jung et al., 2016), reinforces the growing need to understand the long-range influence of wildfires. Increased understanding of long-distance transport is critical for predicting and managing air quality health risks in smoke-impacted areas. During both observed events (Fig. 2), the state of New York issued air quality health advisories in the New York City metro area and Long Island specifically for ozone (on 16, 28, and 29 August; New York Department of Environmental Conservation, 2018), though the implications of the transported emissions for ozone production are not directly evaluated here. This long-distance transport process is also important, since wildfire $\text{PM}_{2.5}$ has been specifically shown to have significant health effects, with respiratory effects that possibly exceed those of other $\text{PM}_{2.5}$ sources, and multi-day wildfire smoke events have even been shown to have short-term health effects on susceptible populations (statistically significant effects at concentrations $> 37 \mu\text{g m}^{-3}$; Liu et al., 2015, 2017). As climate change continues to impact the likelihood, prevalence, and intensity of wildfires across the US and Canada, air quality scientists and policymakers must pay increasing attention to the influence that these emissions have on air pollution issues not only on a local scale but nationally and internationally. This is critical, as increased emissions throughout a prolonged fire season, when coupled with common meteorological transport, can lead to enhanced background concentrations of primary $\text{PM}_{2.5}$ (including BC) and reactive precursors to SOA and ozone (Akagi et al., 2011; Urbanski et al., 2008). In all, these two observed events in the NYC area in August 2018 are examples that demonstrate the role of long-distance transport of biomass burning emissions as important contributors to the evolving air quality challenges facing metro NYC and similar urban areas as local emissions from controllable sources are further reduced (e.g., Khare

and Gentner, 2018; NYC Dept. Health, 2018) and wildfires become increasingly frequent.

Data availability. Data are available upon request to the corresponding author and are in their respective public repositories (LISTOS archive: <https://www-air.larc.nasa.gov/missions/listos/index.html>, Ground-Yale-Coastal Data, 2019; EPA Air Quality System: https://aqs.epa.gov/aqsweb/documents/data_mart_welcome.html, EPA Air Quality System – US Environmental Protection Agency, 2019; and NOAA Hazard Mapping System Fire and Smoke Product: <https://satapsanone.nesdis.noaa.gov/FIRE/fire.html>, NOAA, 2018).

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Author contributions. HMR, JCD, and DRG designed the study and led analysis. JCD managed instruments and collected data at the YCFS. HMR analyzed data and compiled modeling results and satellite imagery. HMR and DRG wrote the paper, and all authors contributed to refining the paper.

Competing interests. The authors declare that they have no conflicts of interest.

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