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Evidence for impacts on surface-level air quality in the Northeastern U.S. from long-distance transport of smoke from North American fires during 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 August 16th-17th and 27th-29th, 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. Backward-trajectory modeling indicates that air masses arriving in coastal Connecticut on August 16th-17th passed over the west coast of Canada, near multiple large wildfires. In contrast, air parcels arriving on August 27th-29th passed over active fires in the southeastern United States. The results of this study demonstrate that biomass burning events throughout the U.S. and Canada (more than 4000 km away), which are increasing in frequency, impact surface-level air quality beyond regional scales, including in NYC and the northeastern U.S.

Keywords: LISTOS (Long Island Sound Tropospheric Ozone Study), biomass burning, wildfires

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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 (CO_2), methane (CH_4), nitrous oxide (N_2O), 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 ≤ 2.5 µm) (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 (O_3) 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 affect not only local air quality, but can be transported 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 backward-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 surface-level in Washington, D.C. 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), as well as examples in Europe and Asia (Diapouli et al., 2014; Jung et al., 2016).

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 U.S., 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

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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 attainment to 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 Northeast U.S. 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 backward-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, one of which occurred during a NYC air quality advisory period for ozone on August 29th (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 backward-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 high time resolution (1 second), which was averaged to 1 hour intervals. An AE33 Aethalometer (Magee Scientific) was used to measure BC; a BAM-1020 (Met One) was used to measure $PM_{2.5}$; and a 48i CO analyzer (Thermo Fisher) was used to measure CO. All

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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 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 (¼" OD) and PM was removed at the inlet using a PTFE filter (Tisch) and PTFE filter holder.

Figure 1: Location of air quality monitoring sites used for $PM_{2.5}$, BC, and CO measurements. Panel A shows all six sites, while panel B shows a close-up of the five sites directly on the Long Island Sound.

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These measurements were compared to data from other field sites (for the pollutants available) in the region (Figure 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 State Park. 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 products website and mapped via Google MyMaps. 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 Backward-trajectory Modeling

The NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) online software (Stein et al., 2015) was used to run backward-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 backward-trajectory model was run using GDAS1.0 meteorological data over a 240 hour (i.e. 10 day) period. While longer backward-trajectories can lead to greater uncertainty, the general trends remain valuable and 10 days is within a time length commonly used in other studies utilizing HYSPLIT backward-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 hours at the YCFS, at a final elevation of 10 m above surface level. We combine all trajectories simulated during each event observed at the YCFS and reported North American fires during the period into collective maps using ArcGIS.

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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 (August 16th-17th and 27th-29th) caused regional concentrations of $PM_{2.5}$, BC, and CO to all significantly increase for approximately two- and three-day 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 are in good agreement with the YCFS up the coast. The Pinnacle Park site, 200+ miles 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 (Figures 3 and 4) and backward-trajectories (Figures 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 seems to be less affected by local urban emissions.

Some smaller pollutant enhancements are observed earlier in August (August 6th-7th and August 10th). However, these events have overall lower concentrations than the two events identified on August 16th-17th and August 27th-29th, and smoke maps show less smoke influence in the NYC region (Figure S2). Thus, they were not included in further analysis.

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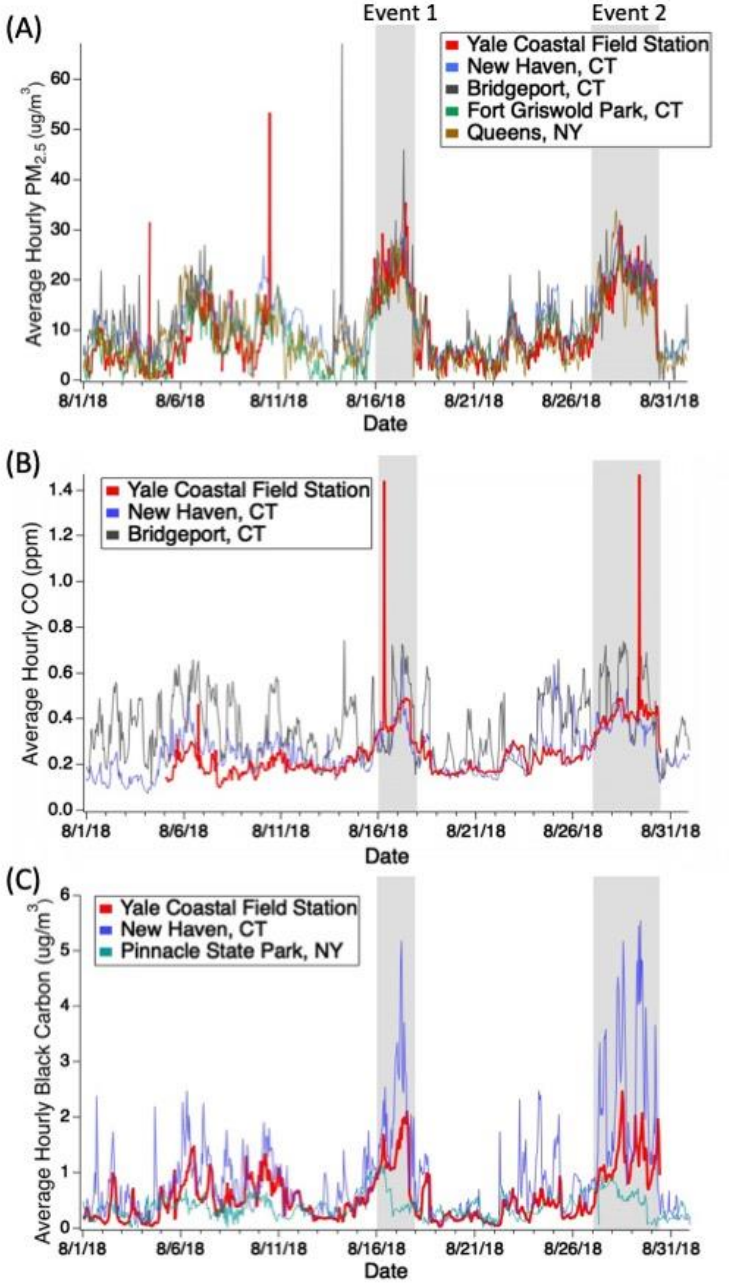

Figure 2: Concentrations of $PM_{2.5}$ (panel A), BC (panel B), and CO (panel C) measured at the YCFS over the month of August, 2018. Gray areas represent the two event periods identified as pollution spikes potentially caused by biomass burning smoke transport (August 16th-17th and August 27th-29th). These events all show simultaneous increases in $PM_{2.5}$, BC, and CO across all field sites, well above baseline concentrations. Meteorological dynamics at Pinnacle State Park, NY (200+ miles west) appear to be significantly different and lead to different absolute concentrations and earlier event dissipation compared to the other sites to the east.

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3.2 Satellite Imagery: NOAA Smoke Maps

NOAA Smoke Maps confirm the presence of smoke in the Long Island Sound area during the regional pollution events with simultaneous enhancements in surface-level concentrations of $PM_{2.5}$, BC, and CO (Figure 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 Figures 3-4 show vertically-integrated smoke density before, during, and after these events. Figure 3 shows the arrival of an aloft smoke plume with the total column smoke density peaking on August 16th and remaining until the 17th, consistent with the surface-level pollution event on the 16th and 17th (Figure 2). The sharp decrease in surface-level concentrations on the 18th is consistent with the departure of the plume in the satellite imagery (Figure 3E). During the second surface-level pollution event at the end of August, smoke was observed in the region, although less dense than in mid-August. Figure 4 shows a plume lingering over the NYC and CT region from August 27th-29th until the morning of the 30th, which is consistent with surface-level data. No smoke plumes are observed in the area on August 31st (Figure 4F), which is consistent with low surface-level concentrations (Figure 2).

While the satellite imagery lacks vertical distribution data, the presence of smoke in the region supports the hypothesis that smoke from aloft may have been transported to the surface and caused the increase in concentrations of $PM_{2.5}$, 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. August 14th-15th, and August 26th). On August 14th-15th leading up to the first event, there are lower levels of smoke aloft over the region that are visible in the satellite imagery (Figure 3A, 3B). On August 26th, leading up to the second event, there is again a low density of smoke over the region (Figure 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 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 vertical-resolved backward-trajectories at higher time resolution.

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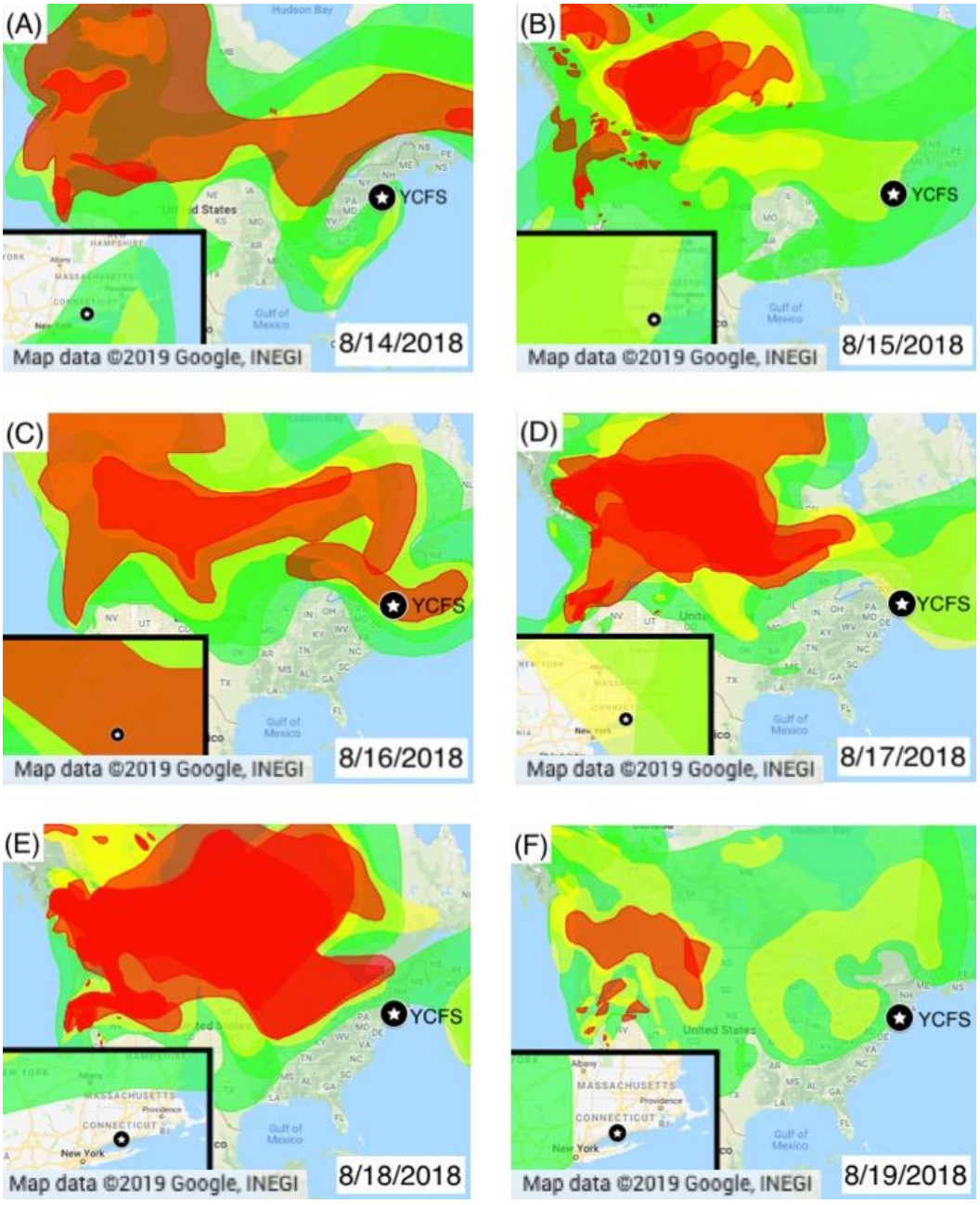

Figure 3. Smoke Maps (NOAA) based on satellite imagery for total column measurements compared to the YCFS (starred) for August 14th-19th, 2018: before (panels A-B), during (panels C-D), and after (panels E-F) the first surface-level pollution event. A new smoke plume begins to arrive aloft on the 15th before the surface-level pollution event on the 16th and 17th with the aloft total column smoke density peaking on the 16th. The decrease in panels E-F is consistent with the sharp decrease in surface-level concentrations on the 18th. 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.

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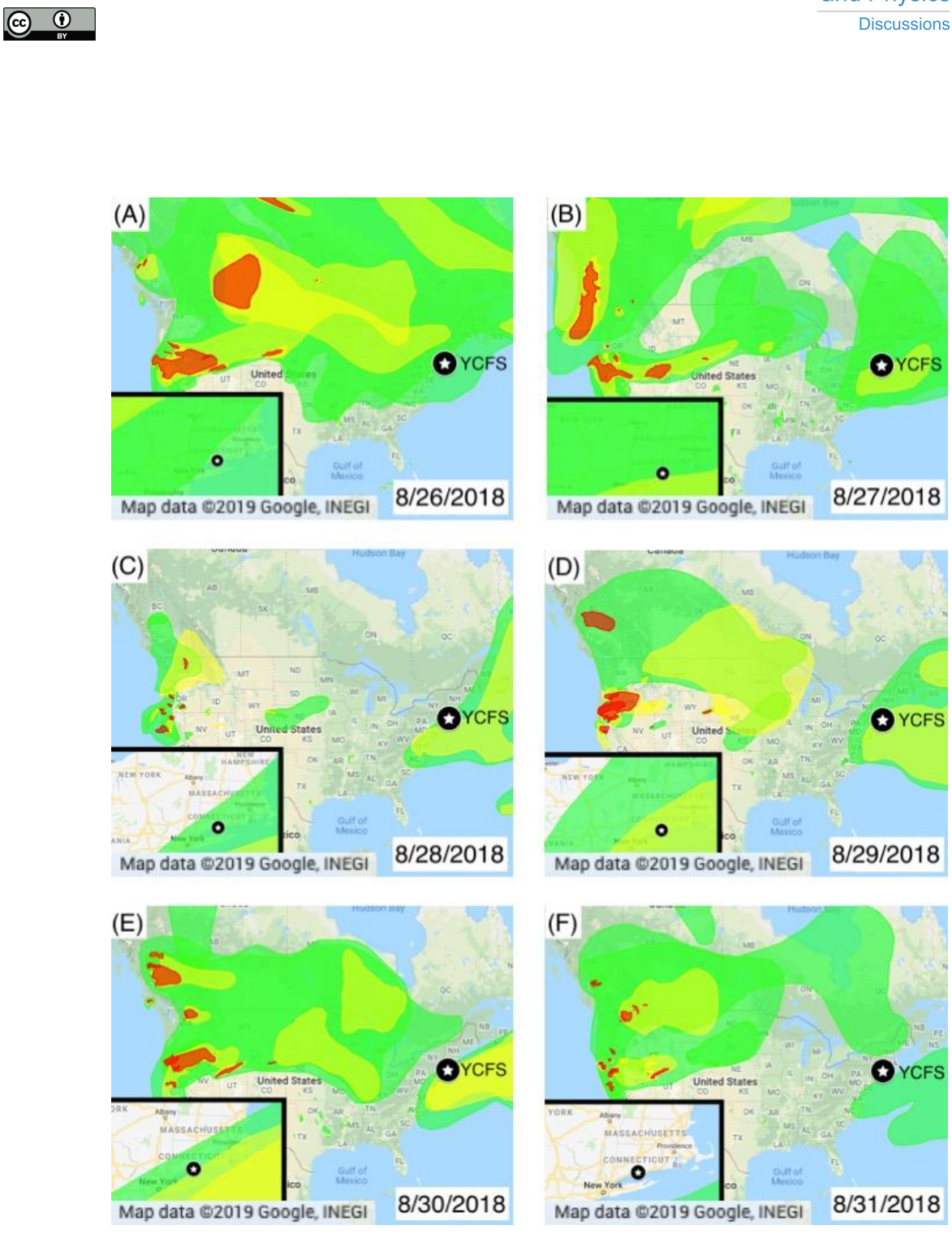

Figure 4: Smoke Maps (NOAA) based on satellite imagery for total column measurements compared to the YCFS (starred) for August 26th-31st, 2018: before (panel A), during (panels B-E), and after (panel F) the second surface-level pollution event. The satellite imagery shows a plume lingering over the region during the period of the surface-level event that spanned from August 27th -29th and continued into the morning of the 30th, 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.

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3.3 HYSPLIT Backward-Trajectory Model Results

Air parcels originating at 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 backward-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 (Figures 5-6).

The backward trajectories for air parcels arriving during the first event (August 16th-17th) show very similar paths passing over the central coast of western Canada (Figure 5), where NOAA's records of fire locations indicate the presence of wildfires in this region during the air parcels' transit. On August 16th, the air parcels' backward-trajectory through Canada and then the northern part of the United States demonstrates that the air parcels passed through an area with numerous active wildfires and descended from aloft to surface-level in the NYC region on August 16th. On August 17th, 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 North American West Coast within the prior ten days, but stayed in the eastern half of the United States and Canada in areas without reported fires (Figure 5B). This change in transport pathways corresponds with a sharp drop in concentrations of pollutants measured at the YCFS observed at the end of August 17th (Figure 2); as wind patterns shifted at the end of August 17th, cleaner air parcels that had not passed through wildfire regions were transported to the YCFS (Figure 5; greyed out), and thus concentrations of associated pollutants dropped. These trajectories re-affirm 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 2,000 meters of the surface (Figure 5B), emissions in forest fire plumes rise due to the heat of combustion and have been shown to commonly reach heights 2,000-7,000 m above ground level (Colarco et al., 2004; Labonne et al., 2007).

For the air pollution event occurring on August 27th, 28th, and 29th, backward-trajectory modeling shows the majority of air parcels originated around the Great Lakes region 10 days prior, then circulated in the southeastern U.S. before arriving to the YCFS. While a few trajectories originate on the West Coast, the majority do not pass through the region during the 10 day period. However, these air parcels pass over the southeastern U.S. near surface

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level (~1500 m and below) where active fires were reported just a few days prior to the observed pollution event in the metropolitan NYC region (Figure 6B). This demonstrates the potential role of biomass burning in the southeastern U.S. for air quality in the NYC region and northeast U.S. 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 August 27th (the start of the second event) show a similar southeastern circulation pattern as August 28th and 29th (Figure S3). The last 2 trajectories on the 29th do not encounter reported fires (Figure 6; greyed out), which is shortly before the dissipation in concentration at the surface site in the early morning on 8/30 (Figure 2).

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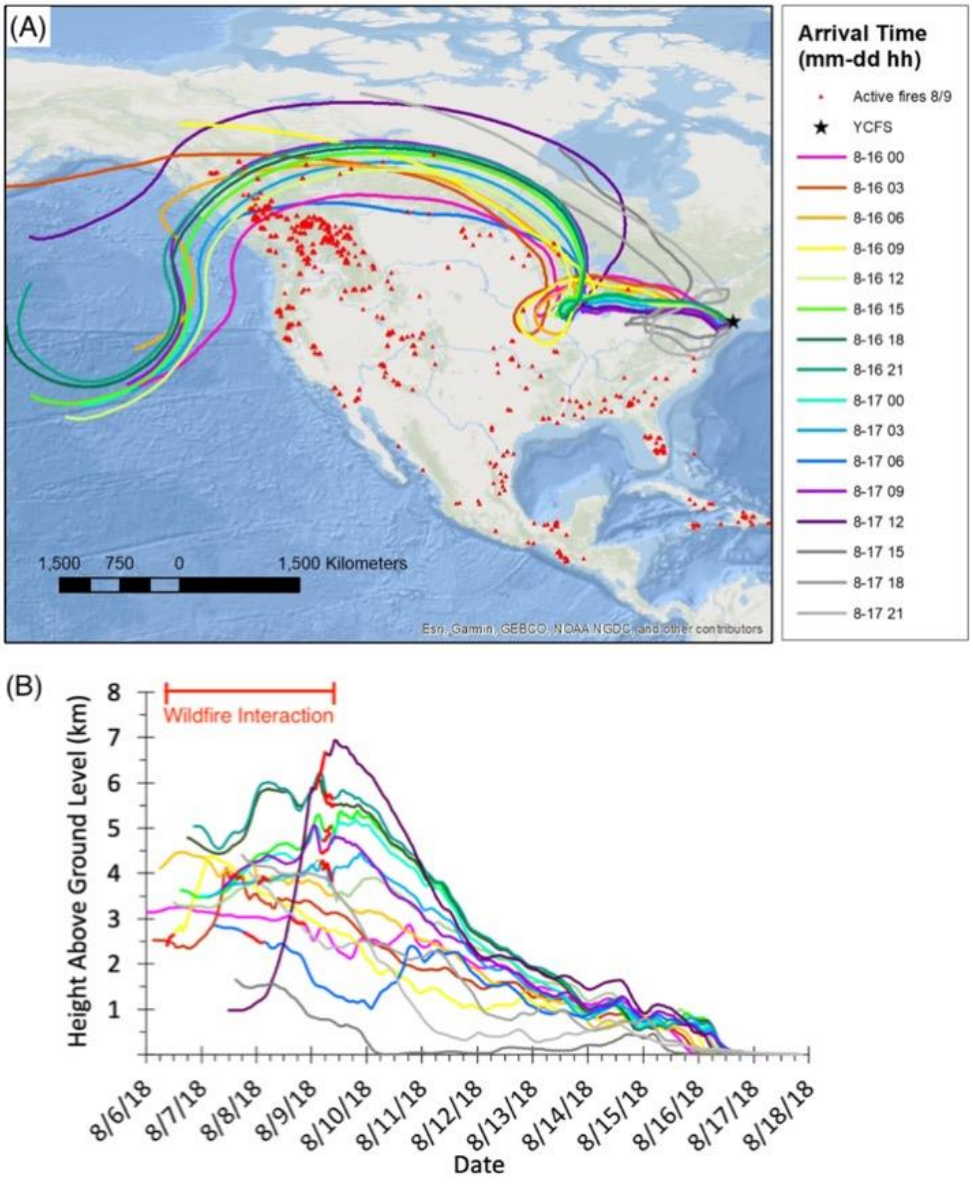

Figure 5: NOAA HYSPLIT Backward-trajectory model results for air parcels arriving on August 16th and 17th, 2018 to surface-level YCFS site. Each line represents the backward-trajectory for an air parcel arriving every three hours throughout the course of the day. The location of wildfires on August 9th (when most trajectories intersect the wildfire zone on the West Coast) is depicted with red triangles (from NOAA HMS fire maps). The top map (A) shows the full 10-day 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 8/17 have no major wildfire interaction, and have thus been colored grey.

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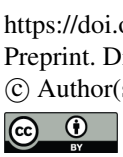

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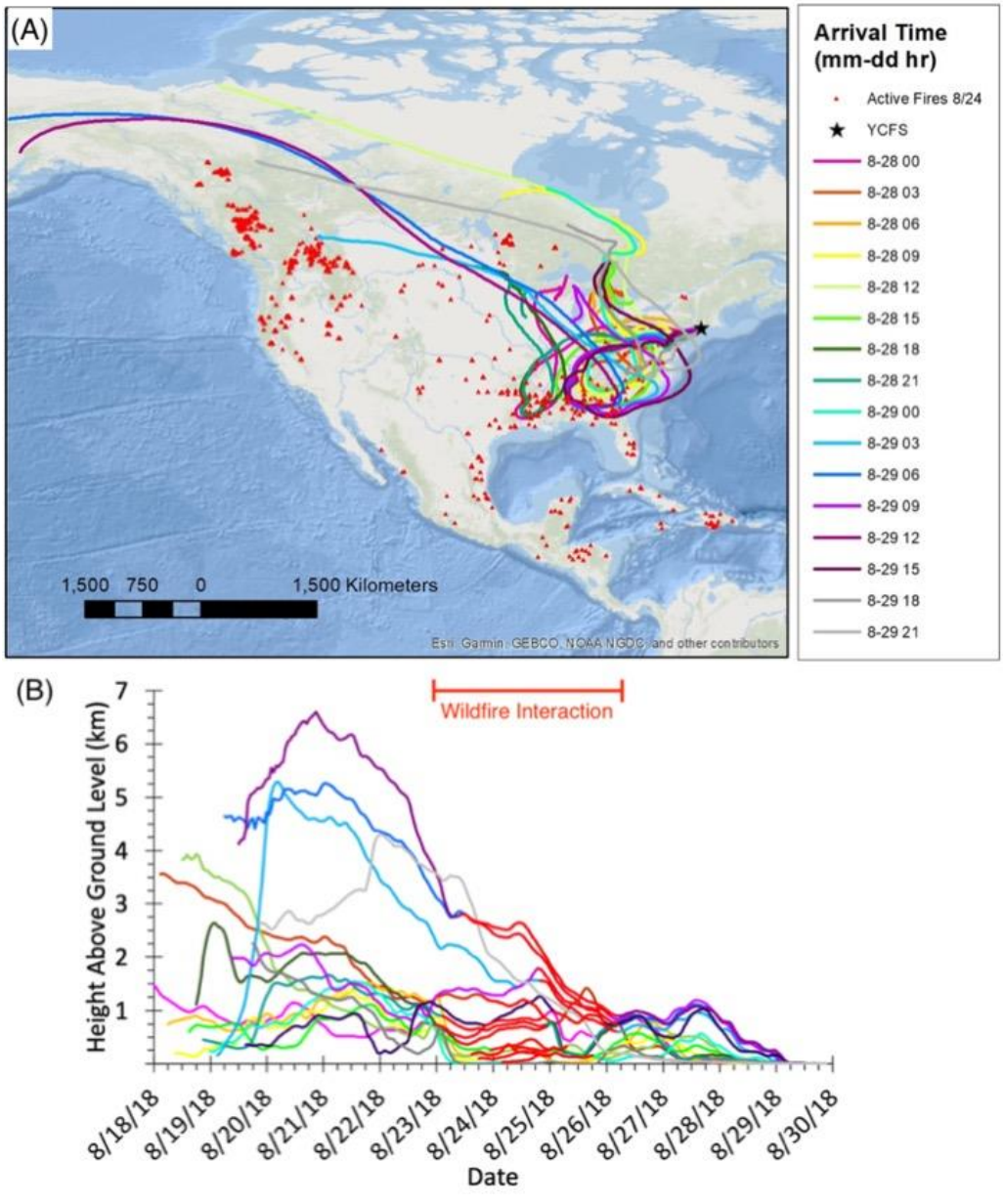

Figure 6: NOAA HYSPLIT Backward-trajectory model results for air parcels arriving on August 28th and 29th, 2018 to surface-level YCFS site. Each color represents the backward-trajectory for an air parcel arriving every three hours throughout the course of the day. The location of wildfires on August 24th (when most trajectories intersect the wildfire zone in the southeast U.S.) is depicted with red triangles (from NOAA HMS fire maps). The top map (A) shows the full 10-day 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 wildfire smoke plumes (highlighted in red on each individual trace). The last two trajectories on 8-29 have no major wildfire interaction, and have thus been colored grey.

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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 U.S. Together, surface-level measurements made at multiple regional sites, satellite smoke plume imagery, and air parcel backward-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 $PM_{2.5}$ and BC across the region. First, prolonged regional concentration enhancements in tracers associated with biomass burning–$PM_{2.5}$, BC, and CO–indicates the potential influence of biomass burning smoke on August 16th-17th and August 27th-29th. Second, NOAA Smoke Maps confirm the arrival and presence of smoke plumes in the Long Island Sound YCFS region on all five days of interest, and their absence after the events. Finally, backward-trajectory models provide additional information on the origin of air parcels and the associated pollutants. Air parcels from August 16th and 17th passed over western Canada, whereas air parcels arriving on August 28th and 29th passed over the southeastern U.S. 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 southeast U.S. 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, Connecticut, and the northeastern U.S.

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. For example, during the second pollution event, on August 29th, New York State issued an air quality health advisory for ozone for New York City Metro and Long Island (New York Department of Environmental Conservation, 2018). This long-distance transport process is also important since wildfire $PM_{2.5}$ has been specifically shown to have significant health effects with respiratory effects that possibly exceed those of other $PM_{2.5}$ sources, and multi-day wildfire smoke events have even been shown to have short-term health effects on susceptible populations (statistically-significant at >37 μg m^{-3}) (Liu et al., 2015; Liu et al., 2017). As climate change continues to impact the likelihood, prevalence, and intensity of wildfires across the U.S. and Canada, air quality scientists and policy makers must pay increasing attention to the influence that smoke has on air pollution issues, not only on a local scale but nationally and internationally. This is critical as increased emissions

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throughout a prolonged fire season, when coupled with common meteorological transport, can lead to enhanced background concentrations of primary $PM_{2.5}$ (including BC) and reactive precursors to SOA and ozone (Akagi et al., 2011; Urbanski et al., 2008).

Author Contributions

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

Competing Interests

The authors declare that they have no conflicts of interest.

Data availability

Data are available upon request to the corresponding author and are in their respective public repositories.

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