*We greatly appreciate the reviewers' thoughtful comments and recommendations that have allowed us to improve our manuscript. After carefully reviewing their feedback, we have incorporated the following changes to our manuscript and provide the following responses.*

<u>Response to Referees' comments:</u>

<u>Anonymous Referee #1:</u>

This paper presents evidence for impacts on surface-level air quality, specifically PM2.5, BC, and CO, in the Northeastern U.S. from long-distance transport of smoke from North American fires in August 2018. They collected hourly data of PM2.5, BC, and CO concentration at the Yale Coastal Field Station (YCFS). In addition, they used publicly available monitoring data at five other locations. NOAA's smoke maps based on satellite imagery were used to provide information on the horizontal distribution and density of the smoke plumes across North America and the sampling region. The satellite imagery generally suggested that during the two fire episodes, large areas in North America were affected by the smoke. Some inconsistencies between the satellite imagery and surface observation were explained as a result of unknown vertical distributions. In order to obtain insights on the origin of the surface air parcels, they further used NOAA HYSPLIT air parcel backward-trajectory models to provide additional information on the horizontally- and vertically-resolved transport pathways. They found that many of trajectories have intercepted locations with wildfire activities observed by satellite imagery. Air parcels in the first episode intercepted fire locations at 2-7 km above the ground level, whereas air parcels in the second episode were closer to the ground level which may also be affected by intentional crop fires in the southeastern U.S. They conclude that this work reinforces the growing need to understand the long-range influence of wildfires.

General Comments:
I believe this work is technically sound and publishable, but I am not convinced that ACP is the right venue. Since the observation data is limited to PM2.5, BC, and CO, I must say that the contribution of this work in terms of providing new data beyond what is already available from routine monitoring is limited. Since the majority of the observational data (5 out of 6 sites), Smoke Maps, and back-trajectories are based on publicly available information, I believe there must be substantial merit in data analysis to warrant publication on ACP.

*<u>Response:</u> We appreciate the reviewer's confidence in the quality of this work. In response to their concern, we affirm that the manuscript does generate new data and contains a new synthesis of data across multiple platforms, which makes the paper more robust than the presentation of any of the sites, model, or satellite data products independently. The conclusions reached in this study are a product of this combined analysis, and provide science- and policy-relevant information that advance the research community's and Atmospheric Chemistry and Physics' objectives. Here, we specifically highlight the new data and results in this paper:*

*This paper's results specifically leverage completely new data from a new field site that our research group set up on the Coast of Connecticut—the Yale Coastal Field Station (YCFS). The YCFS is located strategically to minimize local urban Connecticut influences while also being in the greater Metro New York City area, making it an ideal location for such a study; the results here leverage its role as a regional background site (this clarification was added at lines 102-104). The other ambient data discussed here come from 5 other field stations, and are presented alongside our research group's data to demonstrate regional significance of the wildfire transport events and also their impacts on air quality in the New York City area. Analysis with this data has not been published elsewhere (to our knowledge), and the use of non-public data is not a requirement for publication in Atmospheric Chemistry and Physics. Additionally, our downwind measurements of black carbon represent a valuable contribution to the field; black carbon is not routinely monitored at many sites, as evidenced by the lack of any non-urban measurements in the greater NYC area. Without black carbon measurements, the role of forest fires in this combined dataset would be hard to assess.*

*The NOAA HYSPLIT model is publicly available, but we performed new model runs for the purposes of this manuscript. Similar to other studies (e.g. Cottle et al., 2014 in Atmospheric Environment; Diapouli et al., 2014 in Atmospheric Environment), we use the existing HYSPLIT model but generate new runs tailored to the conditions of interest in our study. Furthermore, the HYPSLIT model is used in a wide-ranging number of publications in the field.*

*Similarly, the NOAA Smoke Maps used here are publicly available, but we show them in our manuscript as a complimentary data source that is independent of the other methods used. Previous studies have also relied upon smoke maps, such as Shrestha et al. (2019)'s paper "Impact of Outdoor Air Pollution on Indoor Air Quality in Low-Income Homes during Wildfire Seasons" (Int. J. Environ. Res. Public Health), to identify event and non-event days.*

Comment: However, it is not clear to me how observation of two events based on PM2.5, BC, and CO that may have originated from smoke plumes in the U.S. benefits the research community.

<u>Response:</u> *The urban air quality research community is working at a time when urban air quality is rapidly evolving with decreases in emissions from traditional (typically anthropogenic combustion-related) sources. This is increasing the relative impact of other sources that have either been under-regulated or are un-controllable (e.g. Khare & Gentner, 2018 ACP, Figure 2), for example, biomass burning. Cities like New York have also made extensive progress on reducing local emissions of $PM_{2.5}$ and other pollutants (a great example can be seen in the New York City Community Air Quality Survey (NYCCAS), 2018). Thus the role of uncontrolled biomass burning emissions and their transport to urban areas like NYC is likely to become a larger fraction of $PM_{2.5}$ contributions, which will be further exacerbated by increases in the frequency and magnitude of forest fires. For example, Figure 2 in our manuscript already shows major increases in $PM_{2.5}$ above the baseline concentrations (~5 ug/m$_3$; consistent with NYCCAS 2016 average range) during the biomass burning transport events (~20 ug/m$_3$).*

*So, this manuscript benefits the research community by documenting the effects of cross-continental smoke transport on the New York City Metropolitan area. To our knowledge, no such study has been performed for the NYC metropolitan area, which is a megacity with a population of over 20 million. The findings are valuable for regional, national, as well as international air quality planning, forecasting, and management. In addition, understanding the impact of wildfire smoke on the NYC metropolitan area will be critical for assessing human exposure to potentially hazardous components of wildfire smoke. These two events can serve as demonstrative examples to the research community that the long-distance transport of smoke from biomass burning has had an impact on the NYC metropolitan area. As wildfires become more frequent, it is valuable to have documented their consequences at national scales beyond the more-common regional scope, to foster future research and planning. To address the reviewer's question, we have added a sentence in the Conclusion section to further emphasize this point (Lines 345-349).*

Comment: Since the Smoke Maps showed nearly the entire U.S. was covered by smoke, it does not seem surprising that back-trajectories intercept with smoke plumes somewhere.

*Response:* *We acknowledge that in some (not all) of the smoke maps do show wildfire plumes aloft over several parts of the U.S., especially the Northern U.S., but the maps do reveal helpful spatial and temporal patterns in smoke coverage that supplement the other data and substantiate the conclusions. It was our intent for the smoke maps to provide different information and interpretation separate from the backward-trajectories. The smoke maps were used to demonstrate that smoke plumes were observed in the immediate vicinity of the YCFS and other nearby sites on the specific days when high concentrations of biomass burning-related tracer species were observed in metro NYC. The presence of a smoke plume above the YCFS confirmed that it was therefore possible that smoke had also had been transported to the surface. In this sense, the degree of smoke plume coverage across other locations in the US was not a determining factor in our assessment of whether or not the smoke maps confirmed the presence of smoke in the NYC metro area.*

*In contrast, the backward-trajectories were mapped in combination with the documented location of the fires before the observed increase in surface-level concentrations of $PM_{2.5}$, BC, and CO at the YCFS. This approach was specifically used since some of the smoke maps indicate multiple, wide-ranging plumes in the U.S., and the smoke maps did not provide any information on the vertical component of the smoke plumes. By illustrating that the backward-trajectories passed over the locations of the wildfires themselves, at altitudes where it was reasonable to expect the concentrated smoke plumes to rise to, we demonstrate that these air parcels could have feasibly picked up the concentrated pollutants associated with biomass burning.*

*To address the reviewer's concerns, a paragraph has been added (Lines 265-274) to clarify the difference in presentation and interpretation of the smoke maps and backward-trajectories. In addition, and in response to both this comment and the recommendation to analyze non-event days in addition to event-days (addressed below), we have added four examples of non-event* *days to the SI section (noted in main text Line 274). These examples show that on a day with low surface-level concentrations of $PM_{2.5}$, BC, and CO (e.g. August 4th, 5th, and 21st), smoke maps do not show a plume above the NYC metropolitan region, nor do backward-trajectories have significant interaction with areas where active fires are burning. Also, we have clarified the language at lines 198-200 regarding the presence of aloft smoke plumes that could mix with the surface layer.*

Comment: I believe the manuscript should substantially expand on data analysis and demonstrate novelty to be considered for publication on ACP or should be published elsewhere.

*<u>Response:</u> We appreciate the referee's previous comments and suggestions, and refer to our longer response above related to novelty, justification, and merits of publication. In summary, our manuscript presents new data and a new multi-platform synthesis of 6 different ground sites, satellite observations, and pollutant transport modeling in order to conclude that emissions from biomass burning in 2 different North American regions were transported to metro NYC where they had a significant impact on regional $PM_{2.5}$ concentrations. These results were more conclusive due to the multi-platform approach discussed here and due to the incorporation of data from a new strategically positioned field site—the YCFS. This study has scientific merit and policy implications for air quality research, management, and planning in metro NYC (a non-attainment area). These findings will also be relevant to many other similar metropolitan areas, especially considering the increased propensity for wildfires with changing climate. Our manuscript shows the potential impact of forest fires, not just in the regions of the fires, but also in major urban areas on the other side of the continent. Based on all the reviewers' comments, we have made modifications and additions to improve the manuscript, including analysis of non-event days, clarification on our current analyses, and discussion of results.*

Specific comments:
Comment: It may be useful to contrast "Event" and "Non-event". If the same analysis is performed on cleaner days between Event 1 and Event 2, do backward-trajectories pass through any wildfire locations?

*<u>Response:</u> Thank you for this valuable addition to our analysis. We have added a section in the SI to show parallel analysis for four examples of non-event days (Section S4). On August 4th, 5th, 13th, and 21st, surface level concentrations measured at the YCFS and other regional stations are lower than during the event days. In addition, NOAA Smoke Maps show no visible smoke clouds above the YCFS on August 4th, 5th, and 21st, and backward-trajectories have minimal interaction with active fires areas. August 13th shows some aloft plumes, but rain as well as over-water transport of air parcel back-trajectories before arriving at the YCFS would have reduced any potential surface-level contributions. While this analysis was not conducted for every single non-event day in the month of August, this provides several examples of non-event days in which the patterns observed in NOAA Smoke Maps and backward-trajectory models differ significantly from the patterns observed on event days.*

*We believe this additional analysis further strengthens the interpretation that during the two event days all three sources of data (field measurements, NOAA Smoke Maps, HYSPLIT backward trajectories) confirm a potential link to long-distance transport of smoke from biomass burning, which does not occur on days when surface-level concentrations are low.*

Comment: Typo - Line 83. Right parenthesis missing.

*Response: We have added the missing parenthesis.*

*Anonymous Referee #2:*

General Comment: The paper describes lines of evidence leading the authors to conclude that two pollution events experienced in the New York City Metro area and along coastal Connecticut during August 2018 were in large part attributable to emissions from biomass burning events. The paper is well written and nicely presented. There is nothing ground-breaking in the results, but it is a solid paper and deserves to be published largely as is.

*Response: We thank the reviewer for their support of our paper, and have addressed their specific comments below.*

Comment: The authors are *mostly* good about being precise in their wording so as not to mislead the reader about what was actually observed. As someone who is sensitive to this I did find a few places where more precise wording is warranted. I have noted these instances as "Technical Corrections".

*Response:*
*We appreciate the technical recommendations for precise wording, which have been addressed in the technical corrections section, below.*

Comment: Lines 38-44: Missing in the introduction is any mention or discussion of aging and chemical transformations that occur in biomass burning plumes. For the present study the authors rely on "persistent" tracers that remain somewhat (or mostly) intact over the multiple days it takes to reach their measurement site. I'm not suggesting a detailed discussion here, but some acknowledgement of the process and how it might affect the study is needed. Maybe just a couple of sentences or a short paragraph?

*Response: Thank you for this recommendation. We have added some discussion (lines 47-59) to acknowledge that aging and chemical transformation does occur in the smoke released from biomass burning. However, $PM_{2.5}$, BC, and CO were selected because they have a relatively long atmospheric residence time compared to than other tracers. Although they become diluted during the long-distance transport, they are much less reactive than other chemicals released during biomass burning.*

Comment: Line 114: The very high CO spikes at the YCFS on 8/16 and 8/29 deserve some attention. It seems likely to me that these spikes are caused by "hyper-local" sources, and they are more than a factor of three greater than the high smoke influenced values and a factor of two higher than anything seen in Bridgeport (and Queens). Maybe a delivery truck idling near the inlet? Or a "dirty" ship sending a plume over the site? I suggest the authors look more carefully at their data to make sure these spikes are not caused by a local contamination source.

*Response: Thank you for the comment. We did not intend to infer that these spikes were related to the long-distance transport of smoke. We agree with the referee's interpretation that the extreme spikes that occurred at the YCFS on 8/16 and 8/29 are likely caused by a hyper-local source. We have added a sentence to the figure caption addressing these points as outliers and the potential that they were caused by a local source (lines 175, 181-183). However, the agreement in the baseline CO concentrations with the other sites reinforces the background CO concentrations, which is the primary purpose of the CO figure. Thus these 2 outlier spikes do not affect the broader interpretations of the data and resulting conclusions in the paper.*

Comment: Lines 130-133: The authors should be aware (and potentially indicate in the paper) that August 5, 6, 7, 10, 16, 28, and 29 were all identified as "Air Quality Health Alert" days in New York State. In each case ozone was predicted to be the pollutant of greatest concern, but since high ozone and high PM2.5 often occur simultaneously, it is not surprising to have high PM levels on August 6, 7, and 10.

*Response: We thank the referee for bringing these other dates to our attention. We have added a sentence at the end of the paragraph (lines 163-165) acknowledging that these days were health advisory days. We fully agree that elevated $PM_{2.5}$ often occurs with ozone due to the secondary production of aerosols. Because we have BC measurements to accompany the $PM_{2.5}$ data, we are confident to ascribe "Events 1 and 2" (labeled in Figure 2) to biomass burning transport.*

Comment: Line 250: Following up on this, the authors only mention that 8/29 was an air quality health alert day. The 16th and 28th (also study days) were also AQHA days for the NYC metro area or nearby communities.

*Response: We have modified this sentence to include reference to all three advisory days which occurred during the two identified events (lines 325-326). Thank you for providing this additional information.*

Comment: Line 269: The data availability sentence seems a little terse. At least identify the public repositories.

*Response: We have added the names of the public repositories to modify the tone of this sentence.*

Technical Corrections:
*Response: We appreciate the referee's careful review of the manuscript's language and technical suggestions. Our responses grouped together were appropriate.*

Comment: Line 16: Insert “at surface-level sites” between “in” and “arriving”.

*Response: The wording has been modified.*

Comment: Line 74: While the AE33 and 48i can be configured to provide 1 second data, I don't think that is the case for the BAM 1020. It is typically configured to provide only 1 hour averaged data.

*Response: This sentence has been modified to reflect the correct time interval of the BAM 1020 (lines 91-92).*

Typographical Comments:
Line 134: The identification of panels A and B are reversed.
Line 141: Change “in” to “over”.
Line 146: Add “at YCFS” between “peaking” and “on”.
Line 155: Suggest rewording this to read, “that smoke from aloft was available for transport to the surface, followed by the increases in . . .”.
Lines 167 and 173: The words “compared to YCFS (starred)” are out of place in the first sentence. I suggest taking them out of this sentence, and adding a second sentence that simply reads, “The YCFS is indicated by a star.”
Line 239: Change “in” to “over”.

*Response: Thank you. All of the above technical language issues have been corrected.*

# 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 16$^{th}$-17$^{th}$ and 27$^{th}$-29$^{th}$, 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 at surface-level sites in coastal Connecticut on August 16$^{th}$-17$^{th}$ passed over the west coast of Canada, near multiple large wildfires. In contrast, air parcels arriving on August 27$^{th}$-29$^{th}$ 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 (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 U.S.

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

## 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 $\leq 2.5$ 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). 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 aloft plumes 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 $PM_{2.5}$ losses due to physical processes will follow similar timescales. Losses of these tracers is 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 $PM_{2.5}$ 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 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 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, both of which coincided with NYC air quality advisory period for ozone on August 16$^{th}$, 28$^{th}$, and 29$^{th}$ (New York Department of Environmental Conservation, 2018).

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## 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 1 hour resolution for $PM_{2.5}$, 1 minute for BC, and 1 second for CO (BC and CO then 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 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. 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.

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**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.**

These YCFS 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 State Park, NY. Sites were selected for regional proximity to the YCFS as well as data availability.

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### 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

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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 studied in past work that utilized 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 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.

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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

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Two main events in August (August 16$^{th}$-17$^{th}$ and 27$^{th}$-29$^{th}$) 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 from the New Haven site are in good agreement with the YCFS site up the coast. The Pinnacle Park site, 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 (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 is generally 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 satellite smoke maps show minimal smoke influence in the NYC region, with the exception of August 6th (Figure S2). Thus, they were not included in the primary analysis. However, it should be noted that August 5th, 6th, 7th, and 10th were all days where New York State issued an Air Quality Health Alert, primarily for high ozone (New York Department of Environmental Conservation, 2018).

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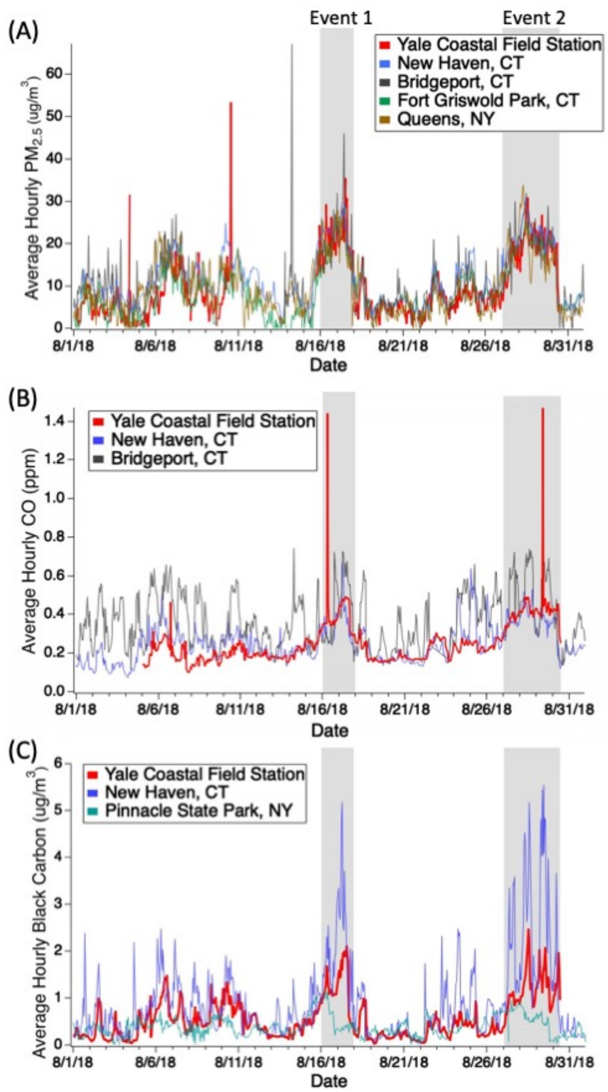


**Figure 2: Concentrations of $PM_{2.5}$ (panel A), CO (panel B), and BC (panel C) measured at the YCFS over the month of August, 2018. Grey areas represent the two event periods identified as pollution spikes potentially caused by biomass burning smoke transport (August 16th-17th and August 27th-29th). 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 State Park, NY (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 (panel B) are not**

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**ascribed to long-distance transport and are likely due to a hyper-local source near the site (e.g. vehicle, 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).**

**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 $PM_{2.5}$, 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 at YCFS on August 16$^{th}$ and remaining until the 17$^{th}$, consistent with the surface-level pollution event on the 16$^{th}$ and 17$^{th}$ (Figure 2). The sharp decrease in surface-level concentrations on the 18$^{th}$ 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 27$^{th}$-29$^{th}$ until the morning of the 30th, which is consistent with surface-level data. No smoke plumes are observed in the area on August 31$^{st}$ (Figure 4F), which is consistent with low surface-level concentrations (Figure 2).

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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 $PM_{2.5}$, 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 14$^{th}$-15$^{th}$, and August 26$^{th}$). On August 14$^{th}$-15$^{th}$ 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 26$^{th}$, 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

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the YCFS and others in the region, which is further explored using vertical-resolved backward-trajectories at higher time resolution.

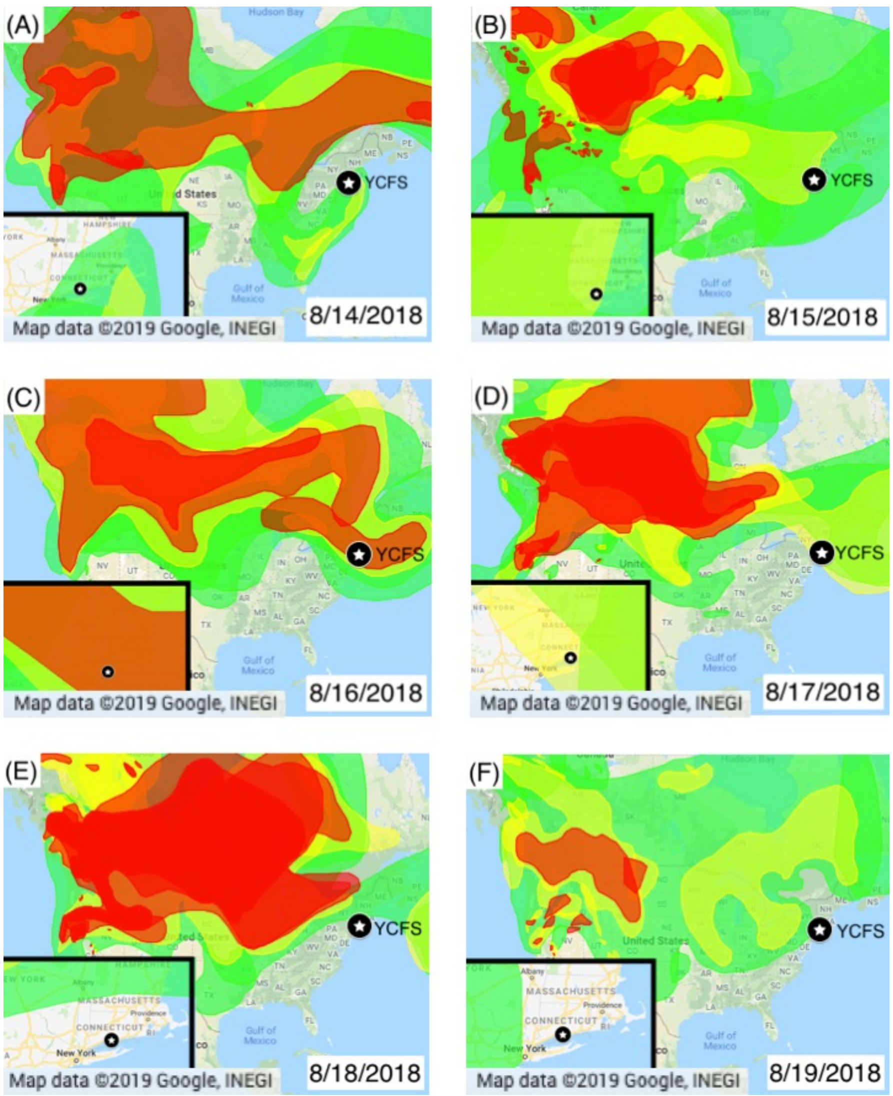


**Figure 3. Smoke Maps (NOAA) based on satellite imagery for total column measurements for August $14^{th}$-$19^{th}$, 2018: before (panels A-B), during (panels C-D), and after (panels E-F) the first surface-level pollution event.** The YCFS is indicated by

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a star. 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.

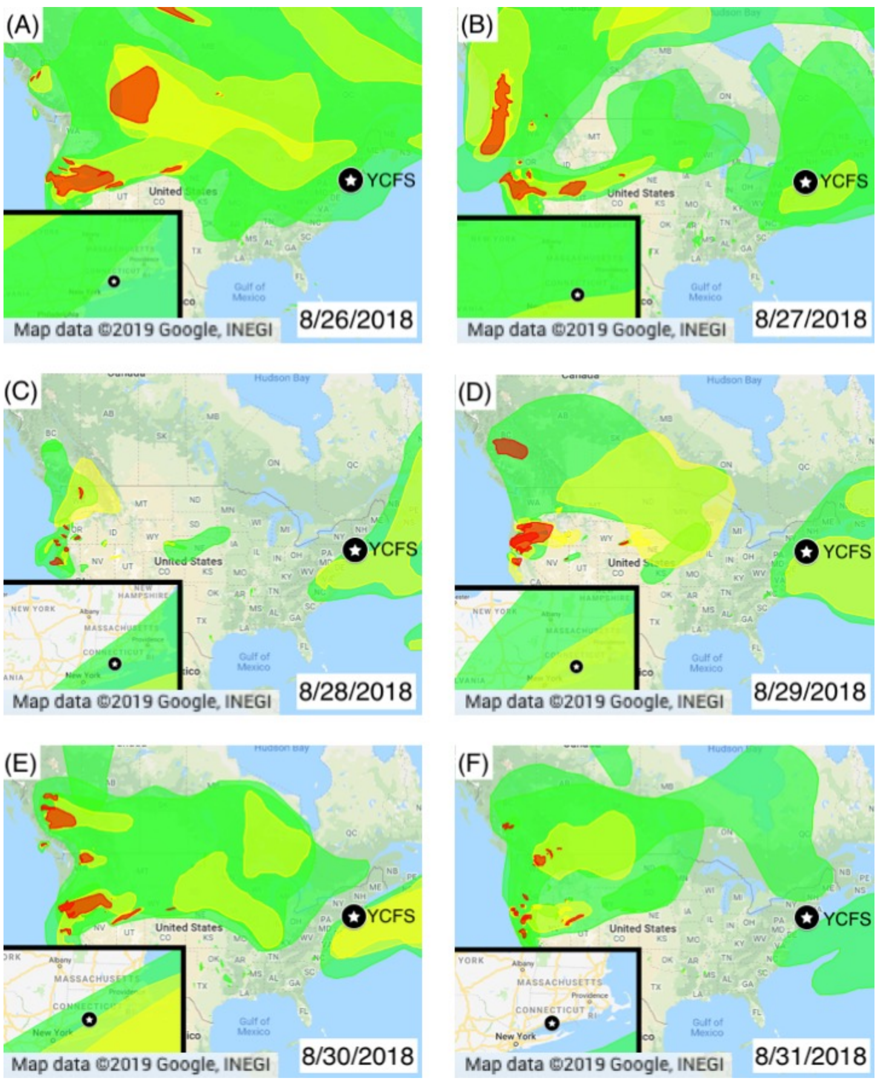


**Figure 4: Smoke Maps (NOAA) based on satellite imagery for total column measurements for August 26th-31st, 2018: before (panel A), during (panels B-E), and after (panel F) the second surface-level pollution event. The YCFS is indicated by a**

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**star. 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.**

### 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 $27^{th}$, $28^{th}$, and $29^{th}$, 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 level (~1500 m and below) where active fires were reported 4-5 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 $27^{th}$ (the start of the second event) show a similar southeastern circulation pattern as August $28^{th}$ and $29^{th}$ (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).

While satellite smoke maps (Figures 3-4) show the spatial distribution of (vertically-integrated) smoke across the U.S. during these 2 events, backward trajectories provide more specific evidence that the air parcels observed at the ground-level YFCS site previously passed over active fires and mixed with biomass burning emissions (e.g. BC, 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 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 Figures 3-4, S4-S7).

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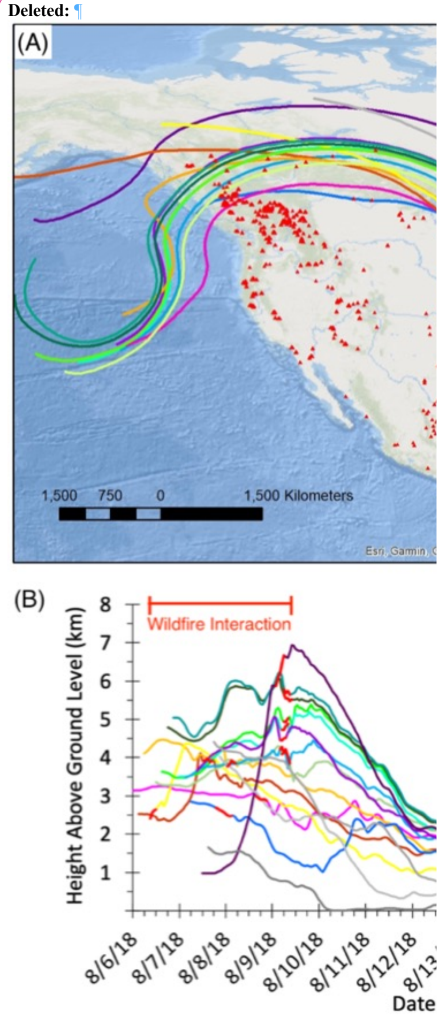

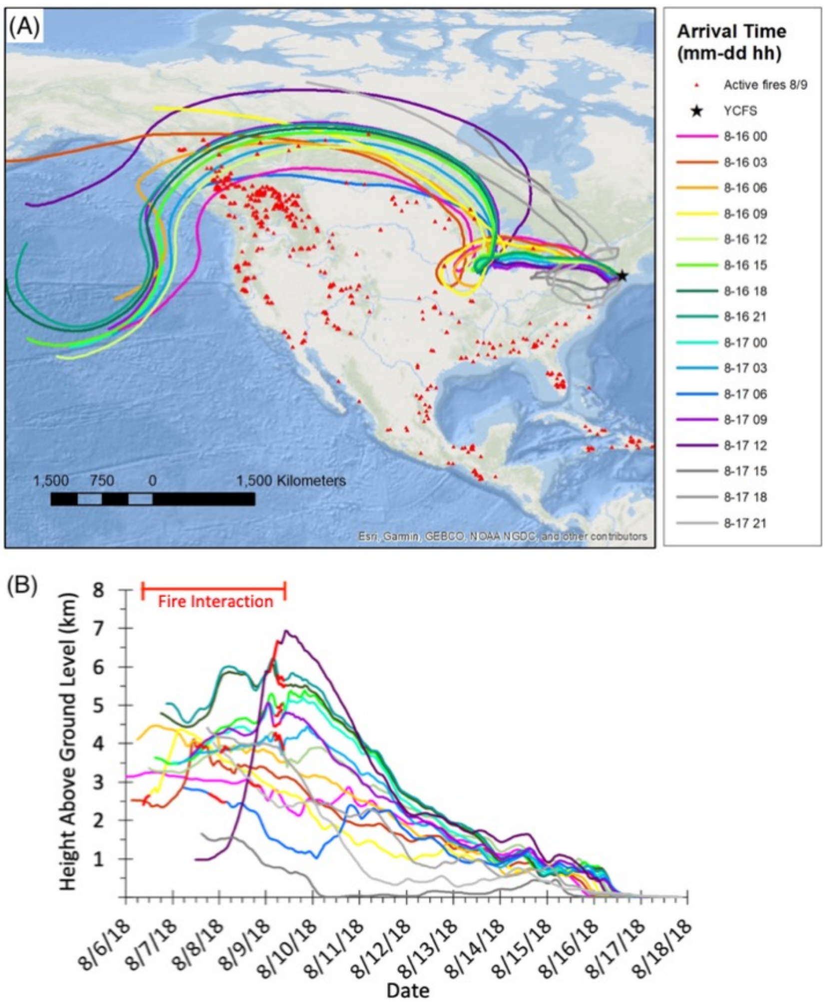


**Figure 5: NOAA HYSPLIT Backward-trajectory model results for air parcels arriving on August 16th and 17th, 2018 to surface-level YCFS site. Each line represents the backward-trajectory for an air parcel arriving every three hours throughout the course of the day. The location of fires on August 9th (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**

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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 fire interaction, and have thus been colored grey.

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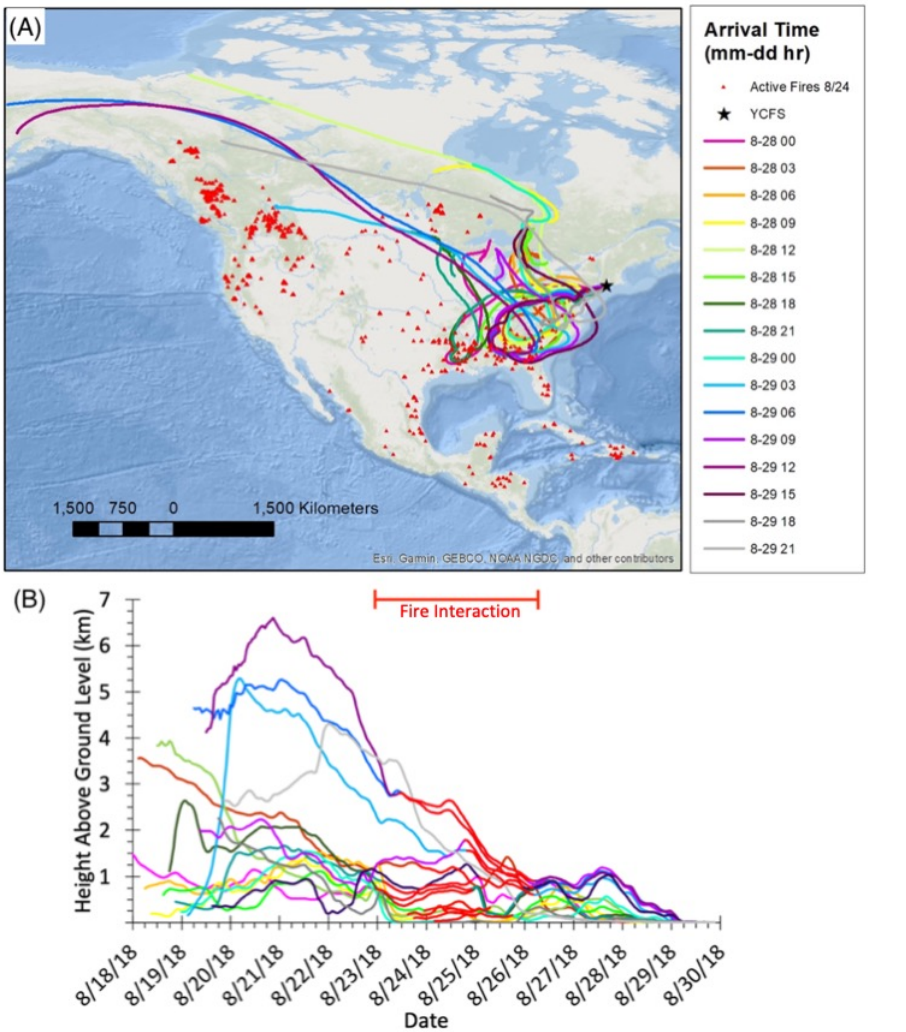


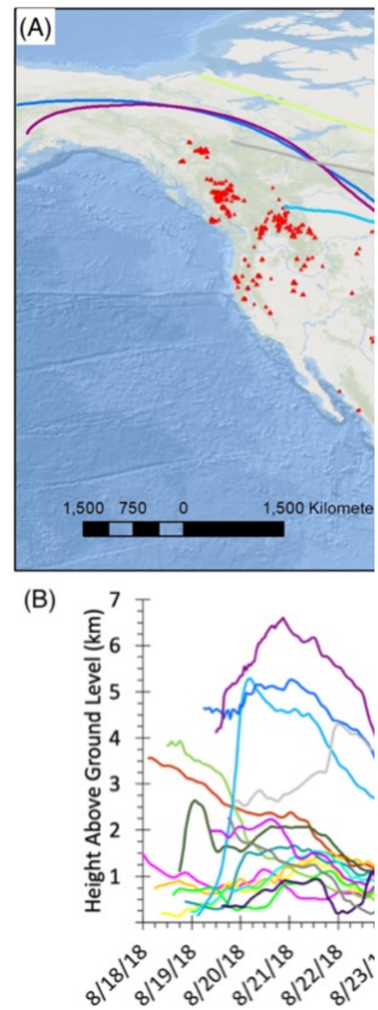

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Figure 6: NOAA HYSPLIT Backward-trajectory model results for air parcels arriving on August 28th and 29th, 2018 to surface-level YCFS site. Each color represents the backward-trajectory for an air parcel arriving every three hours throughout the course of the day. The location of fires on August 24th (when most trajectories intersect the fire 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

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**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.**

## 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 16$^{th}$-17$^{th}$ and August 27$^{th}$-29$^{th}$. Second, NOAA Smoke Maps confirm the arrival and presence of smoke plumes over 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 16$^{th}$ and 17$^{th}$ passed over western Canada, whereas air parcels arriving on August 28$^{th}$ and 29$^{th}$ 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, in Connecticut, and more broadly, in 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 in smoke-impacted areas. During both observed events (Figure 2), New York State issued air quality health advisories in New York City Metro and Long Island specifically for ozone (on August 16$^{th}$, 28$^{th}$, and 29$^{th}$) (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 $PM_{2.5}$ has been specifically shown to have significant health effects with respiratory

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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 effects at concentrations >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 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 $PM_{2.5}$ (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 & Gentner, 2018; NYC Dept. Health, 2018) and wildfires become increasingly frequent.

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## Author Contributions

H.M.R., J.C.D., and D.R.G. designed the study and led analysis. J.C.D. managed instruments and collected data at the YCFS. H.M.R. analysed data and compiled modeling results and satellite imagery. H.M.R. and D.R.G. wrote the paper and all authors contributed to refining the manuscript.

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## 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 (LISTOS archive [https://www-air.larc.nasa.gov/missions/listos/index.html], EPA Air Quality System [https://www.epa.gov/aqs], and NOAA Hazard Mapping System Fire and Smoke Products [https://www.ospo.noaa.gov/Products/land/hms.html]).

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# Supplemental Information for:

# 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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**S1 Elevated CO at the Yale Coastal Field Station and Data From Additional Urban Sites**

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CO data from the urban site located in Queens, NY were also compared to measurements made at the other less urban sites (YCFS, New Haven, Bridgeport, Figure S1). Despite the additional urban sources of CO present at the Queens site, a multi-day peak during the two event periods is consistent across all sites (Figure S1).

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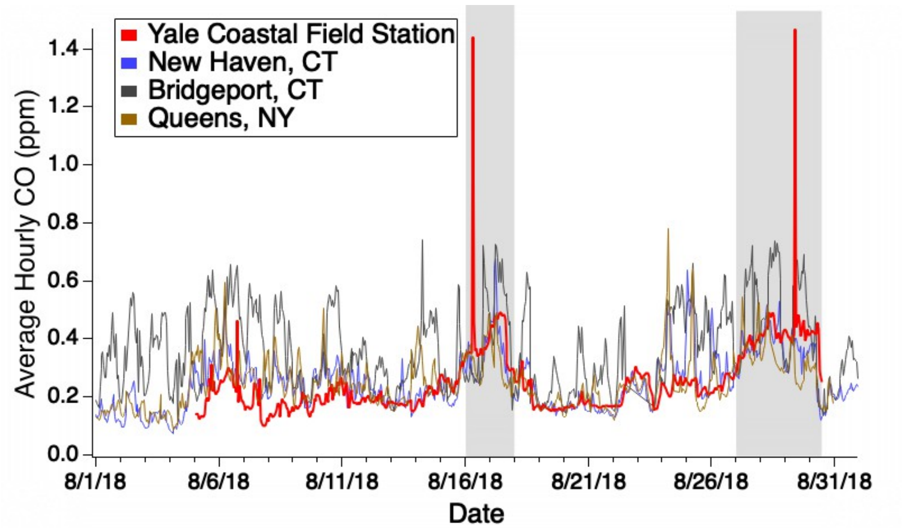


**Figure S1: Average hourly surface-level CO. Data from the Queens, NY urban monitoring site have been included. While there are additional urban sources at the Queens site, the trend in increasing CO during the two event periods remains the same. Grey shading indicates the identified event periods.**

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**S2 Satellite Imagery on Non-Event Days**

Surface-level concentrations of $PM_{2.5}$, BC, and CO indicated possible biomass burning pollution events on August 6-7 and August 10, as evident by the periods of slight pollutant enhancement in Figure 2 on these days. NOAA Smoke Maps show minimal smoke plume influence in the NYC Metro area, therefore these two periods in early August were not examined further (Figure S2).

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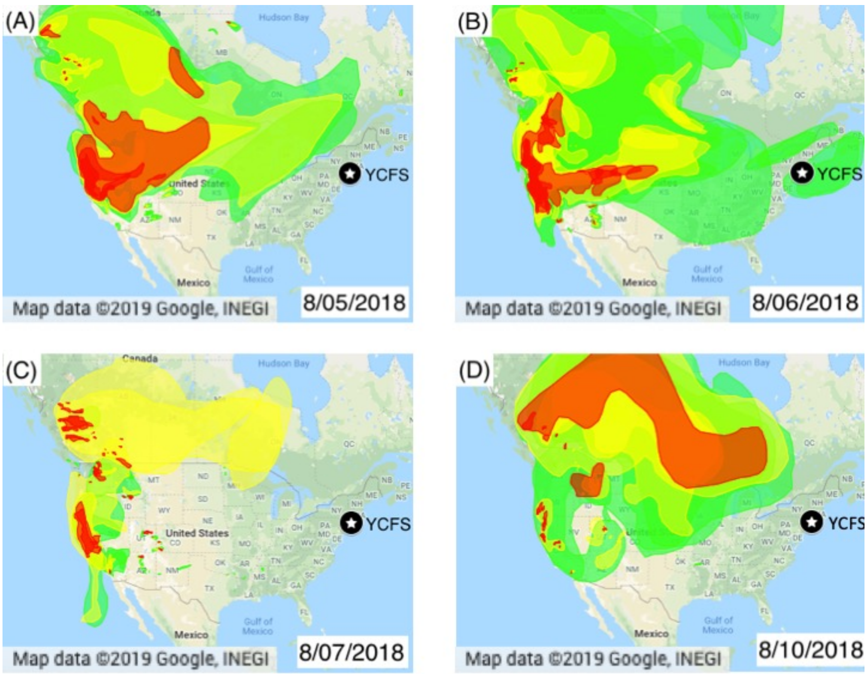


**Figure S2: Smoke Maps (NOAA) based on satellite imagery for total column measurements for August 5-7 (panels A-C) and August 10 (panel D) during relatively smaller increases in $PM_{2.5}$, BC, and CO. The YCFS is marked by the black star. Colors indicate the density of the smoke cloud, with red being the most dense smoke, yellow being intermediate, and green being the least dense. This figure is provided as a supplement to Figures 2-4.**

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**S3 Additional Backward-Trajectory Model Results**

The second identified pollution event occurred on August 27-29, based on surface level data. Backward-trajectories for August 27 (Figure S3) show similar travel paths to those on August 28 and 29 (Figure 6), with circulation in the southeastern US over areas of biomass burning. The earliest trajectories on August 27 pass through central and Northern Canada without major interaction with active fires. However, starting around 6:00 am backward-trajectories begin to circulate in the southeastern United States where they pass over areas of biomass burning. This change in backward-trajectory path on the morning of the 27th aligns with the increase in surface level concentrations on the morning of the 27th.

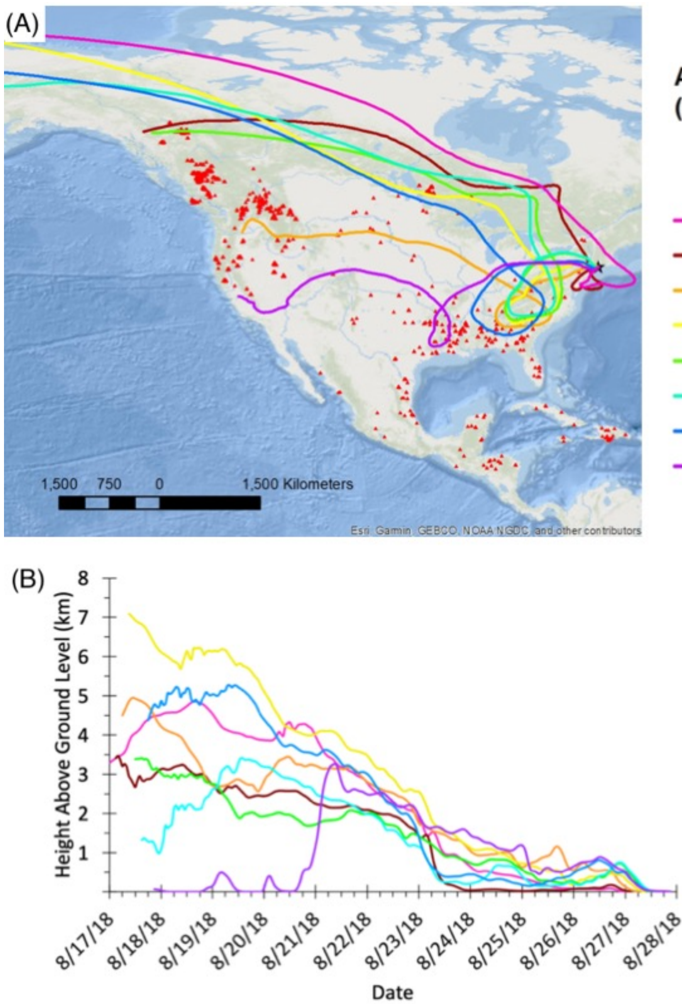


**Figure S3: NOAA HYSPLIT Backward-trajectory model results for air parcels arriving on August 27, 2018 to surface-level YCFS site. Each color represents the backward-trajectory for an air parcel arriving every three hours throughout the course of the day. The location of fires on August 24 (when most trajectories intersect the fire zone in the southeast) 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. Backward-trajectory patters shift to circulation in the south east at approximately the same time as surface level concentrations of biomass burning markers increase (Figure 2).**

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**S4 Example Non-Event Days**

To contrast the patterns observed on the identified event days with those of non-event days, the same analysis across platforms (Smoke Maps, backward-trajectory modelling) was performed for a subset of non-event days. August 4th, 5th, 13th, and 21st were selected as non-event days because low concentrations of biomass burning tracers were observed at the YCFS, and these dates were outside the two identified event periods. On August 4th, 5th, and 21st, NOAA Smoke Maps showed no smoke in the Long Island Sound region and backward trajectories had minimal interaction with fires despite considerable fire activity in several areas of the U.S. (Figure S4-S7). This supports our other comparisons showing that high surface-level concentrations at the YCFS during the transport events are coincident with Smoke Maps showing smoke aloft over the NYC metropolitan region and backward trajectories passing through areas of biomass burning. This is different from these results showing that on non-event days there are no nearby smoke plumes in the satellite data outputs and backward-trajectories travel through air that has not been exposed to major biomass burning events. In the case of August 13th, which shows some smoke aloft and has a few backward trajectories that could have encountered fires, regional rain in the late morning to afternoon and 1-2 days of transport at the water's surface in the marine boundary layer before arriving at the YCFS would have reduced any potential biomass burning-related particle concentrations via deposition, leading to the cleaner conditions observed at the surface-level sites.

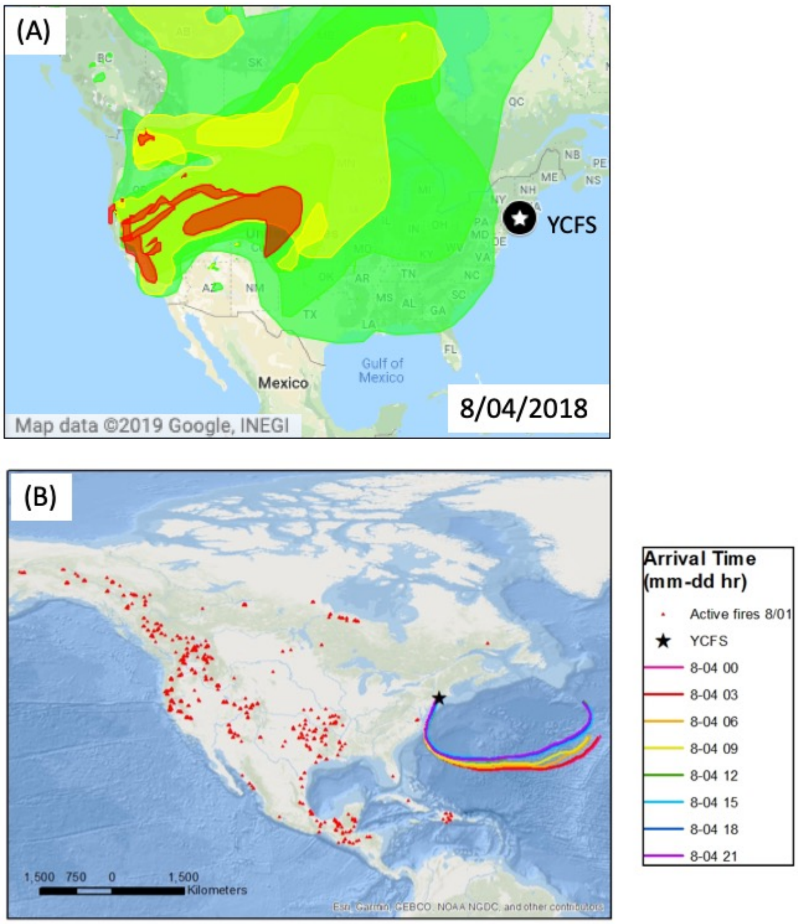


**Figure S4: NOAA Smoke Map (A) and HYSPLIT backward-trajectory model (B) for August 4, 2018, a non-event day when surface level concentrations at the YCFS were lower. On this day, NOAA Smoke Maps show no visible smoke plumes in the NYC metropolitan area and 10-day backward trajectories show minimal interaction with active fires, despite the presence of active fires and fire plumes elsewhere in the U.S. This serves as an example to contrast the patterns observed on event days, where NOAA Smoke Maps show smoke influence in the NYC metropolitan area and backward trajectories pass through regions with active fires.**

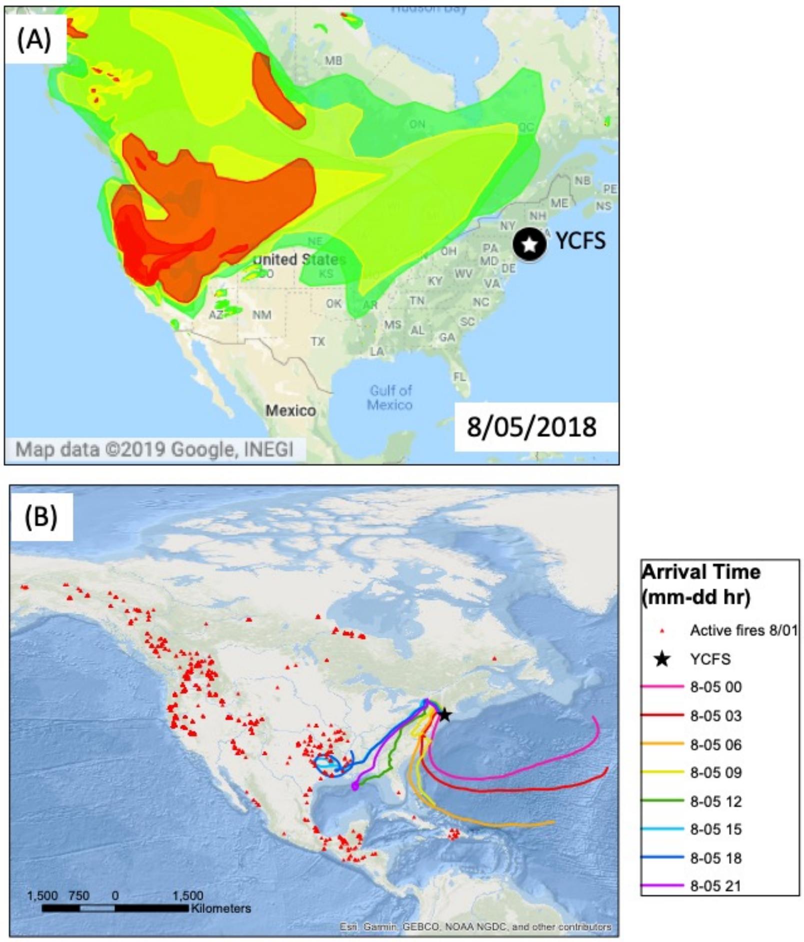


Figure S5: NOAA Smoke Map (A) and HYSPLIT backward-trajectory model (B) for August 5, 2018, a non-event day when surface level concentrations at the YCFS were lower. On this day, NOAA Smoke Maps show no visible smoke plumes in the NYC metropolitan area and 10-day backward trajectories show minimal interaction with active fires, despite the presence of active fires and fire plumes elsewhere in the U.S. This serves as an example to contrast the patterns observed on event days, where NOAA Smoke Maps show smoke influence in the NYC metropolitan area and backward trajectories pass through regions with active fires. Note that some interaction with fires is possible for 2 trajectories later in the day, consistent with slightly higher tracer concentrations at YCFS in the later hours of the day, which is the time period leading up to a potential biomass burning transport event on August $6^{th}$-$7^{th}$ in metro NYC (Figures 2, S2), which was smaller in magnitude compared to the other 2 events.

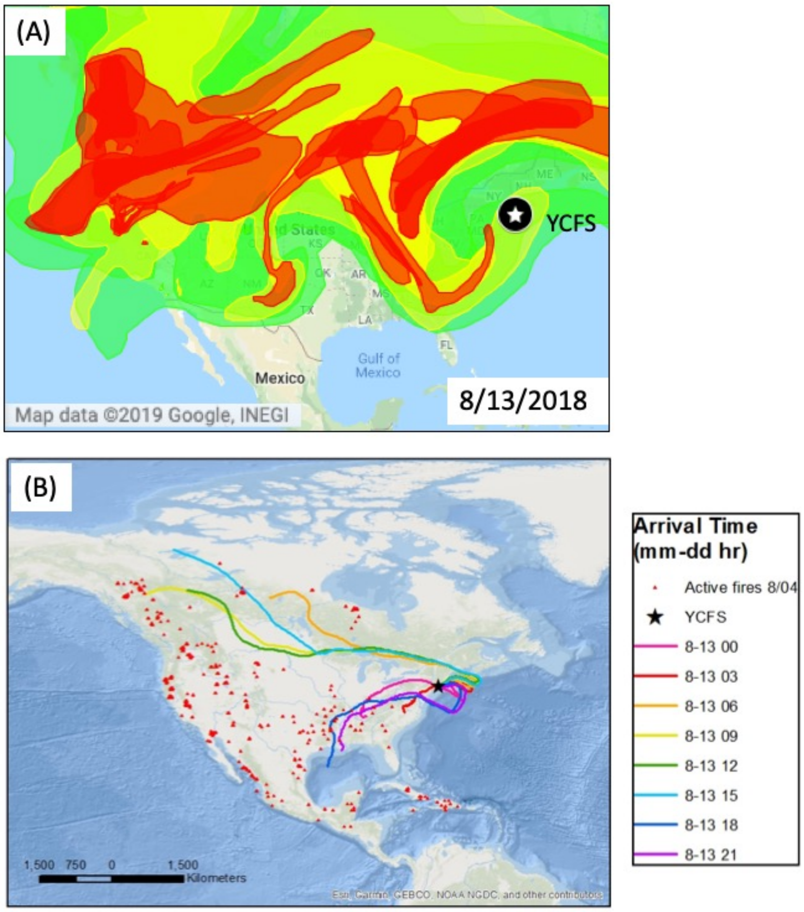


**Figure S6: NOAA Smoke Map (A) and HYSPLIT backward-trajectory model (B) for August 13, 2018, a non-event day when surface level concentrations at the YCFS were lower. On this day, NOAA Smoke Maps do show visible smoke plumes aloft in the NYC metropolitan area and a few of the 10-day backward trajectories show some potential interaction with active fires. However, surface level concentrations at the YCFS remain low due to regional rain in the late morning and afternoon (leading to wet deposition of PM) and additionally air parcel backward trajectories were at immediate surface level over-water for a period of 1-2 days prior to arrival, which would have also enhanced surface deposition of PM.**

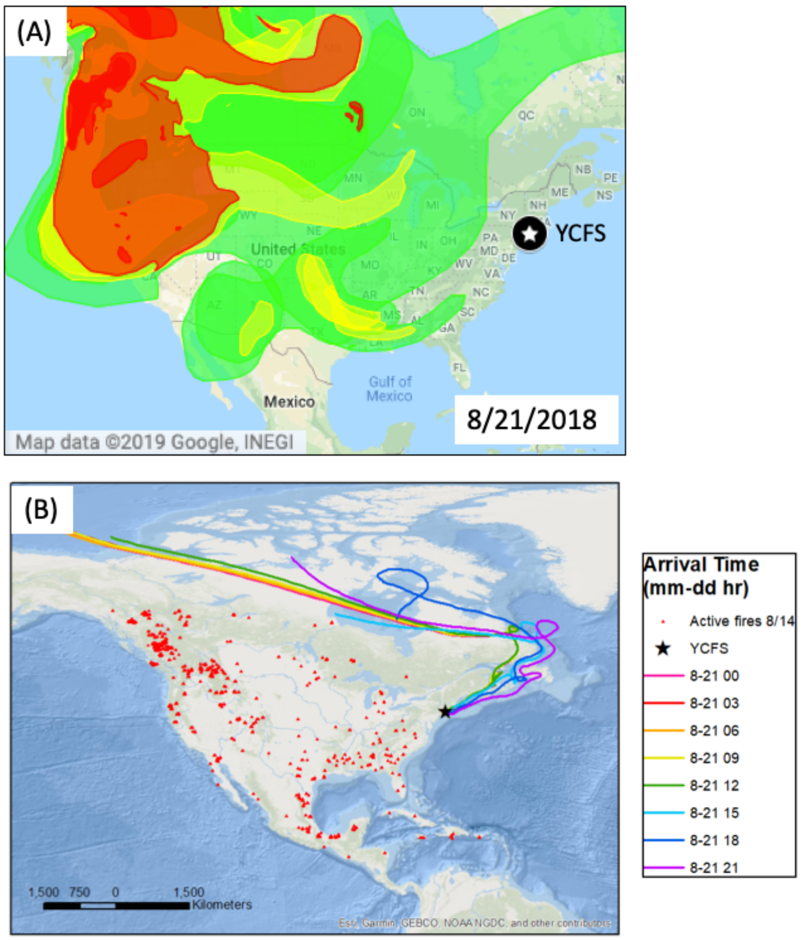


Figure S7: NOAA Smoke Map (A) and HYSPLIT backward-trajectory model (B) for August 21, 2018, a non-event day, when surface level concentrations at the YCFS were lower. On this day, NOAA Smoke Maps show no visible smoke plumes in the NYC metropolitan area and 10-day backward trajectories do not pass over areas of active fires, despite the presence of active fires and fire plumes elsewhere in the U.S. This serves as an example to contrast the patterns observed on event days, where NOAA Smoke Maps show smoke influence in the NYC metropolitan area and backward trajectories pass through regions with active fires.