Response to anonymous Referee #1

General Comments:

This paper examines recent trends in baseline carbon monoxide (CO) and ozone (O$_3$) in the northeast US region using measurements at seven rural sites in New England and upstate New York. The paper documents significant decreasing trends in CO while showing that there was no significant long-term trend in O$_3$. The authors examine in great detail the causes for these results including the impacts of changes in local and global anthropogenic emissions, wildfires and the impacts of meteorological factors such as long-range transport, clouds, temperature, humidity and stratospheric intrusions, and the relationship of these factors to climate indices including the North Atlantic Oscillation (NAS) and Arctic Oscillation (AO). Their scientific arguments are sound and because they can be used to hypothesize about the combined impacts on air quality of future changes to anthropogenic emissions and atmospheric circulation changes resulting from climate change they are highly relevant to current environmental concerns.

There are a couple scientific issues detailed in the Specific Comments section and a number of corrections listed in the Technical Corrections section that should be addressed. However, these do not detract from the overall message of the paper. Therefore I recommend that the paper be published in Atmospheric Chemistry and Physics after these minor revisions are completed.

We would like to thank the reviewer for their constructive remarks and comments on the article. Below we have responded to each one of the reviewer’s comments (shaded). We have taken most of the reviewer’s suggestions to improve the manuscript.

Specific Comments:

Why was the daily maximum solar radiation flux at Thompson Farm so low in spring 2002 (Figures 3 and 9b)? The NAO was positive but it was also positive in other years (e.g. 2004) without the solar radiation flux being so low.

We averaged daily maximum solar radiation flux at Thompson Farm in spring (March, April, and May), and the interannual variation was shown in Figure 3a. The difference between Figure 3a and Figure 9b was that the May data were excluded in Figure 9b. The hourly data of solar radiation flux were obtained from the Climate Reference Network (CRN) run by the National Ocean and Atmospheric Administration’s (NOAA) National Centers for Environmental Information. (http://www.ncdc.noaa.gov/crn/). Missing data were only found on five days in spring 2002 and no mistakes were found in our calculation. It seems that there is no reason to throw out the spring 2002 data.

We compared the difference of geopotential height at 850 hPa in spring 2002 and spring 2004, and found that geopotential height over the eastern US coast was ~30 gpm higher in spring 2002 than in spring 2004 (Figure S1a). In addition, percipitable water over our study region was ~1.5 kg m$^2$ more in spring 2002 than in spring 2004. The NAO index was positive in spring 2002 and spring 2004 (Figure 9a). The geopotential height over the Bermuda high and
the eastern US coast was significantly higher in positive NAO years than in negative NAO years (Figure 10). Rogers (1997) suggested that the North Atlantic storm track paralleled the eastern North American coastline during positive NAO years. With higher geopotential height at 850 hPa over the eastern US coast in spring 2002 (Figure S1a), storm tracks could possibly be more parallel to the east coast in 2002 than in 2004. Consequently, stronger transport of moisture and wet conditions near the eastern US coast (Figure S1b) could lead to more cloudiness and lower solar radiation flux in spring 2002. Further research is needed to fully understand what may have caused the very low solar radiation flux in spring 2002.

We added “More frequent cyclone activities, wetter conditions associated with the North Atlantic storm track parallel to the eastern US coast could be possible factors leading to the very low solar radiation flux in spring 2002. Further research is warranted to fully understand what may have caused this phenomenon.” in L509 – L512.

![Figure S1](Image)

Figure S1. (a) The difference of geopotential height at 850 hPa and (b) precipitable water (kg m$^{-2}$) between spring 2002 and spring 2004.

In Section 3.3.3 the authors show that the NAO does not play a significant role in the interannual variability of baseline CO. Later in the section the authors suggest, citing other studies, that the circulation pattern associated with the positive NAO may work to lower baseline O$_3$ in the northeast US by facilitating continental export. However, wouldn’t those same mechanisms also facilitate export of CO limiting its buildup? Do these findings suggest that the impact of continental export on O$_3$ is small compared to the impacts of decreased stratospheric intrusions and solar radiation flux?

Thank you for this interesting comment. It inspired us to think more deeply about the impact of NAO on air quality in the Northeast US.

Averaged westerly wind speed (247.5–337.5°) was positively correlated with the NAO index at most of our study sites (MWO: $r = 0.76$, $p = 0.02$; CS: $r = 0.68$, $p = 0.06$; TF: $r = 0.57$, $p = 0.09$) (Table 4 and Figure 9c), suggesting that North American continental export could be one factor contributing to the negative correlation between baseline O$_3$ and the NAO index. Negative correlation, although insignificant, was also found between baseline CO and the NAO index (Table 4). Some studies (Creilson et al., 2003; Eckhardt et al., 2004; Stohl et al., 2003) also suggested that transport of particular matter, O$_3$ and its precursors from North
America to Europe was enhanced during positive NAO years. In addition, positive NAO years were accompanied by less stratospheric intrusion, potentially weakening a source of surface O$_3$ and subsequently decreasing baseline O$_3$ levels. However, less stratospheric intrusion could also lead to less dilution of surface CO and thus increase baseline CO levels. The opposite effects of factors such as stratospheric intrusion and continental export could complicate the relationship between the NAO and baseline CO. Without model simulations, it is hard to delineate such effects as well as to quantify the relative contributions of the three factors (export of ozone, stratospheric intrusion, and solar radiation flux) to the variation of baseline O$_3$.

The text was revised to reflect these thoughts. The statement “it should be noted that, no significant correlation was found between the NAO index and baseline CO at any of the sites, which suggests that NAO is not linked to or played an insignificant role in the interannual variability of baseline CO.” was deleted (L693). Instead, we added “Negative correlation, although insignificant, was also found between baseline CO and the NAO index at most of our study sites (Table 4). North American continental export could also impact the variation of baseline CO, while this impact could be confounded by other factors, e.g. stratospheric intrusion. Specifically, during positive NAO years, more continental outflows lead to a decrease in baseline CO, while less stratospheric intrusion would lead to less dilution of surface CO and thus increase baseline CO levels. Further research is warranted to fully understand the relationship between baseline CO and NAO.” (L743 – L749)

**Technical Corrections:**

Thanks for spotting these errors. They have been corrected.

Page 27254, Line 1:

You should define baseline CO and O$_3$ at the beginning of the abstract to inform the reader that it is not exactly the same as the background. The first sentence of the abstract could be something like “We define a baseline CO as the lowest 20$^{th}$ percentile of mixing ratios and a baseline O$_3$ as that corresponding to the baseline CO.”

Baseline CO and O$_3$ were originally defined in the Introduction (L105). To inform the reader earlier and more clearly, the definition of baseline CO and O$_3$ was also added to the beginning of the abstract.

“Baseline carbon monoxide (CO) and ozone (O$_3$) were defined as mixing ratios of CO and O$_3$ under minimal influence of recent and local emissions. In this study, baseline carbon monoxide (CO) and ozone (O$_3$) were examined at seven rural sites in the Northeast US during varying periods over 2001–2010. Specifically, baseline air was determined using the monthly 10$^{th}$ percentile level of CO at Appledore Island (AI), Castle Spring (CS), Pack Monadnock (PM), Thompson Farm (TF), Pinnacle State Park (PSP), and 50$^{th}$ percentile level at Mt. Washington (MWO) and Whiteface Mountain (WFM). Monthly median O$_3$ levels of the baseline air were defined as baseline O$_3$ levels.” (L28 – L35)

Page 27255, Line 2: Add a period after US.
Added “over 2001–2010”. (L60)

Page 27255 starting at Line 13: Consider swapping the order of the first two paragraphs in the introduction to be consistent with the title and the abstract (i.e. CO is discussed before O₃).

Revised as suggested. (L74 – L88)

Page 27256, Lines 25 -26: Change “could be transported downwind and subsequently affect the baseline CO and O₃ levels there” to “could affect the baseline CO and O₃ levels downwind.”

Revised as suggested. (L130)

Page 27257, Line 3: Consider mentioning the new stricter EPA standards governing O₃ exceedances.

We discussed the new EPA O₃ standards in the Summary (L771 – L775). To avoid repeating the discussion, we would like to briefly mention the NAAQS here. (L136)

Page 27257, Line 5: Change “mid-latitudes” to “mid-latitude regions”.

Changed. (L139)

Page 27257, Lines 5 – 8: Consider combining the two sentences into one with the clause “and no consistent trends” after “Asia” to connect the two thoughts. The reference list should then be moved to the end of the new sentence.

Revised as suggested (L138 – L142).

“Studies have been conducted to investigate trends in baseline CO and O₃ across northern hemispheric mid-latitudes regions, such as North America, Europe, and Asia, and no consistent trends have been found (Chan, 2009; Cooper et al., 2010; Cui et al., 2011; Logan et al., 2012; Oltmans et al., 2013; Parrish et al., 2012; Tilmes et al., 2012; Wilson et al., 2012; Xu et al., 2008).”

Page 27257, Lines 28 -29: This is a bit confusing since you start the sentence with “Most studies” but only list two and “episode” is singular.

We would like to point that most studies investigated the impact of wildfires during a few days. Our work was to examine the long-term impact of wildfires.

We changed “Most studies demonstrated elevated CO and O₃ due to fire emissions for an episode (e.g., Dutkiewicz et al., 2011; Honrath et al., 2004).” to “Most studies focused on episodic enhancements in CO and O₃ linked to fire emissions (e.g., DeBell et al., 2004; Dutkiewicz et al., 2011; Honrath et al., 2004).” (L160 – L163)

Page 27258, Line 2: Change after “O₃” to “, and both of these focused on ten years of observations from the 1990s.”
Revised to “To the best of our knowledge, only two studies (Jaffe et al., 2004; Wotawa et al., 2001) examined the impact of wildfires on baseline CO and O$_3$ over time periods of ten years in the 1990s. Thus, more research is warranted to investigate the impact of wildfires on baseline CO and O$_3$ on decadal scales” (L163 – L165)

Page 27258, Line 3: Change “More” to “Thus more”.

Added “Thus” (L165)

Page 27258, Line 16: Add a period after “US”.

Added “over 2001 – 2010” (L178)

Page 27258, Line 28: Insert “with” before “less”.

Added (L189)

Page 27259, Line 9: Hegarty et al., 2007 is the correct reference.

Changed (L197)

Page 27261, Line 21: Add “and” before “potential”.

Added “and” (L258)

Page 27262, Line 13: The meaning of the clause “the center of a cyclone was obtained” seems unclear in this context. Do you mean that if more than one local minimum is found the cyclone position is designated as the center point of the local minima?

There might be several local minima within 720 km. In our algorithm, only the lowest sea level pressure was obtained as the continuation of the previous cyclone.

“The center of a cyclone was obtained” was replaced by “the point with the lowest sea level pressure was designated as the center of a cyclone” (L278)

Page 27264 Lines 25 – 30, and Page 27296, Table 2: I think the numbers in the “Annual CO” column in Table 2 have the wrong sign (positive) except for CS which should be positive. Please check and correct where necessary. Also please check the “Annual O$_3$” column. Based on the seasonal trends it looks like some of the annual trend should be negative but they are all listed as positive.

All numbers in Table 2 were double-checked and errors corrected.

Page 27275, Line 7: Add a period after “US” and capitalize “of”

Changed (L605)

Page 27276, Line 5: Change “ultimate” to “ultimately”.

Changed (L628)
Page 27278, Line 14: Change “known as the positive phase of NAO” to “which is indicative of the positive phase of the NAQ”.

Changed. (L68)


Changed to “On 1 October 2015 the U.S. EPA lowered the NAAQS for ground-level O₃ to 70 ppbv to improve protection of public health and welfare (http://www3.epa.gov/ozonepollution/pdfs/20151001overviewfs.pdf).” (L771–L775)

References


Regional and Hemispheric Influences on Variability and Trends of Baseline Carbon Monoxide and Ozone over the Northeast US Baseline carbon monoxide and ozone in the northeast US over 2001–2010

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Abstract

Baseline carbon monoxide (CO) and ozone (O₃) were defined as mixing ratios of CO and O₃ under minimal influence of recent and local emissions. In this study, baseline carbon monoxide (CO) and ozone (O₃) were examined at seven rural sites in the northeast US during varying periods over 2001–2010. Specifically, baseline air was determined using the monthly 10th percentile level of CO at Appledore Island (AI), Castle Spring (CS), Pack Monadnock (PM), Thompson Farm (TF), Pinnacle State Park (PSP), and 50th percentile level at Mt. Washington (MWO) and Whiteface Mountain (WFM). Monthly median O₃ levels of the baseline air were defined as baseline O₃ levels. Interannual and seasonal variations of baseline CO and O₃ were examined for the effects of changes in anthropogenic emissions, stratospheric intrusion, transport pathways and O₃ photochemistry. Baseline CO generally exhibited decreasing trends at most sites, except at Castle Spring (CS), an elevated (∼ 400 ma.s.l.) site in rural central New Hampshire. Over April 2001–December 2010, baseline CO at Thompson Farm (TF), Pinnacle State Park (PSP), and Whiteface Mountain (WFM) decreased at rates ranging from −4.3 to −2.5 ppbv yr⁻¹. Baseline CO decreased significantly at a rate of −2.3 ppbv yr⁻¹ at Mt. Washington (MWO) over April 2001–March 2009, and −3.5 ppbv yr⁻¹ at Pack Monadnock (PM) over July 2004–October 2010. Unlike baseline CO, baseline O₃ did not display a significant long term trend at any of the sites, resulting probably from opposite trends in NOₓ emissions worldwide and possibly from the overall relatively constant mixing ratios of CH₄ in the 2000s. In looking into long term trends by season, wintertime baseline CO at MWO and WFM, the highest sites, did not exhibit a significant trend, probably due to the competing effects of decreasing CO emissions in the US and increasing emissions in Asia. Springtime and wintertime baseline O₃ at TF increased significantly at a rate of 2.4 and 2.7 ppbv yr⁻¹,
respectively, which was likely linked to nitrogen oxides (NO\textsubscript{x}) emissions reductions over urban areas and possible resultant increases in O\textsubscript{3} due to less titration by NO in urban plumes. The effects of meteorology on baseline O\textsubscript{3} and CO were investigated. A negative correlation was found between springtime baseline O\textsubscript{3} and the North Atlantic oscillation (NAO) index. It was found that during positive NAO years, lower baseline O\textsubscript{3} in the northeast US was linked to less solar radiation flux, weakened stratospheric intrusion, and intensified continental export. The lowest baseline CO at \textit{Appledore Island (AI)}, PM, TF, PSP, WFM and the lowest baseline O\textsubscript{3} at AI, PM, and PSP in summer 2009 were linked to the negative phase of the Arctic oscillation (AO), when more frequent cyclone activities brought more clean Arctic air to midlatitudes. It was also found that forest fires played a major role in determining baseline CO in the northeast US over 2001–2010. In summer, \~{}38\% of baseline CO variability at AI, CS, MWO, TF, PSP, and WFM could be explained by CO emissions from forest fires in Russia and \~{}22\% by emissions from forest fires in Canada. Long-range transport of O\textsubscript{3} and its precursors from biomass burning contributed to the highest baseline O\textsubscript{3} in summer 2003 at AI, CS, MWO, TF, and WFM. The findings of this study suggested impacts of increasing Asian emissions, NO\textsubscript{x} emissions from the Northeast Urban corridor, global biomass burning emissions, and meteorological conditions (e.g. cyclone activity, AO, and NAO) should all be considered when designing strategies for meeting and maintaining National Ambient Air Quality Standards (NAAQS) and evaluating the air quality in the northeast US.
1 Introduction

Carbon monoxide (CO) is a product of incomplete combustion (e.g. fossil fuel, biofuel, and biomass burning) and oxidation of hydrocarbon compounds (Worden et al., 2013). CO is a major sink of hydroxyl radicals (OH), and hence changes in CO can impact many chemically important trace species that are removed via oxidation by OH (Daniel and Solomon, 1998; Petrenko et al., 2013). In the presence of nitrogen oxides (NOx), CO oxidation is important in the tropospheric ozone (O3) budget. Due to its relatively unreactive chemical nature, CO has been used as a tracer of anthropogenic influence and fire emissions (Gratz et al., 2014; Price et al., 2004; Weiss-Penzias et al., 2006).

Tropospheric ozone (O3), which is produced largely by photochemical oxidation of nitrogen oxides (NOx) and volatile organic compounds (VOCs), is a serious and ubiquitous air pollutant affecting humans’ respiratory system, reducing yields of agricultural crops, and damaging natural ecosystems (EPA, 2012). As a precursor of hydroxyl radicals (OH), a dominant oxidant, O3 regulates the atmospheric capacity of oxidation (Prinn, 2003). Tropospheric O3 is also the third strongest greenhouse gas, after carbon dioxide (CO2) and methane (CH4), suggested by the Intergovernmental Panel on Climate Change (IPCC, 2007).

CO is a product of incomplete combustion (e.g. fossil fuel, biofuel, and biomass burning) and oxidation of hydrocarbon compounds (Worden et al., 2013). CO is a major sink of OH, and hence changes in CO can impact many chemically important trace species that are removed via oxidation by OH (Daniel and Solomon, 1998; Petrenko et al., 2013). In the presence of NOx, CO oxidation is important in the tropospheric O3 budget. Due to its relatively unreactive chemical nature, CO has been used as a tracer of anthropogenic influence and fire emissions (Gratz et al., 2014; Price et al., 2004; Weiss-Penzias et al., 2006).
The United States has made enormous efforts to control ambient mixing ratios of criteria pollutants since the 1970s (EPA, 2012). Nationally, annual second maximum 8 h average mixing ratios of CO decreased by 52 %, and annual mean mixing ratios of nitrogen dioxide (NO$_2$) declined by 33 % over 2001–2010 (EPA, 2012). Ambient O$_3$ concentrations in metropolitan areas, such as Los Angeles, New York City, and Chicago, decreased significantly in the past two decades (Bell et al., 2007; Cooper et al., 2010, 2012; Lefohn et al., 2010; Parrish et al., 2011).

Despite the decreasing anthropogenic emissions in Europe and North America, emissions in China and India have increased. Biomass burning emissions vary both spatially and temporally (Granier et al., 2011; Gratz et al., 2014). It remains unclear how such opposing changes in emissions have globally affected baseline CO and O$_3$, which are defined as mixing ratios of CO and O$_3$ under minimal influence of recent and local emissions (Chan and Vet, 2010; HTAP, 2010).

Background or baseline has been used, often interchangeably, to quantify how much O$_3$ produced from recent or local anthropogenic emissions could be allowed to attain the O$_3$ standards (HTAP, 2010; Huang et al., 2015). A few recent studies discussed the difference between background O$_3$ and baseline O$_3$ (HTAP, 2010; Huang et al., 2015; Parrish et al., 2012; Chan et al., 2010). The term “background” was used in modeling studies that estimated the atmospheric mixing ratio of a compound determined by natural sources only, while the term “baseline” was obtained from measurement records by removing data of local influences (HTAP, 2010, Chan et al., 2010; Parrish et al., 2012). Quantitative estimates of baseline CO and O$_3$ are not straightforward since measurements at a particular location include contributions from local anthropogenic precursor emissions (Chan and Vet, 2010). Various methods have been utilized to diagnose baseline conditions, including using measurements at remote sites, analysis of the
probability distribution of pollutants, correlations with reactive nitrogen oxides, and isentropic back-trajectories (e.g., Altshuller and Lefohn, 1996; Lin et al., 2000; Jaffe et al., 2003; Derwent et al., 2007; Parrish et al., 2009; Cui et al., 2011; Wilson et al., 2012). In the literature, air masses with low percentile values (< 20th percentile in the literature) of CO, an excellent anthropogenic tracer for its origin of mobile combustion, are commonly considered background baseline air (e.g., Lin et al., 2000; Mao and Talbot, 2012). Based on Lin et al. (2000), the low percentile value of CO is used as baseline CO, and baseline O$_3$ is then estimated using the data corresponding to CO mixing ratios below the baseline CO level (e.g., Lin et al., 2000; Mao and Talbot, 2012).

The lifetime of CO and O$_3$ in the free troposphere is ~ 2 months and ~ 20 days, respectively (Price et al., 2004; Stevenson et al., 2006). Thus, CO, O$_3$, and other precursors emitted in the upwind region and those produced in transit could affect the baseline CO and O$_3$ levels thereby transported downwind and subsequently affect the baseline CO and O$_3$ levels there (Cooper et al., 2012; Oltmans et al., 2008; Pollack et al., 2013). This has important regulatory implications, because the levels of baseline CO and O$_3$ directly affect emission control of CO and other O$_3$ precursors. Therefore, quantifying trends and variations in baseline CO and O$_3$ is of vital importance to assessing air quality and designing cost-effective emission control plans to meet the National Ambient Air Quality Standards (NAAQS) (http://www3.epa.gov/ttn/naaqs/criteria.html).

Studies have been conducted to investigate trends in baseline CO and O$_3$ across northern hemispheric mid-latitudes regions, such as North America, Europe, and Asia, and no consistent trends have been found (Chan, 2009; Cooper et al., 2010; Cui et al., 2011; Logan et al., 2012; Oltmans et al., 2013; Parrish et al., 2012; Tilmes et al., 2012; Wilson et al., 2012; Xu et al.,...
No consistent trends have been found. Kumar et al. (2013) reported trends of −0.31 and −0.21 ppbv yr$^{-1}$ for CO and O$_3$, respectively, at the Pico Mountain Observatory over 2001–2011.

Gratz et al. (2014) reported that the springtime median mixing ratio of O$_3$ increased at a rate of 0.76 ppbv yr$^{-1}$ at the Mt. Bachelor Observatory over 2004–2013, while median CO decreased at a rate of −3.1 ppbv yr$^{-1}$. Chan and Vet (2010) found that baseline O$_3$ in the eastern US decreased in spring, summer, and fall over 1997–2006, and the decadal trends in the Atlantic coastal region were positive in winter, summer, and fall. For the most part, causes for temporal variability have not been adequately explained. Interpretation of long-term trends is difficult because of significant interannual variability in emissions and climate as well as possibly in photochemistry (Hess and Lamarque, 2007). Climate change may lead to changes in natural emissions (e.g., emissions from wildfires, vegetation, and lightning), pollution transport pathways, and stratosphere-tropospheric exchange (Parrish et al., 2013).

Wildfires release large quantities of O$_3$ precursors, e.g., CO, VOCs, and NOx, every year. For instance, the MACCity emission inventory over 2001–2010 suggested that total global biomass burning emissions of CO ranged from $\sim$ 300 to $\sim$ 460 Tg yr$^{-1}$, close to $\sim$ 590 Tg yr$^{-1}$ anthropogenic emissions (Granier et al., 2011). These chemical species could make a significant contribution to tropospheric CO and O$_3$ budgets, impacting the interannual variability of surface CO and O$_3$ globally (Dutkiewicz et al., 2011; Herron-Thorpe et al., 2014; Honrath et al., 2004; Kang et al., 2014; Wigder et al., 2013; Wotawa and Trainer, 2000). Most studies focused on episodic enhancements in demonstrated elevated CO and O$_3$ linked to due to fire emissions studies (e.g., DeBell et al., 2004; Dutkiewicz et al., 2011; Honrath et al., 2004) for an episode (Dutkiewicz et al., 2011; Honrath et al., 2004). To the best of our knowledge, only two studies (Jaffe et al., 2004; Wotawa et al., 2001) examined the impact of wildfires on baseline
CO and O$_3$ over time periods of ten years in the 1990s using ten-year observations. Thus more research is warranted to determine the impact of wildfires on baseline CO and O$_3$ in the 2000s in northern hemispheric midlatitudes.

Regional climatic processes over the US east coast are influenced by the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) (Archambault et al., 2008; Hess and Lamarque, 2007). Studies suggested a link between NAO and regional distributions of tropospheric trace gases over the northwestern Atlantic Ocean, northern Europe, and the Arctic region based on model simulations or measurements (Christoudias et al., 2012; Creilson et al., 2003; Duncan and Bey, 2004; Eckhardt et al., 2003; Hegarty et al., 2009; Krichak and Alpert, 2005; Li et al., 2002; Pausata et al., 2012; Woollings and Blackburn, 2012). Most studies suggested that trace gases over North America could be transported across the Atlantic Ocean to northern Europe during the high NAO phase, particularly in winter and spring. However, to the best of our knowledge, nearly no studies examined the relationship between NAO and trace gases over the northeast US over 2001–2010. Circulation patterns can not only impact the transport of pollutants to the targeted region but can also influence the export from the upwind region. Hence, upwind trace gases are also likely to change in response to varying intensity of NAO.

The AO is another dominant mode of meteorological variability in the Northern Hemisphere (Creilson et al., 2005; Hess and Lamarque, 2007; Pausata et al., 2012). AO is characterized by winds circulating counterclockwise around the Arctic at around 55°N latitude, (Thompson and Wallace, 2000). In a positive AO phase, surface pressure in the polar region is abnormally low and strong winds around the pole confine cold air masses in the Arctic region; otherwise, more Arctic cold air dives south and increases storminess in the mid-latitude regions.
Oswald et al. (2015) hypothesized that observed higher summertime O₃ levels in the northeast US was associated with less storminess in a positive AO phase. Some modeling studies suggested a weak impact from stratosphere-tropospheric exchange of O₃ on the lower troposphere over the Atlantic basin during a positive AO year (Brand et al., 2008; Hess and Lamarque, 2007; Lamarque and Hess, 2004). The impact of AO on surface O₃ in the northeast US needs to be further investigated using long-term surface measurement data.

Our study used long-term observations at seven rural sites in the Northeast US. Five are located in rural New Hampshire (NH) and two are in rural New York (NY) State. Although numerous studies have been conducted to understand the distributions of surface CO and O₃ in the northeast US and their controlling mechanisms (e.g. Bae et al., 2011; Hegarty et al., 2007; Lai et al., 2012; Mao and Talbot, 2004; Schwab et al., 2009; Zhou et al., 2007), little work was done on baseline CO and O₃ using long-term measurement data for the region. Here, the trends of baseline CO and O₃ were examined at each site for the time period of 2001–2010, and regional to global emissions and large scale circulation patterns were investigated for their roles in the interannual and seasonal variation of baseline CO and O₃.

2 Methods and data

2.1 Measurement data

The seven rural sites selected in this study (Table 1 and Fig. 1) are within a few hundred kilometers of each other. Their elevation varies between 18 and 2100 m. Measurements of CO, O₃, wind direction, wind speed, and relative humidity at Appledore Island (AI), Castle Spring (CS), Mount Washington (MWO), Pack Monadnock (PM), and Thompson Farm (TF) were conducted by the University of New Hampshire (UNH) AIRMAP Observing Network (http://www.eos.unh.edu/observatories/data.shtml). The time resolution of the continuous year-
round measurements at these five sites was one minute. At AI, CO was measured seasonally from May to September over 2001–2006 and year round over 2007–2011, and O\textsubscript{3} was measured seasonally from May to September over 2002–2007 and year-round over 2008–2011. **All of the measurements have undergone rigorous quality controls and** The description of CO and O\textsubscript{3} measurement techniques from the UNH AIRMAP sites can be found in Mao and Talbot (2004). Additionally, hourly data of solar radiation flux were available at TF over January 2002–December 2010 from the Climate Reference Network (CRN) run by the National Ocean and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov/crn/data-access). The one-hour measurement data of CO, O\textsubscript{3}, wind direction, wind speed, and relative humidity at Whiteface Mountain (WFM) and Pinnacle State Park (PSP) began around 1996 (Table 1). The description of CO and O\textsubscript{3} measurement techniques for WFM and PSP can be found in Brandt et al. (2015) and Schwab et al. (2009). The time in all of the datasets was expressed in coordinated universal time (UTC), i.e. local time +5 h for non-daylight saving time and +4 h for daylight saving time (March–November).

### 2.2 Quantification of baseline CO and O\textsubscript{3}

The local afternoon time window (18:00–24:00 UTC) was selected to avoid including the data representing nighttime depletion of O\textsubscript{3} due to dry deposition and titration (Talbot et al., 2005). The planetary boundary layer (PBL) is well mixed in the afternoon. The monthly 10th percentile mixing ratio of CO at AI, CS, PM, TF, and PSP was used to represent the baseline CO levels. As MWO and WFM are located atop the mountains, they are far less impacted by local anthropogenic emissions. Therefore, monthly median values of CO were selected at MWO and WFM to represent the baseline level. To determine baseline O\textsubscript{3} levels, we first created a subset of O\textsubscript{3} data by using the O\textsubscript{3} mixing ratios corresponding to CO mixing ratios below the monthly 10th
percentile values at AI, CS, PM, TF, and PSP and monthly median values at MWO and WFM. The monthly median values of this subset were then defined as the baseline $O_3$ levels for respective sites.

### 2.3 Datasets

The NAO index is a measure of the intensity of NAO, which is defined based on the leading empirical orthogonal function of the normalized sea level pressure difference between the subtropical high and the subpolar low using the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Barnston and Livezey, 1987). The AO index was obtained by projecting the daily 1000 hPa geopotential height anomalies poleward of 20°N onto the loading pattern of the AO (Thompson and Wallace, 2000). The Climate Prediction Center of NCEP (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml) routinely monitors the primary teleconnection patterns. Monthly climate index values of NAO and AO were used in this study to understand the roles of global transport of atmospheric species via large-scale atmospheric circulation.

The Global Fire Emission Data (GFED) combines satellite information of fire activities and vegetation productivities, and contains the gridded monthly burned area and fire emissions. GFED 3 (http://www.globalfiredata.org/) was used in this study to estimate the biomass burning emissions of CO over Russia, Canada, California, and Alaska. Data were available for 2001–2010 at 0.5°× 0.5° horizontal resolution. Monthly mean global CO columns with 1°× 1° resolution obtained from the Measurements of Pollution in the Troposphere (MOPITT) instrument on the satellite Terra (https://www2.acd.ucar.edu/mopitt/) were used for the time period of 2001–2010 over grids containing Russia, Canada, Alaska, and California, when wildfire CO emissions in these grids calculated from GFED were larger than 1 g m$^{-2}$ month$^{-1}$. 
Monthly wind, geopotential height, temperature, relative humidity (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html), and potential vorticity (PV) (http://rda.ucar.edu/datasets/ds090.0) with a spatial resolution of 2.5°×2.5° from the NCEP/NCAR Global Reanalysis Products were used for meteorological conditions and for identifying stratospheric intrusion.

The dataset representing O$_3$ of stratospheric origin, constructed by Liu et al. (2013) (ftp://es-ee.tor.ec.gc.ca/pub/ftpdt/Stratospheric%20Climatology/), was also used to verify the contribution of stratospheric O$_3$ to the two mountain sites and the decadal trends there. This dataset included monthly amounts of stratospheric O$_3$ from the surface to 26 km altitude with 5°×5°×1 km spatial resolution from the 1960s to the 2000s.

Mean sea level pressure data were obtained from NCEP-DOE Reanalysis 2 (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html). The dataset is six hourly with a spatial resolution of 2.5°×2.5°. The data were used to identify and quantify the cyclones that passed over the northeast US.

### 2.4 Mid-latitude cyclone identification and tracking

Many algorithms have been developed since the 1970s to identify mid-latitude cyclones (Hu et al., 2004; Murazaki and Hess, 2006; Racherla and Adams, 2008). The algorithm developed by Bauer and Del Genio (2006) was adopted in this study to track the sea level pressure minima. The first step of the algorithm was to search for the local minimum by a 2 grids × 2 grids matrix. The next step was to search for the local (within 720 km) minimum in the next 6 h time step, assuming that a cyclone cannot move faster than 120 km h$^{-1}$, the same criterion used by Bauer and Del Genio (2006). If more than one local minimum was found, the point with the lowest sea level pressure was designated as the center of a cyclone the center of a cyclone was obtained. Two more criteria were applied, its duration > 24 h and central pressure ≤ 1020
hPa. Long-term cyclone frequency statistics were calculated for the northeast US (37.5–47.5°N, 67.5–82.5°W).

2.5 Statistical methods

The open-air package in the statistical programming language R 3.0.2 was used to determine whether a rate of change was statistically significant. Trends in baseline CO and O$_3$ were reported using SenTheil slopes from the non-parametric Mann–Kendall analysis in ppbv yr$^{-1}$ with 90% confidence intervals. Pearson correlation was computed to determine the relation between variables (e.g. baseline CO, baseline O$_3$, NAO index, relative humidity). The Student t test was conducted to verify statistical significance ($\alpha = 0.10$).

To quantify the contribution to a location of interest from biomass burning emissions over an area, we applied the following linear regression models (Wotawa et al., 2001):

$$\text{CO} = a_0 + a_1 E$$  \hspace{1cm} (1)

Where CO is the mixing ratio of baseline CO at each site, $E$ the total CO column over the area, $a_0$ the intercept value, and $a_1$ the slope value. The combined effect of biomass burning emissions from Russia ($E_{\text{Russia}}$) and Canada ($E_{\text{Canada}}$) was computed using Eq. (2):

$$\text{CO} = b_0 + b_1 E_{\text{Russia}} + b_2 E_{\text{Canada}}$$  \hspace{1cm} (2)

where $b_0$, $b_1$, and $b_2$ are regression parameters. Note that $E_{\text{Russia}}$ and $E_{\text{Canada}}$ were found to be the two emissions sources that contributed significantly to the baseline CO at the seven sites of our study, which is why only these two sources were included in the regression.

3 Results and discussions

3.1 General characteristics

3.1.1 Baseline CO
Baseline CO at CS, MWO, PM, TF, and PSP had maxima uniformly in March and
minima in varying months over August–October (Fig. 2a and b). Averaged annual maxima were
191 ppbv at CS, 180 ppbv at MWO, 155 ppbv at PM, 164 ppbv at TF, and 189 ppbv at PSP over
their respective time periods (Table 1). Averaged annual minima were 131 ppbv in August at CS,
142 ppbv in September at MWO, 109 ppbv in October at PM, 113 ppbv in August at TF, and 128
ppbv in October at PSP. At AI, year-round data were available during 2007–2010, a much
shorter time period compared to those at other sites. The seasonal cycles at AI were consistent
with other sites, with the average annual maximum 149 ppbv in March and minimum 103 ppbv
in September. Previous studies suggested that the annual maximum in cold months resulted from
residential heating, vehicle cold starts, and less loss from oxidation by OH, while the annual
minimum in fall, instead of in June–July when solar radiation and hence OH concentrations
reach annual maxima, was probably the combined effect of biomass burning emissions, mobile
combustion emissions, and loss from oxidation by OH (Kopacz et al., 2010; Miller et al., 2008).

The annual cycle at WFM was different from those at all other sites, with an annual
maximum of 144 ppbv in July and minimum of 103 ppbv in December averaged over January
2001–December 2010 (Fig. 2b). To investigate the potential reasons for this different behavior,
the data at WFM were compared with those at MWO, a site with slightly higher elevation (2 km
a.s.l.) located 208 km to the east (Fig. 1). WFM and MWO are 128 km southwest and 217 km
southeast, respectively, from Montreal, the 9th largest city in North America. Over 2001–2009,
averaged summertime baseline CO (141 ppbv) at WFM was comparable to that (145 ppbv) at
MWO, while averaged wintertime baseline CO (108 ppbv) at WFM was 60 ppbv or 36 % less
than that (168 ppbv) at MWO (Fig. 2a and b). This wintertime contrast was probably associated
with the large difference between the frequency distributions of wind direction at the two sites.
There were 4.7% of the air masses at WFM from the northeast (22.5°–67.5°), compared to 75.4% of the air masses at MWO from the northwest (247.5°–337.5°), the general direction of Montreal. This indicates that MWO was frequently exposed to northwesterly winds carrying air masses potentially influenced by anthropogenic emissions in Montreal, while such influences were rare at WFM. Consequently, much lower baseline CO was found at WFM than at MWO.

From April 2001 to December 2010, baseline CO decreased significantly at a rate of −2.5 ppbv yr\(^{-1}\) at TF, −4.3 ppbv yr\(^{-1}\) at PSP, and −2.8 ppbv yr\(^{-1}\) at WFM. Baseline CO decreased at a rate of −2.3 ppbv yr\(^{-1}\) at MWO over April 2001–March 2009 and −3.5 ppbv yr\(^{-1}\) at PM over July 2004–October 2010 (Table 2). Unlike all other sites, CS exhibited an increasing trend of 2.8 ppbv yr\(^{-1}\) over April 2001–June 2008. Prior to May 2003, the mixing ratio of baseline CO at CS was similar to that at TF. After May 2003, baseline CO at CS was ∼30 ppbv higher than that at TF and PM (Fig. 2a), resulting in the overall increasing trend. The reasons for such unusually high values at CS are unknown.

The U.S. EPA reported a decrease of 52% in the national average of annual second highest 8 h mixing ratios of CO from 2001 to 2010 (EPA, 2012), corresponding to a rate of −7.8 ppbv yr\(^{-1}\) (for an decadal average mixing ratio of ∼150 ppbv), which was larger than that at any of our sites. Because EPA’s trend was estimated using measurements mainly from urban sites with higher concentrations and also focused on the high end of the distribution, it is expected to show larger changes compared to the trend of baseline levels at rural or remote sites from this study, with influence of direct anthropogenic emissions removed.

The total CO column from MOPITT retrievals over the eastern US was found to decrease at a rate of 1.4% yr\(^{-1}\) (or −2.1 ppbv yr\(^{-1}\) for a decadal average mixing ratio of ∼150 ppbv) from 2000 to 2011 (Worden et al., 2013), which was comparable to that of the baseline CO in this
study. These significant decreasing trends of baseline CO and total column CO were probably associated in large part with anthropogenic CO emissions reductions worldwide (Gratz et al., 2014). Globally, anthropogenic CO emissions showed a slight decrease of ~ 1% from 1990 to 2010 (Granier et al., 2011). In the US and Europe, total anthropogenic CO emissions declined at a rate of ~3% yr\(^{-1}\) from 2000 to 2010, while increasing trends were found in India (~ 1.5% yr\(^{-1}\)) and China (~ 3% yr\(^{-1}\)) (Granier et al., 2011). A decreasing trend in CO emissions in China since 2005 was suggested by Tohjima et al. (2014) and Zhang et al. (2009).

3.1.2 Baseline O\(_3\)

The baseline O\(_3\) concentrations from all sites ranged from 22 ppbv in the fall to 56 ppbv in spring, consistent with baseline levels in the Eastern US that were quantified using a principal component analysis and backward air parcel trajectories by Chan and Vet (2010). The time series of baseline O\(_3\) at all sites showed averaged annual maxima in April and minima in August–October (Fig. 2c and d). Annual maxima averaged over their respective periods at the seven sites occurred all in April and were very close in magnitude, ranging from 47 to 51 ppbv. In comparison, averaged annual minima at the seven sites displayed distinct difference in magnitude and timing, varying over 28–37 ppbv, occurring in August at CS, September at AI and PM, and October at TF, PSP, MWO, and WFM. Studies have suggested that monthly surface O\(_3\) over remote continental areas generally had a spring maximum, attributed to enhanced stratospheric input and hemispheric wide photochemical production (Monks, 2000; Parrish et al., 2013). Here, the fact that baseline CO had annual maxima in spring suggested that the springtime annual maxima of baseline O\(_3\) were possibly associated with photochemical processing of O\(_3\) precursors including CO and VOCs that had been built up overwinter on a hemispherical scale (Kopacz et al., 2010; Penkett et al., 1993).
A close examination using the Mann–Kendall test suggested no significant trends in baseline O₃ during the study period at all sites (Table 2). Similar results were found in Mace head, Ireland, which is located on the western coast of Europe (Derwent et al., 2007). From 1987 to 1997, baseline O₃ at Mace Head had a significant increasing trend of 0.14 ppbv yr⁻¹ followed by a small increase over 1997–1999, and stabilized over 2000–2007 (Derwent et al., 2007).

IPCC (2001) suggested that the change of long-term trends in baseline O₃ could be driven by CH₄ oxidation in the presence of NOₓ. In a polluted region, O₃ is produced by photochemical reactions of nonmethane hydrocarbons (NMHCs) and NOₓ (West et al., 2006). In the global troposphere, CH₄ is the primary anthropogenic VOC (Fiore et al., 2002) and affects global background mixing ratios of O₃ due to its long lifetime (8–9 years). Derwent et al. (2007) found the change of baseline O₃ in Mace Head followed the mixing ratios of baseline CH₄ over 1992–2007. West et al. (2006) found that reducing global anthropogenic CH₄ emissions by 20% beginning in 2010 would reduce O₃ mixing ratios globally by ~ 1 ppbv in 2030. Globally, the growth rate of CH₄ declined from ~ 13 ppbv yr⁻¹ in the early 1980s to near zero over 1999–2006 (WMO, 2012). Since 2007, atmospheric CH₄ was increasing again with an average rate of ~ 3 ppbv yr⁻¹ (WMO, 2012). These changes in CH₄ mixing ratios can potentially lead to changes in baseline O₃ mixing ratios.

On the other hand, global NOₓ emissions did not change overall during the study period (Granier et al., 2011). Granier et al. (2011) reported that annual NOₓ emissions decreased at a rate of 1.5 Tg yr⁻¹ in western Europe, 0.7 Tg yr⁻¹ in central Europe, ~ 5 Tg yr⁻¹ in the US over 2001–2010, while increased at a rate of ~ 5 Tg yr⁻¹ in China and ~ 1.5 Tg yr⁻¹ in India. Xing et al. (2015) found varying trends in NOₓ mixing ratios over 1990–2010, with 4.1% in China, −1.4% in the US, and −1.2% in Europe. The annual rates of change in NOₓ concentrations were
comparable to those in emissions (Xing et al., 2015). This suggests that increasing \( \text{CH}_4 \) and opposite trends of \( \text{NO}_x \) emissions worldwide probably contributed to the insignificant trends in baseline \( \text{O}_3 \) over the northeast US during 2001–2010.

### 3.2 Seasonal variation of decadal trends in baseline \( \text{CO} \) and \( \text{O}_3 \)

Generally a decreasing trend was found in baseline \( \text{CO} \) and no trend in baseline \( \text{O}_3 \) during the decade 2001–2010 as shown in the previous section. However, trends of baseline \( \text{CO} \) and \( \text{O}_3 \) were found to vary by season (Table 2). Baseline \( \text{CO} \) at CS was anomalously high since May 2003 (Fig. 2a) and had increased over the decade in all seasons. As the reasons for the unusually high values at CS are unknown, baseline \( \text{CO} \) at CS was not included in the subsequent discussion.

In spring and winter, baseline \( \text{CO} \) at PM, TF, and PSP decreased significantly at a rate between −6.5 to −3.7 ppbv \( \text{yr}^{-1} \), while no significant decreasing trends were found at the two highest sites MWO and WFM (Table 2). In summer, baseline \( \text{CO} \) at MWO, PM, TF, and PSP showed decreasing trends varying between −5.5 and −4.3 ppbv \( \text{yr}^{-1} \). In fall, baseline \( \text{CO} \) at all sites decreased significantly at rates varying between −6.4 and −3.2 ppbv \( \text{yr}^{-1} \).

The overall insignificant change of baseline \( \text{CO} \) at MWO and WFM in spring and winter could be due to the combined effect of decreasing US emissions and increasing Asian emissions. MWO and WFM are the highest sites situated close to the top of the daytime convective boundary layer, which are more likely impacted by free tropospheric air compared to other sites. Thus, the impact of continental to intercontinental transport could be just as important there, and perhaps at times more important, than regional transport. \( \text{CO} \) emissions in the US declined at a rate of \( \sim -3 \ %\text{yr}^{-1} \) over 2000–2010, while an overall increasing trend was seen in China over 1999–2010, despite a small decrease since 2005 (Granier et al., 2011; Tohjima et al., 2014).
Liang et al. (2004), using GEOS-Chem model simulations, found that Asian influence was strongest in spring in the North Pacific lower troposphere, due to the combined effect of efficient ventilation of the Asian boundary layer via midlatitudinal cyclones and convection, long lifetime of CO, and strong springtime biomass burning emissions in southeastern Asia. The same study also found that the Asian influence weakened in summer due to the shorter lifetime of CO and continental export driven most often by convective injection to the upper troposphere, while particularly strong transpacific transport events occurred in spring and winter (Liang et al., 2004).

In fall, baseline O$_3$ did not show significant trends at any of the sites (Table 2). In summer, baseline O$_3$ showed distinct decreasing trends of $-3.1$ ppbv yr$^{-1}$ at AI, $-4.7$ ppbv yr$^{-1}$ at both MWO and WFM during their respective time periods, and no trends were found at other sites (Table 2). TF was the only site where baseline O$_3$ increased significantly at a rate of $2.4$ ppbv yr$^{-1}$ in spring and $2.7$ ppbv yr$^{-1}$ in winter over 2001–2010, while other sites showed no trends during the two seasons.

Tropospheric O$_3$ has been changing over the past four decades in response to changes in anthropogenic and natural emissions, stratosphere-tropospheric exchange, pollution transport pathways and O$_3$ photochemistry (Parrish et al., 2013). Therefore, it was hypothesized that the following factors may have contributed to the significant decreasing trends in summertime baseline O$_3$ at AI, MWO, WFM and significant increasing trends in springtime and wintertime baseline O$_3$ at TF:

1. Decreasing and increasing stratospheric intrusion in summer and winter – spring, respectively;

2. Decreasing and increasing continental to intercontinental transport of anthropogenic and natural O$_3$ precursors in summer and winter – spring, respectively;
3. Decreasing emissions of NO$_x$ from electric power generation and motor vehicles;

and

4. Changing pollution transport pathways in winter, spring, and summer.

Factor #1 was examined using PV data, as one of the physical characteristics of stratospheric air is high value of PV. Time series of PV at 350 K showed no trend in PV over the northeast US during the decade (Fig. 3a). There appeared to be distinct annual cycles in PV with maxima in winter and minima in summer, averaged $1.81 \times 10^{-8}$ and $1.05 \times 10^{-8}$ m$^2$s$^{-1}$kg$^{-1}$, respectively (Fig. 3a). Hence, stratospheric intrusion probably had a larger impact on the surface in winter-spring than in summer, which was supported by previous studies (James et al., 2003; Stohl et al., 2003). Such impact would more likely reach higher than lower elevation locations. No trends in baseline O$_3$ at the two highest sites MWO and WFM appeared to be consistent with what the time series of PV suggested. Moreover, TF, near the sea level (18 m a.s.l.), was less likely influenced by stratospheric intrusion than all other sites. These points were verified using the stratospheric O$_3$ during 2001–2010 from Liu et al. (2013), which suggested, on seasonal average in the area including all our sites, no contribution to the lowest layer (0.5 km) in summer, or no significant trends in such contribution in winter-spring. Therefore, it seemed unlikely that stratospheric intrusion contributed to the springtime and wintertime increasing trends in baseline O$_3$ at TF.

Significant increases have been reported by Cooper et al. (2012) in springtime and wintertime free tropospheric O$_3$ over North America, particularly in air masses originating from East Asia. The western US with elevated terrain was much more likely to be influenced by descending free tropospheric air than the eastern US (Cooper et al., 2012). Even if air masses rich in O$_3$ originating from East Asia reached the US East Coast, they would most likely have a
stronger impact on elevated sites. The fact of no trends at any of the elevated sites in spring or winter suggested that long-range transport of O₃ and its precursors from Asia was probably not a cause of increasing springtime and wintertime baseline O₃ at TF (Factor #2).

In summer, continental export from East Asia is weaker (Wild and Akimoto, 2001) and Asian emissions have less impact on US surface O₃ relative to domestic emissions than in winter and spring (Reidmiller et al., 2009), which ruled out the effect of long-range transport of Asian emissions on summertime trends in baseline O₃ at our sites. Summer sees the peak of forest fires (Wotawa et al., 2001). Therefore, changes in emissions of CO and other O₃ precursors from biomass burning could influence the trends in summertime baseline O₃ and CO (Sect. 3.3.1).

Further analysis suggested that decreasing urban emissions of NOₓ quite likely contributed to the rise in springtime and wintertime baseline O₃ at TF (Factor #3). Tropospheric NO₂ column over the US declined by 41% in spring and 33% in summer during the period of 1996–2011 (Cooper et al., 2012). Emissions of NOₓ in the US were reduced by 48% over 1990–2010, largely due to control of emissions from power plants and mobile sources (Xing et al., 2013). The Northeast US Urban Corridor, extending from Washington D.C. in the south to Boston in the north, was dominated by mobile combustion emissions of NOₓ. Annual mixing ratios of NO₂ in New York City decreased at a rate of −0.3 ppbv yr⁻¹over 1980–2007 (Buckley and Mitchell, 2011). In winter and early spring with weakened photochemical production, decreased NOₓ emissions in urban areas could cause less loss of O₃ via titration by NO (Liu et al., 1987; Jacob et al., 1995; Frost et al., 2006; Jonson et al., 2006), and the result could be enhanced O₃ mixing ratios in urban plumes (Cooper et al., 2010; Wilson et al., 2012). From measurements at our sites, data points of O₃ were selected corresponding to wind from the urban corridor. It was found that the 10th percentile mixing ratio of O₃ at TF in air masses from the urban corridor...
had been increasing at a rate of 1.81 ppbv yr\(^{-1}\)\((p = 0.05)\) in spring and 1.52 ppbv yr\(^{-1}\)(\(p < 0.01\)) in winter (Fig. 3b and c). This strongly suggests that decreased NO\(_x\) emissions in the urban corridor likely had a significant impact on springtime and wintertime baseline O\(_3\) at TF whereas had no similar effects at other sites. In summer with strong photochemistry, decreased emissions of O\(_3\) precursors could lead to reductions in peak summertime O\(_3\) concentrations at surface continental sites (Cooper et al., 2012; Parrish et al., 2013). No significant change was found in summertime 10th percentile mixing ratios of O\(_3\) in air masses from the urban corridor at TF, which was consistent with the relatively constant summertime baseline O\(_3\) at TF as aforementioned.

The implementation of the Acid Rain Program and the NO\(_x\) Budget Trading Program (NBP) also reduced NO\(_x\) emissions from the power plants (Xing et al., 2013). In the Ohio River Valley, where power plants dominate, both NO\(_2\) column and NO\(_x\) emissions decreased by 38 and 34\% over 1999–2005 (Kim et al., 2006). However, the 10th percentile mixing ratio of O\(_3\) in air masses from the southwest did not show any significant change in winter, spring, and summer at PSP, which is located to the northeast of the Ohio River Valley (Fig. 3b–d).

There is interannual variability in transport pathways, temperature, water vapor, solar radiation, and natural emissions (e.g., lightning, forest fires, and vegetation). A close examination of the NOAA CRN data revealed that springtime solar radiation at TF was increasing at a rate of 24.5 W m\(^{-2}\) yr\(^{-1}\)\((p = 0.03)\) over 2002–2010, with the lowest value of 432 Wm\(^{-2}\) in 2002 (Fig. 3a), while no significant trend was found in winter. Without the value in spring 2002, the solar radiation flux at TF increased at a rate of 9.4 W m\(^{-2}\) yr\(^{-1}\) in spring \((p = 0.02)\). This trend in springtime solar radiation at TF was possibly related to cloudiness in response to changing cyclone activity associated with varying atmospheric circulation, which
could have affected baseline O$_3$. *More frequent cyclone activities, wetter conditions associated with the North Atlantic storm track parallel to the eastern US coast could be possible factors leading to the very low solar radiation flux in spring 2002.* Further research is warranted to fully understand what may have caused this phenomenon. The impact of changes in weather conditions and large scale circulation on baseline O$_3$ was further explored in the following section.

### 3.3 Factors controlling baseline CO and O$_3$ in spring and summer

This section further identifies factors impacting the variation of baseline CO and O$_3$. Emphasis was placed on spring and summer, when there are strong intercontinental transport and photochemistry involving O$_3$ and CO (Cooper et al., 2010; Emmons et al., 2003), as well as exceedances of NAAQS.

#### 3.3.1 Impact of wildfires in summer

Large interannual variability in global CO mixing ratios was attributed to variations in biomass burning emissions (Novelli et al., 2003; Wotawa et al., 2001). Studies (Hecobian et al., 2011; Oltmans et al., 2010) suggested that biomass burning effluents from Russia and Canada flowed into North America. In addition, California and Alaska were two US states with considerable fire emissions of CO, which reportedly impacted the air quality over North America (McKendry et al., 2011; Real et al., 2007).

Fire emissions of CO in summer were estimated using the GFED dataset and MOPITT retrievals (Fig. 4a and b). The GFED data suggested that massive wildfires occurred in Russia in 2002, 2003, and 2008 with annual CO emissions of 42.1, 71.1, and 35.8 Tg, respectively. Annual fire emissions from Canada were 17.4 Tg in 2004 and 18.3 Tg in 2010. In Alaska, the largest fires occurred in 2004 with 13.1 Tg CO emitted, while in California the largest fire emissions of
CO were 1.3 Tg in 2008. From 2001 to 2010, the total CO emissions from wildfires in Russia, Canada, Alaska and California varied from 19.9 to 84.3 Tg, with the lowest and the highest in 2007 and 2003, respectively.

To quantify contributions of wildfires from these four areas to summertime baseline CO levels at our sites, a linear regression model was used together with MOPITT total CO column retrievals. Monthly CO columns were first correlated with monthly GFED fire emissions of CO for the four areas. The correlation coefficients were 0.89, 0.81, 0.81, and 0.84 ($p < 0.01$ for the four values) for Russia, Canada, California, and Alaska, respectively, suggesting that the variability in total column CO over those areas was dominated by that of fire emissions.

Further, it was found that the contributions of fire emissions from Russia and Canada to the variability of summertime baseline CO at the sites were averaged to be 37.8 and 22%, respectively (Table 3), and their combined contribution was averaged to be 41%. Contributions from Alaska and California were negligible at these six sites. Globally, there is approximately 1 billion ha closed forest in the boreal region, about two thirds of which is situated in Russia (Harden et al., 2000). CO emissions from wildfires in Russia and Canada contributed 49.5 and 29.6%, respectively, to the total CO emissions from wildfires in Northern Hemispheric midlatitudes ($30\degree$–$90\degree$N). Understandably, baseline CO was well correlated to wildfires in Russia and Canada at most sites except at PSP.

The insignificant correlation between baseline CO at PSP and wildfires emissions from Russia and Canada was possibly due to less dynamical circulation at the site. PSP had the lowest wind speed of 0.47 m s$^{-1}$ amongst all sites based on surface wind speed averaged over summers of 2001–2010 (Fig. 5a). This appeared to be consistent with the position of PSP relative to the pressure systems throughout the year (Fig. 5b–e). The climatological seasonal maps of sea level
pressure suggest that PSP is located either on the periphery of the subtropical high in summer–fall, or the periphery of the North American trough, where wind tends to be the weakest. In comparison, other sites are either located at the top of the boundary layer, and/or tend to be positioned within the North American trough, more directly under the influence of the westerly wind often facilitating global transport.

Since wildfires provide a substantial source of NOx and hydrocarbons, O3 is expected to form in fire plumes. Some of these air pollutants live long enough to travel over long distances, which could elevate baseline O3 globally (Jaffe et al., 2004). Corresponding to the largest fire emissions in summer 2003 in Russia (Fig. 4a), baseline CO in that season at all sites reached the decadal maxima, and baseline O3 was the highest of all summers at AI, CS, MWO, TF, and WFM (Fig. 4c and d). Jaffe et al. (2004) also suggested that emissions from Siberia forest fires in summer 2003 were transported to North America resulting in enhancements of 23–37 and 5–9 ppbv in summertime baseline CO and O3, respectively, at 10 sites in Alaska, Canada, and the Pacific Northwest.

The second largest summertime baseline CO mixing ratio of the decade was found in summer 2004 at CS, TF, and WFM (Fig. 4c), although the total CO emissions from wildfires in Russia and Canada during that season was 20.4 Tg, 16% smaller than 24.4 Tg, the decadal (2001–2010) average annual CO emissions from the two countries. Over Alaska, the geopotential height in summer 2004 was ~ 40 gpm higher than normal years (Fig. 6a–c). This relatively higher pressure field led to drier and warmer conditions over Alaska and southwestern Canada with 82% relative humidity and 12°C surface temperature, the driest and warmest of the decade (Fig. 6d). Such weather conditions are conducive to occurrence of wildfires. In summer 2004, CO emissions from wildfires in Canada and Alaska contributed 48.5 and 36.5%,
respectively, to the Northern Hemispheric total, compared to the decadal (2001–2010) average contributions of 49.5, 10.6, and 29.6% from Russia, Alaska, and Canada, respectively. Correspondingly, the 13.1 Tg CO emissions from wildfires in Alaska were the largest over the decade, and the 17.4 Tg CO emissions from wildfires in Canada were the second largest of the decade, following the largest in summer 2010 (Fig. 4a). On the other hand, the streamlines over Canada suggested an unusually strong northeasterly component in summer 2004. The high pressure system over Alaska and southwestern Canada most likely strengthened the westward transport of wildfires effluents from Alaska and Canada (Fig. 6c). The combination of these two factors resulted in efficient transport of massive CO emissions from fires over Alaska and Canada. Smoke from these fires over the continental United States was observed in satellite images of aerosol optical depth (AOD) from the GOES (Geostationary Operational Environmental Satellites) (Kondragunta et al., 2008) and MODIS (Moderate Resolution Imaging Spectro-radiometer) aboard Terra (Mathur, 2008), and extensive plumes of enhanced CO concentrations were captured in MOPITT (Measurements of Pollutants in the Troposphere) retrievals (Pfister et al., 2005).

Mann–Kendall trend analysis indicated no significant decreasing trends in biomass burning emissions from Alaska, Canada, and California. In contrast, CO emissions from wildfires in Russia decreased at a rate of −0.51 Tg yr\(^{-1}\) (\(p = 0.10\)). Summertime baseline CO at MWO, PM, TF, and PSP decreased at a rate between −5.5 and −4.3 ppbv yr\(^{-1}\) and baseline O\(_3\) at AI, MWO, and WFM decreased at a rate between −4.7 and −3.1 ppbv yr\(^{-1}\) (Sect. 3.2). Based on regression analysis, as a result of a 0.51 Tg yr\(^{-1}\) decrease in CO emissions from wildfires in Russia, baseline O\(_3\) decreased by 0.04–0.07 ppbv yr\(^{-1}\) (\(p = 0.08–0.10\)) at AI, MWO, WFM, and CS, while baseline CO declined by 0.14–0.22 ppbv yr\(^{-1}\) (\(p = 0.01–0.10\)) at AI, TF, MWO, and
Hence, the decreasing trend of biomass burning emissions in Russia was likely a major factor causing the decreasing trends in baseline CO and O₃ in summer at our sites.

### 3.3.2 Impact of cyclone activity and AO in summer

Meteorology is another factor that can influence summertime baseline CO and O₃ across the northeast US over 2001–2010. All the meteorological variables, midlatitude cyclone frequency is an important one that can impact regional air quality greatly. It affects not only boundary layer ventilation, humidity, solar radiation, and temperature but also general circulation of the regional atmosphere (Leibensperger et al., 2008).

Time series of summertime counts of cyclones in the northeast US showed strong interannual variability (Fig. 7a). The counts of cyclones in 2003, 2006, 2008, 2009, and 2010 were greater than 12, the average of summer 2001–2010. Summer 2009 experienced the largest number of cyclones (20) passing the northeast US during the 2001–2010 period. Other summers experienced below-average cyclones. No overall trend was found in the counts of cyclones during the study period. Our calculated numbers of cyclones were consistent with the results for the same years from Leibensperger et al. (2008) and Bauer and Del Genio (2006).

In summer, cyclones tend to move around the 500 hPa vortex, which is over the cold Arctic Ocean with broadly symmetric flow around it (Serreze et al., 2007). On the North American side, the high latitude flow on the 500 hPa pressure level has a southward component, which tends to steer systems away from the Arctic Ocean (Fig. 7b). Composite analyses associated with years of strong (2003, 2006, 2008, 2009, and 2010) vs. weak (2001, 2002, 2004, 2005, and 2007) cyclone activities revealed distinct differences in regional to large scale circulation (Fig. 7c). There turned out to be a pronounced positive difference of ~ 35 gpm centered over Baffin Island (north of the northeast US) and a negative difference of ~ 25 gpm.
centered over the northeast US (Fig. 7c). This difference was related to the negative phase of AO (Fig. 7a), when surface pressure is abnormally high in the polar region and low in the midlatitudes (Archambault et al., 2008). In a negative AO season, Arctic lows and westerlies are weaker, leading to more frequent cold-air outbreaks down to Eurasia and the US, and stormy weather over the Mediterranean (Hess and Lamarque, 2007), and ultimately low baseline CO and O₃ across the northeast US.

A case in point was summer 2009 with the largest cyclone count (20) and the strongest negative AO phase (~0.92) of the decade (Fig. 7a). Consistent with earlier results, the difference of 500 hPa geopotential height between summer 2009 and the 10 year average had negative anomalies up to ~−60 gpm over the North American continent and positive anomalies up to ~65 gpm centered near the pole (Fig. 7d). The sea level pressure field (Fig. 7e) featured a pronounced mean low over southern Canada and the streamlines suggested an unusually strong northeasterly component. Indeed, the frequency distribution of wind direction at each site suggested more frequent occurrence of northeasterly wind (22.5–112.5°), with 21% at PM, 9% at MWO, 42% at TF, 11% at PSP, and 13% at WFM (Fig. 8). In summer 2009, the northeast US was more often under the influence of cold frontal passages associated with the largest number of cyclones passing through the region. As a result, the northeast US was exposed most frequently to air masses of Arctic origin. Moreover, emissions from large scale wildfires clearly had global effects as discussed in Sect. 3.3.1. In summer 2009, ~11.9 Tg CO, the lowest of the decade, was emitted from wildfires in Russia and Canada (Fig. 7f). Hence, the lowest fire emissions of CO and the most frequent cyclone activities were likely two important factors leading to the lowest summertime baseline CO and O₃ in 2009 at the study sites.
A contrasting case was summer 2003, when AO was negative and 15 cyclones passed the region (Fig. 7a), 25% greater than the decadal mean (12), and yet baseline CO and O₃ at the sites reached the decadal maxima (Figs. 4c, d and 7f). According to the analysis above, baseline CO and baseline O₃ were expected to be lower during this summer than the decadal average as a result of above-average passages of cyclones. However, in summer 2003 CO emissions from Russian and Canadian wildfires were the largest of the decade (Sect. 3.3.1), counteracting the effect of the AO. Another interesting example was summer 2007 which had the lowest cyclone activity of the decade (Fig. 7a), and the total CO emissions from wildfires in Russia and Canada were 13.6 Tg, the second lowest of the decade following summer 2009 (Fig. 7f). The site-average baseline CO and O₃ levels in summer 2007 were below the decadal means. Therefore, the effect of biomass burning may dominate over that of AO and cyclone activity during some summers, while the two worked in concert during others.

Overall, no distinct correlation between counts of cyclones and baseline O₃ was found at most sites (AI, CS, MWO, PM, TF, WFM), while no significant correlation between counts of cyclones and baseline CO was found at any of the sites. The only exception was PSP where the count of cyclones was found to be reasonably anti-correlated with baseline O₃ ($r = -0.56, p = 0.05$) in the summer. As discussed in Sect. 3.3.1, PSP was the only site that did not seem to be affected by the Russian and Canadian wildfire emissions as all other sites were, possibly due to its being situated in a region less impacted by large-scale dynamics. Perhaps this very dynamic characteristic cast the site under a predominant influence of synoptic systems, e.g., the Bermuda High and cold frontal passages. As commonly known, high mixing ratios of O₃ in the northeast occur under summertime stagnant, clear sky conditions associated with the Bermuda High (Logan, 1989; Vukovich, 1995; Hegarty et al., 2007; Lai et al., 2012), while low O₃ was often
linked to cold fronts which sweep out polluted air leaving much cooler and cleaner air in the
northeast (Cooper et al., 2001; Leibensperger et al., 2008; Li et al., 2005). Conceivably, with
more frequent cyclones passing the northeast US, lower concentrations of baseline CO and O₃
would be expected, and the predominant effect of such synoptic systems could quite likely lead
to anticorrelation between the baseline CO/O₃ levels and cyclone activities.

3.3.3 Impact of NAO in spring (March and April)

Wildfires in March and April were scarce, with mean CO emissions of 1.78 Tg in Russia
and 0.004 Tg in Canada over 2001–2010, negligible compared to emissions during the fire
season (May–September). To focus on the impact of large circulation patterns on baseline CO
and O₃ in spring, the May data were excluded to avoid the effect of biomass burning. Springtime
baseline O₃ at each site showed strong and consistent interannual variation up to 10 ppbv (Fig.
9a). The baseline O₃ mixing ratio averaged at all the seven sites over the decade was 46.5 ppbv,
and exceeded the average (>46.5 ppbv) in 2001, 2003, 2005, 2008, 2010, and was below average
(≤46.5 ppbv) in 2002, 2004, 2006, 2007, 2009 (Fig. 9a).

The difference of 850 hPa geopotential height between the lower and higher O₃ years is
shown in Fig. 10. There was a pronounced difference up to 40 gpm in the Bermuda/Azores high
and ~−40 gpm in the Icelandic low, which resulted in stronger gradient flow between the two
pressure systems and was indicative of the positive phase of NAO, known as the positive phase
of NAO. Over 2001–2010, NAO index was significantly positive in 2002, 2004, 2007, 2009 and
negative in 2001, 2005, 2008, 2010, which corresponded mostly to the years of below and above
the decadal average baseline O₃, respectively. Significant negative correlation was found between
the NAO index and baseline O₃ at each site (Table 4) (CS: r = −0.75, p = 0.03; MWO: r = −0.68,
p = 0.03; PM: r = −0.81, p < 0.01; TF: r = −0.81, p < 0.01; PSP: r = −0.58, p = 0.06; WFM: r =
The negative correlation between baseline O$_3$ and the NAO index could be a result of multiple factors, such as solar flux, stratosphere-tropospheric exchange, and continental export of O$_3$ produced in North America. It should be noted that, no significant correlation was found between the NAO index and baseline CO at any of the sites, which suggests that NAO is not linked to or played an insignificant role in the interannual variability of baseline CO.

The first possible explanation for the baseline O$_3$ and NAO index anticorrelation was changes in surface solar radiation flux during positive/negative NAO years. During a positive NAO year, the mean North Atlantic storm track parallels the eastern North American coastline before extending northeastward to near Iceland (Rogers, 1997). This storm track and its associated moisture transport and convergence lead to relatively wet conditions near the eastern US coast (Archambault et al., 2008; Hurrell, 1995). During a negative NAO year, the mean North Atlantic storm track is more zonal (Rogers, 1997), leading to relatively dry conditions near the eastern US coast (Archambault et al., 2008; Hurrell, 1995). At our coastal sites around the northeast US coast (CS and TF), significant correlation was found between relative humidity and the NAO index (CS: $r = 0.85$, $p = 0.02$; TF: $r = 0.64$, $p = 0.06$), while the correlation was weaker at inland, elevated sites (PSP and WFM) (PSP: $r = 0.23$, $p = 0.26$; WFM: $r = 0.40$, $p = 0.13$) (Table 4 and Fig. 9b).

During positive NAO years, wetter conditions indicate higher relative humidity and more cloudiness, most likely leading to reduced solar radiation flux near the surface and subsequently less O$_3$ production. As expected, a significant negative correlation was found between relative humidity and solar radiation ($r = -0.67$, $p = 0.05$) (Fig. 9b) and a significant positive correlation between baseline O$_3$ and solar radiation flux ($r = 0.75$, $p = 0.03$) at TF in March and April (Table 4 and Fig. 9b). No significant correlation between these variables was found in other seasons.
Another possible explanation for the negative correlation between NAO index and baseline O$_3$ was the influence of stratospheric intrusion. Dynamically, the North American trough induces descending air on its tailing side and in the upper troposphere it can cause tropopause folding with stratospheric air mixing downward into the troposphere. The difference of the PV patterns between positive NAO years and negative NAO years is illustrated in Fig. 11. Negative anomalies of $\sim -0.6 \times 10^{-9}$ m$^2$ s$^{-1}$ kg were found over the northeast US, suggesting that positive NAO was related to less stratospheric intrusion (Hess and Lamarque, 2007) over the northeast US. This is consistent with lower baseline O$_3$ levels during positive NAO springs. This was further verified using the stratospheric O$_3$ dataset constructed by Liu et al. (2013). Stratospheric O$_3$ was hardly detected at the lowest two layers (i.e., 0.5 and 1.5 km) in April. In March, $\sim 40–60$ ppbv of stratospheric O$_3$ reached the lowest layer in our study area in 2004 and 2006–2008 and reached the 1.5 km layer in 2001–2008. The stratospheric contribution to the 0.5 km layer was the largest in March 2008, when NAO was negative (Fig. 9).

The third possible factor affecting baseline O$_3$ over the northeast US was the effect of North American continental export. During a positive NAO phase, the anticyclonic circulation off the US east coast and the cyclonic circulation across the North Atlantic were amplified with a northward shift (Rogers, 1997). As a result, stronger surface wind was found near 50$^\circ$N across the North Atlantic basin and into Northern Europe (Hess and Lamarque, 2007). Annual wind speed from the west ($247.5–337.5^\circ$) was calculated at the study sites (Fig. 9c). Positive correlation was found between surface wind and NAO index at MWO, CS, and TF (Table 4) most sites (MWO: $r = 0.76, p = 0.02$; CS: $r = 0.68, p = 0.06$; TF: $r = 0.57, p = 0.09$). Eckhardt et al. (2004) found that the warm conveyor belt over the northeast US coast occurred $\sim 12\%$ more frequently in positive NAO years than in negative NAO years. The ending trajectories of the
warm conveyor belt in positive NAO years extended further eastward into western and northern Europe (Eckhardt et al., 2004). It was suggested that in a positive NAO year, the O₃ produced over the northeast US was less likely accumulated in the region, and was more likely transported faster off the continent and across the Atlantic Ocean. These changes were consistent with the positive anomalies of O₃ observed over northwestern Europe (Christoudias et al., 2012; Eckhardt et al., 2003). Negative correlation, although insignificant, was also found between baseline CO and the NAO index at most of our study sites (Table 4). North American continental export could also impact the variation of baseline CO, while this impact could be confounded by other factors, e.g. stratospheric intrusion. Specifically, during positive NAO years, more continental outflows lead to a decrease in baseline CO, while less stratospheric intrusion wound lead to less dilution of surface CO and thus increase baseline CO levels. Further research is warranted to fully understand the relationship between baseline CO and NAO.

4 Summary

Baseline CO and O₃ at seven rural sites in the northeast US were examined for their seasonal and interannual variabilities during the time period of 2001–2010, and potential mechanisms controlling the variabilities were investigated. It was found that baseline CO at most sites (MWO, PM, TF, PSP, and WFM) decreased significantly at a rate between −4.3 to −2.3 ppbv yr⁻¹, while baseline O₃ was relatively constant. No trends were found in baseline O₃ at all sites probably resulting from relatively constant mixing ratios of CH₄ in the 2000s and opposite rates of change in NOx emissions around the world.

In spring and winter, baseline CO at MWO and WFM did not exhibit a significant trend, possibly a result of the combined effect of decreasing emissions in the northeast US and increasing emissions in Asia. TF, a coastal rural site, was the only location where baseline O₃
was found to increase significantly at a rate of 2.4 and 2.7 ppbv yr$^{-1}$ in spring and winter, respectively, most likely caused by the decrease in NO$_x$ emissions over the urban corridor.

It was found that interannual variations of baseline CO and O$_3$ were predominantly influenced by biomass burning emissions, cyclone activities, and NAO. In summer, $\sim 38\%$ of baseline CO variability was attributed to CO emissions from forest fires in Russia and $\sim 22\%$ to emissions from forest fires in Canada. The lowest mixing ratios of baseline CO and O$_3$ at most sites in summer 2009 were linked to frequent cyclone activity, which were induced by the unusually weak low pressure system in the Arctic region. In spring, a significant negative correlation was found between baseline O$_3$ and the NAO index, potentially due to variations of solar flux, stratospheric intrusion, and continental export.

On 1 October 2015 the U.S. EPA lowered the NAAQS for ground-level O$_3$ to 70 ppbv. In December 2014, the U.S. EPA proposed to tighten the 2008 NAAQS for daily maximum 8 h average O$_3$ from 75 ppbv to a level within a range of 65–70 ppbv to provide to improve protection of public health and welfare (EPA, 2014) (http://www3.epa.gov/ozonepollution/pdfs/20151001overviewfs.pdf). As the O$_3$ NAAQS are set closer to background levels, states will face ever increasing challenges with regard to fulfilling their obligation for NAAQS attainment. Through this study it was reinforced that, in addition to domestic emission control, intercontinental transport of anthropogenic emissions and wildfires emissions together with meteorological conditions should be considered for an encompassing, cost-effective emission control strategy that accounts for impacts of regional to global emissions and moreover emissions of multi-pollutants (e.g., CO, CH$_4$, NO$_x$, and NMHCs). In addition, the relationships between baseline O$_3$/CO and various factors (e.g. NO$_x$ emission controls, biomass burning emissions, NAO, and AO) examined in this study can also be used as reference point for
evaluating global/regional air quality modeling systems that are used in air quality management applications. One limitation of this study is that it was based on ten-year observations, and hence it was unlikely to predict the potential changes in natural emissions and AO/NAO signals as well as their impacts on baseline O₃. Future research is warranted to further address the issues identified in this work on climatological time scales.

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Disclaimer. Although this work has been reviewed and approved for publication by the U.S. Environmental Protection Agency (EPA), it does not reflect the views and policies of the agency.

References


Mathur, R.: Estimating the impact of the 2004 Alaskan forest fires on episodic particular matter pollution over the eastern United States through assimilation of satellite-derived aerosol optical


Table 1. Ground stations with geographical coordinates and measurement periods.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Measurement Period (CO)</th>
<th>Measurement Period (O₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appledore Island (AI)</td>
<td>42.97°N</td>
<td>70.62°W</td>
<td>18 m</td>
<td>Jul, 2001 - Jul, 2011</td>
<td>Jul, 2002- Mar, 2012</td>
</tr>
<tr>
<td>Thompson Farm (TF)</td>
<td>43.11°N</td>
<td>70.95°W</td>
<td>23m</td>
<td>Apr, 2001 - Jul, 2011</td>
<td>Apr, 2001- Aug, 2010</td>
</tr>
<tr>
<td>Mt. Washington (MWO)</td>
<td>44.27°N</td>
<td>71.30°W</td>
<td>1917 m</td>
<td>Apr, 2001- Apr, 2009</td>
<td>Apr, 2001- May, 2010</td>
</tr>
<tr>
<td>Castle Spring (CS)</td>
<td>43.75°N</td>
<td>71.35°W</td>
<td>396 m</td>
<td>Apr, 2001- Jun, 2008</td>
<td>Apr, 2001- May, 2008</td>
</tr>
<tr>
<td>Whiteface Mountain (WFM)</td>
<td>44.40°N</td>
<td>73.90°W</td>
<td>1484 m</td>
<td>Jan, 1996- Dec, 2010</td>
<td>Jan, 1996- Dec, 2010</td>
</tr>
<tr>
<td>Pinnacle State Park (PSP)</td>
<td>42.09°N</td>
<td>77.21°W</td>
<td>504 m</td>
<td>Jan, 1997- Dec, 2010</td>
<td>Jan, 1997- Dec, 2010</td>
</tr>
</tbody>
</table>

Note: CO and O₃ at AI were measured seasonally from May to September before 2007/2008. Year-round measurements of CO and O₃ began in May, 2007 and February, 2008, respectively.
Table 2. Trends (ppbv yr\(^{-1}\)) of baseline CO and O\(_3\) in spring, summer, fall, and winter. \(p\)-values are in the parentheses. Boldfaced numbers indicate \(p\)-value < 0.10.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Spring CO</th>
<th>Spring O(_3)</th>
<th>Summer CO</th>
<th>Summer O(_3)</th>
<th>Fall CO</th>
<th>Fall O(_3)</th>
<th>Winter CO</th>
<th>Winter O(_3)</th>
<th>Annual CO</th>
<th>Annual O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>2002-2010</td>
<td>0.8(0.66)</td>
<td>-3.1(0.07)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.8&lt;0.01</td>
<td>0.8(0.39)</td>
</tr>
<tr>
<td>CS</td>
<td>2001-2008</td>
<td>3.4(0.06)</td>
<td>2.4(0.19)</td>
<td>1.1(0.57)</td>
<td>6.1&lt;0.01</td>
<td>4.4(0.01)</td>
<td>0.4(0.86)</td>
<td>2.3&lt;0.01</td>
<td>0.7(0.42)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MWO</td>
<td>2001-2009</td>
<td>-13.2(0.51)</td>
<td>-4.5(0.01)</td>
<td>-4.7(0.01)</td>
<td>-4.4(0.01)</td>
<td>-0.9(0.64)</td>
<td>0.1(0.98)</td>
<td></td>
<td></td>
<td>3.5&lt;0.01</td>
<td>0.8(0.43)</td>
</tr>
<tr>
<td>PM</td>
<td>2005-2010</td>
<td>-6.5&lt;0.01</td>
<td>-1.9(0.39)</td>
<td>-5.5&lt;0.01</td>
<td>-4.2(0.05)</td>
<td>-3.4(0.11)</td>
<td>-5.5(0.01)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF</td>
<td>2001-2010</td>
<td>-3.7(0.02)</td>
<td>2.4(0.10)</td>
<td>-4.5&lt;0.01</td>
<td>-3.2(0.04)</td>
<td>0.2(0.90)</td>
<td>-4.8&lt;0.01</td>
<td>2.7(0.09)</td>
<td></td>
<td>2.5&lt;0.01</td>
<td>0.8(0.29)</td>
</tr>
<tr>
<td>PSP</td>
<td>2001-2010</td>
<td>-4.5&lt;0.01</td>
<td>-0.8(0.57)</td>
<td>-4.2(0.01)</td>
<td>3.9(0.02)</td>
<td>-1.9(0.23)</td>
<td>-0.7(0.68)</td>
<td></td>
<td></td>
<td>4.3&lt;0.01</td>
<td>0.7(0.40)</td>
</tr>
<tr>
<td>WFM</td>
<td>2001-2010</td>
<td>-0.5(0.78)</td>
<td>0.4(0.83)</td>
<td>-4.7&lt;0.01</td>
<td>-6.4&lt;0.01</td>
<td>0.5(0.76)</td>
<td>2.1(0.21)</td>
<td></td>
<td></td>
<td>2.8&lt;0.01</td>
<td>0.9(0.27)</td>
</tr>
</tbody>
</table>
Table 3. The contributions, in $R^2$, of CO emissions from wildfires over Russia, Canada, Alaska, and California to variation ($\hat{\tau}^2$) in baseline CO at each site. The combined effect of wildfire emissions over Russia and Canada was also computed. Boldfaced numbers indicate $p$-value < 0.10.

|        | Russia |    |    |    | Canada |    |    |    | Alaska |    |     |    | California |    |     |    | Combined |    |     |    |
|--------|--------|----|----|----|--------|----|----|----|--------|----|     |    |            |     |     |    |          |    |     |    |
|        | $R^2$  | $p$ | $R^2$ | $p$ | $R^2$ | $p$ | $R^2$ | $p$ | $R^2$ | $p$ | $R^2$ | $p$ |            | $R^2$ | $p$ |
| AI     | 0.39   | 0.01 | 0.12 | 0.15 | 0.13 | 0.19 | 0.12 | 0.21 | 0.41   | 0.02 | |
| CS     | -0.44  | -0.01 | -0.17 | -0.09 | -0.06 | -0.38 | -0.04 | -0.92 | -0.41 | -0.02 | |
| MWO    | 0.41   | 0.01 | 0.13 | 0.15 | 0.01 | 0.77 | <0.01 | 0.88 | 0.43   | 0.02 | |
| TF     | 0.64   | 0.01 | 0.40 | 0.05 | 0.01 | 0.80 | 0.03 | 0.52 | 0.65   | 0.01 | |
| PSP    | 0.32   | 0.01 | 0.32 | 0.01 | <0.01 | 0.90 | 0.01 | 0.69 | 0.38   | 0.03 | |
| WFM    | 0.32   | 0.01 | 0.32 | 0.01 | <0.01 | 0.90 | 0.01 | 0.69 | 0.38   | 0.03 | |
| Mean   | 0.37   | 0.38 | 0.22 | <0.05 | <0.03 | 0.41 | |

Note: PM was not included due to insufficient data; CS was not included, as mixing ratios of baseline CO at this site were unusually high over May 2003 – June 2008.
<table>
<thead>
<tr>
<th>Pair of Variables</th>
<th>CS</th>
<th>MWO</th>
<th>PM</th>
<th>TF</th>
<th>PSP</th>
<th>WFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAO index vs Baseline O(_3)</td>
<td>-0.75 (0.03)</td>
<td>-0.68 (0.03)</td>
<td>-0.81 (0.03)</td>
<td>-0.81 (&lt;0.01)</td>
<td>-0.58 (0.06)</td>
<td>-0.51 (0.10)</td>
</tr>
<tr>
<td>NAO index vs Baseline CO</td>
<td>-</td>
<td>-0.51 (0.12)</td>
<td>-0.06 (0.46)</td>
<td>0.30 (0.22)</td>
<td>-0.14 (0.36)</td>
<td>-0.16 (0.34)</td>
</tr>
<tr>
<td>Relative humidity vs NAO index</td>
<td>0.85 (0.02)</td>
<td>-</td>
<td>-</td>
<td>0.64 (0.06)</td>
<td>0.23 (0.26)</td>
<td>0.40 (0.13)</td>
</tr>
<tr>
<td>Relative humidity vs Solar radiation flux</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.67 (0.05)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Baseline O(_3) vs Solar radiation flux</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.75 (0.03)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Surface wind speed vs NAO index</td>
<td>0.68 (0.06)</td>
<td>0.76 (0.02)</td>
<td>-</td>
<td>0.57 (0.09)</td>
<td>0.44 (0.12)</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: CO at CS was not included, as mixing ratios of baseline CO at this site were unusually high over May 2003 – June 2008.
Fig. 1. Map of the Northeast U.S. The seven measurement sites used in the study are marked with blue dots.
Fig. 2. Monthly baseline CO (ppbv) at (a) AI, CS, MWO, PM, and TF, and PSP, and (b) MWO and WFM. Monthly baseline $O_3$ (ppbv) at (c) AI, CS, MWO, PM, and TF, and PSP, and (d) MWO and WFM.
Fig. 3. (a) Time series of monthly PV \((10^{-9} \text{ m}^2 \text{ s}^{-1} \text{ kg})\) at 350 K over the study region (40°N – 45°N, 70°W – 77.5°W, indicated with dashed box in Fig. 1) and averaged daily maximum solar radiation flux at TF in spring (March, April, and May). Seasonal 10th percentile mixing ratios of \(\text{O}_3\) with wind from the directions aligned with the urban corridor in (b) winter, (c) spring, and (d) summer. Specifically, the wind directions selected for AI: 157.5° - 202.5°; CS: 157.5° - 202.5°; MWO: 157.5° - 202.5°; PM: 112.5° - 157.5°; TF: 157.5° - 202.5°; WFM: 112.5° - 157.5°; PSP: 67.5° - 112.5°. In addition, seasonal 10th percentile mixing ratios of \(\text{O}_3\) at PSP with wind from the directions aligned with the Ohio River Valley was calculate as PSP_SW (202.5° - 247.5°) in (b), (c), and (d).
Fig. 4. (a) CO emissions from biomass burning based on GFED dataset. (b) Total CO columns based on MOPITT retrievals over Russia (black), Alaska (red), Canada (blue), and California (magenta). Summertime averaged baseline (c) CO and (d) O₃ at each site.
Fig. 5. (a) Annual surface wind speed with yearly variation at each site over summer 2001 – 2010. Northeast U.S. sea surface pressure (hPa) in (b) spring, (c) summer, (d) fall, and (e) winter. Red stars indicate the location of PSP.
Fig. 6. Geopotential height at the 850 hPa pressure level during summer in (a) 2001-2010 (b) 2004. (c) The difference of geopotential height at 850 hPa between summer 2004 and the 10-year average. (d) The annual surface temperature and relative humidity over Alaska and southwestern Canada (55°N – 70°N, 110°W – 160°W) over summer 2001 – 2010. Red stars indicated the area of the study sites. (Source: NCEP/NCAR reanalysis)
Fig. 7. (a) Counts of cyclones in the Northeast U.S. (black) and the AO index (blue) in summer. (b) Geopotential height at 500 hPa from the NCEP/NCAR reanalysis data during summer 2001 – 2010. (c) The difference of geopotential height at 500 hPa between years with strong (2003, 2006, 2008, 2009, and 2010) and weak (2001, 2002, 2004, 2005, and 2007) cyclone activities. (d) The difference of geopotential height at 500 hPa between summer 2009 and the 10-year means. (e) The difference of sea level pressure between summer 2009 and the 10-year means. (f) Time series of summertime baseline CO (black) and baseline O₃ (red) averaged over all seven sites, and Time series of CO emissions (blue) from wildfires in Russia and Canada. Dashlines indicate the 10-year means. Red stars indicate the area of the study sites.
Fig. 8. Wind frequency in summer at (a) PM, (b) MWO, (c) CS, (d) WFM, (e) TF, (f) PSP. N: 22.5° – 22.5°; NE: 22.5° – 67.5°; E: 67.5° – 112.5°; SE: 112.5° – 157.5°; S: 157.5° – 202.5°; SW: 202.5° – 247.5°; W: 247.5° – 337.5°; NW: 337.5° – 22.5°
Fig. 9. (a) Baseline $O_3$ and the NAO index averaged in March and April. The thick orange line indicates the baseline $O_3$ averaged over the seven sites and the thick dark blue line indicates the mean value 46.5 ppbv over 2001 – 2010. (b) Averaged daytime (18:00 – 24:00 UT) relative humidity and daily maximum solar radiation flux at TF in March and April. (c) Averaged wind speed ($> 2$ m s$^{-1}$) from the west ($247.5^\circ – 337.5^\circ$) and the NAO index in March and April.
Fig. 10. The difference of geopotential height (m) and streamlines at 850-hPa between the low O$_3$ years (2002, 2004, 2006, 2007, and 2009) and high O$_3$ years (2001, 2003, 2005, 2008, and 2010). The red star indicates the area including the study sites.

Fig. 11. Same as Fig. 10 except that the difference of PV ($10^{-9}$ m$^2$ s$^{-1}$ kg) at 350 K is shown.