## Response to referee comments on "Influence of Synoptic Patterns on Surface Ozone Variability over the Eastern United States from 1980 to 2012"

We thank the referees for their valuable and thoughtful comments, which have improved our manuscript. This document is organized as follows: the Referee's comments are *in italic*, our responses are in plain text, and all the revisions in the manuscript are shown in blue. Boldface blue text denotes text written in direct response to the Referee's comments. The line numbers in this reply refer to the updated manuscript. (Note: Q1-Q6 refer to the comments from Referee 1)

## Referee 2

***Q7***. *Overall summary. The authors examine specific synoptic meteorological conditions and their influence on surface ozone variability over the eastern United States over several decades. The work has implications for projecting future changes in surface ozone directly from general circulation models, and for more deeply understanding the mechanisms responsible for observed variability, and is thus a useful contribution. I share many of the concerns raised by Reviewer 1, and for example agree that the time scales involved in the analysis, and the resulting interpretations, should be more clearly explained.*

**Response**: We thank the reviewer for these suggestions. Our response to Q2 above addresses the issue of the time periods employed in this study, and we have updated our results using all available data in EPA-AQS and CASTNET. Our response to Q3 describes the sensitivity of ozone variability to different AQS site types, including rural, suburban and urban sites. Our response to Q5 provides a new EOF analysis based on seasonal mean ozone and meteorology.

***Q8***. *Perhaps the paper would be better organized if it were separated by daily variability versus inter-annual variations in the summer mean values. Below I outline some specific points to address.*

**Response**: We have made it easier for the reader to see when we are discussing daily vs. interannual variability. The responses to Q2 and Q3 provide some detail about these revisions. Sections 3 and 4 are address daily variability, and we now include "daily" in their headings. Sections 5-8 discuss seasonal variability, and we include "seasonal" in their headings. In addition, we provide a clear signpost at the start of Section 5 to alert the reader to the shift from our focus from daily to seasonal variability.

The titles of Section 3-8 are as follows:
3. Spatial patterns of temporal variability in **daily** JJA surface ozone in the eastern United States
4. Use of empirical orthogonal functions to diagnose drivers of **daily** ozone variability
5. The polar jet as an indicator of **seasonal JJA** surface ozone concentration in the eastern United States
6. Westward extension of the Bermuda High and the impact on **seasonal JJA** surface ozone

7. Variability in the Great Plains low level jet and implications for **seasonal JJA** surface ozone
8. Percent variability in mean **seasonal JJA** MDA8 ozone explained by synoptic patterns and trend analysis.

Below is the paragraph that serves as a signpost to alert the reader of the shift in focus from daily data to seasonal data in Section 5. Our response to Q5 contains more details.

P11, L14.
In the following sections, we take advantage of information gleaned from the EOF analysis to develop a set of metrics that quantify the relationships between surface ozone and synoptic patterns. Such relationships can be implemented in a simple model and readily applied to archive meteorological output from climate models. Although we have so far focused on daily ozone data, we now turn to seasonal mean ozone data for two reasons. First, the patterns of many synoptic circulations are noisy on daily timescales, making it challenging to define the metrics needed for our simple model. Such circulations include cyclone frequency (Leipensperger et al., 2008), jet wind latitude (Barnes and Fiore, 2013), and the Bermuda High west edge (Li et al., 2011, 2012). The windspeed of the GPLLJ is easier to characterize on daily timescales, and we discuss the effects of daily GPLLJ windspeeds and surface ozone in the Supplement (Fig. S2). Second, meteorological output from climate models is more widely available on monthly timescales than on daily timescales. Thus our simple model, if it depends on monthly mean meteorology, will be of greater utility to the community.

*General Comments.*
***Q9***. *Some of the language could be clarified. For instance, the phrase 'jet wind' is used frequently but from the context it seems this is referring to the location of the jet rather than speed. Similarly, the westward edge of the Bermuda High is said to shift northward, which reads a bit awkwardly. Would it be clearer to cast in terms of the 'northernmost extent of the west edge', or is something else intended? For the EOF analysis, it would help to clarify that expansion coefficients are also commonly called principal components (time series) as well as any other commonly used terminology.*

**Response**:
Throughout the paper, we have clarified the phrase "jet wind." We now say "jet wind speed," "jet wind latitude" or "jet wind frequency." Two examples are below.

P1, L18-23. The first three leading EOF patterns explain 53% of the total variance in detrended surface ozone, displaying (1) a widespread **response** of ozone in the eastern United States associated with north-south movement of **jet wind latitude**, ….

P17 L28-30. This result suggests that a northward shift in BH-Lat in the East Regime is sometimes accompanied by a pole-ward shift in the **polar jet latitude**, which further enhances surface ozone in the northeastern United States.

The term "Bermuda High west edge" has been used in previous studies (W. Li et al., 2011; L. Li et al, 2012; Li et al, 2013), and we continue its use here. At the reviewer's suggestion, we no longer say "westward edge of the Bermuda High" when discussing the north-south or east-west movement of the edge, but use "west edge" throughout. In addition, we emphasize that the Bermuda High west edge is actually a point.

P14, L10-12.
The west edge, defined as a latitude-longitude point, serves as an index of the spatial extent of this quasi-permanent high pressure system.

We have changed the 'expansion coefficients' to the 'principal components (PC) time series'. Now we use PC1, PC2 and PC3 to denote the time series for different modes.

P9, L1.
Figure 3b shows that the negative correlation of the principal components timeseries for the first mode (PC1) and daily 500 hPa geopotential height is centered just southwest of the Great Lakes region, indicating that the polar jet in this mode extends further south than its climatological mean position and forms a trough.

P9, L13.
The figure also shows the correlation between PC1 and daily mean 500 hPa wind speeds.

*Specific Comments*

***Q10**. Abstract. Please define terms such as SD and polar jet frequency, and clarify why some of the analysis is only deseasonalized - and why de-seasonalization is necessary when only summer is considered - while other bits are detrended, and why a high SD identifies regions most influenced by weather variability rather than high emissions.*

**Response**: We have made the following changes.
P1, L14-16. Zonally averaged, the **relative standard deviation (SD)** of daily MDA8 JJA ozone shows a bimodal structure, with peaks at 28°-32°N and 40°-45°N, and we show that those regions are **most influenced by the variability in daily weather**.

P1, L25-27. In the Midwest and Northeast, we find that the correlation coefficient *r* between detrended mean JJA MDA8 ozone and the polar jet frequency, **defined as the total number of days the jet traverses the Midwest and Northeast each summer**, ranges between 0.76 and 0.93 over 1980–2012 depending on the time period selected, suggesting that polar jet frequency could provide a simple metric to predict ozone variability in future climate regimes.

We have added text to Section 2 to clarify the reasons for our approach, and we have changed the term "deseasonalize" to "detrend."

P1, L18-23. The first three leading EOF patterns explain 53% of the total variance in detrended surface ozone, displaying (1) a widespread response of ozone in the eastern United States associated with southward movement of jet wind latitude, (2) a north-south pattern linked to the Bermuda High system when its west boundary is located along the East coast, and (3) an east-west pattern characteristic of a westward extension of Bermuda High and an enhanced Great Plains low level jet (GPLLJ).

P5, L23-25. To remove the **effects of intraseasonal variability in meteorology on daily ozone values**, detrended daily anomalies are obtained by subtracting the 30-day moving average from the daily means as in Tai et al. (2010, 2012).

P8, L12-15. In our case, we use *S* (*n*×*p*) to represent the **detrended** daily MDA8 surface ozone concentration in the eastern United States over 1980–2012, where *S* refers to the ozone concentrations over *n* daily time steps in *p* grid boxes.

P21, L1-3. The pattern is also consistent with the day-to-day variability of **detrended** daily JJA MDA8 ozone in the eastern United States diagnosed with Empirical Orthogonal Functions (EOF).

We now focus on relative SD instead of absolute SD to show the bimodal structure as the relative SD removes much of the effect of changing anthropogenic emissions. We refer the reviewer to our responses to Q2 and Q3 above. In addition, the Abstract now reads as follows.

P1, L14-16. Zonally averaged, the **relative SD** of daily MDA8 JJA ozone shows a bimodal structure, with peaks at 30°-35° N and 39°-43° N, and we show that those regions are **most influenced by the variability in daily weather**.

P7, L21-24. The persistence of the bimodal structure in relative SD throughout the time period at all AQS site types and at all CASTNET sites increases our confidence that these peaks signify the influence of meteorology and not that of high emissions of anthropogenic precursors.

***Q11***. *L9 While associated is used, there is a bit of an implication of causation here and so it would be good to right away clarify that the decrease is from emission reductions, as stated later in the abstract.*

**Response**: We have revised the text to make clear that we are not discussing trends here.

P1, L18-23. The first three leading EOF patterns explain 53% of the total variance in **detrended** surface ozone, displaying a widespread response of ozone in the eastern United States associated with north-south movement of jet wind latitude, (2) a north–south pattern linked to behavior of the Bermuda High system when its western edge skims the coastline, and (3) an east-west pattern, linked to deep extension of the Bermuda High into the Great Plains as well as to the strength of Great Plains low level jet (GPLLJ).

**Q12**. L17 What time periods are being considered here? Why use anything shorter than all available data? If the correlation is weaker on longer time periods, as shown in Table 1, might that suggest that other processes play a role in projecting responses to future climate regimes whereas this jet indicator is best on shorter time scales?

**Response**: As discussed in response to Q2, we now use all available data. We have clarified our choice of time periods in Sect. 3 as follows.

P12, L7-13. For example, ozone levels have declined in response to the ~40 % drop in US power plant $NO_x$ emissions beginning in 2002 (Kim et al., 2006; Bloomer, 2008, 2009). **Such rapid changes in emissions make it challenging to remove their effects on ozone concentrations. As a check on our detrending method**, we report the correlation of the detrended JJA MDA8 ozone concentration and the three indices over three time periods: 1980–2012 (the entire period), 1993–2012 (the last 20 years) and 2003–2012 (the last 10 years), all summarized in Table 1.

We have also added new text discussing the increasing correlation coefficient *r* in the more recent timespans.

P12, L22-27. The increasing correlation *r* in more recent decades can be partly explained by the greater number of available observations, which decreases the uncertainty in the calculated relationship between surface ozone and the polar jet indices. In addition, the smaller correlations in the earlier time periods may reflect the challenges in detrending surface ozone, as described above (Kim et al., 2006; Bloomer et al., 2008, 2009).

*Introduction*

**Q13**. p. 13075 L9 seems appropriate to cite early work, e.g., Logan, 1989.
**Response**: Done.

***Q14***. p. 13075 L26 Please check on Eder et al. spelling as it's mis-cited as Edger in a few places.
**Response**: Fixed.

***Q15****. p. 13076 L11-18. Clarify if this study focused on inter-annual or decadal time scales.*

**Response**: We have added the time span of this study.
*P4, L24-25.* In this study, we seek to refine our understanding of the role of synoptic-scale meteorology on the **interannual** variation of surface ozone pollution in the eastern United States **from 1980 to 2012.**

***Q16****. p. 13077. Are the Li et al., 2012 and 2013 studies based on single or multiple models?*
**Response**: We now more clearly describe the Li studies, as follows.

P4, L17-22.
**Using NCEP and ERA-40 Reanalysis data**, both Li et al. (2011) and L. Li et al. (2012) diagnosed a strengthening of the summertime Bermuda High and a westward shift of its west edge over 1948-200. Analysis of an **ensemble of models from the Coupled Model Intercomparison Project (CMIP5) reveal that** the Bermuda High west edge is expected to shift westward by ~5° by 2100 due to the stronger thermal contrast between land and ocean (W. Li et al., 2012; Li et a., 2013)**.**

***Q17***. *Clarify what else would contribute to observed variability in Question 1. In other words, what else would be playing a role? Or is the intent to delve into the specific synoptic meteorological conditions (i.e., different weather systems)?*

**Response**: We now clarify the question.
P5, L5-6. What is the percent contribution of synoptic meteorology (**vs. local meteorology**) to the observed variability in U.S. surface ozone?

***Q18***. *Section 2. Are all sites falling within a 2x2.5 grid cell simply averaged or is something more sophisticated being done to account for uneven spatial sampling? This needs to be stated.* P13079

**Response**: We now clarify our approach.
P5, L14-16. We converted the hourly ozone data to daily maximum 8-hour average (MDA8) ozone, and then interpolated onto 2.5°×2.5° resolution **by averaging all observations within each grid cell**.

***Q19***. *Also, why are annual means being used here when the abstract implied it was summer means?*

**Response**: Fixed.
P5, L26-27. For the **seasonal** ozone values, the 7-year moving average is subtracted from the **seasonal** means.

***Q20***. *What is the rationale for removing a seven-year average to detrend? It's unclear whether this would adequately remove emission trends as they have changed rapidly, with step changes in the early 2000s. Perhaps this could play a role in Table 1 as to why the correlations seem stronger on shorter periods? Somewhere it should be explained that natural emissions respond to meteorology and this is included in the variability attributed to meteorology.*

**Response**: We have added new text.

P5, L26-29. For the seasonal ozone values, the 7-year moving average is subtracted from the seasonal means. The choice of seven years is arbitrary, but we find that it produces good correlations between surface ozone and meteorological patterns. With ozone observations available only since 1980, it is not appropriate to apply more complicated detrending methods.

The reviewer is correct that the rapidly changing emissions may be one reason why we find less tight correlations between ozone and indices of polar jet activity during earlier years (Table 1). We have amended the text, as shown in our response to Q12.

The reviewer makes a good point about the influence of natural emissions. We have added the following sentence in Section 2.

P6, L1. In detrending seasonal mean surface ozone, our intent is to remove the influence of changing anthropogenic emissions of ozone precursors. Emissions of natural ozone precursors, however, are highly dependent on the interannual variability in meteorology, and their influence on ozone is preserved in the detrended time series.

***Q21***. *L12-14. The spatial pattern looks more coherent for the relative SD; isn't that important?*

**Response**: We have decided to focus on relative SD instead of SD in the updated manuscript. Our responses to Q2 and Q3 provide more details of this decision.

***Q22***. *L15. What is the ratio? Either plot as a fraction or discuss as percent for consistency with the figure.*

**Response**: The term "ratio" refers to relative SD. We have amended the text.

***Q23***. *L28 is incomplete.*
**Response**: This sentence has been deleted.

*Section 3.*
***Q24***. *In addition to deseasonalizing, is the data also standardized (normalized by the individual variances) prior to the EOF analysis?*

**Response**: We didn't standardize the data, consistent with the previous work in Eder et al. (1993) and Fiore et al. (2003).
P8, L15. The ozone in each gridbox is detrended but not standardized.

P13082
***Q25***. *L25 This seems misleading as Fig S1 shows the correlation coefficient is very weakly positive in the Northeast in contrast to the Southeast*

**Response**: The reviewer makes a good point. We have revised the text.
P10, L14-17. The daily correlation of JJA MDA8 ozone and GPLLJ is negative in the southern Great Plains but positive **in the Great Lakes region, mid-Atlantic states, and Southeast** as shown in Fig. S1. This pattern suggests that the GPLLJ contributes to the observed EOF3 pattern in the South but not in the North.

***Q26***. *P13083 L 1-2. It would help to explain further how this is consistent with the anomalous high pressure over Louisiana which is the main feature evident in 3i.*

**Response**: We have added more description.
P10, L 21-24. Figure 3i also gives the composite wind anomaly associated with positive PC3, revealing anti-cyclonic anomalous winds centered over Arkansas, Mississippi, and Louisiana. The anomalous winds are **consistent with the enhanced GPLLJ windspeeds to the west of the anticyclone (Fig. 3h)**.

***Q27**. P13084 L 3. Is this done for each year, or for the entire dataset? In other words, are trends still included?*

**Response**: We now clarify as follows:
*P12, L18-20.* The normalization transforms the data to yield zero mean and unit variance, **but preserves potential trends in the windspeeds**.

***Q28**. P 13084 What are the trends in these metrics of jet activity?*

**Response**: We refer the reader to our discussion of trends in Section 8.
P13, L30-31.
In Sect. 8, we discuss potential trends in polar jet activity and the implications for surface ozone.

Section 8.
P20, L14-17. Consistent with the Leibensperger et al. (2008) trend analysis of JJA cyclones crossing Canada, we also find a significant decrease of the polar jet frequency (-0.099 count $a^{-1}$, $p < 0.1$) and polar jet wind speed (-0.067 m $s^{-1}$ $a^{-1}$, $p < 0.05$) over the 1980-2006 time period. However, we find no significant trend in these variables over the extended time period of 1980-2012.

***Q29**. P13086 L27. Is this the climatological spatial mean that is removed? Or the climatology in each grid cell? Are trends removed too? If it's a spatial mean, are the zonal means subtracted to remove the climatological latitudinal gradients in height?*

**Response**: We have clarified our approach as follows.
P15, L11-16. First, we calculate the scaling factors in each year by dividing the 1948-2012 timeseries of mean JJA 850-hPa geopotential heights averaged over the Bermuda High domain (40°-100°W, 20°-40°N) by the climatological mean height at that pressure level for this region (1564 gpm). Second, we divide the 850 hPa geopotential height in each gridbox by the scaling factor in that year.

***Q30**. P13091 L25-28. Bloomer et al., 2010 (Atmospheric Environment) also show that temperature trends would have increased ozone whereas ozone has declined.*

**Response**: We have added the Bloomer citation.
P20, L12-14. Our work is consistent with Bloomer et al.(2010), which found that surface ozone at five CASTNET sites in the eastern United States declined from 1989 to 2007, despite a warming trend (~0.5 °C $decade^{-1}$) in daytime temperatures.

***Q31**. P13094 L25 It is unclear why the Zhang et al. 2014 paper fits here when the sentence is on the eastern U.S. and that paper focuses on the Intermountain west. There are numerous other papers over the past decade or so that discuss background ozone variability in the eastern U.S.*

**Response**: We have updated our citations.

P23, L19-22. However, local meteorological conditions (e.g., Bloomer et al., 2007) and background ozone levels **(e.g., Fiore et al., 2002; Wu et al., 2008; Wang et al., 2009)** also influence ozone variability in the East, and future climate change could alter these other factors as well.

**Reference**:


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