

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 referee 2 for his or her careful reading of the manuscript and the valuable comments. 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 document refer to the updated manuscript.

We also have made some additional changes in the manuscript, which can be found at the end of this reply.

P.1 L20. This isn’t quite right unless there is a trend in the PCI which doesn’t seem to be the case. Rather, it’s a ozone variability associated with north-south movements of the jet wind latitude.

Response: We have amended the text to say “north-south movement.”

P1, L18. 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...

P. 2 L13-14 Won’t trends in U.S. anthropogenic emissions be at least as important?

Response: We have revised the text.

P2, L12-15. Our work underscores the impact of synoptic patterns on ozone variability and suggests that a combination of changing local and synoptic meteorology together with trends in background ozone will **determine the influence of climate change on U.S. ozone air quality in future decades.**

Main Text.

P.5 L23-26. Is this done within each grid cell?

Response: Yes, it is done within each grid cell. We now clarify.

P6, L7-10. To remove the effects of intraseasonal variability in meteorology on daily ozone values, we obtain the detrended daily anomaly in each grid cell by subtracting the 30-day moving average **in that cell** from the daily means as in Tai et al. (2010, 2012).

P6 L4 This is fine as long as there is no long-term trend in the meteorology – might refer to Table 2 here.

Response: This is a good point. We have added one new sentence here.

P6, L18. **As discussed in Section 8 and Table 2, we find no significant trends in these meteorological patterns.**

P6 L28-P7 L2. But then this would mean that the clear trends seen in Figure 1d and the 3rd column of S1 are due to meteorology trends over this period? Why wouldn’t changing

anthropogenic emissions impact the relative variability too? For example, Bloomer et al., 2009 show that there is a decrease in the ozone response to temperature associated with NO_x reductions. This statement further appears in conflict with the conclusions that trends are due to emissions and that there are no trends, just variability, in the synoptic conditions. It's also in direct conflict with the sentence on P7 L6-7. See also SM P1 L18-19.

Response: The reviewer is correct. We made a mistake in the wording of our resubmitted paper and apologize for the confusion. The new text is now consistent with the later discussion.

P7, L12-13. The relative ozone SD can isolate much of the effect of different NO_x emission levels by normalizing with mean JJA ozone.

P7, L28-29. The trend in emissions changes only the magnitude of relative SD, with decreases at all latitudes, but it does not erase the bimodal structure.

P7 L21-24. Are these latitudes where emissions peak? If not, it seems a simpler argument to make that point.

Response: Both NO_x and biogenic VOCs are important precursors to ozone production. The NO_x emissions peak in the northern United States (Russell et al., 2012), while the biogenic VOCs peak in the South. Thus it is not straightforward to tie the peaks in SD to the peaks in emission. But we do show that the peak in ozone concentrations is not co-located with the peaks in relative SD.

SM P1 L9-11. Zonally averaged ozone concentrations at all site types reveal a unimodal structure peaking around 35°N-40°N for all time spans, with an overall trend of decreasing concentrations from 1980 to present.

P7 L27. Isn't this generally true, not just for the N and S edges?

Response: Yes, it is generally true. We have changed “highly” to “especially.”

P8, L5. Because the daily variability in anthropogenic emission is much smaller than that in weather, the bimodal distribution of ozone SD implies that ozone in the northern and southern edges of the eastern United States is especially sensitive to weather variability.

P8 L15. Thank you for clarifying. But this means the variance may just be largest where the mean values are largest. Standardization seems more in line with the argument for looking at relative standard deviations, to try, to the extent possible, to isolate the synoptic patterns. Perhaps it doesn't matter much however as there are connections with the synoptic conditions identified later in the paper.

Response: The reviewer makes a good point. We have also done the EOF analysis with standardized ozone data. The major EOF patterns are almost the same whether we standardize the data or not. In this study, we detrend the data just for the analysis, which is consistent with the approach in previous EOF studies [Eder et al., 1993; Fiore et al., 2003].

P9 L12. 'Positive EOF scores' might be more clear to say, 'when EOF1 is expressed strongly (i.e., positive PC scores) and the region experiences low ozone levels'?

Response: We have changed the text according to the reviewer's suggestion.

P9, L22-25. Figure 3c shows the correlation between PC1 and daily mean 500 hPa wind speeds, as well as the composite 500 hPa wind anomaly **when EOF1 is expressed most strongly (i.e., when the PC1 scores are positive and ozone levels are low).**

P9 L19-20. Seems important to clarify that vice versa is also true.

Response: The reviewer is correct.

P9, L30. Figure 3d implies that ozone levels over the Gulf States are anti-correlated with those in the Northeast in this mode, with decreased ozone over the Gulf States accompanied by increased ozone over the Northeast **and vice versa.**

P9 L28-31. Are the winds moving northward or northeastward?

Response: We now clarify.

P10, L9-10. As these winds move **northeastward**, they likely carry aged polluted air from the Midwest to the Northeast.

P10 L7-8. But the EOF loadings here aren't symmetric as in 3d (i.e., blues aren't as deep as the reds) so isn't this one rather just identifying the Southeast Atlantic region as one that varies cohesively?

Response: We agree that the Southeast Atlantic region is more important in this EOF mode, but we cannot neglect the blue areas over the Great Plains. First, the ozone anomaly in the blue area is 50% of that in the red area, which is not negligible. Second, the drivers of the ozone anomalies in the red and blue areas are closely linked. Keeping our original statement as is conveys more information to the readers.

P11 25-27 This appears to conflict with a later point that daily data are routinely archived (P 13 L27-28 and P21 L26-27) and if daily are closer to the processes that matter, this is potentially an important message in favor of continuing to archive high frequency output.

Response: We have dropped the second reason for our focus on monthly timescales. We now simply say that the patterns of many synoptic circulations are noisy on daily timescales, making it challenging to define the metrics needed for our simple model.

P11, L29. Although we have so far focused on daily ozone data, we now turn to seasonal mean ozone data. 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).**

P12 L18-22. Why not normalize the ozone too, similar to the meteorological indices? Is Figure 4 before detrending? If not, it doesn't seem the trend was removed.

Response: To provide the readers with a clearer sense of ozone magnitudes for 1980-2012, we choose not to normalize the ozone in Figure 4. The conclusion is the same regardless of whether we normalize or not. Also, the data in Figure 4 are not detrended. We clarify this in the Figure 4 caption.

Figure 4 caption. **The black solid line denotes the linear trend of ozone over 1980-2012.**

P12 L23. How are there more observations in a shorter period?

Response: We offer clarification.

P12, L30. The increasing correlation r in more recent decades can be partly explained by the greater number of available observations **per unit time**, which decreases the uncertainty in the calculated relationship between surface ozone and the polar jet indices.

P12 L25. For this point about smaller correlations in earlier time periods, are the time series being compared of equal length?

Response: We have added one sentence.

P12, L29. These correlations also increase over time when computed by decade, **from 0.7 to 0.9.**

P13 L1. Does this include times when the jet is located in the two southern regions, so it's only separating out times when the jet is further north of the Midwest/northeast?

Response: Yes, it includes times when the jet is located in the two southern regions. In our definition, we find the location of maximum wind speed in the 25°N-60°N latitude band. We have clarified this in the text.

P13, L8-11. To locate the polar jet position on each day, we first divide the region **between 25°N-60°N into 2.5° longitude bands** and then identify the grid box within each band with the greatest 500 hPa wind speed.

P18 L12-14. Do we see this in both 7a and 6b?

Response: Figure 7a reveals the relationship between ozone and the Great Plains Low Level Jet (GPLLJ); Figure 6b discusses the correlations between ozone and Bermuda High latitude. Since the Bermuda High latitude appears to be independent of the GPLLJ, we cannot comment on whether we see the GPLLJ effect in Figure 6b and we leave the text as is.

P18 L22. Where do we see the ozone pollution moving northward in Figure 7? Is this consistent with the point in L25-28 made from Fig 7?

Response: We have revised the text to more clearly show that our results are consistent with those of Zhu and Liang (2013).

P18, L27-20. In the shorter timeframe of 1993-2008, Zhu and Liang (2013) found that the GPLLJ could bring clean maritime air to the Gulf States while transporting ozone pollution **from Midwest to the Northeast** and promoting greater stagnation in the Southeast.

P19, L1-3. **In the West Regime, the GPLLJ ventilates the South Central states and the**

westward shift of the Bermuda High leads to stagnation in the Southeast, consistent with Zhu and Liang (2013).

P19 L14-16 Isn't it more relevant to track the big changes occurring and projected from emission control policies?

Response: We now reiterate here points made in the Introduction and Discussion sections.

P19, L21-23. While future cuts in emissions of ozone precursors could greatly improve air quality, it is not known to what extent policymakers should take the “climate penalty” into account.

P20 L21-22. Aren't random variable excursions expected from internal variability in the climate system?

Response: The reviewer makes a good point. We have updated the manuscript.

P20, L27-28. Reasons for these short-term variations in polar jet indices are unknown; the variations may be simply caused by natural variability.

P20 L25. Also mention that inter-annual variability is investigated?

Response: A good idea. We have updated the manuscript.

P21, L2-4. We investigate the effect of synoptic meteorology on the daily and interannual variability of JJA surface ozone in the United States by using observations from EPA AQS and the NCEP/NCAR Reanalysis.

P21 L4. The EOF isn't only showing a decrease but identifying the region as varying cohesively such that there are also increases, presumably with northward excursions of the polar jet wind.

Response: We have changed the text to match the abstract.

P21, L10-12. The first three leading EOF patterns consist of (1) a widespread response of ozone in the eastern United States associated with north-south movement of jet wind latitude...

P22 L18. But Bloomer et al. 2010 did draw a clear conclusion in their analysis that ozone was decreasing despite temperatures increasing, so where is the lack of consensus?

Response: We have updated the text to avoid confusion.

P22, L22. Afternoon surface ozone decreased at a rate of 0.45 ppbv a⁻¹ over the eastern United States during the 1990-2010 period (Cooper et al., 2012). Previously, the trends in surface temperature had been explored as a possible driver of this trend (Cooper et al., 2012).

P22 L25-28. Under which scenarios(s) do these shifts occur? They are likely dependent on the forcing applied in the models.

Response: Both of them are under RCP 4.5. We have updated the manuscript.

P23, L1-6. For example, in their model study, Barnes and Fiore (2013) detected a ~2° poleward

shift of the JJA polar jet wind in the northeastern United States **in the Representative Concentration Pathway 4.5 (RCP4.5) over the 21st century**. For a similar timeframe in **RCP4.5**, Li et al (2013) calculated a $\sim 5^\circ$ westward shift of the Bermuda High west edge due to stronger thermal contrast between land and ocean, a consequence of climate change previously suggested by W. Li et al. (2012).

P23 L6-14. This seems more like material for the introduction.

Response: We have moved this part to the introduction.

P4, L24. Few chemistry-climate studies to date have documented either the model capability in capturing the synoptic patterns important to ozone or the sensitivity of modeled ozone to these patterns. For example, using the GFDL-AM3 model, Rasmussen et al. (2012) evaluated only the relationship of ozone with local temperature and not with synoptic patterns. Turner et al. (2013), however, found that this model underestimates the dependence of ozone in the northeast United States on cyclone frequency. To our knowledge, no model study has examined the effect of the westward extent of the Bermuda High on calculated levels of ozone in the southeast United States. As noted by Fiore et al. (2009) and Parrish et al. (2014), chemical transport models (CTMs) and chemistry climate models (CCMs) have difficulty in simulating observed ozone variability on both seasonal and multi-year timescales, and at least part of this difficulty may be due to model deficiencies in the representation of synoptic patterns and their impact on surface ozone.

P23 L25. This is not a new conclusion. For example, the National Research Council 1991 report “Rethinking the ozone problem...” clearly shows the influence of meteorology on eastern U.S. surface ozone.

Response: We now add this and other citations and emphasize that our work confirms earlier research.

P23, L21. Our work confirms that the influence of regional meteorology on surface ozone is strong, and that future climate change could offset the air quality gains made by planned reductions of ozone precursor emissions (e.g., NRC, 1991; Wu et al., 2008; Wang et al., 2013).

Table 1. The MAP Climatology of Mid-Latitude Storminess lists 6 different reanalysis product. Which is used here, or is it an average across all of them? It is unlikely the trends are the same in all the reanalysis products.

Response: Because we calculate the jet wind indices using NCEP Reanalysis 1, we use the cyclone frequency from the same reanalysis product.

P29, L8. The 1980-2010 timeseries of JJA cyclone frequencies is from Turner et al. [2013], calculated over the Great Lakes (70°W-90°W, 40°N-50°N) **using NCEP Reanalysis 1** from the MAP Climatology of Mid-latitude Storminess and a cyclone tracking algorithm. Cyclone frequencies for 2011 and 2012 are not available.

Figure 3. Caption L7, L11, L14. Isn't this corresponding to days when the PC is positive so the patterns in panels a,d,g are expressed strongly as shown? Otherwise, the low pressure shown in 3c is corresponding to high ozone (i.e., blues would be red in 3a)? Same for Figure S3 L6.

Response: Yes, the reviewer is correct. We have made the following changes to the captions.

Figure 3, Caption.

L6-13. Composite 500 hPa wind anomalies associated with positive PC1 are shown as black arrows in Panel (c). ... The composite 850 hPa wind anomalies with positive PC2 are shown as black arrows in Panel (f).... Panel (i) also shows the composite 850 hPa wind anomalies associated with positive PC3 (black arrows).

Figure S3, Caption.

L5-12. Composite 500 hPa wind anomalies associated with positive PC1 are shown as black arrows in Panel (c). ... The composite 850 hPa wind anomalies with positive PC2 are shown as black arrows in Panel (f).... Panel (i) also shows the composite 850 hPa wind anomalies associated with positive PC3 (black arrows).

Supplemental Text SM P3 L7. The northeast ozone response is weak compared to the eastern TX region.

Response: We have revised the text to better describe the figure.

SM P3, L6-8. The figure shows that a strong GPLLJ ventilates Texas and the central United States, but is associated with slightly increased ozone in the Northeast and Southeast.

The text on SM P4 could be better connected to Figure 3, by explaining that EOF2 and EOF3 have reversed in their rankings. Please check that the appropriate panels in Figure 3 are referenced here. It looks like 3i and S3f are a good match.

Response: We have added a comparison of the EOFs constructed using daily and seasonal data.

SM P4 L1-13. We first describe the similarities between the two EOF analyses. Like EOF1 derived from daily ozone data (Fig. 3a), EOF1 here is linked to north-south movement of the polar jet (Fig. S3a-3c) and explains 48% of the total variance in seasonal JJA ozone. The next two EOFs derived from seasonal data are similar to the next two derived from daily data, but with the order reversed. Like EOF3 with daily ozone data (Fig. 3g), EOF2 here exhibits an east-west pattern characteristic of a westward extension of Bermuda High and an enhanced GPLLJ (Fig. S3d-3f). This EOF explains 15% of the total variance. Finally, like EOF2 with daily ozone data (Fig. 3d), EOF3 here displays a northeast-southwest pattern associated with enhanced 850 hPa meridional wind from the Gulf of Mexico (Fig. S3g and 3h). This EOF explains 11% of the total variance. The key difference between the two EOF analyses can be seen by comparing Fig. 3f and S3i: in the seasonal EOF analysis, the link between EOF3 and 850 hPa geopotential height is much weaker than what we find using daily ozone data.

Additional changes in the manuscript

We have made some minor changes, which won't affect our previous conclusions.

P1, L25. **We define a new metric, polar jet frequency, as the total number of days the jet traverses the Midwest and Northeast each summer.** In the Midwest and Northeast, we find that the correlation coefficient r between detrended mean JJA MDA8 ozone and the polar jet frequency 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.

P9, L4. **As we shall see,** the use of daily ozone in this EOF analysis provides a clearer picture of the synoptic scale meteorological variables contributing to ozone variability.

P23, L9. Our work identifies the synoptic patterns that strongly influence the variability of U.S. surface ozone, and it provides a set of metrics that may be used to evaluate the skill **of CTMs and CCMs in capturing this influence.** By testing the sensitivity of modeled ozone to the synoptic patterns we identify here, a clearer picture of the causes of model discrepancies should emerge.

SM P3, L21. This is because the averaging process from daily to seasonal data can smooth **noisy data.**