Response to Reviews

We thank the reviewer for constructive comments to improve the manuscript. The comments are reproduced below with our responses in blue. The corresponding changes in the manuscript are highlighted in blue.

Reviewer #3

This study examines the correlations between drought and air pollutants (ozone and PM2.5) in the US. The authors use the linear regression slope derived from drought indices and ozone/PM observations to infer the effects of drought and argue that most chemistry-climate models are not able to reproduce the observed relationships. The authors further apply the observed relationships to climate model projected drought occurrences and attempt to estimate the effects of increasing drought on ozone and PM by 2100 compared to the 2000s.

The manuscript is well structured and readable. However, there is a major flaw in the applied method to quantify the impact of drought. The correlations between drought and ozone reported in this study may reflect the common underlying correlation with air stagnation and temperature rather than a causal relationship of drought on ozone. An inspection of the model differences in their Figure 5 supports this statement. None of these models include the effects of soil moisture deficits on BVOC emissions and the reduced efficiency of ozone dry deposition sink to vegetation. Nevertheless, the GISS model with interactive isoprene emissions simulates the SPEI/ozone slope comparable to the observed values over the Southeast. The greater slope simulated in GISS as compared to other models reflects the inclusion of interactive isoprene emissions, which allows the model to simulate ozone enhancements resulting from stronger isoprene emissions during heat waves (see Schnell et al., 2016). Reduced BVOC emissions under drought stress will actually lead to less ozone.
We thank the reviewer for making this important point, which we have careful analyzed and extensively discussed in the revised manuscript. We've added a new session (Section 3.2) and several new figures (Figure 3, Figure S4-S6) to discuss the meteorological factors behind the SPEI-pollutant relationship and the possible compounding effects of stagnation and high temperatures.

In the new Section 3.2, we first acknowledge that there are well-established linkages between air quality and some meteorological parameters (e.g. temperature), thus the drought-pollution association may be partly explained by the effects of drought on these meteorological variables. We then discussed the differences between drought and meteorological parameters (temperature, RH, and winds) and meteorological events, including heat wave and stagnation. The first difference is that drought is not a daily-scale extreme or variable, such as temperature or RH. Drought arises only after a prolonged (> week) period of precipitation shortage that causes soil to dry up. Therefore, we chose the monthly scale to identify the drought-pollution association, differentiating it from day-to-day variability of meteorology. Second, drought is a complex extreme not based on individual meteorological parameters (e.g. temperature, humidity) or a simple combination of them. The prominent feature of drought is water deficit in both the atmosphere and the land component (e.g. soil and vegetation), resulting from the combination of precipitation shortage and increasing evapotranspirative water loss driven in part by high temperatures. As a result, the associated vegetation responses are likely to be more pronounced during drought than those associated with short-term meteorological extremes/events, which are relevant to our later discussion of isoprene changes. The change in isoprene during drought found in our study is consistent with Schnell et al. (2016) in that isoprene tends to increase in most drought conditions (Figure 4); only under extreme drought (SPEI <-2) isoprene is shown to decrease in limited observations.

We then examined the relationships of monthly occurrences of stagnation and heat waves with the SPEI at each 0.5^ox0.5^o grid over the study period; the results are shown in the new Figure S4 in the supplementary material. There are positive correlations between drought-stagnation and drought-heatwave across the US, indicating both events do occur more frequently during drought months. But the squares of these correlations are all below 0.4, with a typical value of 0.1-0.2 for the most parts of the US. This suggests that on the monthly scale stagnation and heat waves would typically be able to explain 10%~20% variability in the SPEI, a non-trivial but small fraction. As shown in the lower panel of Figure S4, stagnation and heat waves have an average 7% and 5% increase in their frequencies during drought months compared to normal months, although the extent of such increases varies greatly by region. The maximal increase of stagnation frequency during drought is about 15% in the west, southern Great Plains and southwest, where stagnation tends to occur frequently even during normal conditions. The largest increase of heat waves during drought is about 20% in the southern Great Plains.

Finally, to quantify the compounding effects of stagnation and heat waves on the drought-pollution association, we re-evaluated the SPEI-pollutant relationships by applying weights to each pair of SPEI and pollutant anomalies (ozone and $PM_{2.5}$). The weights are given as the percentages of days in each month (regardless of drought or non-drought) that are neither stagnation nor heat wave, assuming the two events are mutually exclusive which would give an upper bound for the weights. Since the weights are between 0 and 1, the weighting process effectively scales down the magnitude of pollution anomalies in each month. The weighted correlation and enhancements are shown in the new Figure 3. The weighting does not change the sign or statistical significance of the SPEI-pollutant correlations at all the sites, indicating the covariance of drought with stagnation and heat waves might not be the dominant factor causing the drought-pollutant correlations. The weighting however reduces the magnitude of ozone and $PM_{2.5}$ enhancements associated with drought by an average of 40% when both events are combined. This indicates that more frequent stagnation and heat waves could explain up to 40% of the ozone and $PM_{2.5}$

enhancements during drought, a significant but not majority fraction.

While severe drought can potentially lead to elevated surface ozone by reducing the ozone dry deposition sink to vegetation (see a review by Fowler et al., 2009), this impact has to be demonstrated using a more sophisticated statistical approach (e.g., multi-variate regression) or chemistry-climate model sensitivity experiments to isolate the role of air stagnation and temperature. For example, Lin et al. (2017) showed that reducing ozone Vd by 35% in GFDL-AM3 during the severe North American drought of 1988 simulates 10 ppbv greater ozone enhancements than a BASE simulation with constant Vd, although the BASE simulation still captures observed ozone enhancements during the other warm summers driven by processes other than drought (see their Section 6 and Figs.18 and 19).

We agree with the reviewer that this manuscript is not an attribution analysis (e.g. using chemistry-climate model sensitivity experiments), and we have explicitly stated so in the manuscript: "… attribution of the underlying causes would require chemistry-climate model sensitivity experiments, which is outside the scope of the present study" (pg 10, line 33-36). We've added Lin et al. (2017) as reference when discussing the dry deposition effect.

Without a more careful attribution analysis to separate the influence of stagnation and temperature, you cannot use the terms like "drought-induced", "causes of ozone and PM enhancements by drought" or "effects of droughts". All such terms in the present manuscript will need to be removed or rephrased.

Our new analysis (Section 3.2) showed that the drought-pollution relationship is still significant after discounting the influence of stagnation and temperature on air pollution (see the response to the first comment), which supports our argument that droughts affect air quality. However, we agree with the reviewer that our manuscript is not an attribution analysis by design and thus some of the terms need to be modified. We've modified all the attribution terms throughout the manuscript to non-attribution ones such as "pollutant enhancement associated with droughts" or "drought-pollutant relationship" or "drought-pollutant association".

In summary, the analysis presented in the current manuscript shows a correlation between drought indices and air pollutants but not the causal effects of drought on air quality. The derived slope may serve as a useful diagnostic to evaluate the models, as the authors show, but it cannot be used to quantify the impact of drought on air quality.

We agree. As stated above, we've changed attribution statements to non-attribution ones throughout the manuscript.

Relevant references:

Fowler D, Pilegaard K, Sutton M, Ambus P, Raivonen M, Duyzer J, *et al.* Atmospheric composition change: ecosystems–atmosphere interactions. *Atmospheric Environment* 2009, **43**(33)**:** 5193-5267.

Lin, M., Horowitz, L. W., Payton, R., Fiore, A. M., and Tonnesen, G.: US surface ozone trends and extremes from 1980 to 2014: quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate, *Atmos. Chem. Phys.*, 17, 2943-2970, https://doi.org/10.5194/acp-17-2943-2017, 2017.

Schnell JL, Prather MJ, Josse B, Naik V, Horowitz LW, Zeng G*, et al.* Effect of climate change on surface ozone over North America, Europe, and East Asia. *Geophysical Research Letters*, 43(7)**:** 3509-3518, 2016

Kavassalis, S.C. and Murphy, J.G.: Understanding ozone-meteorology correlations: A role for dry deposition. *Geophysical Research Letters*, 44(6), pp.2922-2931, 2017