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 #1

This study addresses the effects of drought on air quality in the United States through statistical analysis of historical observations at surface monitoring sites and two drought indices, the Standardized Precipitation Evaporation Index (SPEI) and the Palmer Drought Severity Index (PDSI). It also examines the ability of several current climate-chemistry models to simulate observed responses of ozone and fine particulate matter under drought conditions as identified by model-derived SPEIs. Future model projections of SPEI and air quality are examined as well. The relationship of drought and air quality is a timely, highly relevant topic, appropriate for the readership of Atmospheric Chemistry and Physics.

Overall, the manuscript is generally well-written with only a few minor typographical or grammatical areas. There are several technical questions/comments that should be addressed prior to reconsideration for publication:

(1) Have many previous studies examined relationships between drought indices and observed air quality? Previous studies should be identified and to the extent possible discussed in the context of this work. See for example, Tian et al. doi:10.1002/ehs2.1203.

To our knowledge, few studies have examined the relationship between drought indices and observed air quality at a temporal and spatial scale similar to our study (i.e. 25 years, continental US). There are a few papers analyzing on one or two aspects of the drought impact on atmospheric compositions associated with dust and fire emissions (Prospero and Lamb, 2003;Westerling and Swetnam, 2003). Tian et al (2016) analyzed the combined effects of drought and ozone on crop productions in China, but they did not explicitly consider the drought effects on ozone. Our previous work (Wang et al., 2015) conducted a case study of surface $PM_{2.5}$ enhancements associated with the 2011 southern US drought. We have added discussions of all these previous studies in the introduction of the revised manuscript.

(2) Many drought indices exist now and the number will likely further evolve in the future. Are there indices that are particularly relevant for examining the relationship between drought and air quality, and if so why?

Air quality responds to changes not only of the atmosphere but also the land biosphere, thus the drought indices that are most relevant for air quality would be those that measure both meteorological (e.g., temperature and precipitation) and land biosphere conditions (e.g., soil moisture, evapotranspiration, vegetation, etc.)

associated with drought. In addition, the temporal duration of drought is a matter of concern for air quality because air pollutants have different characteristic time scales with respect to transport and chemistry. This requires the relevant drought indices to be explicit of drought duration (e.g., month, year) in their calculation.

Take the Standardized Precipitation Evapotranspiration Index (SPEI) as an example, which is the primary drought index used in our study. The SPEI is based on water balance between precipitation and reference evapotranspiration, the latter dependent on atmospheric water demand related to temperature. Therefore it represents both meteorological conditions and water stress on land biosphere conditions during drought. In addition, the SPEI is multi-temporal and can specify drought duration of monthly, and multi-months. Our study used the 1-month SPEI and the correspondent monthly-mean air pollutant data (ozone and PM2.5) to derive the relationship between drought and air quality. By comparison, the Standard Precipitation Index (SPI) or the PDSI would not be a good drought index for air quality purpose because the SPI considers only meteorology (i.e. precipitation) while the PDSI does not specify drought duration.

The above points were implicit in the original manuscript where the SPEI is introduced (Section 2.1). We've now explicitly expressed them in the revised Section 2.1.

(3) Is there evidence in the historical data that the timing of the onset of drought influences air quality (e.g., late spring vs. early summer vs. late summer)? Is there evidence that prolonged drought more strongly influences air quality over time?
We added a new Figure 2 comparing the different effects of drought onset and prolonged drought on ozone and $PM_{2.5}$ enhancements. Both pollutants show larger enhancements during prolonged drought compared to drought onset across the four regions, except for $PM_{2.5}$ over the northeast. See the detailed discussion about Figure 2 added at the end of Section 3.1.

(4) More explanation as to how model-derived SPEIs were calculated (e.g. what method in the R package was used to determine PET?) and their performance relative to the global SPEI dataset and to each other would be beneficial. Model-derived SPEIs are important to establishing predicted air quality during drought versus nondrought conditions and evaluating model deficiencies relative to observed responses in this work.
The model-derived SPEI were calculated with R package provided by the SPEI developer using model precipitation and temperature as inputs. The SPEI is derived as logistic-normalized distribution of water deficit, estimated as the difference between precipitation and reference evapotranspiration. Both Thornthwaite (Th) and Penman-Monteith (PM) method can be applied for estimation of the reference evapotranspiration. The Thornthwaite (Th) method only requires temperature data while the Penman-Monteith (PM) method requires additional inputs including RH,

wind speed and radiation. Since ACCMIP model archives do not have all the variables required for the PM method, we used the Th method to calculate model SPEI. The global SPEI dataset use the PM method to estimate reference evapotranspiration. The correlation between SPEIs derived with PM and Th method is high (correlation r >0.9) (Beguera et al., 2014), thus the use of Th method may not have large impact on model SPEI calculation. We've clarified this point in the manuscript (Section 2.3).

With regard to the model ability of simulating drought, Figure S7 in the supplementary material presents the model-simulated drought frequencies during the historical period (1990-2014). The models can capture well the observed spatial patterns of drought occurrence frequency. Severe drought (model SPEI < -1.3) occurs ~20% of the time over the west and southern US, consistent with observed SPEI. However, the temporal correspondence (i.e. month-to-month) between model SPEI and global SPEI dataset is weak, largely due to the models deficiency in simulating temporal variability of precipitation. This weak correlation however is not expected to affect the model evaluation because we used the model SPEI to derive the simulated SPEI-pollutants relationships from each model. We've added discussion of the model SPEI in the manuscript (pg 9, line 33-39).

(5) It is acknowledged in the manuscript that the ACCMIP models vary widely in their predicted responses of air quality to drought. More explanation is needed regarding differences in the configuration and input data resources that could contribute to differences in their performance. A key outcome of this study should be to recommend specific paths forward for research that could lead to improvements in chemistry-climate model performance.

Agreed. Emissions, deposition, and chemistry are the most important aspects of model configurations affecting the drought-pollutants relationship. Anthropogenic emissions and biomass burning emissions were specified, but natural emissions were not, so the models treated natural emissions differently, which is a key factor in the different performance between models. For example, only the GISS-E2-R model simulates isoprene emissions as coupled with its meteorology (mostly temperature), thus allowing for isoprene emissions to increase with increasing temperatures. The other three models used prescribed BVOC emissions, thus representing different responses of those emissions to meteorology and climate change. All the ACCMIP models include dry and wet deposition of pollutants. While they all show large reductions of wet deposition during drought, the dry deposition is not sensitive to drought. With regard to aerosol chemistry, all the models overestimate the sulfate reduction, but at the same time underestimate the OA increase during drought. Both problems might be caused by the model misrepresentation of cloud sensitivity to changing drought severity, although the OA bias could also be caused by uncertainties of fire and BVOC emissions in the models. We've expanded the modeling discussion in Section 3.4 (last paragraph).

(6) Table 1, Fig. 2, Table S2 etc suggest that there are regional differences in

contributions to drought effects to air quality, but the discussion is too limited in this regard. Are there opportunities to better understand model performance via examining regional responses?

This is a good point. We've expanded the discussion of regional differences in the revised Section 3.1 when presenting the regional-mean pollutants enhancements associated with drought (e.g. new Figure 2), as well as in the newly added Section 3.2 when presenting regional differences in meteorology during drought (e.g. new Figure 3 and Figure S4). A detailed region-to-region comparison is however outside the scope of the current manuscript and will be a future endeavor, as our main goal here is to provide observational evidence of the robustness and spatial prevalence of pollution enhancements during drought across the US.

Minor corrections:
First paragraph, introduction: Line 2: "matters" should be matter;
Line 4: missing "the" at the of the line; Line 10: missing noun after "recurring", Line 11: missing "the" before "atmosphere". Page 6, Line 2: "primarily resulted from" should be "primarily result from"
All are corrected.

References:

Beguera, S., Vicente‐Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, *International Journal of Climatology*, 34, 3001-3023, 2014.

Prospero, J. M., and Lamb, P. J.: African droughts and dust transport to the Caribbean: Climate change implications, *Science*, 302, 1024-1027, 2003.

Tian, H., Ren, W., Tao, B., Sun, G., Chappelka, A., Wang, X., Pan, S., Yang, J., Liu, J., and S Felzer, B.: Climate extremes and ozone pollution: a growing threat to China's food security, *Ecosystem Health and Sustainability,* 2, 2016.

Wang, Y., Xie, Y., Cai, L., Dong, W., Zhang, Q., and Zhang, L.: Impact of the 2011 southern US drought on ground-level fine aerosol concentration in summertime, *Journal of the Atmospheric Sciences*, 72, 1075-1093, 2015.

Westerling, A. L., and Swetnam, T. W.: Interannual to decadal drought and wildfire in the western United States, *EOS, Transactions American Geophysical Union*, 84, 545-555, 2003.