Response to the reviews on "Toward enhanced capability for detecting and predicting dust events in the Western United States: the Arizona Case Study" by Huang et al., 2015

Min Huang on behalf of the authors, Oct 2015

We appreciate the valuable comments and corrections from both reviewers, which helped improve this manuscript. Please see below our point-to-point response to both reviewers' general and specific comments. The original comments and our responses are in black and blue, respectively.

Response to the comments by Dr. Janae Csavina

Huang et al. are presenting on research that hits almost every item in the scope of ACP: chemical and physical processes using atmospheric modelling, field measurements, and remote sensing. The title clearly presents the contents of the manuscript with the subject matter of better detecting and predicting dust events being highly relevant in the scientific community today and highly needed to mitigate the deleterious societal impacts. The authors combine a multitude of relevant observational datasets available to the community to present the novel approach of improved prediction. The authors' navigation through the different datasets was a little hard to follow at times but the presentation of the comparison between datasets and overall thoughts on inconsistencies with supported literature is helpful. The information on the data, methods, results and supplemental datasets provide the necessary path for other scientists to perform similar work. While as a reader, I wanted more out of the conclusions and suggestions, I believe this is more a reflection on the need for improvement in this research area than a lack in significance of the manuscript and the combination of these datasets available to the community is a novel and possibly necessary approach well illustrated in the results.

Thanks for this comment. Conclusions and suggestions on future directions have been refined or expanded (as also summarized below). Many changes also addressed the comments by the other reviewer.

On observation:

- Characterizing dust composition and improving the identification of dust source regions by using satellite measurements (e.g., land, soil and composition products such as NH_3) and in-situ measurements of trace gases and aerosol compositions;
- Using hourly measurements (e.g., AQS/AirNow and meteorology) for timely identifying dust events;
- Expecting newer/improved products from polar-orbiting instruments, and future products from geostationary satellites that will sample more frequently.

On modeling and evaluation:

- Integrating observations (satellite soil moisture and land products) into regional dust emission modeling;
- Comprehensive model evaluation using surface hourly measurements (e.g., AQS/AirNow and meteorology) along with available satellite observations;
- Improving the capability of well simulating both ozone and PM when dust storm and stratospheric ozone intrusion concur.

There are specific recommendations below that would help the reader better and more quickly understand the material:

~Provide a summary table of the datasets (acronyms, source, data product [soil moisture; vegetation; drought; PM10; PM2.5], data input [temp & precip; satellite imagery; HiVol field measurement; modeled PM measurements]) and possibly overall conclusions/benefits/suggestions about the dataset.

Good suggestion. A summary table (current Table 1) has been created, which includes the information of all datasets used in this paper.

~Section 2.5 refer to the NAM model and GEOS-Chem without much explanation.

The NAM model was first introduced in Section 2.4 (current Section 2.5), as one option of the meteorological fields for the HYSPLIT calculations. We expanded the introduction and references of both models in Sections 2.5 and 2.6, and also in the current Table 1.

~The introduction needs to include why stratospheric ozone in important for dust storm impact/prediction. On Lines 18 through 21 on 20760 "It's known that stratospheric ozone intrusion...." needs to be covered prior to the results (maybe just move this point).

Related background information is now included in Section 1.

~Line 15 on 20755 says "impact" but does not indicate whether this is an improved impact on modeling.

We expect an overall improvement. This paragraph has been rewritten, and some discussions on MODIS-derived dust source areas have been added, as suggested by the other reviewer.

~There are a couple instances in the results where it is unclear where the authors' results end and where the literature support begin (Line 15 on 20755 and Line 18 on 20756).

This paragraph starting from line 15 on 20755 has been rewritten for clarity, and some discussions on MODIS-derived dust source areas have been added. Literature (including Kim, D. et al., 2013) now can be found in Section 2.2. We did not cite any literature near Line 18 on 20756, so we are not sure what this part of the comment referred to.

Some technical issues:

~Many figures need better explanation of the scale being presented (Fig 1a & b, 2, 3b) either in the discussion or figure caption.

The linear color scales in Figure 1a-b were determined by the range of satellite NDVI and soil moisture in the southwestern Arizona in selected years. Specifically, NDVI spanned from <0.1 to >0.3 for these years, and soil moisture ranged from ~0.05 to >0.15. Values larger than 0.4 (NDVI) and 0.2 (soil moisture), mostly out of the southwestern Arizona region that we mainly focus on, are colored in purple.

The linear color scale for Figure 2 was determined also by the range of satellite DOD values from 2005-2013. In general, the DOD values fell within the range of 0-0.6 (note that we now use deep blue collection 6).

Figure 1c and Figure 3b (current Figure 4b) show the anomalies of different variables, and the anomaly is defined as the ratio of annual mean value over the multi-year mean value, in Section 3.1. We now also define this in Figure captions. In both plots, the ranges of the y axes were determined by the ranges of anomalies during 2005-2013 for the plotted variables.

~Figure 1 needs some clarification. I believe the numbers in the upper left hand of 1a indicate years chosen to study due to dry and wet conditions observed from analysis in 1c.

This understanding is correct. For clarity, we added in the caption of Figure 1 "The text in the upper left corner of each panel of (a) and (b) indicates the year of data."

It almost seems like 1c should be presented on first if that is the case and clarifying that these are indeed years and why chosen is necessary.

The order of (a)-(c) of Figure 1 is consistent with the order they are cited in the main text, and in the text 1a-1b were mentioned before 1c in Section 3.1. Figure 1a-b show the conditions over the entire state of Arizona on "selected moderate to severe wet or dry years in the southwestern Arizona", while Figure 1c shows only the inter-annual variability over the southwestern Arizona, where dust activity is in general more intense than the rest of the state. The "southwestern Arizona" is defined in the figure.

~Figure 2, the purple star is not discernible.

The size of this purple star in current Figure 2a has been doubled.

~Line 10 on 20747 and Line 5 on 20749 are missing "("

Corrected.

Response to the comments by Dr. William Sprigg

General Comments: This paper does report on some significant findings over the past decade regarding elevated dust detection and modeling. A partial list is provided in specific, following remarks. While the approach is novel, and introduces use of new tools, the authors' case could be made stronger for, "This study develops dust records in Arizona in 2005–2013. . ." In particular, their study report is vague about agriculture sources and their variability, not very specific about the influence of extant sources, and the frequency by which sources should be identified and monitored in order to make a reliable dust record using consistent methods.

Thanks for this comment. The manuscript has been revised to elaborate the sources of dust.

First, on a large spatial scale (i.e., southwestern Arizona/western US), we now specified dust source areas from barren, cropland/agriculture, and open shrubland using MODIS land products, following the method in Vukovic et al. (2014). The details of this method are in Section 2.2. This analysis is to mainly support our discussions on the correlations between drought conditions and dust activity during the past decade, near the end of Section 3.1: Dust source areas (determined by land cover and NDVI data) and soil moisture varied between dry and wet years, and both factors would affect dust production. Barren and cropland contributed most and least to the total dust source areas in these regions, respectively. And the dust sources from open shrubland were most temporally variable. In future, we recommended exploring satellite observations of dust co-emitted species (e.g., NH_3 to indicate the anthropogenic sources, particularly from agriculture, as in Ginoux et al., 2012a) for indicating the dust sources and their variability.

Second, on a much smaller scale, we examined the relationships between co-located hourly surface trace gases (NO_x and CO) and PM measurements in Phoenix (in Section 3.3), as well as the PM2.5/PM10 ratios. This method helped exclude the high PM events strongly influenced by anthropogenic and/or biomass burning sources. Further, HYSPLIT trajectories also helped identifying the upwind dust sources during these dust events. However, better characterizing and attributing the observed dust in Arizona from different sources will need further study, which can benefit from speciated aerosol measurements, and referring to the criteria from previous measurement studies: e.g., High organics and PO4 may indicate that dust was originated from cattle feedlot; Metals such as Cu, Pb, Sb and Zn can be used to distinguish human sources from the others (e.g., Upadhyay et al., 2015; Clements et al., 2013); The Fe/Ca ratio can be used to distinguish distant sources (e.g., Asian) from local sources (e.g., Van Curen et al., 2005). Currently, there are only very limited routine aerosol composition measurements (e.g., at IMPROVE sites) in the studied areas, and adding sites that monitor aerosol speciation more frequently would be helpful for better understanding the sources of PM and their temporal changes.

We have added related discussions and suggestions in Sections 3.1, 3.3 and 4.

The authors include a nice example of how models (HYSPLIT and CMAQ) may apply in understanding the observed "dust record" for Arizona, but this reviewer felt the connection between modeling a dust event (with CMAQ) and creating a dust record needed more explanation. If the authors cannot explain why the CMAQ run adds significantly to new, important findings shown in this paper, the CMAQ component should be extracted. The paper should be published only after addressing the main points of this review.

We have substantially rewritten Section 3.4 that contains the CMAQ results. Section 3.4 introduces a recent dust event when high PM (mostly from dust) and ozone (influenced by stratospheric ozone intrusion) were observed in several western states including Arizona. As this reviewer pointed out, demonstration of such events is a significant contribution from this study. This selected case study includes a number of observational (AirNow, IMPROVE, AIRS) and modeling (CMAQ and RAQMS) datasets. The CMAQ base and sensitivity results contribute to this case study in terms of how dust affected the surface PM distributions during this event, and therefore, it is important to keep these results together with the other datasets in this case study.

In addition, there are two major connections between the decadal dust records and regional dust/air quality modeling, and these have been made clearer in the revision:

1) Evaluate the trends and variability of dust record and emphasize the importance of timely and accurately modeling dust events under the changing climate, in order to reduce their negative impacts in time.
2) Suggest the usefulness and limitation of using current observations for evaluating and further improving this dust modeling system (e.g., IMPROVE vs. AQS/AirNow; using satellite-based dynamical vs. static dust source regions in the dust emission modeling).

Scientific quality: Are the scientific approach and applied methods valid? Are the results discussed in an appropriate and balanced way (consideration of related work, including appropriate references)? Relevant work by others is missed, lowering readers' confidence in the thoroughness of the study being reported upon. E.g. Mahler, Yin, Vukovic, Sprigg, Morain, the USGS (e.g. Reynolds et al.) and NASA JPL (e.g. Painter)

We have cited related literature (not limited to those suggested here) in multiple sections of the paper.

1 Does the paper address relevant scientific questions within the scope of ACP? Yes

2 Does the paper present novel concepts, ideas, tools, or data? Yes, combining a variety of satellite-based (MODIS) and surface-in-situ (AirNow & IMPROVE), models (HYSPLIT, CMAQ, NAM) to assess potential relationships of interannual drought and airborne dust.

3 Are substantial conclusions reached? Stratospheric ozone intrusion and other synoptic weather patterns combine to generate dust, hence a forecast system should account for both. This is an important conclusion, for this phenomenon may not be important for much of the rest of the world. Identifying its importance in Arizona and the SW US is useful. Substantial conclusions are not reached in the sections describing CMAQ. One storm, one example, at 17 km spatial resolution, does not appear to add much to extending the dust record. Nor does this one model test tell us much about how to use dust sources to improve model simulations of dust concentrations. Too, the paper's Abstract concludes that the, ". . . 12km CMAQ model during a recent strong dust event in the western US 20 accompanied by stratospheric ozone intrusion . . . (shows) that the current modeling system well captures the temporal variability and the magnitude of aerosol concentrations during this event . . ." This statement needs a definition of "well captured." There is at least one other modeling system (e.g. Vukovich, et al., 2014; Sprigg, et al., 2014) that if compared, arguably would affect this wording.

We agree that the combined stratospheric intrusion and dust impact on air quality is one of this paper's highlights. Taken the other reviewer's suggestion, the combined stratospheric intrusion and dust impact is now introduced in Section 1. We also added AIRS ozone and CO as observational evidence of the stratospheric intrusion.

In Section 3.4, we show the poor surface air quality in the western US during a period when stratospheric ozone intrusion and high dust concurred using the CMAQ and RAQMS model results, along with the observational evidence (e.g., satellite ozone and dust products, surface PM).

The broader spatial coverage (i.e., over the entire continental US) is one of the advantages of this CMAQ modeling system, compared to many of the cited modeling studies (including those suggested by the reviewer) that used similar or finer resolutions but mainly focused on Arizona. With this broader spatial coverage, this system is suitable for studying dust events over various source and receptor regions in the

US. For example, during this May 11, 2014 event, both CMAQ and observations showed that dust was originated from California on the previous day, and Arizona was just one of the affected states.

In this case study, the current CMAQ modeling system is used to assess the impact of dust emission on regional air quality, rather than to explore how sensitive dust emission/atmospheric concentration to the dust source input. However, according to previous studies and the findings in previous sections of this paper, we suggested that dynamical dust source should be experimented in the future in this modeling system. The CMAQ model performance was quantitatively evaluated (Section 3.4), and we agree that vague statements including "well captured" should be avoided.

4 Are the scientific methods and assumptions valid and clearly outlined? They are clearly outlined, but an unwritten assumption by the authors is that their methods of monthly satellite measures of soil moisture and NDVI are adequate in covering the highly variable contributions of agriculture (e.g. irrigation, crop cycles) to dust sources and emissions. This assumption is doubtful.

In Section 3.1, we averaged the daily satellite soil moisture and monthly-mean NDVI data through the dust seasons (March-August) for each year during 2005-2013. The inter-annual variability of these drought indicators over the dustiest region in Arizona (i.e., southwestern AZ) was compared with those of the observed dust activity (e.g., satellite DOD). In this analysis, our assumption is that the satellite products can reasonably well (i.e., to the similar degree of the satellite DOD. Note that we now use the MODIS deep blue collection 6 and cited previous validation study on the change in AOD bias through the past decade) represent the drought conditions on large spatial (southwestern AZ) and temporal (inter-annually) scales. In fact, generally, averaging satellite data over large spatial/temporal scales can reduce the uncertainty. We agree that satellites could have some limitations to precisely represent the surface conditions and the variability of soil moisture, as well as to capture all dust events (as in concluded from Section 3.3).

More discussions have been added to Sections 3.1 and 4, stating that satellite products in finer spatial and temporal resolutions (including those from newer sensors such as SMAP and VIIRS) would be more beneficial for locating dust source regions and dust emission modeling, and better quantifying and reducing their uncertainty should be encouraged. This not only applies to dust sources from cropland/agriculture, which contributes to a very small fraction of the total dust source regions in the southwestern US (consistent with the findings by Ginoux et al. (2012b) and Nordstrom and Hotta (2004))--As we show in Section 3.1, based on MODIS land products, dust sources from open shrubland were more temporally variable than cropland and contributed more to the total dust source areas than the cropland.

See, e.g., papers by:

a) Vukovic A., Vujadinovic M., Pejanovic G., Andric J., Kumjian M.J., Djurdjevic V., Dacic M., Prasad A.K., El-Askary H.M., Paris B.C., Petkovic S., Nickovic S., and W.A. Sprigg (2014) "Numerical Simulation of 'An American Haboob"', Atmos. Chem. Phys., 14, 3211-3230, 2014, doi:10.5194/acp-14-3211-2014

b) Sprigg W., Nickovic S., Galgiani J.N., Pejanovic G., Petkovic S., Vujadinovic M., Vukovic A., Dacic M., DiBiase S., Prasad A. and H. El-Askary (2014) Regional dust storm modeling for health services: the case for valley fever, J. Aeolian Res. http://dx.doi.org/10.1016/j.aeolia.2014.03.001; Elsevier, AEOLIA-D-13-00085R1

c) Yin, D. and W. A. Sprigg (2010) Modeling Airbourne Mineral Dust: A Mexico - United States Trans-boundary Perspective. Pp. 303- 317 in W. Halvorson, C. Schwalbe, and C. van Riper, III (eds), Southwestern Desert Resources. University of Arizona Press, Tucson, AZ, 359 pp.

d) Yin, D., S. Nickovic and W.A. Sprigg (2007) The impact of using different land cover data on wind-blown desert dust modeling results in the southwestern United States. Atmospheric Environment, DOI.10.1016/j.atmosenv.2006.10.061.

e) Yin, D., S. Nickovic and W.A. Sprigg (2007) Effect of wind speed and relative humidity on atmospheric dust concentrations in semi-arid climates; J. Atmos. Env. 41(10):2214-2224; Science of the Total Environment 04/2014: 487C:82-90. DOI.10.1016/j.scitotenv.014.03.138

f) Mahler, A-B., K. Thome, D. Yin, W. A. Sprigg (2006) Dust transport model validation using satelliteand ground-based methods in the southwestern United States; SPIE, Vol. 6299;ISBN: 9780819463784

A search of the literature by the authors would have revealed modeling, forecasting and simulating dust concentrations in the exact area (and time) of their study. References are first noticed missing on pages 20746 - 7.

We have extensively cited related literature in multiple sections of the paper, including but not limited to these suggested above.

5 Are the results sufficient to support the interpretations and conclusions?

6 Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes

7 Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Note author oversight of literature and work on dust source identification and monitoring, and dust modeling, simulation and forecasting in the region of their study, Arizona.

As in the response to your previous comments: Related works have been added in various sections to support discussions and conclusions of this study.

8 Does the title clearly reflect the contents of the paper? Yes

9 Does the abstract provide a concise and complete summary? I think it risky to state, as in the abstract, "Studies have revealed intensified dust activity in the western US during the past decades . . ." An intention of the authors' research is to determine this. I am unaware of solid evidence of such, which makes the authors' research timely and important.

The Brahney et al. (2013) study that we cited in Section 1 (Line 5, 20745) reported overall increasing trends of dust production and deposition in the inter-mountain west, the midwest, and the northwest US from 1994 to 2010. Motivated by such studies, we explore the conditions on a state level (for Arizona), extend the records till more recent years, and use diverse observation datasets, particularly those with broad spatial coverage (such as satellite observations). Our study furthers such previous studies, and differs from theirs in terms of spatial scales, temporal ranges, and the methods/data.

10 Is the overall presentation well structured and clear? Yes

11 Is the language fluent and precise? Yes

12 Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes

13 Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Yes, the section on CMAQ modeling should either be eliminated or elaborated upon significantly.

Please see our response to your previous comments, regarding the importance of CMAQ-related contents.

14 Are the number and quality of references appropriate? No. See previous remarks.

As in the response to your previous comments: Related works have been added in various sections to support discussions and conclusions of this study.

15 Is the amount and quality of supplementary material appropriate? Yes

References (in addition to the reviewers' suggestions)

Clements, A. L., Fraser, M. P., Upadhyay, N., Herckes, P., Sundblom, M., Lantz, J., and Solomon, P. A.: Characterization of summertime coarse particulate matter in the Desert Southwest—Arizona, USA, Journal of the Air & Waste Management Association, 63(7), 764-772, doi:10.1080/10962247.2013.787955, 2013.

Ginoux, P., Clarisse, L., Clerbaux, C., Coheur, P.-F., Dubovik, O., Hsu, N. C., and Van Damme, M.: Mixing of dust and NH3 observed globally over anthropogenic dust sources, Atmos. Chem. Phys., 12, 7351-7363, doi:10.5194/acp-12-7351-2012, 2012a.

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M.: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products, Rev. Geophys., 50, RG3005, doi:10.1029/2012RG000388, 2012b.

Nordstrom, K. F. and Hotta, S.: Wind erosion from cropland in the USA: A review of problems, solutions and prospects, Geoderma, 12(3–4), 157–167, doi: doi:10.1016/j.geoderma.2003.11.012, 2004.

Upadhyay, N., Clements, A. L., Fraser, M. P., Sundblom, M., Solomon, P., and Herckes, P.: Size-Differentiated Chemical Composition of Re-Suspended Soil Dust from the Desert Southwest United States, Aerosol and Air Quality Research, 15, 387–398, doi: 10.4209/aaqr.2013.07.0253, 2015.

Van Curen, R. A., and T. A. Cahill: Asian aerosols in North America: Frequency and concentration of fine dust, J. Geophys. Res., 107, 4804 (D24), doi:10.1029/2002JD002204, 2002.