Atmos. Chem. Phys. Discuss., 15, 20743–20774, 2015
www.atmos-chem-phys-discuss.net/15/20743/2015/
doi:10.5194/acpd-15-20743-2015

Atmospheric Chemistry and Physics Discussions
Open Access

Toward enhanced capability for detecting and predicting dust events in the Western United States: the Arizona Case Study

M. Huang[1,2], D. Tong[1,2,3], P. Lee[1], L. Pan[1,3], Y. Tang[1,3], I. Stajner[4], R. B. Pierce[5], J. McQueen[6], and J. Wang[1]

[1]NOAA/OAR/ARL, NOAA Center for Weather and Climate Prediction, College Park, MD 20740, USA
[2]Center for Spatial Information Science and Systems, George Mason University, Fairfax VA 22030, USA
[3]Cooperative Institute for Climate and Satellites, University of Maryland, College Park, MD 20740, USA
[4]NOAA/NWS/OST, Silver Spring, MD 20910, USA
[5]NOAA/NESDIS, Madison, WI 53706, USA
[6]NOAA/NWS/NCEP/EMC, NOAA Center for Weather and Climate Prediction, College Park, MD 20740, USA

Received: 13 July 2015 – Accepted: 16 July 2015 – Published: 3 August 2015

Correspondence to: M. Huang (mhuang10@gmu.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Dust aerosols affect human life, ecosystems, atmospheric chemistry and climate in various aspects. Studies have revealed intensified dust activity in the western US during the past decades despite the weaker dust activity in non-US regions. It is important to extend the historical dust records, to better understand their temporal changes, and use such information to improve the daily dust forecasting skill as well as the projection of future dust activity under the changing climate. This study develops dust records in Arizona in 2005–2013 using multiple observation datasets, including in-situ measurements at the surface Air Quality System (AQS) and Interagency Monitoring of Protected Visual Environments (IMPROVE) sites, and level 2 deep blue aerosol product by the Moderate Resolution Imaging Spectroradiometer. The diurnal and inter-annual variability of identified dust events are shown related to observed weather patterns (e.g., wind and soil moisture) and vegetation conditions, suggesting a potential for use of satellite soil moisture and vegetation index products to interpret and predict dust activity. Back-trajectories computed using NOAA's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model indicate that the Sonoran and Chihuahuan deserts are important dust source regions during identified dust events in Phoenix, Arizona. Finally, we evaluate the performance of the US National Air Quality Forecasting Capability (NAQFC) 12 km CMAQ model during a recent strong dust event in the western US accompanied by stratospheric ozone intrusion. It is shown that the current modeling system well captures the temporal variability and the magnitude of aerosol concentrations during this event, and the usefulness and limitations of different observations in model evaluation are discussed. Directions of integrating observations to further improve dust emission modeling in CMAQ are also suggested.

1 Introduction

Dust aerosols, generated by anthropogenic or natural sources, present strong spatial and temporal variability (Ginoux et al., 2001, 2010, 2012; Carslaw et al., 2010; Prospero et al., 2002; Zender et al., 2004), and affect human life, ecosystems, atmospheric chemistry and climate in many aspects. Degraded visibility during dusty periods prevents normal outdoor activities and transportation, and dust activity may be associated with a number of human diseases such as "valley fever", "Haboob Lung Syndrome" and certain eye diseases (Goudie, 2013; Panikkath et al., 2013; Liu et al., 2009a). Dust nourishes forests (Yu et al., 2015), neutralizes acid rain (Hedin and Likens, 1996), and the deposited nutritional or harmful contents in dust particles interact with the ocean ecosystems (Gassó et al., 2010; Chen et al., 2013). Also, dust absorbs sunlight, reduces the planetary albedo over bright surfaces such as snow, ice and deserts, and modifies cloud properties and precipitation (Zhao et al., 2012; Creamean et al., 2013, 2015). The deposition of dust on snow and ice can accelerate their melting and affect regional climate (Carslaw et al., 2010). In addition, mineral dust aerosols affect atmospheric chemistry through surface adsorption and reactions (Grassian, 2001; Underwood et al., 2001; Fairlie et al., 2010).

North America contributes to a small proportion of the world's total dust emissions, ranging from < 0.1 to 5 % as reported in previous studies (Miller et al., 2004a, b; Tanaka and Chiba, 2006; Zender et al., 2003; Ginoux et al., 2004), and the important emitters include the four major deserts in the western US, i.e., Great Basin, Mojave, Sonoran, and Chihuahuan deserts. Dust storms in the western US usually last for 2–21 h, due to various mechanisms (Lei and Wang, 2014). Surface and satellite observations, along with modeling analysis, have provided evidence that the western US is not only affected by local dust emissions, but is also susceptible to dust transported from the overseas (e.g., Van Curen et al., 2002; Fischer et al., 2009; Uno et al., 2009; Fairlie et al., 2007; Chin et al., 2007; Eguchi et al., 2009; Stith et al., 2009; Dunlea et al., 2009; Liu et al., 2009b). Using a global transport model, Fairlie

ACPD
15, 20743–20774, 2015

et al. (2007) reported that dust from the overseas contributed to < 30 % of the total dust in the southwestern US and > 80 % of the total dust in the northwestern US in Spring 2001, and these non-US contributions were much larger than in other seasons. Recent dust observations have revealed rapid intensification of dust storm activity in the western US (e.g., Brahney et al., 2013), despite the weaker dust activity in many non-US regions (e.g., Mahowald et al., 2007; Zhu et al., 2008; Shao et al., 2013). This increasing trend enhances the concerns about their various impacts or even another "Dust Bowl", which occurred in the 1930s due to severe drought conditions (http://www.ncdc.noaa.gov/paleo/drought/drght_history.html) and inappropriate farming methods http://www.livinghistoryfarm.org/farminginthe30s/water_02.html) and at that time led to significantly negative agricultural and ecological impacts in the western/central US.

Surface and satellite observations have been used to study dust trends and variability, as well as for model evaluation (e.g., Tong et al., 2012; Appel et al., 2013; Torres et al., 2002; Ginoux and Torres, 2003; Draxler et al., 2010). Surface observations used in many of these studies are sparsely and infrequently sampled, and there is delay for obtaining some of these datasets which prevents timely updates on the observed dust records. The capability of satellite aerosol optical depth products to capture the dust events depends on various factors such as sensor characteristics, cloud conditions, surface reflectance and dust mineralogy (e.g., Baddock et al., 2009). There still lacks comprehensively developed observational dust records with broad spatial coverage till the very recent years, and accurately simulating dust aerosols is challenging. Therefore, it is important to extend the temporal changes of observed dust activity to recent years using diverse observations. These various observations can assist evaluating the chemical transport model skills especially during dust events. Furthermore, better understanding the linkages between the temporal changes of dust observations and the observed land use/weather conditions can be beneficial for advancing the dust emission modeling skills via improving the meteorology and land cover input data, as well as for projecting future dust activity under the changing climate.

This study develops decadal dust records in the state of Arizona using multiple in-situ and satellite observation datasets, and relates the diurnal and inter-annual variability of observed dust activity to the observed weather patterns (e.g., wind and soil moisture) and vegetation conditions (Sect. 3.1–3.3). We also evaluate the performance of the US National Air Quality Forecasting Capability (NAQFC) 12 km Community Multi-scale Air Quality (CMAQ) regional model simulation during a recent strong dust event in the western US (Sect. 3.4). In the analysis, we discuss the usefulness and limitations of different types of observations for identifying dust events and for the CMAQ model evaluation. We also suggest future directions of integrating observations into dust emission modeling in the western US for its further improvement.

2 Data and method

2.1 Drought indicators

Three datasets were analyzed to interpret the observed inter-annual variability of the drought conditions from 2005 to 2013 in Arizona, an important dust source and receptor region in the western US. They are: Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on NASA Aqua satellite, a European soil moisture dataset that merged both passive and active satellite sensor data, and the Palmer Drought Severity Index (PDSI).

NDVI is the most commonly used vegetation index, calculated using the reflected visible and near-infrared light on vegetation (Scheftic et al., 2014; Brown et al., 2006). Smaller NDVI values refer to little vegetation coverage areas. For example, NDVI values from NOAA's Advanced Very High Resolution Radiometer (AVHRR) instrument are usually below 0.15 over the bare ground, which has high potential of emitting dust, and this threshold can vary by satellite instruments (D. Kim et al., 2013). NDVI has been used for monitoring land cover changes and indicating drought (Tucker and Choudhury, 1987; Karnieli et al., 2010; Wan et al., 2004), and it has been shown correlated with meteorological based drought index such as Standardized Precipitation Index (Ji and Peters, 2003). In this study we used the monthly-mean 1 km MODIS NDVI product version 5, which temporally aggregated the 16 day 1 km MODIS NDVI using a weighted average. Only the flagged good quality data were used following the instructions in its users' guide http://vip.arizona.edu/documents/MODIS/MODIS_VI_UsersGuide_01_2012.pdf). To avoid the known effects from sensor degradation of Terra MODIS (e.g., Wang et al., 2012), only the NDVI data from Aqua MODIS (MYD13A3) was used.

Soil moisture has also been used for drought monitoring, and several studies have found that satellite and modeled soil moisture is related to dust outbreaks in Asian countries (Liu et al., 2004; Y. Kim et al., 2013; Kim and Choi, 2015). This study used a multi-sensor satellite soil moisture product from the European Satellite Agency (ESA) within the soil moisture Climate Change Initiative (CCI) project that merged all available passive and active products and preserved the original dynamics of these remote sensing observations (http://www.esa-soilmoisture-cci.org). The data are produced on a $0.25^{\circ} \times 0.25^{\circ}$ horizontal resolution grid. Long-term soil moisture changes in the US based on the CCI soil moisture product contributed to the US National Climate Assessment report (http://nca2014.globalchange.gov/report, pp. 72–73).

Monthly PDSI data http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers.php), calculated from temperature and precipitation (Palmer, 1965; Alley, 1984), is widely used for identifying long-term and abnormal moisture deficiency or excess. Studies have found that PDSI is moderately or significantly correlated ($r = 0.5$ to 0.7) with observed soil moisture content within the top 1 m depth during warm-season months in various regions (Dai et al., 2004). In this study, we analyzed the inter-annual variability of PDSI in two NOAA climate regions in Arizona (Karl and Koss, 1984; http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php). Drought conditions are defined with negative PDSI values (e.g., negative 2 is moderate drought, negative 3 is severe drought, and negative 4 is extreme drought), and positive PDSI values indicate wet conditions.

2.2 Aerosol observations

Both remote sensing and in-situ aerosol observations were used to explore the dust aerosol distributions in Arizona. We first demonstrate the large-scale spatial distributions of aerosols using satellite aerosol products, and discuss their diurnal (e.g., late morning vs. early afternoon times) and inter-annual variability linking to the weather and vegetation conditions. We mainly focus on spring and summer time periods when dust activity is generally strong in Arizona as found by Ginoux et al. (2012) for the 2003–2009 period. In-situ observations at Arizona surface monitoring sites were also analyzed, focusing on their temporal variability in the populated Phoenix urban area (i.e., with a population of ∼ 1.5 million). Finally, we identified dust events in Phoenix using hourly surface observations and discuss the time of occurrence of these identified dust events.

2.2.1 MODIS deep blue Aerosol Optical Depth (AOD) and Dust Optical Depth (DOD)

We generate DOD maps over Arizona on a $0.1^{\circ} \times 0.1^{\circ}$ horizontal resolution grid, using the MODIS level 2 deep blue aerosol product (Hsu et al., 2004) collection 5.1 during 2005–2013 (data ordered from: http://ladsweb.nascom.nasa.gov/data/). This product includes the values of AOD and single scattering albedo (SSA) at 412, 470, 550 nm, and 670 nm, as well as Angstrom exponent between 412 and 470 nm. It is recommended for identifying both dust sources and plumes at high spatial resolution (e.g., Baddock et al., 2009). Following the method in Ginoux et al. (2012), DOD was selected by screening the 550 nm AOD data based on three criteria to represent the scenes dominated by dust aerosols: (1) Angstrom exponent < 0, which selects the particles in large sizes, (2) SSA at 412 nm < 0.95, which selects the absorbing aerosols and efficiently eliminates the sea salt dominated scenes, (3) difference of SSA between 412 and 670 nm is positive, due to the specific optical property of dust that there is a sharp increase of absorption from red to deep blue. Deep Blue collection 5.1 data for Aqua

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
15, 20743–20774, 2015

Toward enhanced capability for detecting and predicting dust events

M. Huang et al.

MODIS is available throughout the study period, but this dataset is only available during 2005–2007 for Terra MODIS due to the known calibration issues after 2007 (e.g., as mentioned in Shi et al., 2013).

2.2.2 Particulate matter (PM) measurements from the surface Interagency Monitoring of Protected Visual Environments (IMPROVE) sites

Most IMPROVE surface sites are located in rural regions, many of which are at the national parks to measure background pollution levels. We here analyzed the temporal variability of observed particulate matter mass PM_{10} (i.e., $< 10\,\mu m$ in diameter), along with the fine (i.e., $< 2.5\,\mu m$ in diameter) soil particles at the Phoenix site (PHOE1, latitude/longitude: 33.5038° N/112.0958° W) within the IMPROVE network during 2005–2013 (data from: http://views.cira.colostate.edu/fed/DataWizard/Default.aspx). IMPROVE's fine soil data is computed based on five (Al, Si, Ca, Fe, and Ti) soil-derived trace metals in their assumed oxidized form measured at the IMPROVE site http://vista.cira.colostate.edu/improve/publications/graylit/023_SoilEquation/Soil_Eq_Evaluation.pdf). Daily mean IMPROVE data is available every three days, and there is approximately a year of delay for obtaining these data.

2.2.3 Air Quality System (AQS) and AirNow PM and trace gas measurements

In general the US Environmental Protection Agency (EPA) AQS sites are designed to monitor air quality in populated urban or suburban areas. In this study the AQS hourly PM_{10} and $PM_{2.5}$ data during 2005–September 2013 (downloaded from: http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm) and AirNow during September–December 2013 (downloaded from: www.epa.gov/airnow/2013) at the Phoenix JLG supersite (co-located with the IMPROVE PHOE1 site, AQS site #040139997) were analyzed to study the temporal variability of dust events on hourly temporal resolution. In the case study on the dusty year of December 2006–November 2007, AQS trace gas measurements (i.e., carbon monoxide (CO) and oxides

ACPD
15, 20743–20774, 2015

of nitrogen (NO_x)) were used as tracers of anthropogenic or biomass burning sources to evaluate the dust events that are identified based on the hourly PM observations. The AQS data qualifier codes were also examined which provide clues of the event types (e.g., high winds, long-range transport of PM from non-US regions).

2.2.4 NOAA Hazard Mapping System Fire and Smoke text product

Achieved NOAA Hazard Mapping System (HMS) text product (http://www.ssd.noaa.gov/PS/FIRE/smoke.html) narratively describes the observed smoke and dust events based on images of multiple satellites. It qualitatively indicates the dust locations and the intensity, which in this study supports the analysis during a recent strong event we selected for case study in Sect. 3.4.

2.3 Observed wind speed and direction

Observed hourly surface wind speed and direction in December 2006–November 2007 at the Phoenix Encanto site (latitude/longitude: 33.4792° N/112.0964° W, within the Arizona meteorological network (AZMET), http://ag.arizona.edu/azmet/index.html) were used for identifying the dust events together with the hourly AQS PM observations. Phoenix Encanto is the closest site to the Phoenix JLG supersite within the AZMET that had available meteorological observations during this period.

2.4 Backward airmass trajectory analysis and MODIS land cover type data

Backward airmass trajectories were computed to locate the sources of dust aerosols observed at the Phoenix JLG site during the identified dust events in December 2006–November 2007. These trajectories were calculated using NOAA's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model, version 4 (Draxler and Rolph, 2015; Stein et al., 2015, http://ready.arl.noaa.gov/HYSPLIT.php). The accuracy of the trajectories depends on the resolution of the wind data (Draxler and Hess, 1998), and we calculated these trajectories based on the 3 hourly North America Regional Reanal-

ACPD
15, 20743–20774, 2015

ysis (NARR) data (Mesinger et al., 2006) on 32 km horizontal resolution with 9 vertical levels below 800 hPa. NARR is the finest meteorology HYSPLIT can currently run with for studying this year, as HYSPLIT can only run with the horizontally finer (12 km) North American Mesoscale Forecast System (NAM, Janjic et al., 2004) wind fields for the time after May 2007. These trajectories were initiated at 500 m above Phoenix's ground level at identified dust periods and were computed for 24 h.

To discuss the land cover types of the HYSPLIT-indicated airmass origins during the Phoenix dust events, we also used the primary International Geosphere Biosphere Programme (IGBP) land cover classification in the MODIS land cover type product (MCD12Q1, 500 m resolution in tile grid, Friedl et al., 2010) collection 5.1 for the year of 2007.

2.5 Chemical transport model base and sensitivity simulations

The US NAQFC 12 km CMAQ (Byun and Schere, 2006) model simulations were used to depict the PM distributions during a recent strong dust event in the western US that was accompanied by stratospheric ozone intrusion. Dust emissions for NAQFC's CMAQ simulations were calculated by the FENGSHA dust emission model based on modified Owen's equation, which is a function of wind speed, soil moisture, soil texture and erodible land use types (Tong et al., 2015). Both the FENGSHA and CMAQ model calculations were driven by meteorological fields from the NAM model. The CMAQ base simulation was evaluated against surface observations at the AirNow and IMPROVE sites, and we focused on $PM_{2.5}$ concentrations in that it is a standard NAQFC product. To quantify the impact of western US dust emissions on $PM_{2.5}$ concentrations during this event, an additional sensitivity simulation was conducted in which no dust emissions were included. NAQFC CMAQ lateral chemical boundary conditions were downscaled from monthly mean output from a global GEOS-Chem simulation of year 2006 (Chai et al., 2013; Pan et al., 2014), and therefore this system does not well treat chemical species transported from outside of the model domain. Stratospheric ozone intrusion during this dust event is indicated by meteorological conditions and chemical fields from the global 1° × 1° Realtime Air Quality Modeling System (RAQMS) (Pierce et al., 2007) which assimilated satellite ozone observations.

3 Results and discussions

3.1 Decadal drought indicators and satellite DOD in Arizona

We first review the spatial and inter-annual variability of the drought conditions during 2005–2013 in Arizona in the dusty seasons (i.e., spring and summer from March to August), based on satellite NDVI (Fig. 1a) and soil moisture (Fig. 1b) products. These observations show that southwestern and south central Arizona, a region close to the Sonoran Desert, is overall drier than the rest of the state with less greenness. Most of these dry regions fall into two NOAA climate divisions (i.e., "South Central" including the Maricopa and Pinal counties and "South West" including the La Paz and Yuma counties). The mean PDSI values in spring and summer in these two climate divisions were calculated (Fig. 1c), indicating moderate to severe dry conditions under warm weather in these regions in the past decade, except 2005 (extreme wet), 2008 (near neutral), and 2010 (moderate wet). PDSI values were then correlated with the anomalies of satellite NDVI and soil moisture, defined as the ratio of annual mean value over the multi-year mean value. In general, Fig. 1c shows that the PDSI-indicated drought conditions are consistent with those observed by the satellite NDVI and soil moisture products: i.e., with correlation coefficient r(PDSI vs. NDVI anomaly) and r(PDSI vs. soil moisture anomaly) of 0.96 and 0.84, respectively.

Gridded MODIS DOD maps are shown in Fig. 2 for each year's dusty season during 2005–2013 and they were related to the satellite-based weather and vegetation conditions (Fig. 1c). In all maps, high DOD values (> 0.2) are seen in the dry southwest and south central climate divisions. Aqua MODIS observed higher DOD than in Terra MODIS DOD during 2005–2007 by 19–37 %, indicating higher dust in the early afternoon than in the late morning. Inter-annual variability is also seen from these

ACPD
15, 20743–20774, 2015

Toward enhanced capability for detecting and predicting dust events

M. Huang et al.

DOD maps over large spatial scales, with smaller DOD values in the dusty regions in wetter years (e.g., 2005 and 2010). The correlation coefficients between the anomalies of DOD and the three drought indicators (NDVI, soil moisture, and PDSI) in the past decade are −0.86, −0.60, −0.78, respectively. Such anti-correlations suggest the importance of drought monitoring to the interpretation and prediction of dust activity. Particularly, it is noted that satellite can provide soil moisture measurements of much broader spatial coverage than the surface sites (e.g., there is only one site of Walnut Gulch in Arizona within the Soil Climate Analysis Network), and drought monitoring can be better assisted by newer satellite soil moisture observations, such as those from NASA's newly launched Soil Moisture Active Passive (SMAP).

The time-varying drought conditions and DOD maps also indicate that the source regions that have potential to emit dust particles are changing with the weather conditions rather than being static as currently treated in some dust emission models. Using dynamic dust source regions derived from satellite observations such as NDVI can have impact on dust emissions and chemical transport modeling (e.g., D. Kim et al., 2013).

3.2 Decadal surface in-situ PM measurements in Phoenix

We then analyze the long-term surface PM measurements at the AQS and IMPROVE monitoring sites in the Phoenix area. The time series of PM_{10} from AQS/AirNow and IMPROVE sites in Phoenix are shown in Fig. 3a during 2005–2013 in their original temporal resolution. It is shown that the 24 h mean IMPROVE PM_{10} data missed the extreme values (e.g., > 150 $\mu g\,m^{-3}$) that were captured by the hourly AQS/AirNow observations at this location. The nine-year mean PM_{10} concentration at the AQS site (31.6 $\mu g\,m^{-3}$) is slightly higher than at the IMPROVE site (28.2 $\mu g\,m^{-3}$) due to the different sampling frequency and methods. Another advantage of AQS/AirNow observations over those at the IMPROVE sites is that they are timely made available. IMPROVE fine soil particles demonstrate the similar temporal variability to IMPROVE PM_{10} with a correlation coefficient r of ∼ 0.8. To explore the inter-annual variability of PM_{10} in dust seasons (spring-summer) at this site, we calculated the anomalies for each variable in each year (Fig. 3b). Similar to the results from satellite observations, the inter-annual variability of surface PM observations are anti-correlated with regional soil wetness and vegetation cover. Inconsistency exists among the anomalies of these three variables, due to different sampling methods and densities, and also because that the particle size distributions depend on soil wetness (Li and Zhang, 2014). Due to the different observation methods and sampling strategies (spatial and temporal), the anomalies of surface PM concentrations are closer to the MODIS DOD anomalies under significantly wet or dry conditions.

3.3 Phoenix dust events in 2007 identified by hourly surface observations

We take the dry and dusty year of December 2006–November 2007 (Fig. 3b) as an example to introduce a novel approach of identifying dust events using hourly observations. We first calculated the seasonal averages of PM_{10} and wind speed in Phoenix based on the AQS PM_{10} and AZMET wind speed observations. It is shown that in this year dominant westerly and easterly winds in spring and summer times carried much PM_{10} to Phoenix (Fig. S1), whereas most PM_{10} in autumn and winter time came from the north and east. Hourly mean wind speed is highly correlated with the hourly maximum wind speed ($r = 0.95$, slope = ∼ 0.5), and faster winds were observed during spring and summer (Fig. S2). Two steps followed to identify the individual dust events. In the first step, any period that PM_{10} and wind speed exceeded the seasonal mean values for no shorter than 2 h (the lower end of dust storm duration in the western US reported by Lei and Wang, 2014) are defined as a dusty period. The second step screened the dust events selected in the first step using their median values of PM_{10} (55 $\mu g\,m^{-3}$) and $PM_{2.5}/PM_{10}$ (∼ 0.2) as lower and upper thresholds, and therefore relied on data availability of both $PM_{2.5}$ and $PM_{10.}$ After these two steps of selection, 29 high dust periods are found as denoted in Fig. S3 on 7 December, 10, 27; 27 March; 8 April, 11 (twice), 12 (twice), 16, 18, 20; 19 July, 28, 30; 13 August–

ACPD
15, 20743–20774, 2015

14, 19, 20, 24, 25; 4 September, 5, 7, 15, 19; 5 October, 13, 16; and 15 November. Around 76 % of these events lasted for no longer than 5 h, consistent with the findings by Lei and Wang (2014) that the majority of the exceptional dust storms in Arizona during 2003–2012 lasted for 2–5 h mainly due to meso- or small-scale weather systems (e.g., thunderstorms, convections along dry lines, gusty winds caused by high pressure systems). Hourly PM_{10} during these high dust periods ranged from 57–8540 $\mu g\, m^{-3}$, with $PM_{2.5}/PM_{10}$ ratio between ∼ 0.07 and ∼ 0.2, and $PM_{2.5}$ was highly correlated with PM_{10} during these periods ($r > 0.9$). In April–May 2007, the Pacific Dust Experiment (PACDEX) was carried out to study dust emission and transport from Asia (Stith et al., 2009). The University of Iowa STEM chemical transport model tracer calculations (http://data.eol.ucar.edu/codiac/dss/id=96.013) estimated dust to be ∼ 2 $\mu g\, m^{-3}$ in average (and not exceeding 10 $\mu g\, m^{-3}$ during transport events) at∼ 5.3 km in Arizona during this period, which can serve as the upper limit of extra-regional dust impacts on the surface PM concentrations. During our identified dust events, PM_{10} concentrations were much higher than this magnitude and therefore they were mainly due to the impact from local dust emissions.

The identified high dust periods were validated using the hourly AQS trace gas observations. Figure S4 includes the scatterplots of AQS CO and NO_x over the PM_{10} measurements at the Phoenix JLG AQS site. Two distinct slopes are shown in both scatterplots, representing the times mainly affected by anthropogenic/biomass burning sources and dust. PM_{10} values during most of the identified dust events fall into the flat legs in these scatterplots. Using $PM_{2.5}/PM_{10}$ as an additional constraint (as suggested in Tong et al., 2012 and Lei and Wang, 2014) in the second step of selection excluded some less strong events interfered by anthropogenic/biomass burning emission sources, but possibly also some real dust events. After the second step of selection, higher-than-median CO or NO_x values were observed at only ∼ 10 % of the identified dust times. In addition, AQS qualifier codes provide useful information for interpreting the event types: e.g., the “IJ” and “RJ” flags https://aqs.epa.gov/aqsweb/codes/data/QualifierCodes.html) inform that 19–20 July was a high wind event.

ACPD
15, 20743–20774, 2015

Independent IMPROVE and satellite observations can also assist validating these identified dust events. IMPROVE observations were only available on ∼ 29 % of these identified dusty days (7, 10 December; 12, 18 April; 13, 19, 25 August; 15 September), and they were more likely to be able to indicate exceptionally strong and long-lasting events due to the 24 h sampling duration. Tong et al. (2012) reported two strong dust storm events at the PHOE1 IMPROVE site (∼ 12 April; ∼ 20 July) using total PM concentrations and its speciation, both of which were also captured by our method. In addition, ∼ 48 % of the days impacted by strong blowing dust were possibly captured by MODIS (i.e., dust events occurred during 9–15 local times: 10 December; 27 March; 11, 12, 16, 18, 20 April; 19, 30 July; 7, 15 September; 15 November). To further demonstrate the advantages of using frequently sampled observations for capturing dust events, we plotted the time of occurrence of these AQS/AZMET-based dust periods in Phoenix for this year (Fig. 4a). Dust events occurred more frequently during Aqua overpassing times than during the Terra overpasses, consistent with the findings from Fig. 2. Most of these dusty events occurred at 15–21 local times, when winds were stronger (also in Fig. 4a) and the soil was drier (by looking at NAM soil moisture at the top soil layer in recent years, not shown), rather than at MODIS overpassing times from late morning to early afternoon times. Similar long-term diurnal variability of the dust event occurrence has been found in Utah based on analyzing weather code (Hahnenberger and Nicoll, 2012). Therefore, current polar orbiting satellites are unable to observe all dust events, and the hourly sampling frequency of the future geostationary satellites can help better capture dust events together with the surface monitoring network. Such conclusions were also drawn by Schepanski et al. (2012) for the African dust source regions.

We classified PM mass by wind direction observed at Phoenix AZMET site, which indicates the dominant westerly/southwesterly winds at the Phoenix high dust times. Further, based on the NARR meteorology, HYSPLIT airmass trajectories were originated from 500 m above the ground level (a.g.l.) of Phoenix at the identified dusty periods to locate the origins of Phoenix dust episodes and indicate the regional transport patterns. The endpoints of these HYSPLIT back trajectories are overlaid on MODIS land classification map (Fig. 4b), showing that most of the transported dust particles were at the shrublands or deserts (primarily Sonoran, also Chihuahuan) 0–12 h before arriving in urban Phoenix areas at below ~ 900 hPa. The NDVI values in many of these airmass source regions are below 0.2 (Fig. 1a), similar to the definition of the "bare ground" by D. Kim et al. (2013).

3.4 Case study: modeling analysis of a recent strong dust event accompanied by stratospheric ozone intrusion

Current NAQFC dust forecasting skill was evaluated during a recent strong dust event on 11 May 2014 in the western US, using surface PM measurements. NOAA's HMS text product describes this event visible by multiple satellites: http://www.ssd.noaa.gov/PS/FIRE/DATA/SMOKE/2014/2014E111659.html; http://www.ssd.noaa.gov/PS/FIRE/DATA/SMOKE/2014/2014E120143.html): Dust was originated from southern California on the previous day, sweeping across northern Baja California and Arizona, entering New Mexico after cold-frontal boundary and impacted Texas, Oklahoma and Kansas on the following day. NAQFC 12 km CMAQ simulations produced 24 h mean $PM_{2.5}$ over 50 µg m^{-3} in western Arizona and > 15 µg m^{-3} in southwestern Arizona on this day (Fig. 5a). Sensitivity analysis using the base and no-dust simulations indicates that over 50 µg m^{-3} of hourly $PM_{2.5}$ during this event were contributed from dust emissions in populated urban regions in Arizona (such as Phoenix in the Maricopa county and Tucson in the Pima county), and in average, dust contributed to > 70 % of the total $PM_{2.5}$ in most Arizona grid cells (Fig. 5b).

The evaluation of modeled $PM_{2.5}$ (a standard NAQFC air quality product) was focused on two Arizona counties Maricopa and Pima where both IMPROVE and AirNow observations were available during this event. Time series of observed and modeled $PM_{2.5}$ are shown in Figs. 5e and f. AirNow observations indicate daily maxima to be over 100 µg m^{-3} in Maricopa and over 50 µg m^{-3} in Pima, with $PM_{2.5}/PM_{10}$ ratios at the dusty hours below 0.2 (not shown). Both the model and observations show significant

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
15, 20743–20774, 2015

Toward enhanced capability for detecting and predicting dust events

M. Huang et al.

temporal variability (standard deviations), indicating the advantages of the AirNow data for capturing the extremely high PM concentrations during the dust events. In general, CMAQ fairly well captured the timing of the daily maxima at the AirNow sites, with median/high correlation coefficients of 0.7–0.9 with the observations (Table 1). CMAQ underpredited the daily maxima in Maricopa by a factor of ∼ 2, while slightly overpredited them in Pima. PM was measured at more AirNow sites than at the IMPROVE sites in both counties on this day. The observed 24 h mean concentration at the AirNow sites was lower than at the IMPROVE sites in Maricopa, but those in Pima were close. This can be mainly due to the different sampling areas that AirNow and IMPROVE networks cover. The model underpredicted the 24 h mean values in both counties, with more significant negative biases in Maricopa than in Pima.

Stratospheric ozone intrusion occurred during this event as shown from a RAQMS model simulation that assimilated ozone columns from the Ozone Monitoring Instrument and ozone profiles from the Microwave Limb Sounder (Fig. 5d). Descending dry air containing rich ozone enhanced surface ozone concentrations in eastern Arizona and New Mexico at late morning times, when dust was strongly impacting the similar locations (Fig. 5c). Observed surface ozone at Petrified Forest National Park in eastern Arizona (AQS/AirNow site # 040170119) at this time exceeded 65 ppbv. It's known that stratospheric ozone intrusion can be accompanied by high winds and trigger windblown dust in the western US (e.g., http://acmg.seas.harvard.edu/aqast/meetings/2012_jun/AM_20120614/1000_AQAST%20June%202012%20Reddy.pdf). Therefore, it is important to accurately simulate both ozone and PM concentrations under such conditions, and assess their combined public health and environmental impacts. However, the current NAQFC CMAQ modeling system is unable to capture the exceptional high ozone during stratospheric intrusion episodes, as the CMAQ lateral boundary conditions were downscaled from monthly-mean GEOS-Chem simulation in 2006, and no upper boundary conditions were used.

4 Conclusions and suggestions

We developed dust records in Arizona in 2005–2013 using multiple observation datasets, including MODIS level 2 deep blue aerosol product and in-situ measurements at the surface AQS and IMPROVE sites in Phoenix. Both satellite and surface aerosol observations were anti-correlated with three drought indicators (i.e., NDVI, soil moisture, and PDSI). Dust events were stronger and more frequent in the afternoon times than in the morning due to faster winds and drier soil, and Sonoran and Chihuahuan deserts are important dust source regions during identified dust events in Phoenix. These findings suggest a potential for use of satellite soil moisture and vegetation index products to interpret and predict dust activity. We also emphasized the importance of using hourly observations for better capturing dust events, and expect the hourly geostationary satellite observations in the future to well complement the current surface PM and meteorological observations considering their broader spatial coverage. Continued development of products from the polar-orbiting satellites is also important, in that they can provide higher spatial resolution observations for each swath due to their lower orbit level.

We also evaluated the performance of the NAQFC 12 km CMAQ model simulation during a recent strong dust event in the western US accompanied by stratospheric ozone intrusion. The current modeling system well captured the temporal variability and the magnitude of aerosol concentrations during this event. Satellite weather and vegetation observations are being integrated into the dust emission modeling for future improvement in NAQFC's PM forecasting skill. It's important but still challenging to well predict both PM and ozone under such conditions.

The Supplement related to this article is available online at doi:10.5194/acpd-15-20743-2015-supplement.

ACPD
15, 20743–20774, 2015

Acknowledgements. This study was mostly supported by a NASA ROSES grant (NNX13AO45G). We thank the useful information from NASA Air Quality Applied Science Teams, SMAP early adaptor working teams, NAQFC and HYSPLIT groups at NOAA ARL. We also acknowledge the open access to the used surface and satellite observations (the sources of data were included in the main text). The views, opinions, and findings contained in this paper are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or US Government position, policy, or decision.

References

Alley, W. M.: The Palmer drought severity index: limitation and assumptions, J. Climate Appl. Meteorol., 23, 1100–1109, 1984.

Appel, K. W., Pouliot, G. A., Simon, H., Sarwar, G., Pye, H. O. T., Napelenok, S. L., Akhtar, F., and Roselle, S. J.: Evaluation of dust and trace metal estimates from the Community Multiscale Air Quality (CMAQ) model version 5.0, Geosci. Model Dev., 6, 883–899, doi:10.5194/gmd-6-883-2013, 2013.

Baddock, M. C., Bullard, J. E., and Bryant, R. G.: Dust source identification using MODIS: a comparison of techniques applied to the Lake Eyre Basin, Australia, Remote Sens. Environ., 113, 1511–1528, 2009.

Brahney, J., Ballantyne, A. P., Sievers, C., and Neff, J. C.: Increasing Ca^{2+} deposition in the western US: the role of mineral aerosols, Aerosol. Res., 10, 77–87, 2013.

Brown, M. E., Pinzon, J. E., Didan, K., Morisette, J. T., and Tucker, C. J.: Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-Vegetation, SeaWiFS, MODIS and Landsat ETM+, IEEE T. Geosci. Remote, 44, 1787–1793, 2006.

Byun, D. and Schere, K. L.: Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system, Appl. Mech. Rev., 59, 51–77, 2006.

Carslaw, K. S., Boucher, O., Spracklen, D. V., Mann, G. W., Rae, J. G. L., Woodward, S., and Kulmala, M.: A review of natural aerosol interactions and feedbacks within the Earth system, Atmos. Chem. Phys., 10, 1701–1737, doi:10.5194/acp-10-1701-2010, 2010.

Chai, T., Kim, H.-C., Lee, P., Tong, D., Pan, L., Tang, Y., Huang, J., McQueen, J., Tsidulko, M., and Stajner, I.: Evaluation of the United States National Air Quality Forecast Capability experimental real-time predictions in 2010 using Air Quality System ozone and NO_2 measurements, Geosci. Model Dev., 6, 1831–1850, doi:10.5194/gmd-6-1831-2013, 2013.

Chen, H. and Grassian, V. H.: Iron Dissolution of Dust Source Materials during Simulated Acidic Processing: the Effect of Sulfuric, Acetic, and Oxalic Acids, Environ. Sci. Technol., 47, 10312–10321, doi:10.1021/es401285s, 2013.

Chin, M., Diehl, T., Ginoux, P., and Malm, W.: Intercontinental transport of pollution and dust aerosols: implications for regional air quality, Atmos. Chem. Phys., 7, 5501–5517, doi:10.5194/acp-7-5501-2007, 2007.

Creamean, J. M., Suski, K. J., Rosenfeld, D., Cazorla, A., DeMott, P. J., Sullivan, R. C., White, A. B., Ralph, F. M., Minnis, P., Comstock, J. M., Tomlinson, J. M., and Prather, K. A.: Dust and biological aerosols from the Sahara and Asia influence precipitation in the western US, Science, 339, 1572–1578, 2013.

Creamean, J. M., Ault, A. P., White, A. B., Neiman, P. J., Ralph, F. M., Minnis, P., and Prather, K. A.: Impact of interannual variations in sources of insoluble aerosol species on orographic precipitation over California's central Sierra Nevada, Atmos. Chem. Phys., 15, 6535–6548, doi:10.5194/acp-15-6535-2015, 2015.

Dai, A., Trenberth, K. E., and Qian, T.: A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, J. Hydrometeorol., 5, 1117–1130, 2004.

Draxler, R. R. and Hess, G. D.: An overview of the HYSPLIT_4 modeling system for trajectories, dispersion, and deposition, Aust. Meteorol. Mag., 47, 295–308, 1998.

Draxler, R. R. and Rolph, G. D.: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model, available at: http://ready.arl.noaa.gov/HYSPLIT.php, NOAA Air Resources Laboratory, Silver Spring, MD, last access: June 2015.

Draxler, R. R., Ginoux, P., and Stein, A. F.: An empirically derived emission algorithm for wind-blown dust, J. Geophys. Res., 115, D16212, doi:10.1029/2009JD013167, 2010.

Dunlea, E. J., DeCarlo, P. F., Aiken, A. C., Kimmel, J. R., Peltier, R. E., Weber, R. J., Tomlinson, J., Collins, D. R., Shinozuka, Y., McNaughton, C. S., Howell, S. G., Clarke, A. D., Emmons, L. K., Apel, E. C., Pfister, G. G., van Donkelaar, A., Martin, R. V., Millet, D. B., Heald, C. L., and Jimenez, J. L.: Evolution of Asian aerosols during transpacific transport in INTEX-B, Atmos. Chem. Phys., 9, 7257–7287, doi:10.5194/acp-9-7257-2009, 2009.

Eguchi, K., Uno, I., Yumimoto, K., Takemura, T., Shimizu, A., Sugimoto, N., and Liu, Z.: Trans-pacific dust transport: integrated analysis of NASA/CALIPSO and a global aerosol transport model, Atmos. Chem. Phys., 9, 3137–3145, doi:10.5194/acp-9-3137-2009, 2009.

Fairlie, T. D., Jacob, D. J., and Park, R. J.: The impact of transpacific transport of mineral dust in the United States, Atmos. Environ., 41, 1251–1266, 2007.

Fairlie, T. D., Jacob, D. J., Dibb, J. E., Alexander, B., Avery, M. A., van Donkelaar, A., and Zhang, L.: Impact of mineral dust on nitrate, sulfate, and ozone in transpacific Asian pollution plumes, Atmos. Chem. Phys., 10, 3999–4012, doi:10.5194/acp-10-3999-2010, 2010.

Fischer, E. V., Hsu, N. C., Jaffe, D. A., Jeong, M.-J., and Gong, J. C.: A decade of dust: asian dust and springtime aerosol load in the US Pacific Northwest, Geophys. Res. Lett., 36, L03821, doi:10.1029/2008GL036467, 2009.

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., and Huang, X.: MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets, Remote Sens. Environ., 114, 168–182, 2010.

Gassó, S., Grassian, V. H., and Miller, R. L.: Interactions between mineral dust, climate and ocean ecosystems, Elements, 6, 247–253, doi:10.2113/gselements.6.4.247, 2010.

Ginoux, P. and Torres, O.: Empirical TOMS index for dust aerosol: applications to model validation and source characterization, J. Geophys. Res., 108, 4534, doi:10.1029/2003JD003470, 2003.

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., and Lin, S.-J.: Sources and distributions of dust aerosols simulated with the GOCART model, J. Geophys. Res., 106, 20255–20274, 2001.

Ginoux, P., Prospero, J. M., Torres, O., and Chin, M.: Long-term simulation of global dust distribution with the GOCART model: correlation with North Atlantic Oscillation, Environ. Modell. Softw., 19, 113–128, doi:10.1016/S1364-8152(03)00114-2, 2004.

Ginoux, P., Garbuzov, D., and Hsu, H. C.: Identification of anthropogenic and natural dust sources using Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue level 2 data, J. Geophys. Res., 115, D05204, doi:10.1029/2009JD012398, 2010.

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, 2012.

Goudie, A. S.: Desert dust and human health disorders, Environ. Int., 63, 101–113, doi:10.1016/j.envint.2013.10.011, 2013.

Grassian, V. H., Heterogeneous Uptake and Reaction of Nitrogen Oxides and Volatile Organic Compounds on the Surface of Atmospheric Particles Including Oxide, Carbonate, Soot and Mineral Dust: implications for the Chemical Balance of the Troposphere, International Reviews of Physical Chemistry, 20, 467–548, doi:10.1080/01442350110051968, 2001.

Hahnenberger, M. and Nicoll, K.: Meteorological characteristics of dust storm events in the eastern Great Basin of Utah, USA, Atmos. Environ., 60, 601–612, doi:10.1016/j.atmosenv.2012.06.029, 2012.

Hedin, L. O. and Likens, G. E.: Atmospheric dust and acid rain, Sci. Am., 275, 88–92, 1996.

Hsu, N. C., Tsay, S.-C., King, M., and Herman, J. R.: Aerosol properties over bright-reflecting source regions, IEEE T. Geosci. Remote, 42, 557–569, 2004.

Janjic, Z., Black, T., Pyle, M., Chuang, H., Rogers, E., and DiMego, G.: An Evolutionary Approach to Nonhydrostatic Modeling, Symposium on the 50th Aniversary of Operational Numerical Weather Prediction, College Park, MD, American Meteorology Society, 2004.

Ji, L. and Peters, A. J.: Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices, Remote Sens. Environ., 87, 85–98, 2003.

Karl, T. R. and Koss, W. J.: Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895–1983, Historical Climatology Series 4–3, National Climatic Data Center, Asheville, NC, 38, 1984.

Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., and Gutman, G. G.: Use of NDVI and land surface temperature for drought assessment: merits and limitations, J. Climate, 23, 618–633, 2010.

Kim, D., Chin, M., Bian, H., Tan, Q., Brown, M. E., Zheng, T., You, R., Diehl, T., Ginoux, P., and Kucsera, T.: The effect of the dynamic surface bareness to dust source function, emission, and distribution, J. Geophys. Res., 118, 1–16, doi:10.1029/2012JD017907, 2013.

Kim, H. and Choi, M.: Impact of soil moisture on dust outbreaks in East Asia: using satellite and assimilation data, Geophys. Res. Lett., 42, 2789–2796, doi:10.1002/2015GL063325, 2015.

Kim, Y., Ou, M.-L., Ryoo, S.-B., Chun, Y., Lee, E.-H., and Hong, S.: Soil moisture retrieved from microwave satellite data and its relationship with the Asian dust (Hwangsa) frequency in East Asia during the period from 2003 to 2010, Asia-Pacific J. Atmos. Sci., 49, 527–534, 2013.

Lei, H. and Wang, J. X. L.: Observed characteristics of dust storm events over the western United States using meteorological, satellite, and air quality measurements, Atmos. Chem. Phys., 14, 7847–7857, doi:10.5194/acp-14-7847-2014, 2014.

ACPD
15, 20743–20774, 2015

Li, X. L. and Zhang, H. S.: Soil moisture effects on sand saltation and dust emission observed over Horqin Sandy Land area in China, J. Meteorol. Res., 28, 445–452, 2014.
Liu, J., Mauzerall, D. L., and Horowitz, L. W.: Evaluating inter-continental transport of fine aerosols: (2) Global health impact, Atmos. Environ., 43, 4339–4347, 2009a.
Liu, J., Mauzerall, D. L., Horowitz, L. W., Ginoux, P., and Fiore, A. M.: Evaluating Inter-continental transport of fine aerosols: (1) Methodology, global aerosol distribution and optical depth, Atmos. Environ., 43, 4327–4338, doi:10.1016/j.atmosenv.2009.03.054, 2009b.
Liu, X., Yin, Z.-Y., Zhang, X., and Yang, X.: Analyses of the spring dust storm frequency of northern China in relation to antecedent and concurrent wind, precipitation, vegetation, and soil moisture conditions, J. Geophys. Res., 109, D16210, doi:10.1029/2004JD004615, 2004.
Mahowald, N. M., Ballantine, J. A., Feddema, J., and Ramankutty, N.: Global trends in visibility: implications for dust sources, Atmos. Chem. Phys., 7, 3309–3339, doi:10.5194/acp-7-3309-2007, 2007.
Mesingera, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., Jovic, D., Woollen, J., Rogers, E., Berbery, E. H., Ek, M. B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D., and Shi, W.: North American Regional Reanalysis, B. Am. Meteorol. Soc., 87, 343–360, doi:10.1175/BAMS-87-3-343, 2006.
Miller, R. L., Perlwitz, J. P., and Tegen, I.: Feedback upon dust emission by dust radiative forcing through the planetary boundary layer, J. Geophys. Res., 109, D24209, doi:10.1029/2004JD004912, 2004a.
Miller, R. L., Tegen, I., and Perlwitz, J. P.: Surface radiative forcing by soil dust aerosols and the hydrologic cycle, J. Geophys. Res., 109, D04203, doi:10.1029/2003JD004085, 2004b.
Palmer, W. C.: Meteorological Drought. Res. Paper No. 45, 58 pp., Dept. of Commerce, Washington, DC, 1965.
Pan, L., Tong, D. Q., Lee, P., Kim, H., and Chai, T.: Assessment of NO_x and O_3 forecasting performances in the US National Air Quality Forecasting Capability before and after the 2012 major emissions updates, Atmos. Environ., 95, 610–619, doi:10.1016/j.atmosenv.2014.06.020, 2014.
Panikkath, R., Jumper, C. A., and Mulkey, Z.: Multilobar lung infiltrates after exposure to dust storm: the Haboob Lung Syndrome, Am. J. Med., 126, 5–7, 2013.
Pierce, R. B., Schaack, T., Al-Saadi, J. A., Fairlie, T. D., Kittaka, C., Lingenfelser, G., Natarajan, M., Olson, J., Soja, A., Zapotocny, T., Lenzen, A., Stobie, J., Johnson, D., Avery, M. A., Sachse, G. W., Thompson, A., Cohen, R., Dibb, J. E., Crawford, J., Rault, D., Martin, R., Szyk-

man, J., and Fishman, J.: Chemical data assimilation estimates of continental US ozone and nitrogen budgets during the Intercontinental Chemical Transport Experiment–North America, J. Geophys. Res., 112, D12S21, doi:10.1029/2006JD007722, 2007.

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, Rev. Geophys., 40, 1002, doi:10.1029/2000RG000095, 2002.

Schepanski, K., Tegen, I., and Macke, A.: Comparison of satellite based observations of Saharan dust source areas, Remote Sens. Environ., 123, 90–97, doi:10.1016/j.rse.2012.03.019, 2012.

Shao, Y., Klose, M., and Wyrwoll, K.-H.: Recent global dust trend and connections to climate forcing, J. Geophys. Res.-Atmos., 118, 11107–11118, doi:10.1002/jgrd.50836, 2013.

Shi, Y., Zhang, J., Reid, J. S., Hyer, E. J., and Hsu, N. C.: Critical evaluation of the MODIS Deep Blue aerosol optical depth product for data assimilation over North Africa, Atmos. Meas. Tech., 6, 949–969, doi:10.5194/amt-6-949-2013, 2013.

Stein, A., Draxler, R., Rolph, G., Stunder, B., Cohen, M., and Ngan, F.: NOAA's HYSPLIT atmospheric transport and dispersion modeling system, B. Am. Meteorol. Soc., doi:10.1175/BAMS-D-14-00110.1, online first, 2015.

Stith, J. L., Ramanathan, V., Cooper, W. A., Roberts, G. C., DeMott, P. J., Carmichael, G., Hatch, C. D., Adhikary, B., Twohy, C. H., Rogers, D. C., Baumgardner, D., Prenni, A. J., Campos, T., Gao, R., Anderson, J., and Feng, Y.: An overview of aircraft observations from the Pacific Dust Experiment campaign, J. Geophys. Res., 114, D05207, doi:10.1029/2008JD010924, 2009.

Tanaka, T. Y. and Chiba, M.: A numerical study of the contributions of dust source regions to the global dust budget, Global Planet. Change, 52, 88–104, 2006.

Tong, D. Q., Dan, M., Wang, T., and Lee, P.: Long-term dust climatology in the western United States reconstructed from routine aerosol ground monitoring, Atmos. Chem. Phys., 12, 5189–5205, doi:10.5194/acp-12-5189-2012, 2012.

Tong, D. Q., Bowker, G. E., He, S., Byun, D. W., Mathur, R., and Gillette, D. A.: Development of a windblown dust emission model FENGSHA: description and initial application in the United States, in review, 2015.

Tucker, C. J. and Choudhury, B. J.: Satellite remote sensing of drought conditions, Remote Sens. Environ., 23243–23251, 1987.

Underwood, G. M., Song, C. H., Phadnis, M., Carmichael, G. R., and Grassian, V. H.: Heterogeneous reactions of NO_2 and HNO_3 on oxides and mineral dust: a combined laboratory and modeling study, J. Geophys. Res., 106, 18055–18066, doi:10.1029/2000JD900552, 2001.

Uno, I., Eguchi, K., Yumimoto, K., Takemura, T., Shimizu, A., Uematsu, M., Liu, Z., Wang, Z., Hara, Y., and Sugimoto, N.: Asian dust transported one full circuit around the globe, Nat. Geosci., 2, 557–560, doi:10.1038/ngeo583, 2009.

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

Yu, H., Chin, M., Yuan, T., Bian, H., Remer, L. A., Prospero, J. M., Omar, A., Winker, D., Yang, Y., Zhang, Y., Zhang, Z., and Zhao, C.: The fertilizing role of African dust in the Amazon rainforest: a first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations, Geophys. Res. Lett., 42, 1984–1991, doi:10.1002/2015GL063040, 2015.

Wan, Z., Wang, P., and Li, X.: Using MODIS land surface temperature and normalized difference vegetation index products for monitoring drought in the Southern Great Plains, USA, Int. J. Remote Sens., 25, 61–72, 2004.

Wang, D., Morton, D., Masek, J., Wu, A., Nagol, J., Xiong, X., Levy, R., Vermote, E., and Wolfe, R.: Impact of sensor degradation on the MODIS NDVI time series, Remote Sens. Environ., 119, 55–61, 2012.

Zender, C. S., Newman, D., and Torres, O.: Spatial heterogeneity in aeolian erodibility: uniform, topographic, geomorphic, and hydrologic hypotheses, J. Geophys. Res., 108, 4543, doi:10.1029/2002JD003039, 2003.

Zender, C. S., Miller, R. L. L., and Tegen, I.: Quantifying mineral dust mass budgets: terminology, constraints, and current estimates, Eos T. Am. Geophys. Un., 85, 509–512, doi:10.1029/2004EO480002, 2004.

Zhao, C., Liu, X., and Leung, L. R.: Impact of the Desert dust on the summer monsoon system over Southwestern North America, Atmos. Chem. Phys., 12, 3717–3731, doi:10.5194/acp-12-3717-2012, 2012.

Zhu, C., Wang, B., and Qian, W.: Why do dust storms decrease in northern China concurrently with the recent global warming?, Geophys. Res. Lett., 35, L18702, doi:10.1029/2008GL034886, 2008.

Table 1. Evaluation of NAQFC CMAQ $PM_{2.5}$ prediction during a recent dust storm event on 11 May 2014.

County in Arizona	Site Type	# of sites	Observed $PM_{2.5}$*	Modeled $PM_{2.5}$*	Correlation coefficient (observed vs. modeled)
Maricopa	AirNow	8	23.7 ± 37.6	9.6 ± 16.2	0.7
	IMPROVE	2	33.7	9.5	/
Pima	AirNow	5	16.7 ± 12.6	10.9 ± 15.8	0.9
	IMPROVE	2	16.3	13.8	/

* Unit in $\mu g\,m^{-3}$; mean ± standard deviation during this 24 h period shown for the AirNow results.

ACPD
15, 20743–20774, 2015

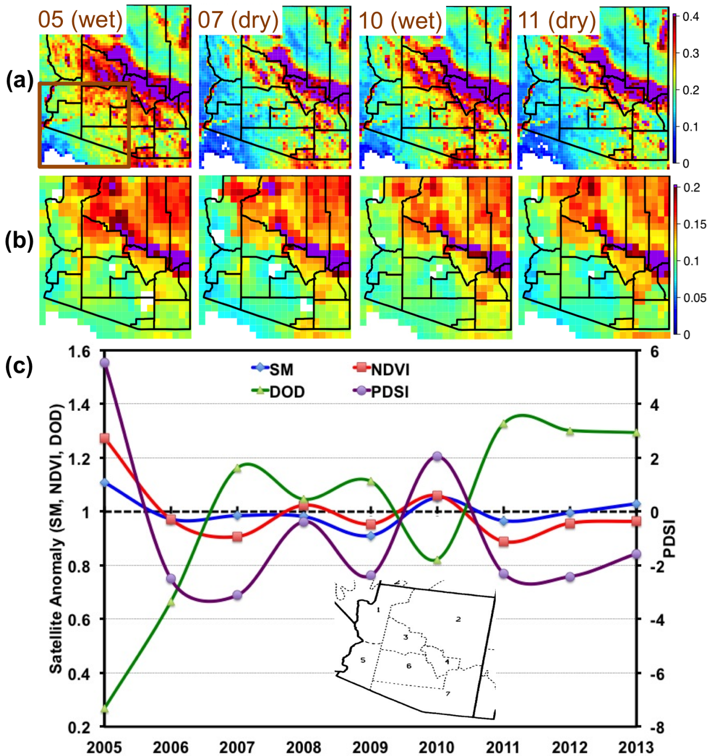

Figure 1. Inter-annual variability of drought indicators in dust seasons: **(a)** MODIS NDVI on 0.1° × 0.1° horizontal resolution and **(b)** ESA multi-sensor soil moisture (SM) product on 0.25° × 0.25° resolution are shown on moderate to severe dry and wet years. **(c)** Time series of PDSI and the anomalies of satellite SM, NDVI and Aqua MODIS DOD. The anomalies of satellite data were calculated using data within the box defined in **(a)**. The inner panel in **(c)** shows the NOAA climate divisions, and PDSI values in the South West (region 5) and South Central (region 6) regions were used in the time series plot.

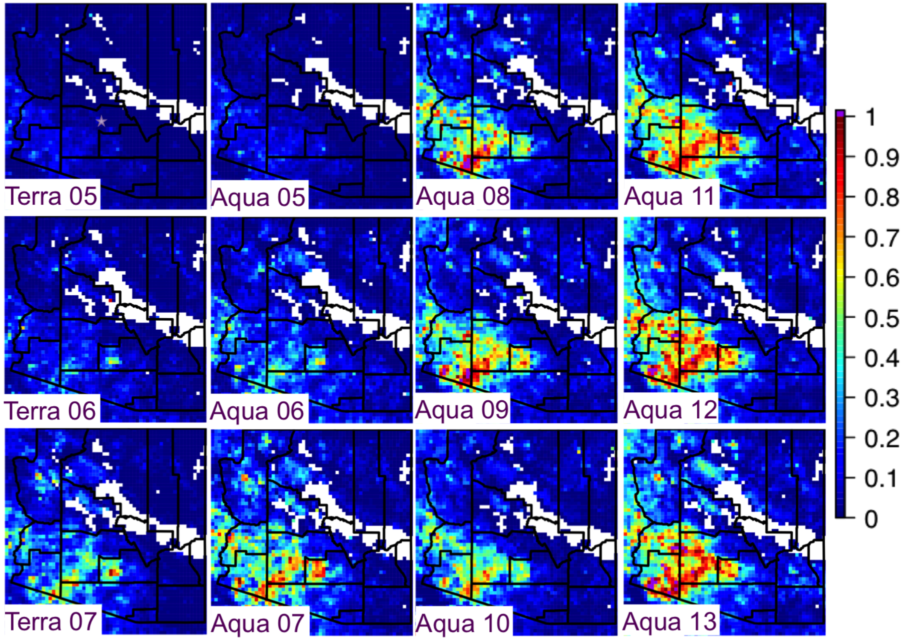

Figure 2. MODIS DOD maps during 2005–2013. The deep blue aerosol product is available during 2005–2007 for Terra MODIS, and during 2005–2013 for Aqua MODIS. The purple star in the upper left panel indicates the location of Phoenix.

ACPD
15, 20743–20774, 2015

Toward enhanced capability for detecting and predicting dust events

M. Huang et al.

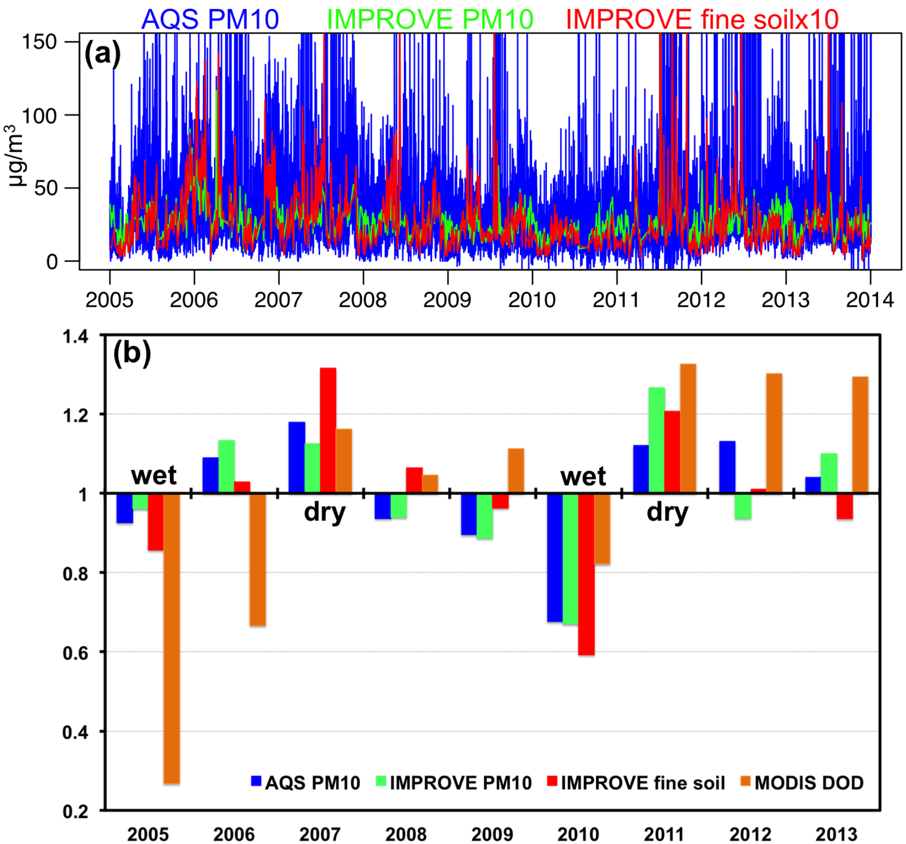

Figure 3. Time series of surface PM data at AQS and IMPROVE sites in Phoenix. These observations are shown in their original temporal resolution in **(a)**, and their anomalies in each year's dust season are shown in **(b)**, along with the Aqua MODIS DOD anomalies.

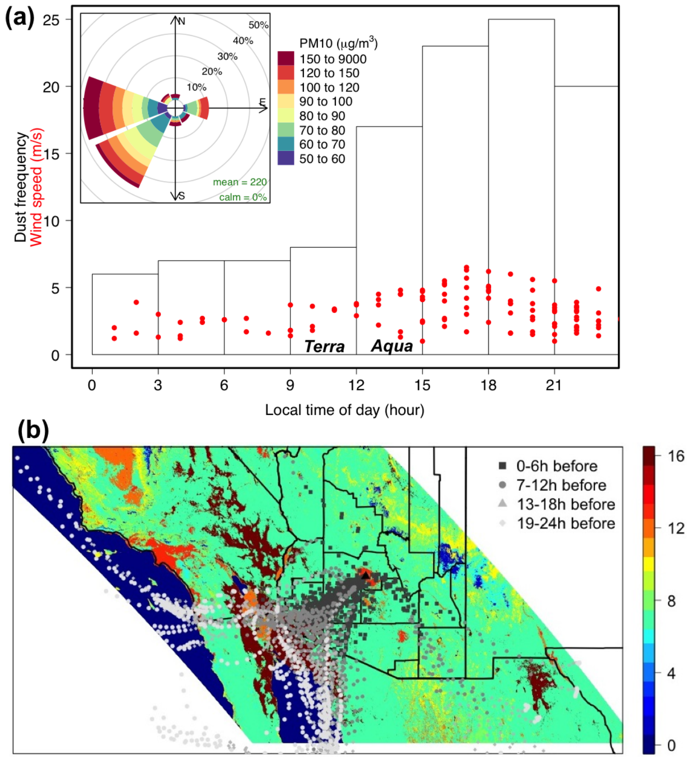

Figure 4. (a) Frequency of identified dust storms in Phoenix in 2007 as a function of the time of occurrence. Hourly mean wind speed (~ half of the hourly maximum, with correlation coefficient of ~ 0.93) during these dust storms is shown in red dot, and the inner panel shows the frequencies of PM_{10} within various concentration intervals by wind direction during these dust storms. **(b)** Hourly HYSPLIT endpoints colored by four time intervals, overlaid on a 500 m MODIS land cover type image. The MODIS land cover types mentioned in the text and their corresponding numbers are: Barren or sparsely vegetated: 16; Urban and built-up: 13; open shrublands: 7. (Source: https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd12q1).

ACPD
15, 20743–20774, 2015

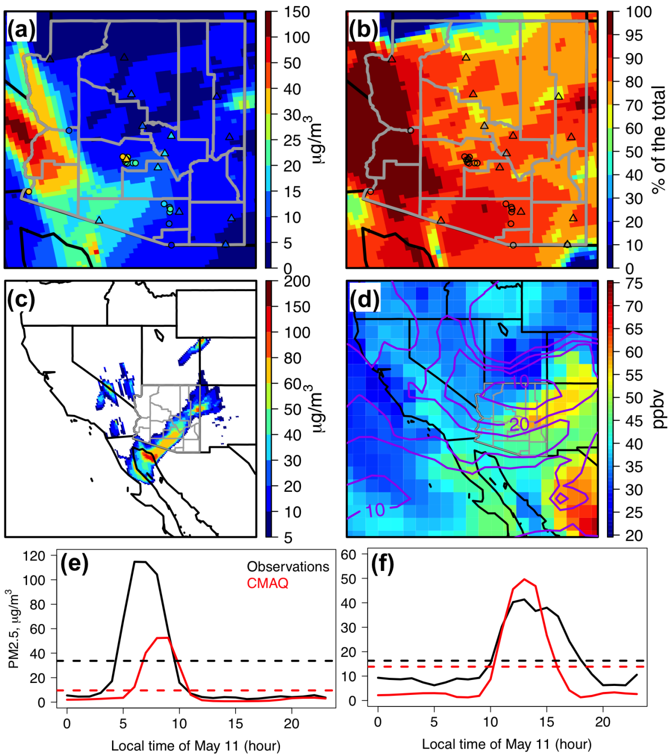

Figure 5. (a) NAQFC 12 km CMAQ modeled 24 h mean surface $PM_{2.5}$ on 11 May 2014, with the AirNow (circles) and IMPROVE (triangles) observations overlaid. **(b)** CMAQ modeled dust contributions (%) to the total $PM_{2.5}$ on this day. Locations of AirNow (circles) and IMPROVE (triangles) are shown. **(c)** CMAQ modeled dust contributions to $PM_{2.5}$ and **(d)** RAQMS modeled surface ozone at 11 Mountain Standard Time on 11 May 2014. The purple contour lines in **(d)** indicate RAQMS relative humidity (%) at the upper troposphere (~ 300 hPa). Observed (black) and modeled (red) surface $PM_{2.5}$ in **(e)** Maricopa and **(f)** Pima counties on this day, at AQS (solid lines) and IMPROVE (dash lines) sites.

ACPD
15, 20743–20774, 2015

Toward enhanced capability for detecting and predicting dust events

M. Huang et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion