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Key Points:

- Fine dust concentrations have increased across the southwestern United States in spring
- The onset of the spring dust season has shifted earlier by 1 to 2 weeks
- Trends in spring dust are influenced by large-scale climate variability and drier, windier, and less vegetated conditions in the region

Supporting Information:

- Supporting Information S1

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Earlier onset of the spring fine dust season in the southwestern United States

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Abstract Particulate matter $(PM)_{2.5}$ dust concentrations (mineral particles with aerodynamic diameters less than 2.5 μm) typically peak in spring and early summer at rural and remote sites across the southwestern United States. Trend analyses indicate that springtime regional mean $PM_{2.5}$ dust concentrations have increased from 1995 to 2014, especially in March ($5.4\%\ \text{yr}^{-1}$, $p < 0.01$). This increase reflects an earlier onset of the spring dust season across the Southwest by 1 to 2 weeks over the 20 year time period. March dust concentrations were strongly correlated with the Pacific Decadal Oscillation index ($r = -0.65$, $p < 0.01$), which was mostly in its negative phase from 2007 to 2014, during which the region was drier, windier, and less vegetated. The positive spring trend and its association with large-scale climate variability have several important implications for visibility, particulate matter, health effects, and the hydrologic cycle in the region.

1. Introduction

Local sources in arid southwestern (SW) North America, including the Mojave, Great Basin, Sonoran, and Chihuahuan deserts and Southern Great Plains, give rise to the highest aeolian dust concentrations in the United States [*Prospero et al.*, 2002]. Concentrations peak in spring and early summer due to synoptic-scale meteorological patterns that transport dust across the region and continent [*Brazel and Nickling*, 1986; *Novlan et al.*, 2007; *Park et al.*, 2007; *Rivera Rivera et al.*, 2009; *Hahnenberger and Nicoll*, 2012]. Dust in this region has several important environmental implications, such as its contribution to visibility degradation [e.g., *Kavouras et al.*, 2009; *Hand et al.*, 2011, 2014; *Ashley et al.*, 2015], respiratory health impacts [e.g., *Grineski et al.*, 2011], heterogeneous chemistry in the atmosphere [e.g., *Krueger et al.*, 2004], influence on the hydrologic cycle in the Intermountain West [e.g., *Painter et al.*, 2007], transport of bioaerosols [e.g., *Hallar et al.*, 2011], removal and transport of topsoil, and influence on ecosystem dynamics [*Field et al.*, 2010], as well as direct and indirect climate effects [e.g., *Arimoto*, 2001].

Characterization of SW dust has been performed using a diversity of data sets, such as column optical depth from satellite [e.g., *Ginoux et al.*, 2012], low-visibility meteorological records, and ground-based ion deposition [e.g., *Okin and Reheis*, 2002; *Brahney et al.*, 2013], and other ground-based assessments that differ in measurement size range and definitions of dust episodes [e.g., *Reheis and Urban*, 2011; *Tong et al.*, 2012; *Neff et al.*, 2013]. Aerosol data from the remote and rural Interagency Monitoring of Protected Visual Environments (IMPROVE) network have been used to reconstruct particulate matter $(PM)_{2.5}$ dust concentrations (mineral particles with aerodynamic diameters less than 2.5 μm, hereafter referred to as "fine") using an algorithm that assumes common oxide forms of typical mineral species found in soil [*Malm et al.*, 1994]. Fine dust concentrations (as estimated using the IMPROVE dust algorithm) are highest during the spring season in the SW (typically April and May) and regional in extent [*Sorooshian et al.*, 2011; *Hand et al.*, 2012a]. Characterizing fine dust concentrations is important for assessing their role in visibility degradation and health impacts. Dust contributes to the worst haze days in the SW [*Kavouras et al.*, 2007, 2009] and currently contributes over 50% to the $PM_{2.5}$ mass budget in the SW during spring months. Fine dust has the capacity for long-distance transport and tends to have regional impacts relative to the more localized impact of coarse dust.

Dust sources in the SW have been associated with ephemeral lakes (playas) and disturbed soils such as agricultural (range and crop) lands [e.g., *Baddock et al.*, 2011; *Ginoux et al.*, 2012]. The Chihuahuan and Sonoran deserts are transport capacity limited in that dust emissions tend to be limited by wind rather than sediment availability, while the Mojave desert is limited by sediment availability. Dust sources in the Southern Great Plains and Chihuahuan desert were identified in previous studies as largely anthropogenic in origin, such as disturbed sand sheets and alluvial lowlands used for agriculture [*J. A. Lee et al.*, 2009, 2012; *Rivera Rivera et al.*, 2010; *Bullard et al.*, 2011]. Many of the dust events identified by *Rivera Rivera et al.* [2010] appeared to develop nearly simultaneously and merge into regional-scale events. Dust that contributed to worst haze days from 2001 to 2003 was primarily transported from upwind, regional sources susceptible to wind erosion, followed by local and undetermined sources; a minor contribution was associated with Asian transport [*Kavouras et al.*, 2009].

SW dust sources, whether natural or anthropogenic, are subjected to influences from drought, climate variability, or anthropogenic perturbations. Current drought conditions in the SW have been documented and predicted to likely worsen due to climate change [*Cayan et al.*, 2010; *Gao et al.*, 2014; *Cook et al.*, 2015; *Prein et al.*, 2016], and the increase in aridity will likely cause reductions in vegetation cover, leading to increased potential for erosion of bare soils [*Seager et al.*, 2007; *Munson et al.*, 2011]. Linkages between drought and increased dust emissions and deposition have been established in this region [*Reheis and Urban*, 2011; *Brahney et al.*, 2013] and elsewhere [e.g., *Mahowald et al.*, 2007; *Notaro et al.*, 2015]. Drought in the SW has also been linked to large-scale climate variability such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) [e.g., *Dettinger et al.*, 1998; *Brown and Comrie*, 2004; *McCabe et al.*, 2004; *Weiss et al.*, 2009; *Dai*, 2013; *Wang and Kumar*, 2015; *Barnston and Lyon*, 2016]. In addition, the PDO has been associated with storm track intensity in the North Pacific [*Weiss et al.*, 2009; *S.S. Lee et al.*, 2012; *Dai*, 2013; *Sung et al.*, 2014], a region known to influence weather patterns and drought conditions in the SW [*Prein et al.*, 2016]. Temperature has increased in the region [*Munson et al.*, 2011; *Wang et al.*, 2011], as has the length of the growing season (~10–15 days since the mid-1980s) [*Hoerling et al.*, 2013], along with an earlier shift in spring blooms [*Ault et al.*, 2015]. Population and economic activity in the SW have also increased [*Theobald et al.*, 2013]. Changes in climate and land use can lead to drier, less vegetated, and disturbed surfaces that may be more available for dust emission.

The changing environmental conditions in the SW are potential drivers for higher dust emissions and ambient concentrations. We evaluated temporal trends in fine dust concentrations at remote and rural IMPROVE sites in the SW over the past 20 years (1995–2014). This study takes advantage of the consistent monitoring and analysis strategy of the IMPROVE network. Focusing on fine dust allows for the investigation of regional patterns influenced by both local and regional dust sources. Dust trends are interpreted in the context of changes in climate indices (i.e., PDO and ENSO), vegetation index, and meteorological variables (i.e., precipitation and surface wind speeds).

2. Data

The IMPROVE network [*Malm et al.*, 1994] has collected 24 h $PM_{2.5}$ and PM_{10} (particles with aerodynamic diameters less than 10 μm) aerosol samples every third day at remote and rural sites across the United States and currently operates about 160 sites. Speciated analysis is performed on $PM_{2.5}$ samples, including X-ray fluorescence (XRF) for elemental concentrations. $PM_{2.5}$ and PM_{10} mass concentrations are determined through gravimetric weighing, and coarse mass is calculated from the difference ($PM_{10} - PM_{2.5}$). Ambient concentrations are reported as mass per air volume at local temperature and pressure. Details regarding IMPROVE site locations, sampling, and analysis methodology and detailed descriptions of network operations and data analysis have been previously reported [*Hand et al.*, 2011, 2012a]. IMPROVE data advisories were followed for the data reduction and analysis (see http://vista.cira.colostate.edu/improve/Data/QA_QC/Advisory.htm).

A recent XRF reanalysis of historical IMPROVE filters by *Hyslop et al.* [2015] demonstrated that changes in analytical methods over time introduced spurious trends in some XRF species that compose mineral aerosols, such as silicon, titanium, and aluminum. These species, along with calcium and iron, are commonly used to reconstruct fine dust concentrations assuming common oxides [e.g., *Malm et al.*, 1994]. To avoid introducing potential uncertainty in the trends, iron (Fe) was chosen as a proxy for mineral dust concentrations due to the demonstrated consistency with which it was measured over time. Fe emissions in the SW are primarily due to mineral sources [*Wang et al.*, 2015], and therefore, fine dust was assumed to be 3.5% Fe based on crustal abundances [*Taylor and McLennan*, 1985]. Spatial and temporal trends in Fe were corroborated against other stable mineral species such as calcium. No attempt was made to distinguish dust from different sources (e.g., natural and anthropogenic). Fine mineral dust concentrations are assumed to be associated with the fine tail of the coarse-mode size distribution. Coarse mass was not used in the analysis since it is the difference of two measurements and potentially affected by changes to the PM_{10} inlet. Coarse mass also has nonmineral contributions [*Malm et al*., 2007] that, along with its short atmospheric lifetime, may obscure regional trends in dust.

Month-specific trends in dust were computed for the years 1995 to 2014 using a linear Theil regression [*Theil*, 1950] following the methods used by *Hand et al*. [2012b, 2014]. Selection of this time period was based on the XRF reanalysis study [*Hyslop et al*., 2015]. Trends were calculated from monthly means, a valid month requiring 50% data completeness and a trend requiring valid months in 14 of the 20 years. Normalized trends (% yr^{-1}) were computed by dividing the slope from the regression by the median of the relevant monthly mean concentrations. Significance levels (p) were computed using Kendall tau statistics. Trend isopleths were generated by interpolating site-specific trends using an ordinary kriging algorithm [*Isaaks and Mohan Srivastava*, 1989]. Regionally aggregated concentrations and trends were computed for long-term (LT) sites operating continuously over the 20 year time period in the SW region, defined here to include sites in Utah, Colorado, Arizona, New Mexico, and southwestern Texas (15 sites; see Table S1 in the supporting information). These sites and region were chosen based on similar aerosol composition and seasonal patterns [*Hand et al*., 2012a].

Meteorological variables and climate indices from 1995 to 2014 were also analyzed. These data sets include gridded (4 km × 4 km), monthly mean total precipitation from Oregon State University's Parameter-elevation Regression on Independent Slopes Model (PRISM) Climate Group; monthly mean, gridded (2.5° × 2.5°) surface wind speed from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al*., 1996]; Moderate Resolution Imaging Spectroradiometer gridded (0.05° × 0.05°), monthly enhanced vegetation indices (EVIs) for 2001–2014 from the U.S. Geological Survey [*Huete et al*., 2002]; monthly PDO index from the Joint Institute for the Study of the Atmosphere and Ocean [*Mantua et al*., 1997]; and 3 month running mean Oceanic Niño Index ENSO indices from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. Gridded data were regionally averaged over the SW according to the regions depicted in the supporting information.

3. Results

Regional, monthly mean fine dust concentrations have increased during spring months, primarily in March, as shown in Figure 1a for two different time periods (1995–2006 and 2007–2014). Figures 1b–1e show the meteorological variables and climate indices averaged over the same time periods and will be discussed later. The increase in fine dust in March occurred across the region; in fact, 36 IMPROVE sites across the SW and other western states were associated with trends of 5% yr^{-1} or higher (Figure 2a). Fine dust trends in April and May were not as high or regionally extensive (see Figures 2b and 2c, respectively). The SW regional March mean trend for LT sites was 5.4% yr^{-1} ($p < 0.01$), compared to 2.0% yr^{-1} ($p = 0.07$) for April and 1.5% yr^{-1} ($p = 0.11$) for May. Trends in the 10th, 50th, and 90th percentile March dust concentrations were similar (all near 5% yr^{-1}), suggesting that low-dust and high-dust conditions in March have both increased.

The dramatic increase in March fine dust concentrations represents an earlier onset of the spring dust season. The earlier onset was quantified by determining the change in the day of year (DOY) when LT sites recorded half of their cumulative annual dust burden. Cumulative dust frequency distributions were calculated for the combined dust concentrations at the LT sites (see Figure S1 in the supporting information). The DOY associated with the 0.5 cumulative probability was determined for each year from 1995 to 2014, and the DOY anomaly was computed by subtracting the 1995–2014 DOY climatological mean from the DOY for each year.

March monthly mean fine dust concentrations started increasing around 2007 (with the exception of 2010, which was an El Niño year; see Figure 3a), and the shift toward an earlier dust season started around the same time (Figure 3b). Between the two time periods (1995–2006 and 2007–2014), the regional mean fine dust season shifted earlier by an average of 10 days and ranged from 3 days in White River National Forest, CO, to 18 days in Guadalupe Mountains National Park, TX (see Table S1 in the supporting information).

Also starting around 2007 were increased dust concentrations in the Arabian Peninsula [*Notaro et al*., 2015]. The increase was associated with a period of a negative-phase PDO index and related severe drought in the region. Drought conditions in the SW also have been associated with a negative phase of the PDO and ENSO [e.g., *Weiss et al*., 2009]. Strong (e.g., $p < 0.01$) correlations between March PDO and dust ($r = -0.65$) suggest

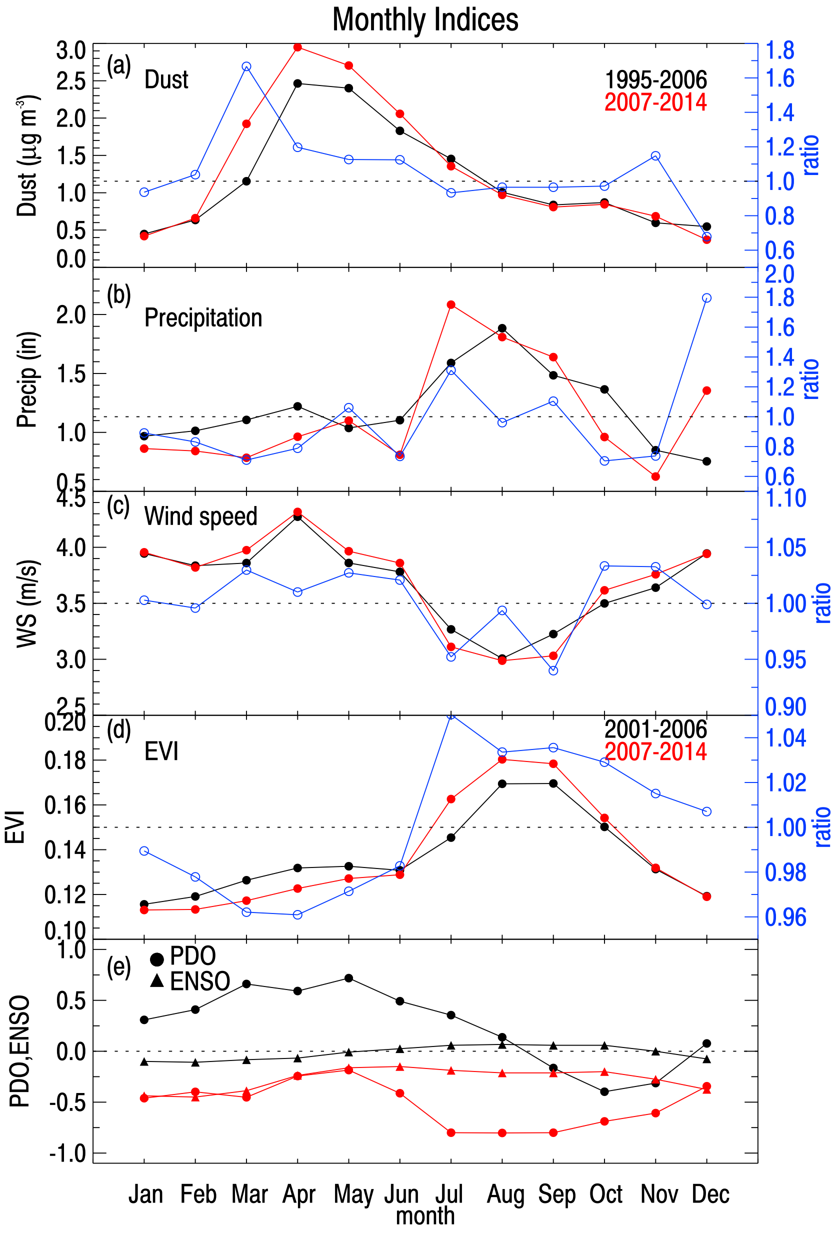

Figure 1. Southwest regional monthly mean (a) fine dust ($\mu g\,m^{-3}$) for 1995–2006 (black) and 2007–2014 (red) and the ratio of the later to the earlier period on the right axis (blue), (b) precipitation (inches), (c) surface wind speed ($m\,s^{-1}$), (d) enhanced vegetation index (EVI), and (e) monthly Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) plotted at the center of 3 month running mean.

some influence of large-scale climate variability on SW fine dust concentrations (see Figure 3a). Regional mean fine dust and PDO were both strongly correlated with regional mean precipitation ($r = -0.67$ and $r = -0.56$, respectively) and regional mean EVI ($r = -0.55$ and $r = -0.56$, respectively) in March but to a lesser degree in April and May (see Table 1). Dust and the ENSO index were correlated in March (see Figure 3a) and April ($r = -0.47$ and $r = -0.51$, respectively) but not in May ($r = 0.30$). Finally, fine dust and regional mean surface wind speeds were weakly correlated for all months (lowest in April; see Table 1). Timelines of dust with these indices are shown in Figure S2 in the supporting information.

The two time periods (1995–2006 and 2007–2014) corresponded to (mostly) positive and negative PDO indices, respectively (Figure 1e). During spring months, especially March, the later period was generally associated with dustier (~60%), drier (~30%), windier (~3%), and less vegetated conditions (~4%), as shown

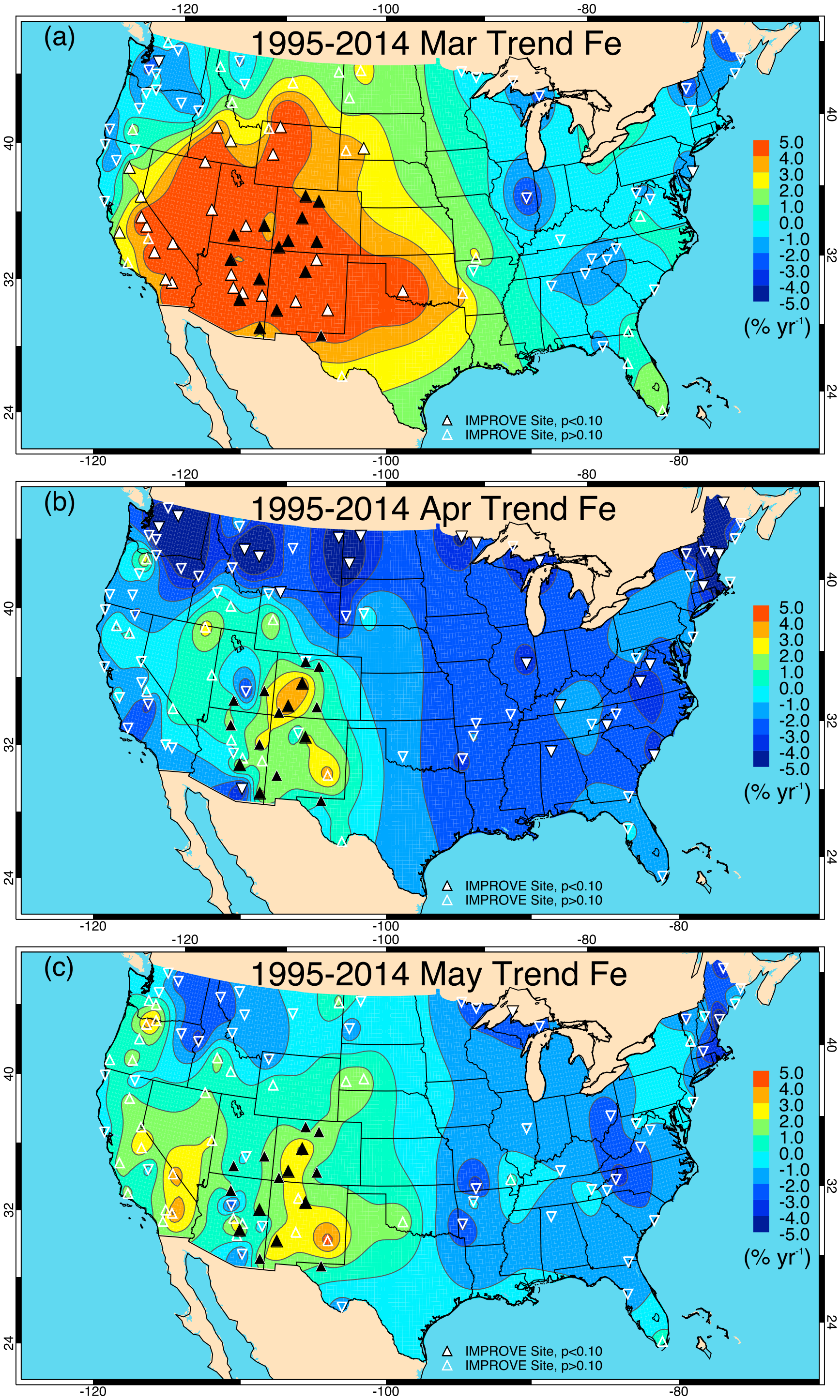

Figure 2. IMPROVE 1995–2014 monthly mean trends (% yr^{-1}) in PM$_{2.5}$ (fine) iron (Fe) mass for (a) March, (b) April, and (c) May. The triangles correspond to the IMPROVE sites that met the trend criteria; the filled triangles correspond to the significance levels of $p < 0.10$. The black filled triangles correspond to the long-term sites with continuous data over the 20 year period.

in Figures 1a–1d, respectively. The ENSO index was also negative during the second period (Figure 1e). Differences in the spatial variability in precipitation, wind speed, and EVI between these two time periods (see Figures S3, S4, and S5 in the supporting information, respectively) suggest that many of these differences occurred in dust source regions [e.g., *Ginoux et al.*, 2012].

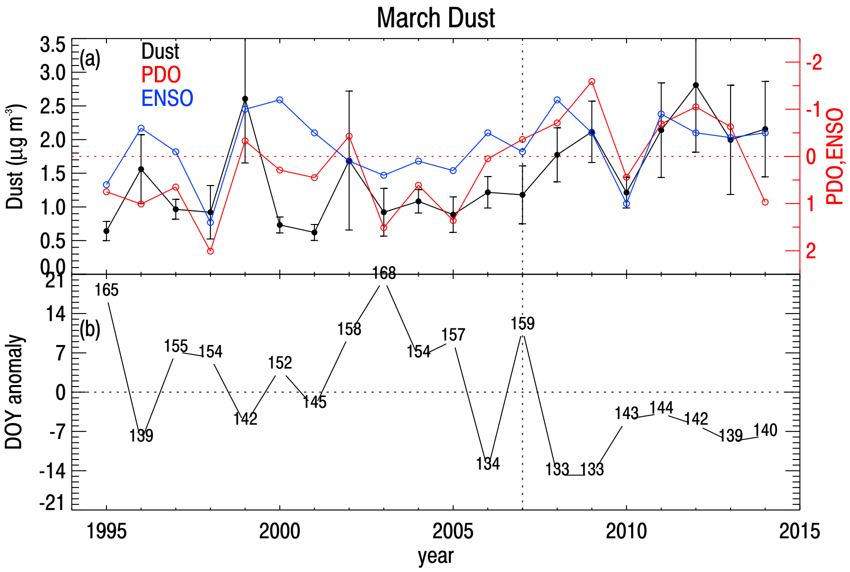

Figure 3. (a) Southwest regional March monthly mean fine dust concentrations (μg m^{-3}) and one standard error for long-term IMPROVE sites. March Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) are shown on the right axis (notice inverted axis). (b) Day of year (DOY) anomaly for the Southwest. The day of year is used as the symbol. The vertical dashed line corresponds to the year 2007 for reference.

4. Discussion

March mean fine dust concentrations have increased over the past two decades at remote sites across the southwestern United States, reflecting an earlier onset of the spring dust season by approximately 10 days. Since 2007 the March PDO was mostly negative and the region was generally drier, windier, and less vegetated. Strong correlations between fine dust and the PDO suggest that large-scale climate variability may be associated with an increase in regional fine dust being transported across the SW, and to our knowledge this is the first time this association has been reported for the region. Strong correlations between March dust and precipitation suggest that drier conditions likely influenced the increased dustiness, although the relationship between dust emission and aridity is complex and dependent on source type/location [*Okin and Reheis*, 2002; *Reynolds et al.*, 2009; *Lewis et al.*, 2011; *Reheis and Urban*, 2011; *Hahnenberger and Nicoll*, 2014; *White et al.*, 2015]. However, other contributing factors cannot be ruled out, such as intensified land use and disturbed lands, including from wildfires [*Miller et al.*, 2012; *Hahnenberger and Nicoll*, 2014], increased population and economic activity [*Theobald et al.*, 2013], and impacts from climate change [e.g., *Cayan et al.*, 2013]. In addition, the possible influence of long-range transport of African [*Perry et al.*, 1997] or Asian dust cannot be dismissed;

Table 1. Correlation Coefficients (r) Between Various Monthly and Regional Mean Indices for March, April, and May for 1995 Through 2014, Except for EVI (2001–2014)[a]

Correlation Coefficients (r)	March	April	May
Dust and Pacific Decadal Oscillation (PDO)	−***0.65***	−**0.50**	−**0.51**
Dust and El Niño–Southern Oscillation (ENSO)[b]	−**0.47**	−**0.51**	−0.30
Dust and precipitation	−***0.67***	−**0.54**	−0.41
Dust and wind speed	0.35	0.27	0.27
Dust and enhanced vegetation index (EVI)	−**0.55**	−0.10	−***0.66***
PDO and precipitation	***0.56***	0.07	0.19
PDO and wind speed	−0.26	−0.13	−0.12
PDO and EVI	***0.56***	0.52	0.48
ENSO and EVI	0.26	0.46	0.19
EVI and precipitation	0.47	0.48	0.29

[a] Bold: $p = 0.05$, bold + italics: $p < 0.01$.
[b] ENSO indices were correlated with the center month of the 3 month running mean.

however, the insignificant and mostly negative trends at sites in the northwestern United States that are often influenced by Asian dust [*Creamean et al.*, 2014] suggest low influence (see Figure 2a).

The implications of an earlier fine dust season in the SW are significant. Fine dust from this region is transported long distances and regularly deposits and influences the timing of snowmelt and the hydrologic cycle in the San Juan Mountains of southern Colorado [*Painter et al.*, 2007, 2012; *Neff et al.*, 2008; *Lawrence et al.*, 2010]. Increased dust concentrations also have implications for visibility degradation and health impacts. Visibility has improved significantly across the United States, except in areas of the West and SW [*Hand et al.*, 2014] where the combined contribution of fine dust and coarse mass to total aerosol extinction has increased from ~15% to ~30% on the haziest days from 1995 to 2014. Fine dust exacerbates respiratory illnesses such as asthma [e.g., *Grineski et al.*, 2011], and spring dust contributions to $PM_{2.5}$ mass across the SW have increased from 20% to 50% from 1995 to 2014. Dust also serves as a transport mechanism for bioaerosols [*Hallar et al.*, 2011] and is a host for coccidioidomycosis (valley fever), a respiratory disease associated with a soil-dwelling fungus, with cases that have reportedly increased in the SW, especially starting around 2008 [*Centers for Disease Control and Prevention*, 2013]. Understanding the role of large-scale climate variability and its influence on fine dust concentrations in the SW is important for accurately quantifying, perhaps predicting, and mitigating future impacts of anthropogenic perturbations and climate change on dust emissions and their consequent impacts on the environment.

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