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Drought-sensitivity of fine dust in the U.S. Southwest: Implications for air quality and public health under future climate change

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ABSTRACT

We investigate the present-day sensitivity of fine dust levels in the U.S. Southwest to regional drought conditions and use the observed relationships to assess future changes in fine dust levels and associated health impacts under climate change. Empirical Orthogonal Function analysis reveals that the most dominant mode of fine dust interannual variability for each season consists of a pattern of large-scale co-variability across the Southwest. This mode is strongly correlated to the Standardized Precipitation-Evapotranspiration Index (SPEI) accumulated over 1-6 months in local and surrounding regions spanning the major North American deserts. Across the seasons, a unit decrease in 2-month SPEI averaged over the U.S. Southwest and northern Mexico is significantly associated with increases in Southwest fine dust of 0.22-0.43 μg m^{-3}. We apply these sensitivities to statistically downscaled meteorological output from 22 climate models following two Representative Concentration Pathways (RCPs), and project future increases in seasonal mean fine dust of 0.04-0.10 μg m^{-3} (5-8%) under RCP2.6 and 0.15-0.55 μg m^{-3} (26-46%) under RCP8.5 relative to the present-day (2076-2095 vs. 1996-2015). Combined with the same projections of future population and baseline incidence rates, annual premature mortality attributable to fine dust exposure could increase by 140 (24%) deaths under RCP2.6 and 750 (130%) deaths under RCP8.5 for adults aged ≥30 years, and annual hospitalizations due to cardiovascular and respiratory illnesses could increase by 170 (59%) admissions under RCP2.6 and 860 (300%) admissions under RCP8.5 for adults aged ≥65 years in the Southwest relative to the present-day. Our results highlight a climate penalty that has important socioeconomic and policy implications for the U.S. Southwest but is not yet widely recognized.

INTRODUCTION

Fine mineral dust, defined here as soil-derived particulate matter smaller than 2.5 μm aerodynamic diameter ($PM_{2.5}$), is a significant component of $PM_{2.5}$ air pollution and visibility reduction in the southwestern U.S. due to abundant wind-erodible dryland surfaces. At peak concentrations in the spring, fine dust can contribute up to 50% to total $PM_{2.5}$ [1]. The southern Great Plains, the Colorado Plateau, and the North American Deserts (Chihuahuan, Mojave, and Sonoran) have been identified as major dust sources for the Southwest [2–5]. Changes in dust activity in the Southwest over the recent and historical past have been associated with hydroclimate variability and human land disturbance [6–9]. A robust result across climate models is a shift toward warmer and drier conditions in southwestern North America in response to strong greenhouse gas forcing, most likely due to general drying of the subtropics and poleward expansion of subtropical dry zones [10–13]. Indeed, multiple studies estimate severe drought conditions for the Southwest towards the end of this century due to climate change [10,14–16]. However, the extent to which such increases in aridity could impact airborne levels of dust has not been quantified, but would significantly contribute to improving our understanding of the climate impacts on $PM_{2.5}$ in the United States [17].

Model studies that have previously investigated the future response of global atmospheric dust to climate change yielded contradictory results, leading to a "low confidence" of such projections according to the IPCC AR5 classification [18]. For example, Woodward et al. found a tripling of the global dust loading in 2100 relative to present-day due to large increases in bare soil [19], whereas Mahowald et al. found a 60% decrease under a doubled-CO_2 concentration scenario due to the effect of CO_2 fertilization on vegetation [20]. These discrepancies are in large part due to uncertainties in the response of vegetation cover to greenhouse gas forcing [21], and to challenges in capturing dust mobilization and transport in 3-D dynamical models [22]. For example, accurate representation of sub-grid surface winds and of surface roughness, soil moisture, and soil composition are important in simulating dust fluxes but remain a challenge to achieve in models [23–25].

The linkages between $PM_{2.5}$ exposure and adverse human health effects, ranging from cardiovascular and pulmonary illnesses to premature mortality, are well-documented by numerous epidemiological studies [26–30]. Fann et al. estimated that U.S. $PM_{2.5}$ levels in 2005 led to 130,000 premature deaths nationwide that year [31]. Although the potency and health outcomes of specific $PM_{2.5}$ components remain poorly differentiated [32,33], evidence suggests that soil-derived particles contribute to the adverse health effects of $PM_{2.5}$ [34,35].

For example, Crooks et al. found that dust storms in the United States were associated with an increase of ~3% in daily non-accidental mortality over a lag period of 0-5 days between 1993 and 2005 [36]. Meng and Lu reported that dust events in China led to an increased relative risk of hospitalization for respiratory and cardiovascular diseases by ~1% [37]. In an *in vitro* toxicology study, Veranth et al. found that dust collected from certain sites in the western U.S. induced cellular respiratory injury [38]. Silica, which makes up ~60% of windblown dust from desert regions [39], is known to cause chronic lung inflammation and fibrosis, lung cancer, and systemic autoimmune diseases [40,41].

Despite these concerns, few studies have examined the impacts on air quality and public health of the projected hydroclimate changes in the southwestern United States. Wang et al. estimated that due to changes in local drought severity alone, March-October levels of surface $PM_{2.5}$, including fine dust, could increase by 1-16% in the U.S. in 2100 compared to the 2000s under three different Representative Concentration Pathways (RCP2.6, RCP4.5, and RCP8.5) [42]. These authors also found that four models participating in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) failed to reproduce observed responses of atmospheric $PM_{2.5}$ to drought occurrences in the present-day. Conversely, Pu and Ginoux [43] estimated that the springtime frequency of extreme dust events in the Southwest would decrease by ~2% in the future (2051-2100) under RCP8.5 compared to historical levels (1861-2005), driven by reductions in surface bareness and wind speeds.

In a previous study, we found that fine dust interannual variability across the western U.S. during the spring months of 2002-2015 display large-scale spatiotemporal behaviors associated with fluctuations in regional hydroclimate and trans-Pacific transport of Asian dust, which are in turn partially influenced by the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) [9]. In this study, we explore the sensitivity to drought conditions in all seasons and use the observed relationships to estimate future changes in fine dust during the late-21st century, using statistically downscaled meteorological output from 22 models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) following RCP2.6 (low-emissions) and RCP8.5 (high-emissions) scenarios. This approach, in which observed relationships of dust and drought are applied to future climate projections, is not dependent on the ability of any given climate model to capture the relevant dust processes and provides an observational foundation for rapid assessment of future dust activity under a range of climate change scenarios. Our approach is similar to previous studies that have explored future changes in surface ozone [42,43], total $PM_{2.5}$ [44–46], and wildfire activity [47] in the United States. We focus solely on the effects of droughts because the general warming and drying of southwestern North America under future climate change appears to be a robust response across climate models, whereas large uncertainties remain in the projections of other potential controlling factors such as vegetation cover [21], ENSO and PDO [48], and surface wind fields [24]. Together with projections of future population and baseline incidence rates, and results from epidemiological studies of health risks due to $PM_{2.5}$ exposure, we also estimate the excess premature mortality and morbidity associated with the projected changes in annual mean fine dust.

DATA AND METHODS

We provide here a brief overview of data and methods used; detailed descriptions are provided in the Supplement. Throughout this study, we use $p < 0.05$ as the threshold for statistical significance. We define 1996-2015 as our present-day period, and 2076-2095 as the future.

We rely on ground-based measurements from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network to calculate surface fine dust concentrations in the southwestern U.S. (defined here as 31°-41°N, 115°-103°W; spanning Arizona, Colorado, New Mexico, and Utah) [49]. We use the iron content of $PM_{2.5}$ as a fine dust proxy, following the approach first proposed by Hand et al. [7] and subsequently updated by Achakulwisut et al. [9], to calculate monthly mean fine dust concentrations. The locations of the 35 selected sites are shown in Figure 1. Due to the relative lack of IMPROVE data before 2000, the present-day period over which we quantify the relationships between dust and drought is restricted to 2000-2015.

We first examine the dominant spatial patterns of fine dust interannual variability across the U.S. Southwest and its correlations to drought and other meteorological variables over western North America (15°-50°N, 125°-85°W) using Empirical Orthogonal Function (EOF) analysis. We use the gridded 0.5° × 0.5° global monthly mean Standardized Precipitation-Evapotranspiration Index (SPEI, v2.5) from the Spanish National Research Council as a drought proxy [50,51]. The SPEI uses gridded 0.5° × 0.5° precipitation and potential evapotranspiration values from the Climatic Research Unit of the University of East Anglia (CRU TS dataset version 3.24.01) to determine the water balance, which can be aggregated over different timescales to monitor drought conditions in different hydrologic sub-systems, compared to a reference period of 1950-2010. The gridded CRU TS dataset is constructed from monthly observations at meteorological stations across global land areas (~440 of which are located in western North America) [52]. Drought classification based on the SPEI is shown in

Table S1. We consider SPEI values calculated over 1, 2, 3, 6, 12, 24, and 48 months. We chose the SPEI over other common drought indices, the self-calibrating Palmer Drought Severity Index (SC-PDSI) and the Standardized Precipitation Index (SPI), because the SC-PDSI lacks a multi-timescale feature and the SPI only considers the effects of precipitation, which may underestimate the risk of future droughts in the southwestern United States [15]. In addition, we use surface temperature, precipitation, potential evaporation, relative humidity, wind speed, vegetation, and 500 mb geopotential heights from the North American Regional Reanalysis (NARR) [53].

Next, we quantify the sensitivity of the anomalies in seasonal mean fine dust averaged over the Southwest domain to seasonal mean SPEI02 anomalies averaged over regions displaying the strongest correlations using simple linear regression. To assess whether the linear sensitivities are statistically different from zero, a 95% confidence interval for the regression coefficients are calculated using the two-tailed Student's t-test and by bootstrap resampling with 10,000 replicates and the bias-corrected and accelerated (BCa) confidence interval method [54].

To calculate future changes in drought conditions, we use meteorological output from an ensemble of 22 CMIP5 climate models (Table S2) following the historical and two future scenarios, RCP2.6 and RCP8.5 [55]. These RCPs represent the lower and upper limits of the projected radiative forcing values by 2100 used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. RCP2.6 is characterized by a "peak-and-decline" mitigation scenario, whereas RCP8.5 is characterized by increasing greenhouse gas emissions over time [56]. In order to capture regional-scale hydroclimate impacts, we use the gridded 12 km × 12 km temperature and precipitation from the bias-corrected and spatially-disaggregated CMIP5 Climate and Hydrology Projections (BCSD5), as the coarse-grid CMIP5 models cannot reproduce the mean and standard deviation of monthly mean surface temperature and total precipitation averaged over the Southwest for 1996-2015 (Figure S1) [57]. We use the R package "SPEI" (version 1.7) to calculate SPEI from the monthly mean daily maximum and minimum temperature and total precipitation, using 1950-2010 as the reference period as in the SPEI global database, and the Modified-Hargreaves equation to model potential evapotranspiration (PET) [51]. The widely used FAO Penman-Monteith PET equation requires additional variables not available from the BCSD5 archive, and Droogers and Allen [58] demonstrated that the Modified-Hargreaves is a robust alternative.

Since there is presently insufficient information to determine the specific health effects of fine dust exposure [32,33], we approximate the health burden due to the projected changes in fine dust using well-documented results from epidemiological studies based on total $PM_{2.5}$. Estimating premature mortality and morbidity attributable to $PM_{2.5}$ exposure requires knowledge of Concentration-Response (C-R) Functions, which are empirically derived from cohort studies and are typically based on a log-linear relationship between relative risk (RR) and pollutant concentration [31,59,60]:

$$\Delta M_n = y_{0_n} \times \left(1 - e^{-\beta_n \Delta x}\right) \times P, \tag{1}$$

where n denotes the all-cause or cause-specific health endpoint, ΔM is the excess or avoided mortality or morbidity, y_0 is the baseline incidence rate, β is the C-R coefficient relating a one-unit change in $PM_{2.5}$ to the change in a given health endpoint, Δx is the change in $PM_{2.5}$ concentration, and P is the exposed population. Annual mean concentration is the standard metric for assessing health effects from chronic $PM_{2.5}$ exposure. In this study, Δx is defined as the change in annual mean fine dust in 2076-2095 under RCP2.6 or RCP8.5 relative to 1996-2015. In order to evaluate the health impacts due to future changes in fine dust alone and by the combined effects of future changes in fine dust, population, and baseline incidence rates, we calculate ΔM using two different assumptions for each RCP scenario: (1) holding population and baseline incidence rates at the present-day level; and (2) using 2095 population and baseline incidence rates. We also estimate the premature mortality and morbidity due to present-day levels of annual mean fine dust relative to zero concentrations as a benchmark against which future excess mortality or morbidity can be compared. The 95% confidence intervals reported are derived using low, central, and high estimates for each RR value. The health endpoints assessed in this study are (1) total all-cause mortality and two subgroups (cardiopulmonary disease and lung cancer), and (2) hospitalizations due to cardiovascular and respiratory disorders. Table S3 summarizes the health endpoints, epidemiological studies, and risk estimates used in this study. Final present-day and future baseline incidence rates are shown in Table S4. Final population estimates are shown in Table S5.

RESULTS

Present-day sensitivity of fine dust to regional hydroclimate on interannual timescales

EOF analysis reveals that from 2000 to 2015, the most dominant mode of variability (EOF1) in monthly mean fine dust anomalies for each of the four seasons captures 40-53% of the total interannual variance and consists of a pattern of in-phase co-variability across almost all of the 35 IMPROVE monitoring sites in Arizona, Colorado, New Mexico, and Utah (Figure 1, top row). This pattern is indicative of large-scale influence by controlling factors and/or source emissions. The principal component time series associated with each EOF1 (PC1) is significantly negatively correlated, to varying extents, to the 1, 2, 3, 6, and 12-month SPEI in local and surrounding areas spanning northern Mexico, southern California, and southern Great Plains. These areas partially encompass the Great Basin, Mohave, Sonoran, and Chihuahuan Deserts. The correlation maps between fine dust PC1 and SPEI02 are shown in Figure 1 (middle Row); Figure S2 displays the same for SPEI calculated on the other timescales. Less extensive negative correlations are found for the 24-month SPEI for all seasons except DJF; 48-month SPEI shows correlations with fine dust for JJA only (not shown). Short time scales of the SPEI (1-6 months) are mainly related to soil water content, medium time scales to reservoir storage, and longer time-scales to groundwater storage [61,62].

In addition, for all seasons, PC1 is significantly positively correlated to anomalies in the 500 mb geopotential heights positioned over the west coast of California and northern Mexico (Figure 1, bottom row). These results indicate that years with higher-than-average fine dust concentrations across the Southwest are associated with regional drought conditions, which in turn are driven by large-scale anticyclonic atmospheric circulations in the mid-troposphere that can block or reduce moisture transport from the Pacific Ocean and/or the Gulf of Mexico. Our results are consistent with previous findings that have found associations between droughts in western North America and persistent blocking highs, which influence temperature, precipitation, and storm tracks [63–65]. In addition, Pu and Ginoux [66] found that summertime dusty days in the central Great Plains are associated with a westward extension of the North Atlantic subtropical high that intensifies surface wind speed and creates anomalous subsidence. While PC1 displays significant and extensive correlations with SPEI and other hydroclimate variables (precipitation, potential evaporation, and relative humidity; Figure S3), we find no significant correlations with surface vegetation or wind speed.

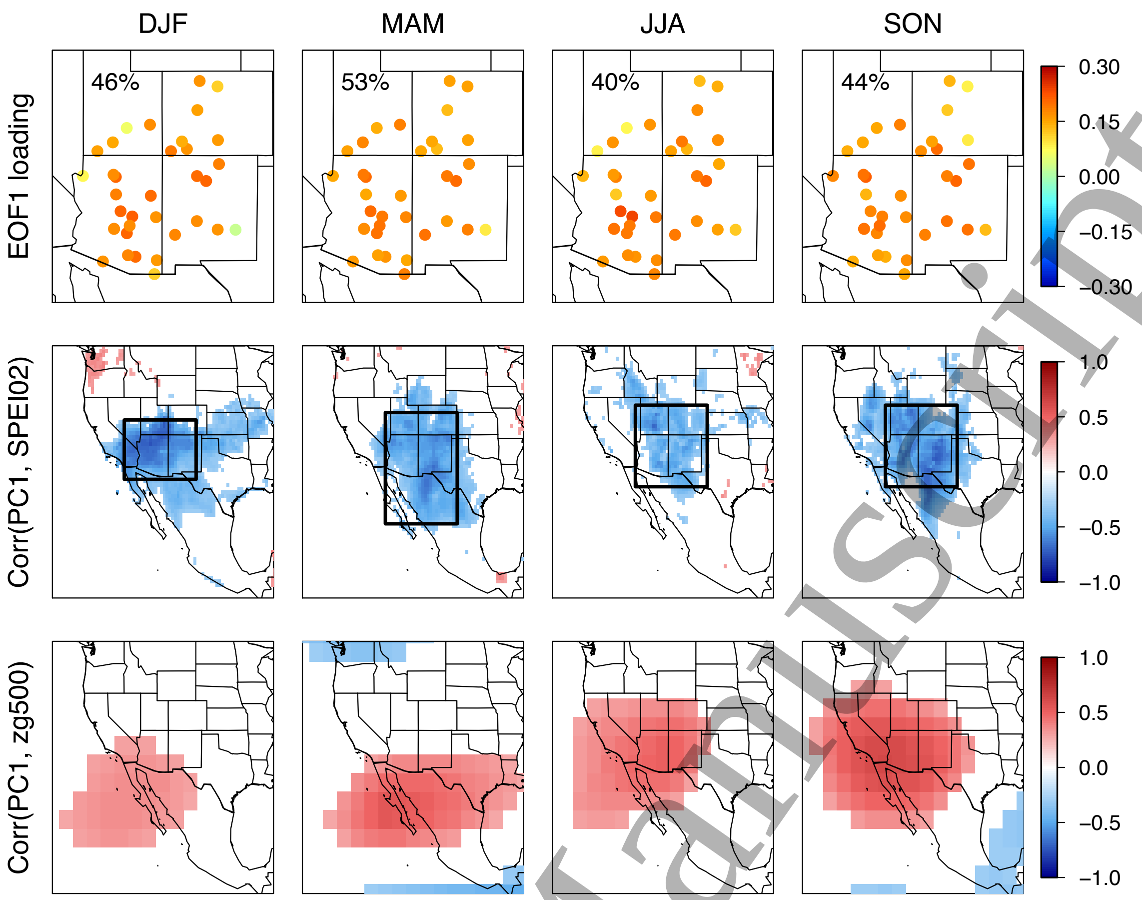

Figure 1. Relationships between detrended and deseasonalized monthly mean fine dust, the 2-month Standardized Precipitation-Evapotranspiration Index (SPEI02), and 500 mb geopotential heights for different seasons from 2000 to 2015. Top row panels: The 1st EOF (EOF1) loadings of standardized anomalies of fine dust concentrations measured at IMPROVE sites located in the southwestern United States (31°-41°N, 115°-103°W). The percentage of total variance explained by each EOF1 is displayed inset. Middle row panels: The heterogeneous correlation maps between the time series of the principal components of the 1st EOF mode (PC1) and SPEI02 anomalies. SPEI02 is representative of soil moisture. Black boxes outline the domain used to calculate regional mean SPEI02 in subsequent analyses. Bottom row panels: The heterogeneous correlation maps between PC1 and 500 mb geopotential height anomalies. In the middle- and bottom-row panels, only those grid cells with statistically significant correlations ($p < 0.05$) are shown.

In sum, we find that during each season, fine dust anomalies co-vary across almost all sites in the Southwest domain and that these anomalies show spatially extensive correlations with 1-6 month SPEI anomalies. These findings allow us to derive linear sensitivities of fine dust to drought conditions using regional and seasonal averages. Because SPEI02 displays the most spatially extensive and strongest correlations across all seasons, we focus on SPEI02 in subsequent analyses. The SPEI accumulated over short timescales (1-6 months) is often used as a proxy for soil moisture [62,67]. Comparing SPEI02 to a record of 2000-2014 monthly mean soil moisture measured at two sites located in Arizona and New Mexico from the Soil

Climate Analysis Network (SCAN), we find significant correlations between SPEI02 and observed soil moisture at 5, 10, and 20 cm depths ($r = 0.40\text{-}0.59$; Figure S4). The domains over which the strongest correlations between PC1 and SPEI02 are observed for different seasons are all within the region of 25°-41°N and 117°-102°W, and spans the U.S. Southwest and northern Mexico (hereafter "SWM"; outlined by black boxes in Figure 1, middle row). Using simple linear regression, we find that a unit decrease in SPEI02 is significantly associated with increases of 0.22-0.43 $\mu g\ m^{-3}$ in seasonal mean fine dust, depending on the season. These regression fits capture 39-71% of the interannual variability in seasonal mean fine dust anomalies (Table 1 and Figure S5).

Table 1. Sensitivity of seasonal mean fine dust (FD) to SPEI02 anomalies. Fine dust anomalies are averaged over the Southwest domain (units of $\mu g\ m^{-3}$); SPEI02 anomalies are averaged over different domains within 25°-41°N and 117°-102°W for each season (see Figure 1). The 95% confidence interval (CI) of the slope value is calculated by bootstrap resampling.

Season	**Linear Regression fit**	**95% CI of slope**	R^2
DJF	FD = -0.22×SPEI02	-0.12, -0.33	0.71
MAM	FD = -0.43×SPEI02 – 0.01	-0.28, -0.61	0.67
JJA	FD = -0.39×SPEI02	-0.18, -0.76	0.39
SON	FD = -0.24×SPEI02	-0.13, -0.35	0.55

Multi-model ensemble projections of fine dust changes associated with drought conditions in the late-21st century

In the present-day, seasonal mean SPEI02 averaged over the SWM domain are -0.12 (DJF), -0.15 (MAM), -0.05 (JJA), and 0.09 (SON). Under RCP2.6, the projected multi-model mean decreases are -0.21 (DJF), -0.18 (MAM), -0.26 (JJA), and -0.17 (SON), with 5-8 models predicting significant decreases, depending on the season. Under RCP8.5, the projected multi-model mean decreases are -0.67 (DJF), -1.15 (MAM), -1.41 (JJA), and -0.87 (SON), with 17-22 models predicting significant decrease, depending on the season. These estimates indicate that the spring and summer seasons will experience long-term, anomalous "moderately dry" conditions according to the drought classification of SPEI values (Table S1). For all seasons under both RCP scenarios, the multi-model mean changes in SPEI02 are significantly different from zero (Figure S6). We find that future changes in the land surface water balance in southwestern regions are mainly driven by changes in surface temperature rather than precipitation (Figures S7-S8), which is consistent with previous studies [15,68].

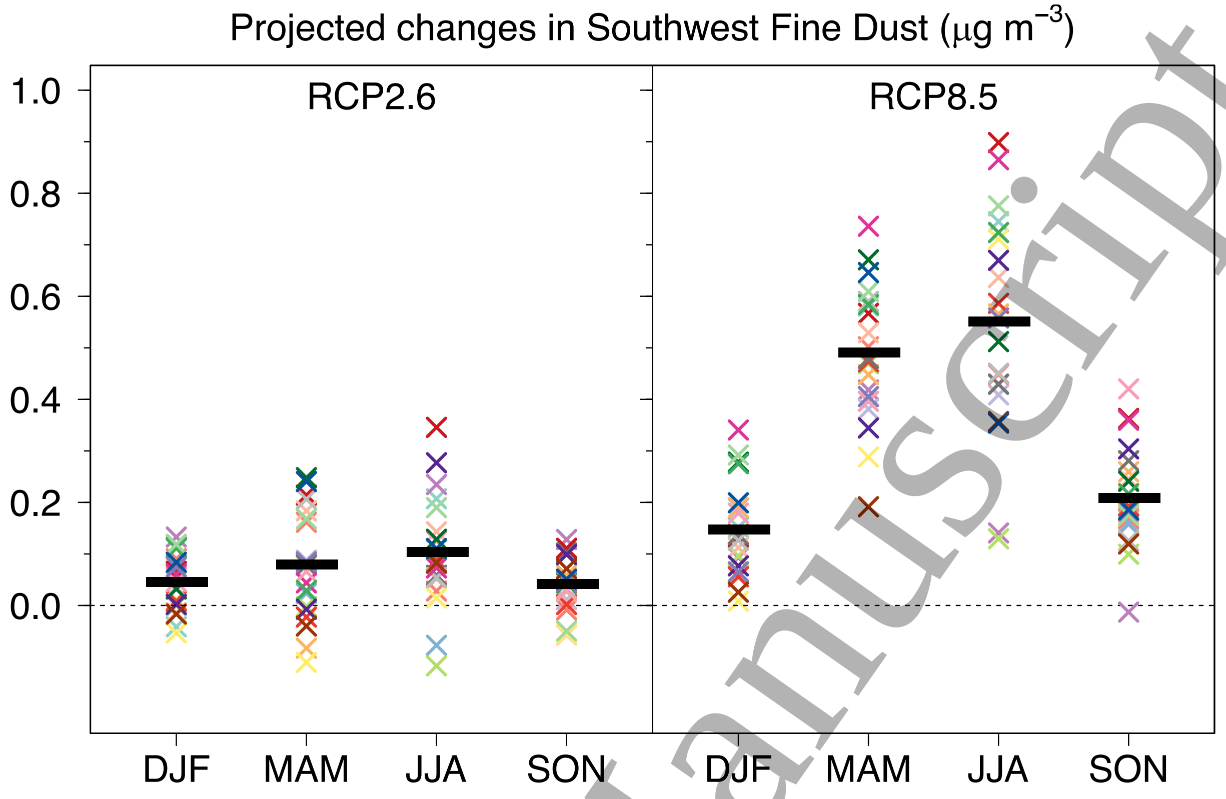

Figure 2. Projected changes in future (2076-2095) seasonal mean fine dust averaged over the Southwest relative to the present day (1996-2015) under RCP2.6 and RCP8.5 scenarios due to changes in the drought index, SPEI02. Different colored symbols denote results from different CMIP5 models, and the thick horizontal black lines show the multi-model means. The multi-model mean values for each season and scenario are all statistically significant, as determined by a Student's t-test ($p < 0.05$).

We project future drought-driven changes in seasonal mean fine dust assuming that the empirically-derived linear relationships between Southwest fine dust and SWM SPEI02 in the present-day remain the same in the future. Results are shown in Figure 2 and Table 2. Depending on the season, we estimate increases in Southwest fine dust of 0.04 to 0.10 $\mu g\ m^{-3}$ under RCP2.6 and 0.15 to 0.55 $\mu g\ m^{-3}$ under RCP8.5. For all seasons under both RCP scenarios, the multi-model mean changes in fine dust are significantly different from zero. For both scenarios, the largest increases occur in spring and summer during which Southwest fine dust concentrations are highest in the present-day. Compared to present-day observed fine dust concentrations, these values represent relative increases of 5-8% for RCP2.6 and 26-46% for RCP8.5 across the four seasons.

Table 2. Present-day (2000-2015) observations of and ensemble projections of future (2076-2095) changes in seasonal and annual mean fine dust (FD) concentrations averaged over the U.S. Southwest. Values in parentheses show percentage increases relative to present-day values.

Season	Present-day FD ($\mu g\ m^{-3}$)[a]	ΔFD ($\mu g\ m^{-3}$) RCP2.6[b]	ΔFD ($\mu g\ m^{-3}$) RCP8.5[b]
DJF	0.56 ± 0.17	0.04 ± 0.05 (7%)	0.15 ± 0.09 (27%)
MAM	1.51 ± 0.30	0.08 ± 0.10 (5%)	0.49 ± 0.13 (32%)
JJA	1.19 ± 0.22	0.10 ± 0.11 (8%)	0.55 ± 0.21 (46%)
SON	0.80 ± 0.18	0.04 ± 0.05 (5%)	0.21 ± 0.10 (26%)
Annual	1.02 ± 0.22	0.07 ± 0.04 (7%)	0.35 ± 0.07 (34%)

[a] Values are shown as $\bar{u} \pm \sigma$, where $\bar{u}$ is the long-term average and σ is the corresponding standard deviation.
[b] Values are shown as the multi-model mean changes in $\bar{u}$ ± the standard deviation of the ensemble projections. These changes are calculated from changes in modeled SPEI02 values in the future relative to the present-day.

Estimates of public health impacts due to projected changes in fine dust

From the projected seasonal mean changes in fine dust, we calculate annual mean changes of 0.07 $\mu g\ m^{-3}$ under RCP2.6 and 0.35 $\mu g\ m^{-3}$ under RCP8.5. Table 3 shows the number of excess premature mortality (all-cause, cardiopulmonary, and lung cancer) and morbidity (cardiovascular and respiratory) due to the projected changes in annual mean fine dust for the U.S. Southwest population per year. In Estimate #1, for which the population and baseline incidence rates are held at present-day values, the predicted excess all-cause premature mortality rates for adults aged ≥30 years are 39 (95% CI: 26-51) deaths y^{-1} under RCP2.6 and 200 (140-270) deaths y^{-1} under RCP8.5. Cardiopulmonary-related deaths constitute a large fraction of all-cause premature mortality. In terms of total excess hospitalization rates due to cardiovascular and respiratory illnesses for adults aged ≥65 years, we predict 20 (12-26) admissions y^{-1} under RCP2.6 and 100 (64-140) admissions y^{-1} under RCP8.5.

In Estimate #2, we consider the combined effects of future changes in fine dust, population, and baseline incidence rates. The resulting excess all-cause premature mortality rates are 140 (96-190) deaths y^{-1} under RCP2.6 and 750 (500-980) deaths y^{-1} under RCP8.5. The excess hospitalization rates are 170 (110-140) admissions y^{-1} under RCP2.6 and 860 (550-1,200) admissions y^{-1} under RCP8.5. The larger excess in estimate #2 for all health endpoints are primarily driven by projected increases in population and baseline incidence rates. Age-standardized baseline incidence rates are projected to increase by 170-230%, primarily driven by increases in the fraction of the total population of older age groups (Tables S5-S7). The U.S. Southwest population is projected to increase by 180% for adults aged ≥30 years and by 380% for adults aged ≥65 years. Compared to present-day observed fine dust concentrations, the annual mean values increase by 7% under RCP2.6 and by 34% under RCP8.5 (Table 2).

Table 3. Estimates of present-day (1996-2015) and future (2076-2095) premature mortality and morbidity per year due to annual mean fine dust concentrations in the southwest United States. The present-day burden is quantified relative to zero concentrations. The future excess burdens are due to projected changes in annual mean fine dust under RCP2.6 and RCP8.5 scenarios relative to the present-day and are calculated using two different assumptions. For estimate #1, we hold population and baseline incidence rates at present-day levels; for estimate #2, we use 2095 population and baseline incidence rates. The values shown are multi-model mean estimates with 95% confidence intervals in parenthesis, with the uncertainties due to the relative risks. All numbers are rounded to two significant figures.

	Health endpoint	**Present-day burden**	**Estimate #1 of excess burden**		**Estimate #2 of excess burden**	
			RCP2.6	**RCP8.5**	**RCP2.6**	**RCP8.5**
Premature mortality (Adults aged ≥30 years, y^{-1})	All-cause	590 (400–780)	39 (26–51)	200 (140–270)	140 (96–190)	750 (500–980)
	Cardiopulmonary	480 (370–580)	31 (25–38)	160 (130–200)	130 (98–150)	660 (510–800)
	Lung Cancer	69 (31–110)	5 (2–7)	24 (11–37)	14 (6–21)	71 (32–110)
Hospital Admissions (Adults aged ≥65 years, y^{-1})	All cardiovascular	160 (110–210)	11 (7–14)	56 (38–74)	94 (65–120)	490 (340–650)
	All respiratory	130 (74–180)	9 (5–12)	45 (26–63)	71 (41–100)	370 (210–520)

In all instances, the magnitude of excess premature mortality or morbidity is ~5 times greater under RCP8.5 relative to RCP2.6. For context, Table 3 also provides estimates of the premature mortality and morbidity due to present-day levels of annual mean fine dust relative to zero concentrations. Compared to the present-day, projected changes in fine dust alone could lead to annual all-cause mortality and total morbidity to each increase by ~7% under RCP2.6 and ~30% under RCP8.5. Combined with future growths in population and baseline incidence rates, the annual all-cause premature mortality attributable to fine dust could potentially increase by ~20% under RCP2.6 and ~130% under RCP8.5, and annual morbidity could increase by ~60% under RCP2.6 and ~300% under RCP8.5.

DISCUSSION AND CONCLUSIONS

This study quantifies the impacts of hydroclimate changes on airborne fine dust pollution and public health risks in the U.S. Southwest during the late-21st century (2076-2095) under two climate change regimes. We demonstrate that the 2000-2015 interannual variability of monthly mean fine dust concentrations across the southwestern United States is influenced by drought conditions in local and surrounding areas, including large regions of the four North American deserts. Based on empirically-derived relationships between fine dust and the 2-month Standardized Precipitation Evapotranspiration Index (SPEI02) anomalies, we project future drought-driven increases in seasonal mean fine dust of 0.04-0.10 μg m^{-3} (5-8%) under RCP2.6 and 0.15-0.55 μg m^{-3} (26-46%) under RCP8.5. The largest absolute increases coincide with the seasons during which fine dust concentrations are highest in the present-day (spring and summer). Taking future population and baseline incidence rates into account, these increases in fine dust could lead to 140 (24%, RCP2.6) or 750 (130%, RCP8.5) excess all-cause premature deaths each year for adults aged ≥30 years in the Southwest, and 170 (59%, RCP2.6) or 860 (300%, RCP8.5) excess hospital admissions due to cardiovascular and respiratory illnesses each year for adults aged ≥65 years, relative to the present-day. Our results further suggest that the incidence of dust-borne diseases such as Valley Fever could also increase in the U.S. Southwest. Despite the spread of model projections in future changes in precipitation, averaging results across the CMIP5 ensemble reveals a robust increase in temperature and subsequent decrease in soil moisture in response to increasing greenhouse gases, giving us confidence in our main results.

The negative correlations between fine dust and SPEI02 observed in this study are consistent with numerous wind tunnel experiments and observational studies that have examined the effects of soil moisture on wind erosion, demonstrating that the threshold wind speed increases with soil moisture [69–71]. Moreover, the drying of surface water bodies has been linked to increased dust emissions in many locations globally [72,73]. Many local-scale studies in the U.S. Southwest have reported the influence of antecedent precipitation, temperature, and/or soil moisture on wind erosion through controlling vegetation cover and soil stability [74–77]. These physical mechanisms linking soil moisture to dust emissions give us confidence in assuming that this relationship will remain valid in the future.

Using observed correlations between present-day $PM_{2.5}$ and local drought severity (derived from the 1-month SPEI), Wang et al. [42] estimated an increase of 0.25 μg m^{-3} (RCP2.6) and 1.0 μg m^{-3} (RCP8.5) in total $PM_{2.5}$ levels during March-October in the western United States in 2100 relative to 2000 due to the effects of droughts alone. Our work extends the study of Wang et al. by: (1) focusing solely on fine dust in the Southwest; (2) considering the effects of water balance deficits on different timescales and thus in different hydrologic sub-systems; (3) considering not just local but also regional-scale influences of droughts; and (4) quantifying the potential health impacts of drought-driven changes in fine dust for the U.S.

Southwest population. Our results are consistent with those of Wang et al., and further demonstrate that fine dust is strongly sensitive to local and regional drought conditions in various hydrologic sub-systems, especially to soil moisture. Using model output from the ACCMIP ensemble and projections of future population and baseline mortality rates, Silva et al. [78] estimated that in the U.S., $PM_{2.5}$-related premature mortality attributable to climate change under RCP8.5 will increase by 19,400 deaths y^{-1} in 2100 relative to 2000, with the majority of increases occurring over the eastern United States. Our results and those of Wang et al., who showed that some of the ACCMIP models cannot capture the observed responses of $PM_{2.5}$ to drought, suggest that climate change penalties on soil-derived $PM_{2.5}$ may be underestimated in such projections derived from the ACCMIP ensemble.

Our results appear to differ with those from the recent study by Pu and Ginoux [43], who estimated changes in 2051-2100 seasonal dust event frequencies in the U.S., using a multiple linear regression model and projected changes of precipitation, surface bareness, and surface wind speed from 16 CMIP5 models (13 of which are also used in this study) under RCP8.5. The authors projected no change in JJA and SON dust event frequency over their western U.S. domain, and a 2% decrease in DJF and MAM primarily driven by reductions in surface bareness in the future. There are several possible reasons for the discrepancies in our results. First, we focus on fine dust concentrations (derived from ground-based measurements), while Pu and Ginoux studied extreme dust events (derived from satellite observations). Second, we focus on the effects of droughts alone, as we do not find significant correlations between seasonal mean fine dust anomalies and surface wind speed or vegetation on interannual timescales. Third, Pu and Ginoux considered only local changes in controlling factors, while we consider the influence of soil moisture across a large region, including northern Mexico. Fourth, unlike these authors, we use the bias-corrected and spatially-disaggregated CMIP5 Climate and Hydrology Projections, as the coarse-grid CMIP5 models cannot reproduce the mean and standard deviation of monthly mean surface temperature and total precipitation averaged over the Southwest for 1996-2015 (Figure S1). Finally, the reliance of Pu and Ginoux on surface bareness as an explanatory variable in their regression model meant that only a small fraction of grid cells in their western U.S. domain could be included in their analysis. This scant spatial coverage arose because surface bareness was derived from sparse measurements of remotely-sensed leaf area index. In contrast, our study domain spans Arizona, New Mexico, and much of Colorado and Utah.

There are several limitations and caveats in this study. First, long-term and spatially extensive measurements of soil-derived $PM_{2.5}$ are not available, so here we use $PM_{2.5}$-Iron as a fine dust proxy. Second, it remains unclear how the ENSO and PDO – known to affect hydroclimate in southwestern North America – will respond under future climate change [48,79,80]. Third, we have not considered the climate feedback effect of dust aerosols, which could potentially lead to increased precipitation from the summertime southwestern North American monsoon [81]. Fourth, we approximate the future health impacts of fine dust using results from epidemiological studies based on total $PM_{2.5}$ and for the range of present-day concentrations. The relative risks of premature mortality due to fine dust exposure may be even greater under lower concentrations of anthropogenic $PM_{2.5}$ emissions in the future [82]. In addition, our reliance on annual mean concentrations may not fully capture the health impacts from extreme dust events, though it remains inconclusive whether the frequency and/or intensity of such events will increase in the future.

Previous observational studies investigating the climate impacts on dust activity in the western U.S. have focused on grid-specific changes in meteorology [42,43]. Our results demonstrate the importance of also considering regional changes, especially over active dust source regions. Additionally, our findings highlight the need to better constrain both the potential climate change penalty due to dust emissions and the specific health impacts of acute and chronic exposure to fine dust in the southwestern United States and other populated arid regions vulnerable to climate change. Despite several uncertainties and limitations, our results suggest that future droughts driven by climate change could lead to enhanced fine dust levels, posing a potentially substantial public health burden in the U.S. Southwest, especially under the worst-case climate change scenario.

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